Case No. 84739

IN THE SUPREME COURT OF THE STATE OF NEVADA

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ADAM SULLIVAN, P.E., NEVADA STATE ENGINEER, et al.

Appellants,

vs.

LINCOLN COUNTY WATER DISTRICT, et al.

JOINT APPENDIX

VOLUME 8 OF 49

Test Impacts and Availability of Water Pursuant to Applications Pending Under Order 1169

Presentation to the Office of the Nevada State Engineer

U.S. Fish and Wildlife Service
Bureau of Land Management
National Park Service

June 28, 2013

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Summary of Analyses and Conclusions from the Order 1169 Pumping Study/Test

Summary of Analyses

In 2002, the Nevada State Engineer issued Order 1169, which stated that all pending and new water right applications in the carbonate-rock aquifer in Coyote Spring Valley (Basin 210), Black Mountains Area (Basin 215), Garnet Valley (Basin 216), Hidden Valley (Basin 217), the Muddy River Springs Area, a.k.a. Upper Moapa Valley (Basin 219), and Lower Moapa Valley (Basin 220) would be held in abeyance pending further study (NSE, 2002a). California Wash (Basin 218) was later added to the list through Ruling 5115 (NSE, 2002b). The applications were held in abeyance because the State Engineer believed he needed more information on the effects of groundwater pumping from the carbonate-rock aquifer before making a determination on pending water right applications in the listed basins. The order called for a study covering a *"5-year minimum period of time during which at least 50% of the water rights then currently permitted in the Coyote Spring Valley groundwater basin are pumped for at least two consecutive years."*

The study/pumping test was delayed due to permitting issues and officially started several years later on November 15, 2010. Carbonate pumping in Coyote Spring Valley (CSV), which began in 2006 and averaged about 2,000 acre-feet per year (afy) from 2006 to 2009, more than doubled to 5,400 afy during the pumping test from November 15, 2010 to December 31, 2012. Groundwater pumping in adjacent basins remained relatively constant during the period of the pumping test. The volume of pumping in CSV during the test was approximately one-third of the groundwater rights currently permitted in the basin. The State Engineer declared in an amendment to Order 1169 (NSE, 2012e) that the test was completed on December 31, 2012, saying he believed that sufficient information had been obtained from the test and related monitoring to make a determination on the pending water right applications. However, while the pumping test ended, the pumping in CSV has continued, to date, at approximately the same rate as during the test. In the amended Order, the State Engineer invited study participants to file a report interpreting the monitoring results and the information from the Order 1169 test.

The U.S. Fish and Wildlife Service, National Park Service, and Bureau of Land Management have prepared this report in response to the State Engineer's request for information related to the pumping test. The report uses the monitoring data collected within the Study Area (**Figure S-1**) to address the three questions posed by the Nevada State Engineer in Order 1169A (NSE, 2012e):

- What information was obtained from the pumping study/test?
- What were the impacts of pumping under the pumping test?
- What is the availability of water pursuant to the pending applications?

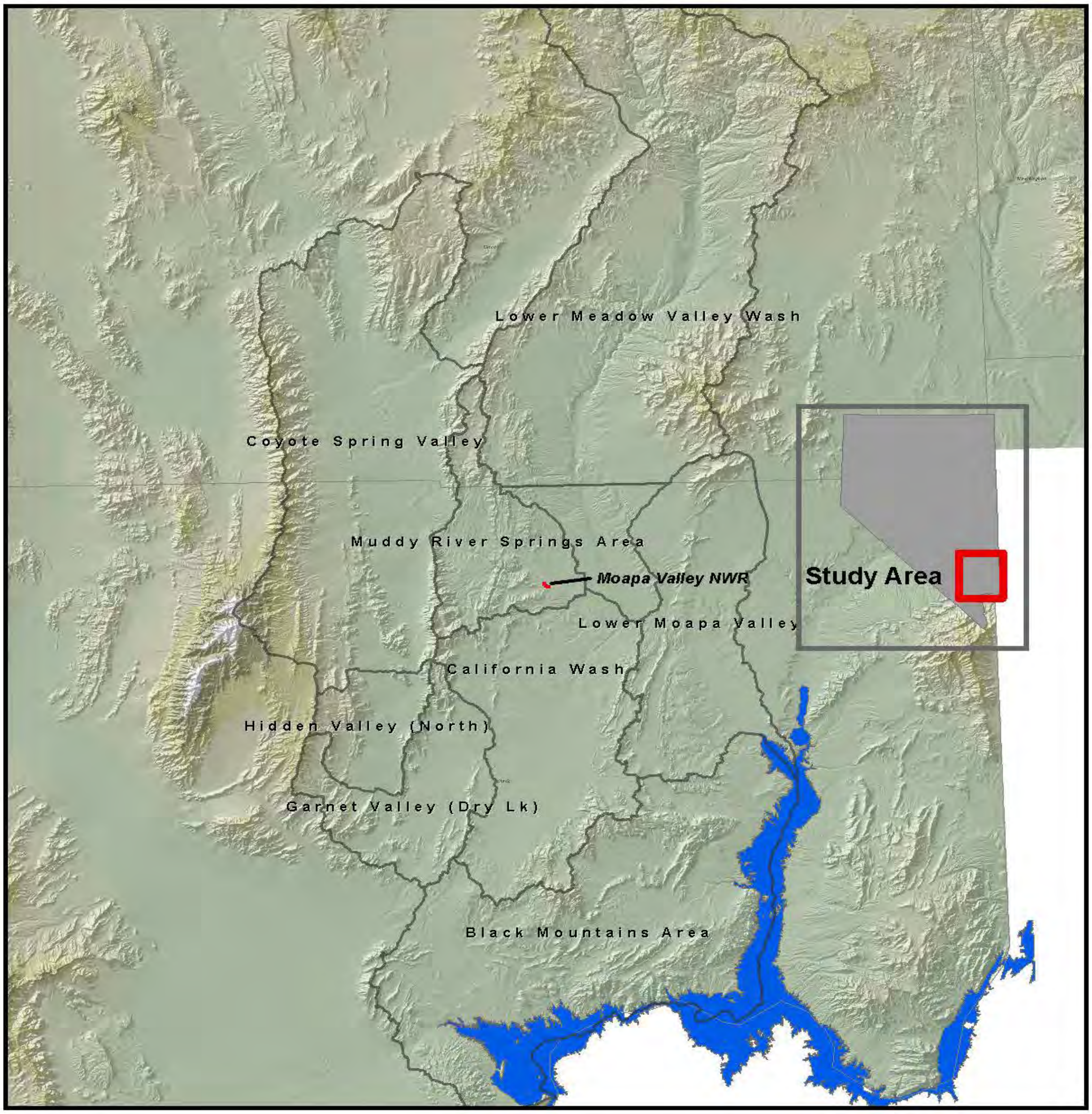

Figure S-1. The Study Area is defined as the area in which hydrologic data (groundwater level, production, and spring/stream discharge measurements/estimates) were collected as part of the 2-year pumping test/study conducted in response to Order 1169, specifically: Coyote Spring Valley (Basin 210), the Muddy River Springs Area (Basin 219), Hidden Valley (Basin 217), Garnet Valley (Basin 216), the Black Mountains Area (Basin 215), California Wash (Basin 218), Lower Moapa Valley (Basin 220), and Lower Meadow Valley Wash (Basin 205).

In this report, we analyze groundwater level, pumping, spring/stream discharge, and climatic data collected before and during the Order 1169 pumping test to address these three questions. In Section 1, we present a detailed evaluation of the impacts of pumping on groundwater levels and spring discharge. In Section 2, we present results from a numerical groundwater model that was used to evaluate impacts at future times and under varying pumping scenarios. We also use the model to evaluate the recovery of the system following curtailment of pumping. In Section 3, we address the central question of availability, given what was learned from the pumping test and previous water budget and perennial yield information. In Section 4 of the report, we briefly discuss the potential implications of decreased spring/stream discharge on groundwater-dependent resources, such as Moapa dace and the Moapa Valley National Wildlife Refuge (NWR). In the last section, we summarize our findings and conclusions.

Summary of Conclusions

What information was obtained from the pumping test?

Groundwater level, pumping, and spring/stream discharge data collected before and during the Order 1169 pumping test are sufficient to:

- Document the immediate effects of the test pumping, including pumping approximately one-third of existing permitted groundwater rights in CSV, on groundwater levels and spring/stream flows in the Study Area.
- Delineate a portion of the carbonate-rock aquifer, a subset of the Order 1169 Study Area, in which pumping results in roughly equal drawdown throughout the area in a relatively short period of time.
- Develop a conceptual model of the delineated portion of the carbonate-rock aquifer with significant implications for the impacts of carbonate pumping anywhere within the area on spring and stream flows and phreatophytic vegetation in the MRSA and California Wash.
- Estimate the extent to which pumping was captured from groundwater storage (a lowering of groundwater levels) as opposed to spring/stream discharge as of the end of the test, and consequently the degree to which the full impacts of the test on spring/stream flows and phreatophytic vegetation have been realized to date.
- Determine the availability of water pursuant to applications pending under Order 1169.

What were the impacts of pumping under the pumping test?

Based on our analyses of groundwater level data from the pumping test, we have delineated a portion of the carbonate-rock aquifer, consisting of five hydrologic basins within the Study Area, in which carbonate pumping results in drawdown of nearly uniform magnitude everywhere within the five basin area within a period of months. The delineated area encompasses almost 700,000 acres, or 1,100 square miles, and includes the following hydrographic basins: CSV, the MRSA, Hidden and Garnet valleys, and

California Wash. Drawdown during the pumping test ranged from 1.9 to 2.5 ft throughout this portion of the carbonate-rock aquifer, with over half of the drawdown attributable to MX-5 pumping in CSV. The observed declines in groundwater levels are unprecedented in the record.

The near uniformity and large areal extent of drawdown indicates a high degree of hydrologic connectivity throughout the five basins and suggests that carbonate pumping anywhere within these five basins will affect groundwater levels throughout the delineated area. We hypothesize that this portion of the carbonate-rock aquifer acts as a high-transmissivity (high-diffusivity) reservoir with fixed inflows. The potential for pumping to induce additional groundwater inflow into this portion of the carbonate-rock aquifer system is very limited. As a consequence, carbonate pumping would eventually capture the only major forms of natural groundwater discharge in the area – spring/stream discharge and ET in the MRSA and California Wash.

The drawdown observed, to date, has resulted in a small capture of spring discharge, and possibly ET, in the MRSA and California Wash. Almost all the springs and flow monitoring sites in the MRSA showed some level of decline during the pumping test. The degree to which spring discharges were impacted is a function of the land surface elevation of the springs, with the higher elevation springs showing the greater relative declines in discharge. The discharge at Pederson Spring, the highest elevation spring in the MRSA, declined about 63% during the pumping test. If the current rate of carbonate pumping and drawdown continues, this spring will be dry in another 1.5 years. The discharge at Pederson East Spring, the second highest elevation spring in the MRSA, declined about 45% during the test and will be dry in another 2.5 to 3 years, if the current rate of pumping and drawdown continues. Flows at Warm Spring West flume declined about 9% during the test. Relative changes in flows at other lower elevation springs and flow sites during the pumping test were -6% at Iverson Flume, -4% at both Jones Spring and Baldwin Spring, and +19% per year at Muddy Springs. The flow increase at Muddy Springs may be partially due to upstream effects from the July 2010 fire in the MRSA.

We estimate that 80 to 90% of groundwater withdrawn during the pumping test was captured from groundwater storage, with only a small fraction captured from natural groundwater discharge. We interpret this to mean that the system has not yet reached equilibrium with respect to the increased carbonate pumping imposed during the test. The potential for drawdown to induce more inflow into the area is very low because the increase in hydraulic gradient will be 1% or less. Therefore, all pumping from the carbonate-rock aquifer in this area must eventually capture the only forms of natural groundwater discharge in the area before a new state of equilibrium can be established. Consequently, we expect the longer-term impacts from the current level of pumping on spring discharge and ET rates in the MRSA and California Wash to be much greater as the system transitions from capture of groundwater storage to capture of groundwater discharge.

Although the pumping test has been completed, SNWA has chosen so far to continue the pumping at MX-5 in CSV at approximately the same rate, presumably to augment water supply for Las Vegas. It is not known how much longer this pumping will continue. Numerical pumping simulations performed by Tetra Tech (2012b) show that pumping in the carbonate-rock aquifer at the rates imposed during the test (or greater) can be expected to result in substantial additional declines in groundwater levels and spring and stream flows beyond those observed as of the end of the test. The results of the 'post-audit' simulation of the second year of the test suggest that the Tetra Tech Version 1.0 Model used to perform these pumping simulations (Tetra Tech, 2012a) underestimates the amount of drawdown created by pumping and the impacts to spring discharges, and overestimates the timeframes in which the projected impacts will occur, but the areal extent of drawdown is simulated accurately.

The recovery simulation, in which MX-5 pumping was simulated as being stopped as of the end of the test, suggests that recovery of water levels from the effects of MX-5 pumping would take years, and that in the MRSA, recovery from the MX-5 test pumping would be approximately 70% complete after 15 years. Longer periods or greater volumes of pumping will result in even slower recovery. This has some serious implications for the effectiveness of management strategies aimed at reducing or curtailing pumping in order to protect spring flows, biological resources, and downstream water rights.

While the pumping test yielded much information, there are some things that are still uncertain. The level of pumping in CSV during the test was only one-third of the annual volume allocated in CSV under existing water right permits, although the Order required that 50% of the existing permitted rights be pumped. Therefore, the impacts of pumping half or all of the permitted allocation in this basin were not evaluated. The effectiveness of pumping reductions or curtailment was simulated with the modeling but was not directly evaluated during the test. If the higher elevation springs stop flowing completely, it is not known how fast or how effectively the system will respond to adjustments in pumping and whether biological resources may be adversely affected in the process.

What is the availability of water pursuant to the pending applications?

Our review of earlier water budget and perennial yield information for CSV, as presented in Order 1169 (NSE, 2002a), leads to the conclusion that there is no water available for appropriation within the five-basin area delineated through our groundwater analyses (CSV, the MRSA, Hidden and Garnet valleys, and California Wash). The water budget information and pumping test results suggest that all available water in CSV is appropriated and our additional analysis of information in recent rulings suggests that the basin may currently be over-appropriated. Additionally, the groundwater modeling simulation results, which examined progressively greater pumping of pending water rights in these five basins, provide supporting evidence to the wide-ranging effects that can be expected in these five basins with increased pumping.

An average of 5,400 afy of groundwater was withdrawn in CSV over the period of the test. This is only one-third of the 16,300 afy of existing permitted rights to groundwater already appropriated in CSV. The pumping test provides evidence that even this reduced volume of groundwater pumping cannot be developed long-term without adverse impacts to springs, endangered fish, Federal trust resources, and downstream senior water rights. Consequently, we conclude that no additional groundwater is available for appropriation to satisfy the pending water right applications that are currently being held in abeyance for this portion of the carbonate-rock aquifer.

Section 1 - Impacts of Pumping under the Order 1169 Pumping Test

Impacts to Groundwater

In this section of the report, we analyze the impact of the Order 1169 pumping test on groundwater levels throughout the Study Area. Interpretations presented in this section focus largely on the analysis of groundwater level observations and production from the carbonate-rock aquifer.

Data Sources

Groundwater level and production data used in these analyses, including the source, frequency, period of record, monitoring agency or organization, and location and physical characteristics of wells utilized in these analyses are summarized in **Table A.1 (Appendix A)**. **Figure 1.1** shows the locations of these monitoring and production wells within the Study Area. Data interpreted in this section can be found on a data exchange Web site maintained by the Nevada State Engineer for the Order 1169 pumping test as of the time of this report (NDWR 2012).

Monthly precipitation data from Nevada Climate Division 4 (Extreme Southern Nevada) are used to represent precipitation in the Study Area. Nevada Climate Division 4 includes CSV and the MRSA (see appended data file: NV Climate Divisional 3_4 and PRISM pcp data 1985-2012.xlsx for maps). Mayer and Congdon (2008) found that 24-month moving average precipitation data from this division correlated best with carbonate water levels in the MRSA. Climate division data through 2012 are available at http://www.wrcc.dri.edu/spi/divplot2map.html. For comparison, we also examined monthly precipitation data from Nevada Climate Division 3 (South Central Nevada), which is north of the CSV-MRSA area, and monthly PRISM precipitation data, compiled for the area of the Moapa Valley NWR and for the entire White River Flow System. PRISM data are available at http://prism.oregonstate.edu/.

Summary of Analytical Methods

For the purposes of these analyses, we assume the pumping test started on September 15, 2010 and ended on December 31, 2012. The official start date of the test was November 15, 2010. However, significant pumping was initiated at carbonate production well MX-5 in CSV on September 15, 2010. While MX-5 pumping was discharged to Pahranagat Wash from September 15 through October 29, 2010, we see no evidence that this affected carbonate water levels in the area in any major way **(Figure A.2-1)**. Lastly, we informally refer to the test as a “2-year pumping test” in this section even though the test length actually exceeded two years by several months.

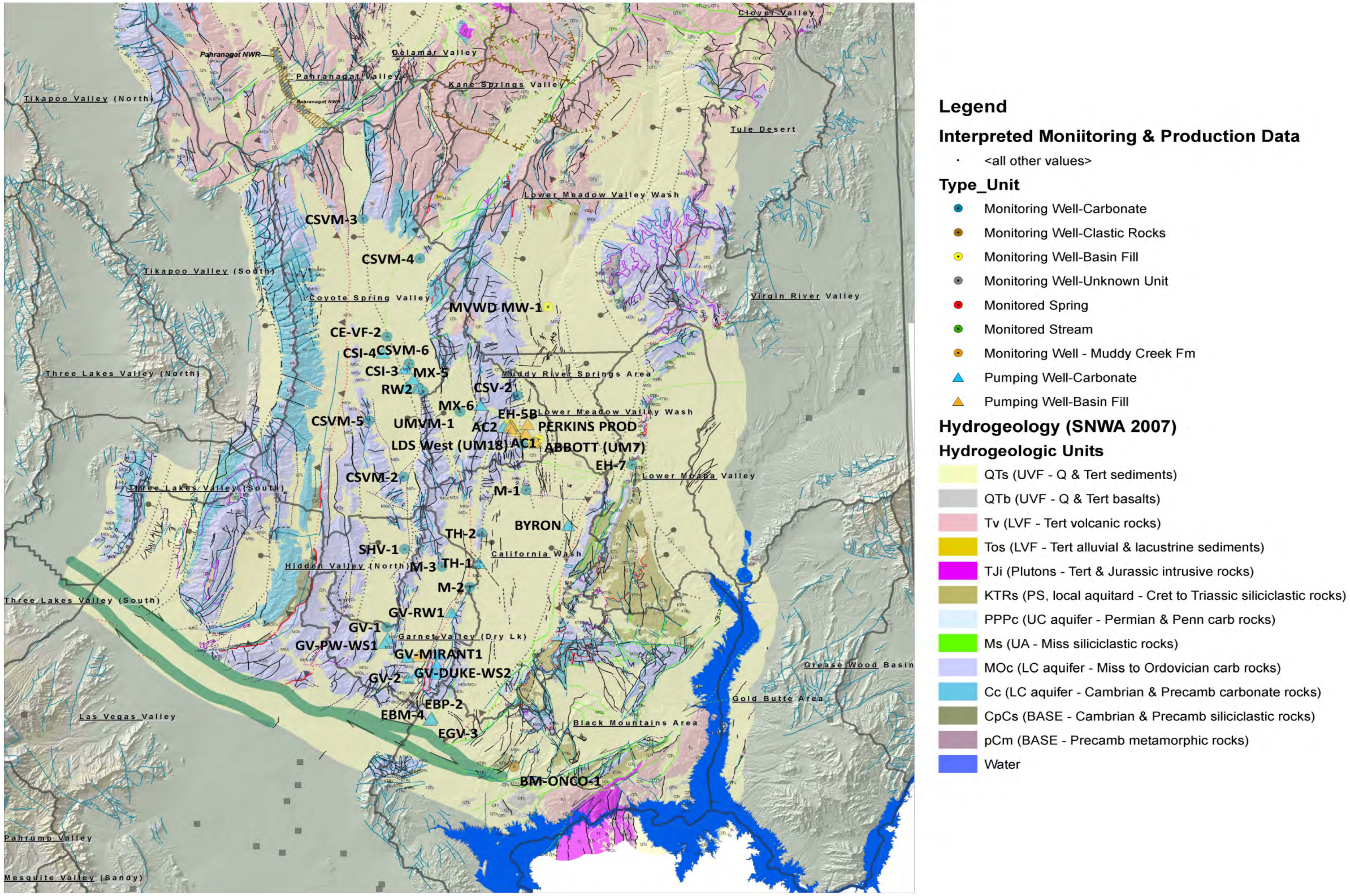

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Figure 1.1. Map showing the locations of monitoring and production wells utilized in analyses presented in this report (on a base map of surficial hydrogeology prepared by SNWA 2007a)

We computed water year (Oct-Sept) precipitation from 1987 to 2012 from the four sources of monthly precipitation referenced in the Data Sources section above: NV Climate Division 3 and 4 and PRISM data for two separate geographic areas. Water year was used rather than calendar year so as not to split the winter precipitation season arbitrarily. We primarily utilize NV Climate Division 4 data in subsequent analyses since it encompasses CSV and the MRSA, but also examine the other sources of precipitation data to emphasize the consistency in wet and dry years throughout the region.

Our evaluation of groundwater level and production data includes several different forms of analysis to evaluate the effects of the Order 1169 pumping test:

- time series hydrographs of groundwater levels, drawdown, and pumping for carbonate monitoring and production wells throughout the Study Area;
- multiple linear regression with time and terms that account for seasonality to determine the drawdown rate in EH-4 during the period of the pumping test.
- multiple linear regression of the average annual water level in EH-4 from 1987 to 2012 with water year precipitation and annual carbonate pumping in CSV and the MRSA.
- distance-drawdown hydrographs along two transects through the Study Area;
- SeriesSEE analyses of groundwater level data collected during and prior to the pumping test in a range of monitoring wells throughout the Study Area, accounting for all major pumping in the area;
- development of a conceptual model leading to identification of a portion of the carbonate-rock aquifer in which pumping causes water level declines of roughly equal magnitude throughout this part of the aquifer, depletion of the Muddy River Springs, and capture of other forms of natural discharge in the MRSA and California Wash; and
- an assessment of the extent to which the test pumping was captured from groundwater storage, as opposed to natural discharge (spring and stream discharge and evapotranspiration), as of the end of the test.

For the time series hydrographs and distance-drawdown hydrographs, drawdown was estimated as the change in groundwater elevation from the beginning to the end of the pumping test (9/15/2010 to 12/13/2012, the last date of available water level data for sites with periodic measurements). Because the SeriesSEE analyses interpret changes in groundwater levels during the test that are, in part, due to pumping that predated the test, this analysis evaluates drawdown over a longer period, 1/1/2008 to 12/13/2012.

No corrections have been made for changes in groundwater levels due to earth tides and fluctuations in barometric pressure in any of these analyses. We believe that these corrections, had they been made in estimating drawdown, would be on the order of a few tenths of a foot, the magnitude of corrections made to carbonate water levels in California Wash during a previous study (Waddell and Roemer, 2006). Likewise, no corrections have been made for longer-term (regional) trends in groundwater levels given continued uncertainties concerning the availability of a 'reference' well that can be used to make such corrections[1]. Additional information concerning methods employed to analyze groundwater level and production data are provided later in this section.

Results and Discussion

Table 1.1 summarizes average production rates and volumes from major production wells listed in **Table A.1** over the 2-year test period, pumping which influenced groundwater level and spring/stream discharge data collected during the test. The appended data file (Order_1169_Monthly_Pumpage data.xls) summarizes the historical carbonate and basin-fill pumping data from five basins in the Study Area (CSV, the MRSA, Garnet Valley, California Wash, and the Black Mountains Area) from 1987 to 2012. Basin-fill pumping in the MRSA has been ongoing for decades and has been relatively constant, averaging about 5,000 afy since 1987. Significant carbonate pumping first began in the Study Area in 1992 in the MRSA, averaging about 1,000 afy from 1992 to 1997. Carbonate pumping in the MRSA more than doubled in 1998, when pumping at the Arrow Canyon well began, and has averaged about 2,300 afy from 1998 to 2012. Carbonate pumping in CSV essentially began in 2006, averaging about 2,000 afy, and increased to more than 5,000 afy in 2010 with the start of the pumping test. There was 7,500 afy of combined carbonate pumping from CSV and the MRSA during the period of the pumping test, with 5,400 afy, or 70%, of this occurring in CSV. The 5,400 afy in CSV represents only about one-third of the total annual pumping rate currently appropriated through existing water right permits in CSV. Carbonate pumping in Garnet Valley has been ongoing since at least 2000, but at a fairly small rate. It averaged about 800 afy from 2000-2005 and about 1,200 afy from 2006-2012 and did not change substantially during or just before the pumping test. Carbonate pumping in California Wash has been very small, about 20 afy from 2009 to 2012, with no pumping prior to that. The total carbonate pumping during the test in CSV, the MRSA, Hidden and Garnet valleys, and California Wash was about 8,540 afy or 19,900 af in total.

The appended data file for precipitation data (NV Climate Divisional 3_4 and PRISM pcp data 1985-2012.xlsx) shows water year precipitation in both NV Climate Divisions as well as PRISM data for the area of the Moapa Valley NWR and the area of the White River Flow System. Data for all areas and sources are consistent in terms of wet and dry years (see the correlation matrix in the appended data file). All four data sources indicate that there was above average precipitation in water year 2011, which begins October 2010 and coincides with the start of the pumping test. Consequently, the first year of the pumping test was conducted during fairly wet conditions. We only present NV Climate Division 4 (Extreme Southern Nevada) precipitation data for the remainder of the report.

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[1] The HRT identified CSVM-3 as a potential reference well, however, our SeriesSEE analyses presented later in this section suggest that changes in groundwater levels in CSVM-3 since 2008 include the effects of MX-5 pumping, superimposed on the more pronounced effects of a reduction in pumping at carbonate production well CSI-3 in CSV, rather than a long-term (regional) trend.

Table 1.1. Average production rates from major (utility- and industrial-scale) production wells within the Order 1169 Study Area during the test (9/15/2010 to 12/31/2012).

Basin Name	Wells	Average Production Rate 9/15/10 - 12/31/12 (afy)	Total Volume of Pumping 9/15/10 - 12/31/12 (af)
CSV	**MX-5**	4,072	9,332
CSV	**MX-5, CSI-1, CSI-2, CSI-3, CSI-4**	5,383	12,325
Total MRSA (carbonate)	**MX-6, Arrow Canyon-1, Arrow Canyon-2**	2,094	4,800
Total CSV and MRSA (carbonate)		**7,477**	**17,125**
Central Garnet Valley	**GV-Migrant 1, GV-Duke-WS1 and -WS2, GV-PW-WS1, GV-RW1**	637	1,459
Southern Garnet Valley	**Chem-Lime Old, Chem-Lime New, Republic Wells 1, 2, 5, and 6**	558	1,278
Total Garnet Valley		**1,194**	**2,737**
California Wash	**TH-1, ECP-1, ECP-2, ECP-3**	23	52
Total CSV, MRSA (carbonate), Garnet, & CA Wash		**8,539**	**19,914**
Black Mountains Area	**All NV Cogen Carbonate Wells**	1,463	3,353
Total MRSA (basin-fill)	**All Nevada Energy Basin-Fill Wells**	3,649	8,363

Time Series Hydrographs of Groundwater Levels and Drawdown in the Carbonate-Rock Aquifer

Water level hydrographs are presented for carbonate monitoring wells EH-4, EH-5b, CSV-2, UMVM-1, CSVM-1, MX-4, and CSVM-6 in CSV and the MRSA (**Figures 1.2, 1.3, and A.2-2 to A.2-8**). We focus first on EH-4 and EH-5b, two carbonate monitoring wells located in the MRSA (**Figure 1.1**) that have some of the longest records of any of the carbonate monitoring wells in the Study Area. The water level records at these two wells reflect an annual seasonal cycle, long-term declines related primarily to the carbonate-rock aquifer pumping (**Figure 1.2**), and wet year responses in 1992, 1993, 2005, and, to a lesser degree, 1998 and 2011 (**Figure 1.3**). In contrast to the obvious wet year responses, there is no indication that dry years cause a comparable response in water levels. For example, the declining trend in water levels from 1998 to 2004 seems unaffected by water year 2002, which was extremely dry. Mayer and Congdon (2008) showed statistically that carbonate water level response to precipitation was asymmetric, with the groundwater system being much more responsive to wet years than dry years.

The seasonal cycle observed in the early part of the records of carbonate monitoring wells EH-4 and EH-5b (**Figure 1.2**) is likely related to evapotranspiration (ET) and/or basin-fill pumping, both of which are seasonal. Basin-fill pumping in the MRSA from 1987 to 1997 was fairly constant and averaged about 4,000 afy. There was very little carbonate pumping during this period. There was a slight decline in water levels in both EH-4 and EH-5b from 1987 to 1992 which may have been a response to basin-fill pumping. The increase in water levels in 1992 and 1993 was likely a response to wet years. Water levels were fairly stable from 1994 to 1997.

Increased carbonate pumping at the Arrow Canyon well in the MRSA, beginning in 1998, increased the seasonal variation and caused water levels in EH-4 and EH-5b to decline considerably from 1998 to 2004 (**Figure 1.2**). The Arrow Canyon pumping is also mainly seasonal and greatest in the summer. There is little evidence in the precipitation record that suggests the multi-year decline was a response to climate (**Figure 1.3**), as is discussed further in the multiple regression analysis below. The 1998 to 2004 declines were interrupted by the extreme wet year in 2005 but resumed again from 2006 to 2010. Increased carbonate pumping with the initiation of the pumping test in late 2010 caused the declines to accelerate significantly. The steepest decline in carbonate water levels occurred during the pumping test, specifically following the initiation of MX-5 pumping from the carbonate-rock aquifer in southern CSV at an annual-mean rate of 4,072 afy (**Table 1.1**). The annual rate of drawdown in EH-4 during the pumping test was 0.92 ft per year based on a multiple linear regression with time and seasonal effects (see appended data file: Order 1169 EH4 Data_NDWR_Dec 2012.xlsx).

The lowest carbonate water levels in the 25 years of record for both EH-4 and EH-5b occurred in December 2012, at the end of the pumping test. These unprecedented declines in carbonate water levels were accompanied by unprecedented declines in the discharge of the two highest-elevation warm springs in the Muddy River Springs Area, Pederson and Pederson East springs, as well as declines in the discharge at the Warm Springs West gage in the Moapa Valley National Wildlife Refuge (Moapa Valley NWR) (**Figures 1.4 and 1.5**). Impacts to spring discharges are analyzed and discussed further below.

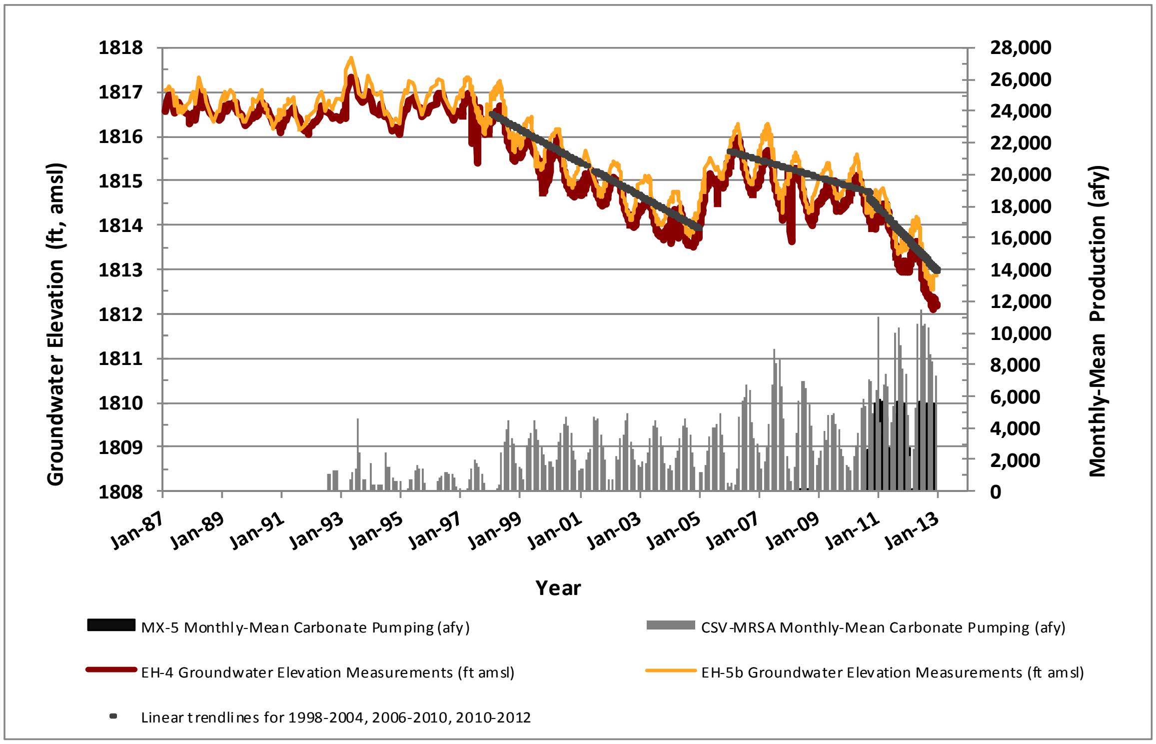

Figure 1.2. Groundwater elevations in carbonate monitoring wells EH-4 and EH-5b in the MRSA and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012. Linear trendlines are shown for 1998-2004, 2006-2010, and 2010-2012.

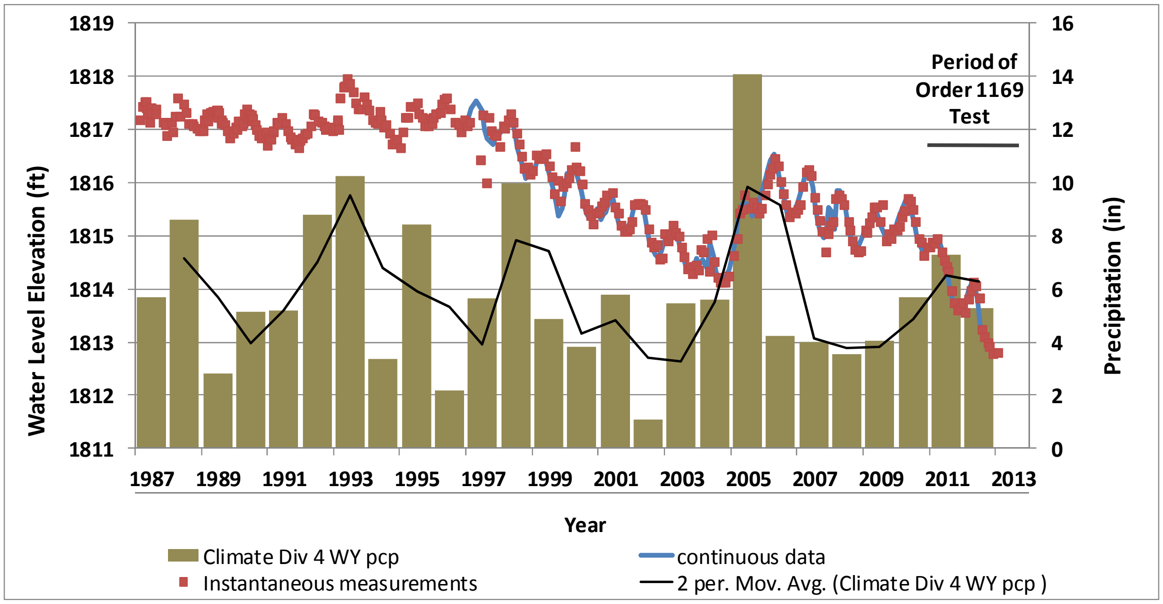

Figure 1.3. Groundwater elevations in carbonate monitoring well EH-4 in the MRSA and Nevada Climate Division 4 water year precipitation (centered on April of each water year) for the period 1987 to 2012. The black line shows the 2-year moving average of precipitation.

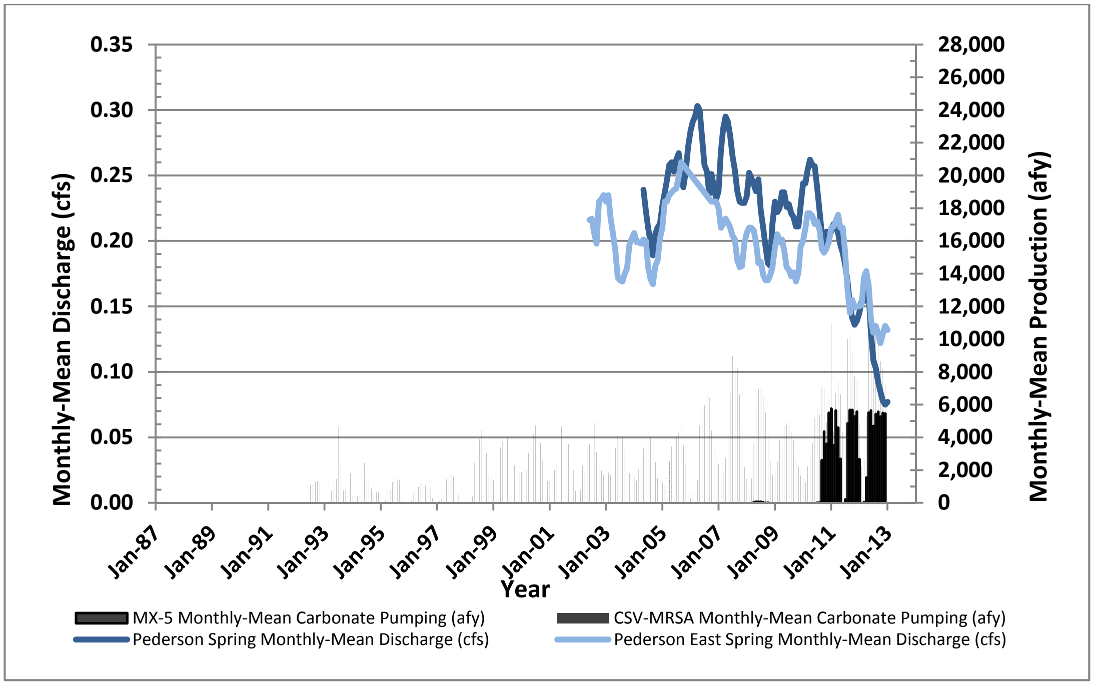

Figure 1.4. Monthly-mean discharge of Pederson and Pederson East springs in the MRSA (Moapa Valley National Wildlife Refuge), January 2004 to January 2013 and June 2002 to January 2013, respectively, and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1992 to 2012.

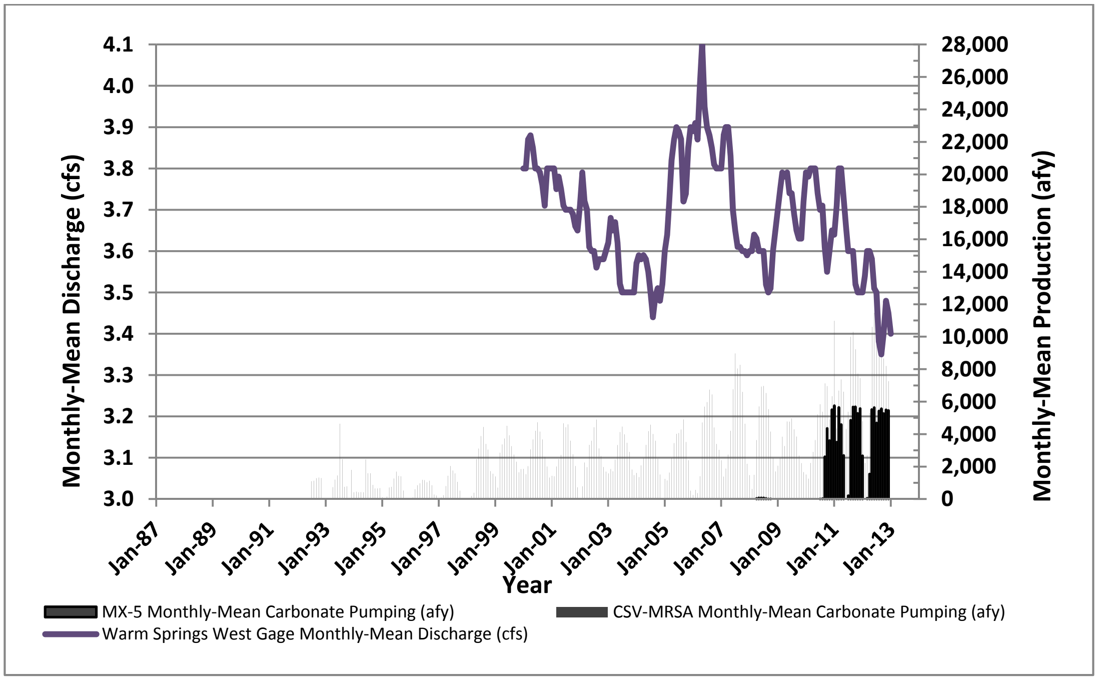

Figure 1.5. Monthly-mean discharge at the Warm Springs West gage on Pederson stream in the MRSA (Moapa Valley National Wildlife Refuge), January 2000 to January 2013, and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1992 to 2012.

Regression analysis demonstrates the influence of precipitation and carbonate pumping on carbonate water levels in the MRSA. A multiple linear regression with three explanatory variables: the square transform of 2-year moving average Climate Division 4 WY precipitation; annual carbonate pumping in the MRSA; and annual carbonate pumping in the CSV, explains 83% of the variance in average annual carbonate water levels in EH-4 from 1987 to 2012 (adjusted r^2=0.834, **Figure 1.6**). The regression coefficients are positive for precipitation (indicating increases in water levels with greater precipitation) and negative for the two carbonate pumping terms (indicating decreases in water levels with greater pumping). The value of the regression coefficient was slightly more negative for carbonate pumping in the MRSA than in CSV, which may indicate a slightly higher sensitivity of EH-4 water levels to carbonate pumping in the MRSA. Mayer and Congdon (2008) explored the influence of precipitation and pumping in greater detail.

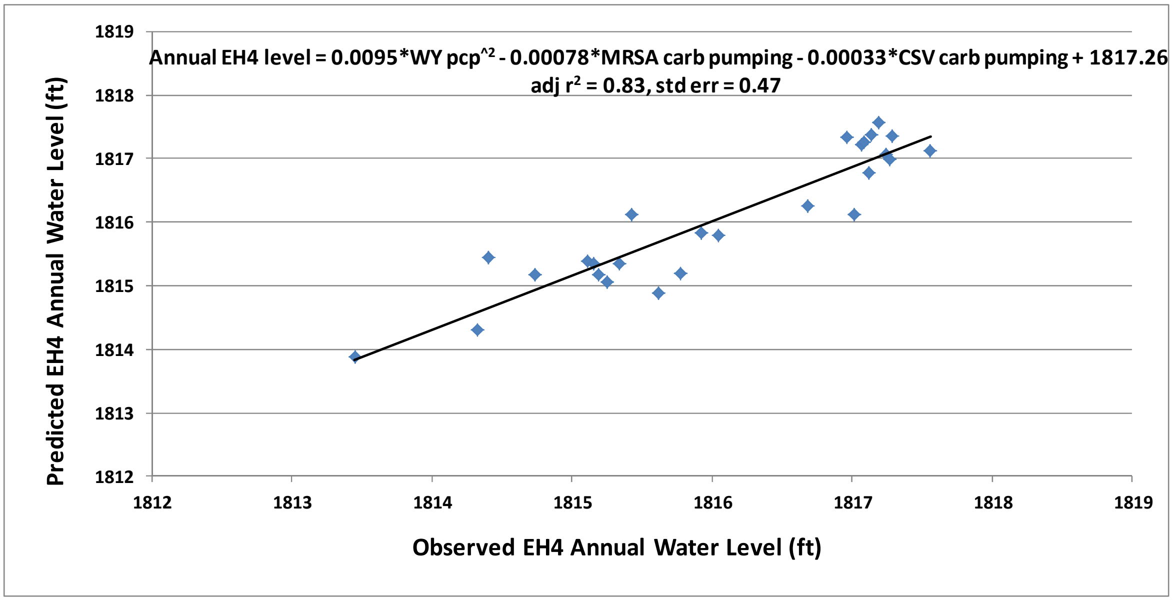

Figure 1.6. Predicted and observed annual average carbonate water levels in EH-4 for the period 1987 to 2012. The three explanatory variables are described in the text. Units are inches for precipitation, and acre-feet/year for pumping. The multiple regression explains 83% of the variance in annual water levels in EH-4.

While all three explanatory variables were statistically significant, the two carbonate pumping terms are much more important than the precipitation term in explaining variance in annual carbonate water levels. Without the precipitation term, the two carbonate pumping terms still explain 80% of the variance in annual EH-4 water levels. However, using the precipitation term only, without terms for carbonate pumping in the regression, explains only 3% of the variance and the precipitation term is not even statistically significant in the regression (p=0.34). This strongly suggests that the long-term declines in water levels observed in EH-4 and EH-5b, which comprise most of the variance being explained in the regression, were caused by carbonate pumping rather than climate. Annual alluvial pumping in the MRSA was not a significant explanatory variable in the multiple linear regression.

Based on these observations (primarily the response to MX-5 pumping), we conclude that saturated carbonate rocks of southern CSV and the MRSA are part of a single carbonate-rock aquifer system and the warm springs of the MRSA discharge from this aquifer. That is, the warm springs, already known to discharge from the carbonate-rock aquifer based on their temperature and chemistry (Eakin, 1966), and the aquifer, are one hydrologic system. Consequently, the warm springs can be impacted by drawdown induced by pumping in the carbonate-rock aquifer in CSV and the MRSA.

Water level hydrographs for carbonate monitoring wells M-3, M-2, and GV-1 in Garnet Valley, and TH-2 and M-1 in California Wash, along with carbonate pumping in those same basins are presented in **Figure 1.7**. Groundwater records for carbonate monitoring wells in CSV, Garnet Valley and California Wash (**Figures 1.7 and A.1-2 to A.1-9**) are generally shorter than those for EH-4 and EH-5b (**Figure 1.2**), but for the overlapping periods all the hydrographs are similar. Groundwater levels in all of the monitoring wells declined from 2001 to 2004 (where data are available), increased in response to the extreme wet year in 2005, resumed their decline from 2006 to 2010, and began to decline much more rapidly with the initiation of the pumping test in late 2010. We acknowledge that none of these records have been corrected for the effects of barometric pressure fluctuations and earth tides. However, these corrections, had they been made, would be on the order of tenths of feet, an order of magnitude less than the trends observed in the carbonate wells. Therefore, the overall trends cannot be due to these other factors.

The effects of MX-5 pumping in southern CSV appear to be present in groundwater level hydrographs for carbonate monitoring wells in Garnet Valley and California Wash (**Figure 1.7**). Specifically, combined pumping in carbonate production wells in Garnet Valley, the Black Mountains Area, and California Wash has been relatively stable since 2006; yet groundwater levels in carbonate monitoring wells in Garnet Valley and California Wash dropped to unprecedented levels following the introduction of MX-5 pumping in southern CSV in 2010 (**Figure 1.7**). Moreover, groundwater level hydrographs for carbonate monitoring wells in Garnet Valley and California Wash closely resemble those for wells in CSV and the MRSA that clearly include the signature of MX-5 pumping (**Figures 1.2, 1.7, A.1-2 to A.1-4, A.1-8, and A.1-9**). This suggests, at a minimum, that carbonate pumping in CSV produces drawdown in the carbonate-rock aquifer in Garnet Valley and California Wash, as well as the MRSA (the source of the Muddy River Springs and Muddy River).

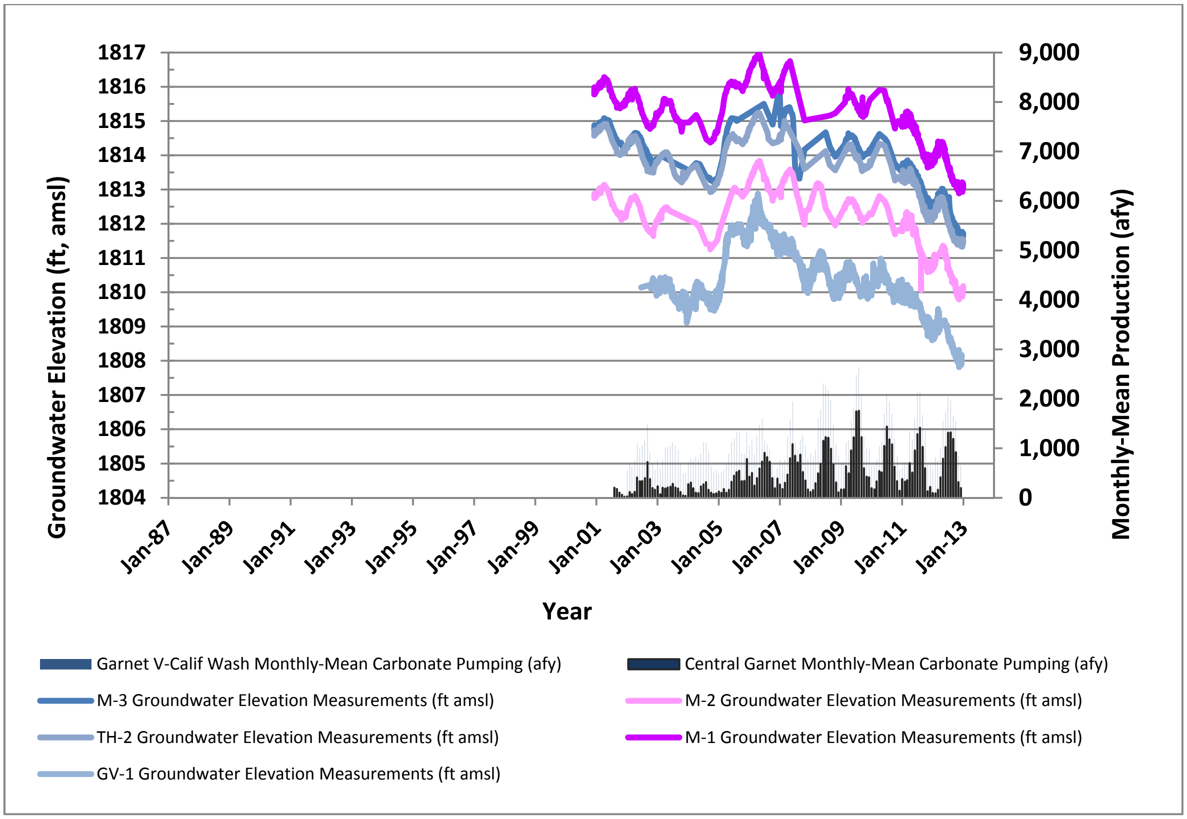

Figure 1.7. Groundwater elevations in carbonate monitoring wells M-3, M-2, and GV-1 in Garnet Valley and TH-2 and M-1 in California Wash and monthly-mean production rates from the carbonate-rock aquifer in central Garnet Valley (GV-MIGRANT 1, GV-DUKE-WS1, GV-DUKE-WS2, GV-PW-WS1, and GV-RW1) and Garnet Valley and California Wash as a whole from 2001 to 2012.

There appears to be a groundwater divide in the carbonate-rock aquifer at the southern end of CSV based on water level elevations in carbonate monitoring well CSVM-2 which are consistently higher than those in nearby carbonate monitoring wells CSVM-1, to the north, and SHV-1, to the south in Hidden Valley. We interpret this to be due to the development of local cones of depression in the CSV-MRSA area and Garnet Valley in response to long-term pumping in the MRSA and Garnet Valley, respectively. We note, however, that the presence of this groundwater divide does not preclude the propagation of drawdown due to pumping in CSV and (or) the MRSA into Hidden and Garnet valleys or California Wash, or vice versa, through the carbonate-rock aquifer.

Hydrographs showing drawdown in carbonate monitoring wells of CSV and the MRSA during the pumping test and monthly-mean production in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area are presented in **Figures 1.8 to 1.10**. Hydrographs showing drawdown in carbonate monitoring wells of Hidden and Garnet valleys and California Wash during the pumping test and combined monthly-mean production in the carbonate-rock aquifer at MX-5, in the combined CSV and MRSA area, central Garnet Valley (the Apex area), and Garnet Valley and California Wash are presented in **Figures A.3-1 to A.3-4**. The timing and magnitude of increases and decreases in drawdown in carbonate monitoring wells of CSV, the MRSA, Garnet Valley, and California Wash are similar and coincide with periods of pumping and shutdowns at MX-5 in CSV (subject to time lags on the order of months). Additionally, total drawdown in the carbonate-rock aquifer in the four basins as of the end of the test was similar in magnitude, ranging from 1.9 to 2.5 feet. Again, this suggests that carbonate pumping in CSV produces drawdown in the carbonate-rock aquifer in Garnet Valley and California Wash, as well as the MRSA, and that the entire area is hydrologically-connected.

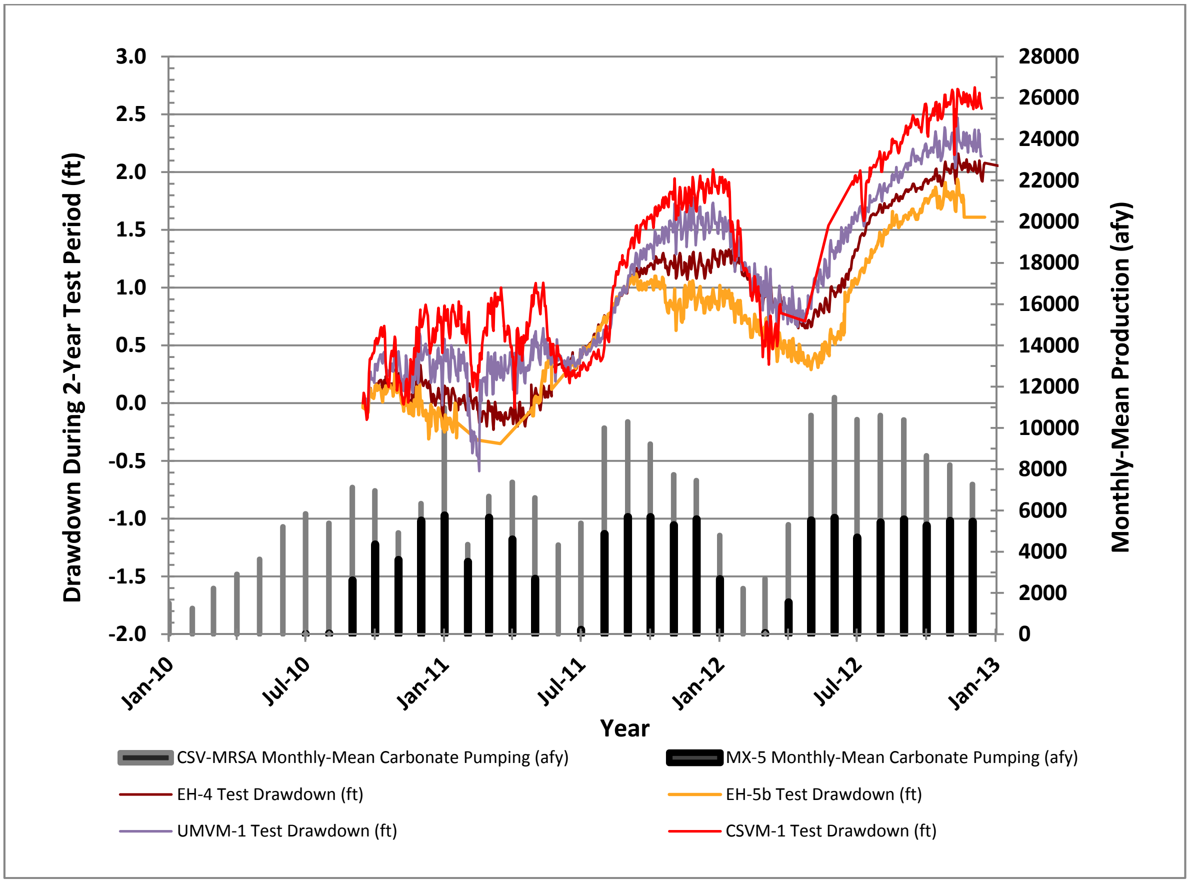

Figure 1.8. Drawdown in carbonate monitoring wells CSVM-1 in CSV and UMVM-1, EH-5b, and EH-4 in the MRSA, versus monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area, from September 15, 2010, to December 31, 2012, i.e., during the 2-year pumping test.

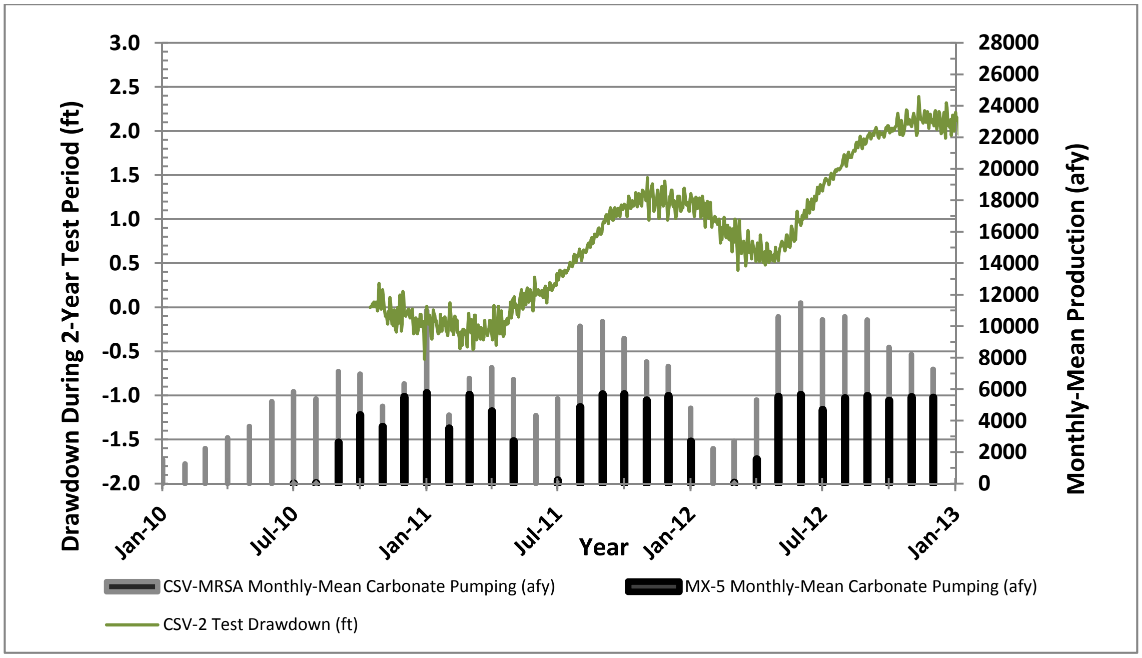

Figure 1.9. Drawdown in carbonate monitoring well CSV-2 in the MRSA versus monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area, from September 15, 2010, to December 31, 2012, i.e., during the 2-year pumping test.

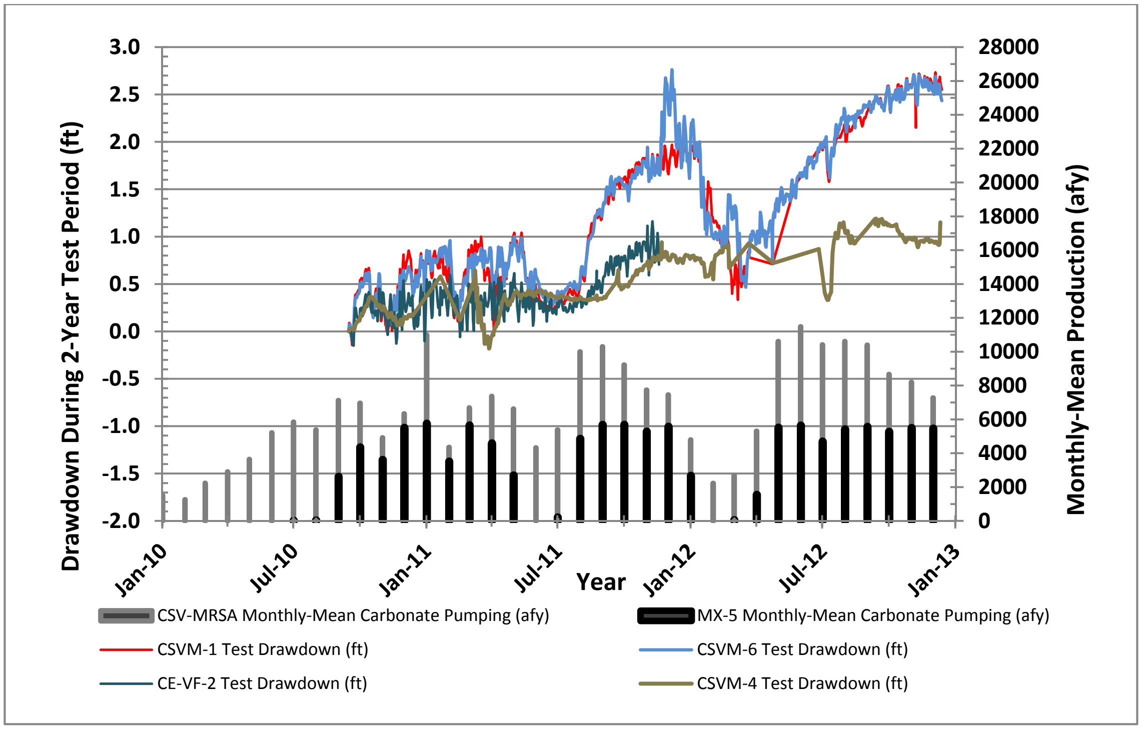

Figure 1.10. Drawdown in carbonate monitoring wells CSVM-1, CSVM-6, CE-VF-2, and CSVM-4 in CSV, versus monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area, from September 15, 2010, to December 31, 2012, i.e., during the 2-year pumping test.

Distance-Drawdown Hydrographs in the Carbonate-Rock Aquifer

Drawdown as a function of distance along two transects through the Study Area, CSV to the MRSA and CSV to California Wash through Hidden and Garnet valleys, respectively, is presented in **Figures 1.11** and **1.12** for the following times during the test:

- 10/29/2010, the end of the first MX-5 pumping period (after 1.5 months of MX-5 pumping);
- 5/15/2011, the end of the second MX-5 pumping period (after a 1-month shut-down and an additional 5.5 months of MX-5 pumping);
- 7/10/2011, the end of a ~2 month recovery period from MX-5 pumping;
- 1/14/2012, the end of the third MX-5 pumping period (after an additional ~5 months of MX-5 pumping);
- 4/22/2012, the end of a ~3.5 month recovery period from MX-5 pumping; and
- 12/13/2012[2], the end of the fourth MX-5 pumping period and end of the test (after an additional ~7.5 months of continuous MX-5 pumping).

The transect from CSV to the MRSA represents a zone of known high transmissivity within the carbonate-rock aquifer[3], consequently a likely path for the propagation of drawdown originating in CSV. The transect from CSV to California Wash through Hidden and Garnet valleys is likewise a physically plausible path for the propagation of drawdown originating in CSV given the apparent presence of a MX-5 pumping signature in water level hydrographs for carbonate monitoring wells in Garnet Valley and the results of SeriesSEE analyses presented later in this report.

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[2] 12/13/2012 was the date of the last groundwater level measurement in a large number wells monitored as part of the Order 1169 test.

[3] Based on the calibration of flow models to date.

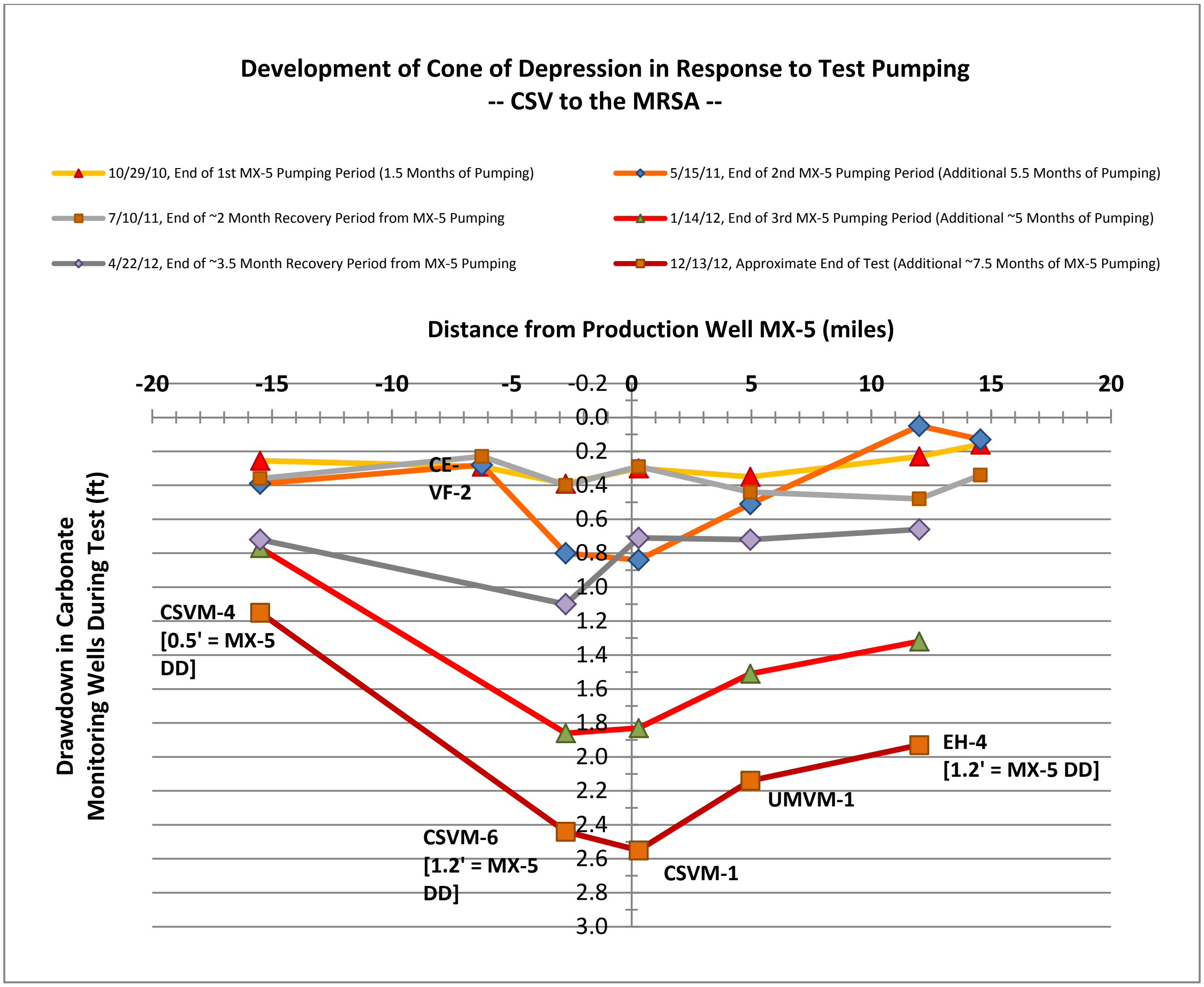

Figure 1.11. Distance-drawdown hydrographs along a transect from northern CSV to the MRSA at a series of times during the 2-year test period.

The shapes of the distance-drawdown hydrographs presented in **Figures 1.11** and **1.12** indicate that drawdown in the carbonate-rock aquifer was at a maximum at the location of production well MX-5 in southern CSV throughout the 2-year test, except for periods of recovery following intermittent shut-downs of MX-5. During periods of recovery from MX-5 pumping, the greatest rebound in groundwater levels occurred in the area of MX-5, as expected. The introduction of MX-5 pumping at an average rate of 4,070 afy during the test represented a significant stress on the carbonate-rock aquifer system. The rate of MX-5 pumping during the test exceeded the combined rate of pumping at all other carbonate production wells in the CSV-MRSA area (3,405 afy) and significantly exceeded the combined rate of carbonate pumping in Garnet Valley and California Wash (1,220 afy). Consequently, drawdown was at a maximum at the location of MX-5 during all phases of the test in which MX-5 was pumping.

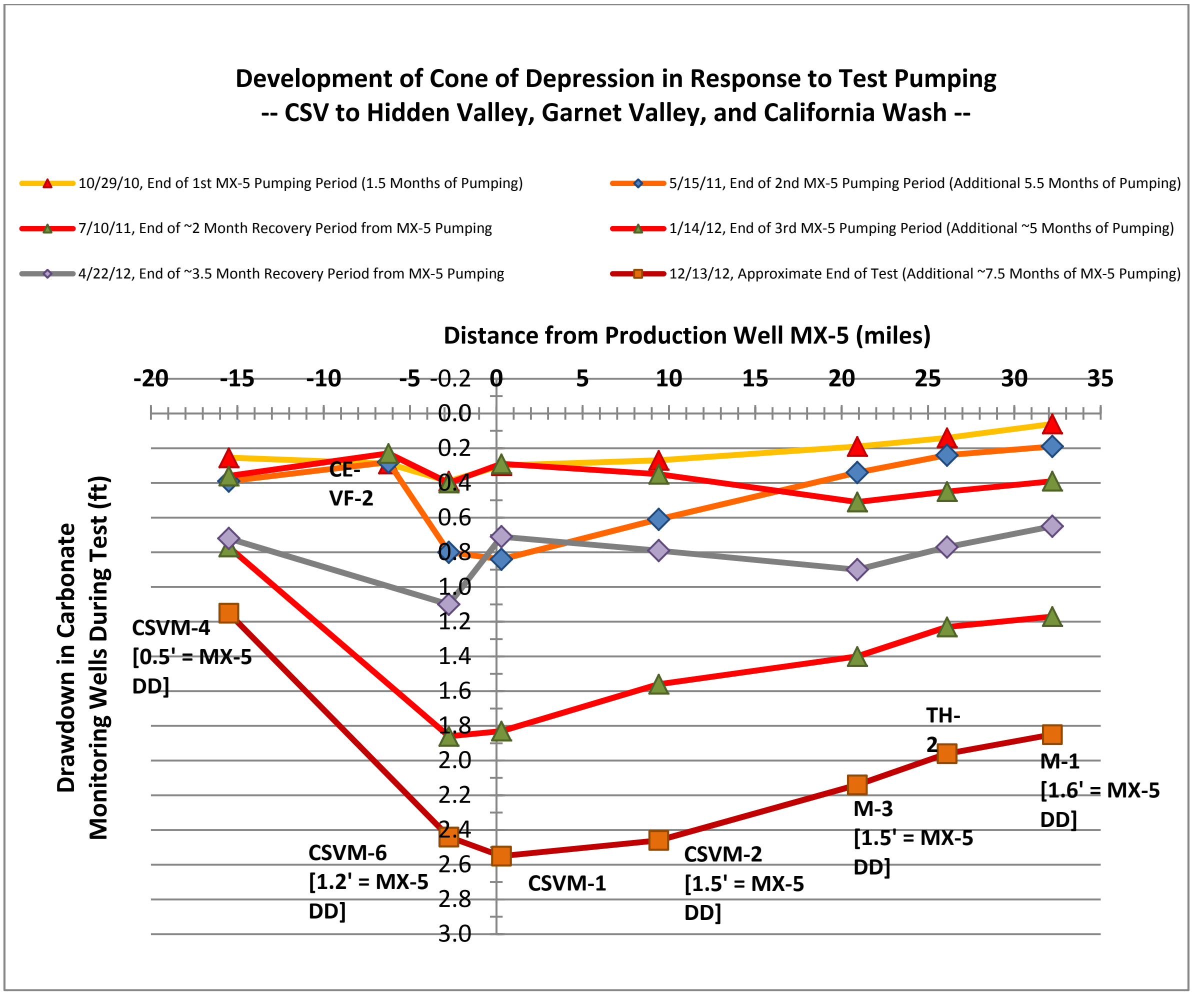

Figure 1.12. Distance-drawdown hydrographs along a transect from northern CSV to California Wash through Hidden and Garnet valleys at a series of times during the 2-year test period.

As of mid-May 2011, following 7 months of MX-5 pumping and a 1-month recovery period, drawdown due to the test pumping extended over a distance of at least 7 miles in the carbonate-rock aquifer from central CSV (well CSVM-6) to western MRSA (well UMVM-1) and at least 22 miles from central CSV (CSVM-6) to northern Garnet Valley (well M-3). As of mid-January 2012, following 13 months of MX-5 pumping in 3 periods and 3 months of recovery in 2 rest periods, drawdown in the carbonate-rock aquifer extended over a distance of about 27 miles from the northern end of CSV (well CSVM-4) to the Muddy River Springs (well EH-4) and 47 miles from northern CSV (CSVM-4) to California Wash (wells TH-2 and M-1) through Hidden and Garnet valleys.

The cone of depression that developed in the carbonate-rock aquifer between CSV and the MRSA following initiation of the test is shallow, relatively flat, and areally extensive (**Figure 1.11**). This is consistent with the known high transmissivity and hydraulic diffusivity of this portion of the regional carbonate-rock aquifer based on documented low hydraulic gradients under pre-test conditions, as well as the calibration of two groundwater flow models (the CCRP Model by SNWA and Tetra Tech Model Version 1.0 developed for the DOI agencies). Distance-drawdown hydrographs for carbonate monitoring wells in CSV, Garnet Valley, and California Wash (**Figure 1.12**) are likewise flat, or flatter. We interpret this to be the result of Garnet Valley pumping superimposed on the effects of carbonate pumping in CSV and the MRSA.

The effects of earth tides and fluctuations in barometric pressure on water levels in the carbonate-rock aquifer should be roughly equal throughout the Study Area at any given time. Consequently, the shapes of the distance-drawdown hydrographs presented in **Figures 1.11** and **1.12**, which represent conditions in the carbonate-rock aquifer at particular times, should be unaffected by the absence of these corrections. Likewise, longer-term (regional) changes in carbonate water levels should be similar throughout the area given the high transmissivity and diffusivity of this portion of the carbonate-rock aquifer, subject to minimal differences in timing. Consequently, the shapes of the distance-drawdown hydrographs should be minimally affected by the absence of a correction for long-term regional trends.

Isolation of Drawdown from MX-5 Pumping using SeriesSEE Analysis

Drawdown observed in the carbonate-rock aquifer and other hydrogeologic units during the test was the result of pumping at a large number of production wells, including the 39 utility- and industrial-scale (major) production wells listed in **Table A.1**. For illustrative purposes, these production wells have been grouped into four major pumping centers in **Figure 1.13**: Q_CSI, Q_EAST, Q_SOUTH, and Q_MX-5. Average annual pumping from all major production wells in the Study Area ranged between 9,500 to 14,000 afy (**Figure 1.14**) over the last 10 years. Monthly pumping from major pumping centers in the area varies seasonally and typically fluctuates between 6,400 and 19,300 afy. Q_EAST, located east-southeast of well MX-5 in the MRSA (**Figure 1.13**), is the primary pumping center in the Study Area. Pumping in the MRSA ranges seasonally from 4,800 to 12,900 afy. Monthly-mean pumping at well MX-5 in CSV was 4,070 afy during the test and ranged between 0 and 5,800 afy from September 2010 to August 2012.

We have employed SeriesSEE analysis (the method of Halford et al. 2012) to isolate, i.e., differentiate, drawdown induced by pumping at carbonate production well MX-5 from drawdown induced by pumping at other major production wells (carbonate and basin fill) that were operating in the Study Area during the test. Specifically, we have used SeriesSEE analysis to estimate the magnitude of drawdown induced by MX-5 pumping as of 12/13/2012[4] at a range of locations within the Study Area *as a means of identifying the high-connectivity portion of the carbonate-rock aquifer that includes the MRSA*.

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[4] 12/13/2012 was the date of the last groundwater level measurement in a large of number wells monitored as part of the Order 1169 test.

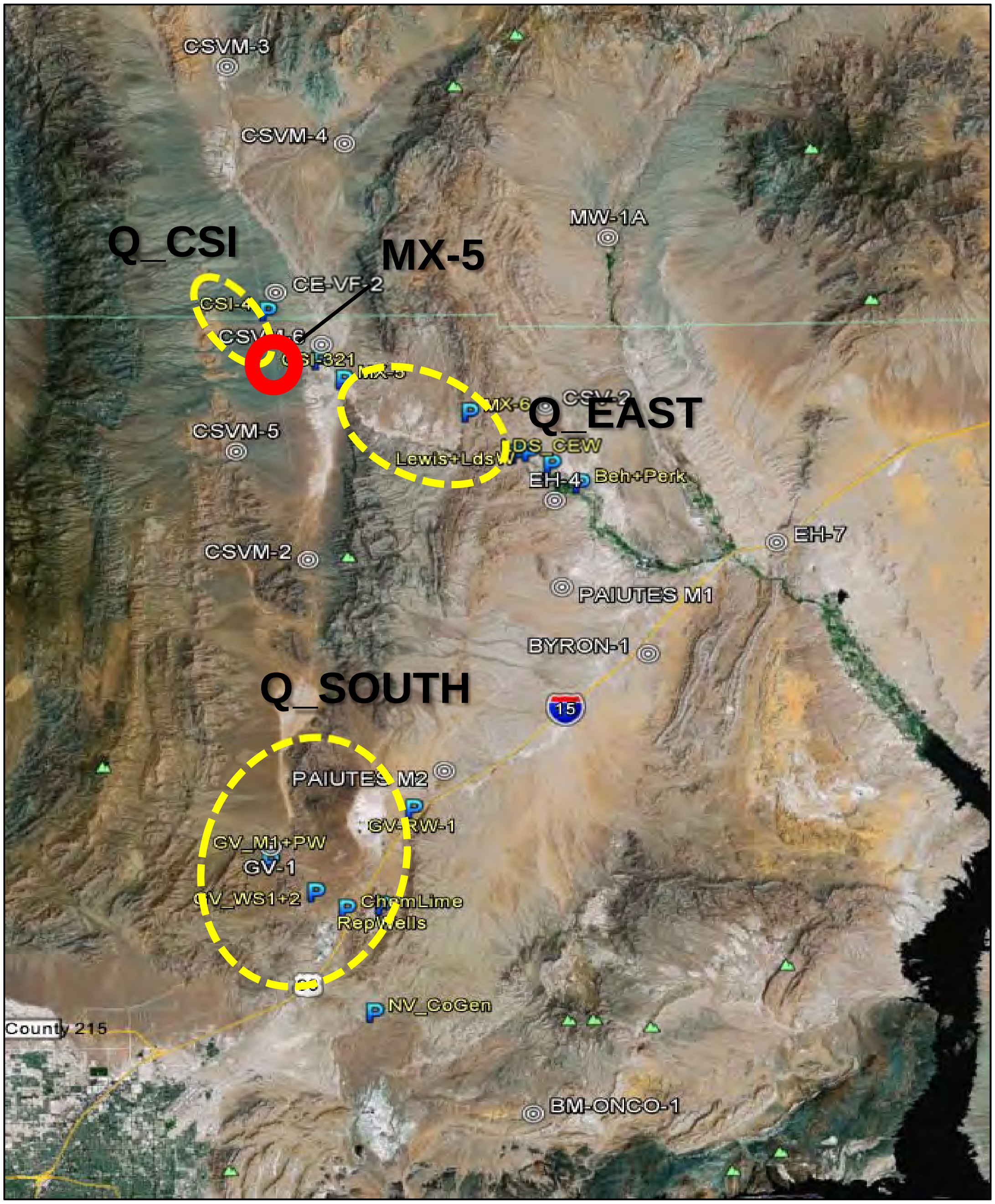

Figure 1.13. Major pumping centers within the Study Area.

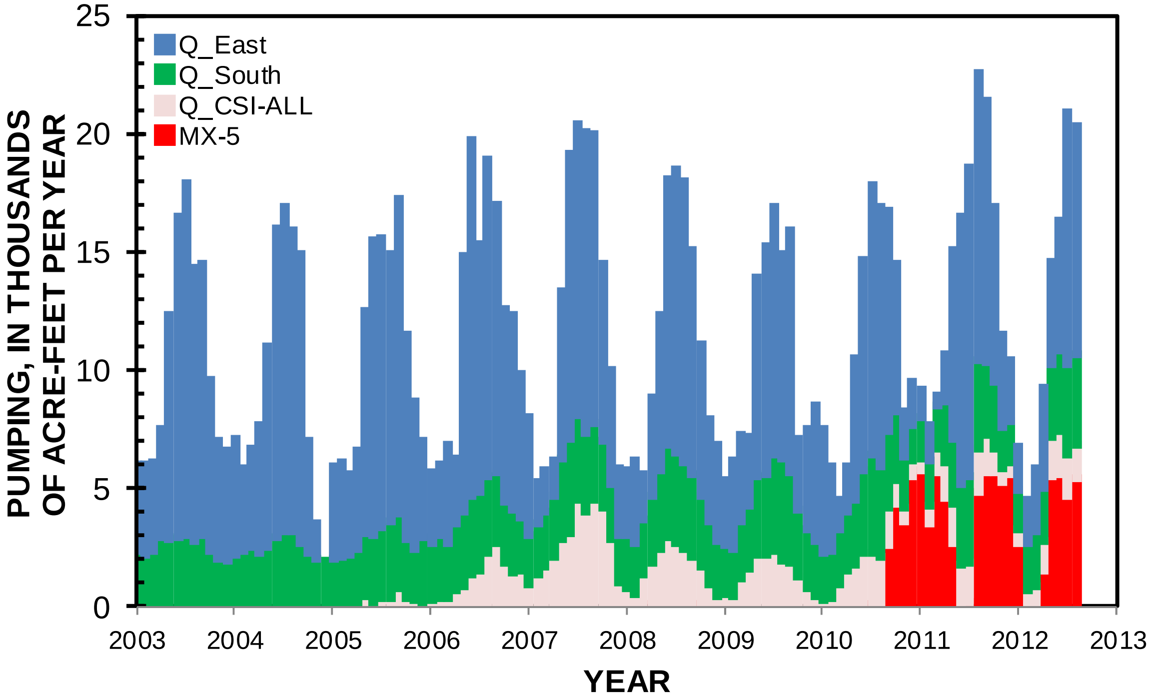

Figure 1.14. Monthly pumping from Q_East, Q_South, Q_CSI, and MX-5 for the period 2003 to August 2012.

In particular, we have modeled groundwater level data collected in 14 monitoring wells in the MRSA, CSV, Garnet Valley, the Black Mountains Area, California Wash, Lower Moapa Valley, and Lower Meadow Valley Wash using SeriesSEE (Halford at al., 2012) to estimate the magnitude of drawdown induced by MX-5 pumping as of the end of the test (12/13/2012). Drawdown induced by pumping at all 39 major production wells listed in **Table A.1** was simulated analytically using Theis transforms, where step-wise pumping records of discharge are transformed into water-level changes using multiple superimposed Theis solutions. Theis transforms can approximate drawdowns, as well as the measurement resolution of transducers, even in complex hydrogeologic systems (Garcia et al., 2013). Groundwater-level fluctuations from environmental stresses such as barometric changes, earth tides, and regional trends in groundwater levels were not modeled.

Pumping at the 39 major production wells listed in **Table A.1** was simulated from 1/1/2008 to 12/13/2012, grouped into the 13 pumping centers shown in **Figure 1.15** (each depicted with a 'P'). Groundwater level data for this same period was interpreted for the following monitoring wells[5]:

- CSVM-3 (carbonate monitoring well at the north end of CSV);
- CSVM-4 (carbonate monitoring well in northern CSV, immediately south of Kane Springs Valley on the southeast side of the Kane Springs Wash Fault);
- CE-VF-2 (carbonate monitoring well in north-central CSV);
- CSVM-6 (carbonate monitoring well in central CSV);

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[5] Simulated production rates were monthly-mean values. The frequency of modeled groundwater level measurements varied according to what is available; in some cases modeled groundwater level data were intermittent tape-downs, in other cases they were daily-mean values from continuous transducer records.

- CSVM-5 (carbonate monitoring well in an elevated portion of southern CSV);
- CSV-2 (carbonate monitoring well in the MRSA, north of the Arrow Canyon wells);
- EH-4 (carbonate monitoring well in the MRSA ,close to Pederson and Pederson East springs of the Muddy River Springs);
- M-2 (carbonate monitoring well in northern Garnet Valley);
- GV-1 (carbonate monitoring well in southern Garnet Valley close to central Garnet Valley/Apex area pumping);
- BM-ONCO-1 (monitoring well completed in clastic rocks in the Black Mountains Area south of central Garnet Valley/Apex area pumping)
- M-1 (carbonate monitoring well in northern California Wash, close to the MRSA);
- Byron-1 (carbonate monitoring well in southern California Wash);
- EH-7 (monitoring well completed in younger carbonate rocks of Lower Moapa Valley); and
- MW-1A (basin-fill monitoring well in Lower Meadow Valley Wash).

Our SeriesSEE analyses span the period 1/1/2008 to 12/13/2012 because groundwater level measurements collected during the test (9/15/2010 to 12/13/2012) were, in part, due to pumping that predated the test. The 14 monitoring sites listed above represent a combination of locations that were judged *a priori* to be located within and outside the high-connectivity portion of the carbonate-rock aquifer based on an inspection of available groundwater level hydrographs. All but two of the monitoring wells, MW-1A in Lower Meadow Valley Wash and EH-7 in Lower Moapa Valley, are completed in the carbonate-rock aquifer. Well MW-1A is a shallow well completed in basin fill; EH-7 is completed in carbonate rocks that are younger than the Paleozoic carbonate rocks comprising the regional carbonate-rock aquifer.

Our estimates of MX-5 induced drawdown in the 14 monitoring wells as of 12/13/2012 are summarized in **Figure 1.15**. The results of these analyses are provided in graphical form in **Appendix A.4-4** (rates of MX-5 pumping and total pumping within the Study Area provided as points of reference). In particular, no drawdown due to MX-5 pumping was identified in the records of:

- carbonate monitoring well CSVM-5 in an elevated portion of southern CSV (an area of possible low permeability accounting for the slow rise in groundwater levels in this well over that last several years);

- clastic monitoring well BM-ONCO-1 in the northern Black Mountains Area (south of the central Garnet Valley/Apex production wells);

- carbonate monitoring well Byron-1 in northwestern California Wash; or

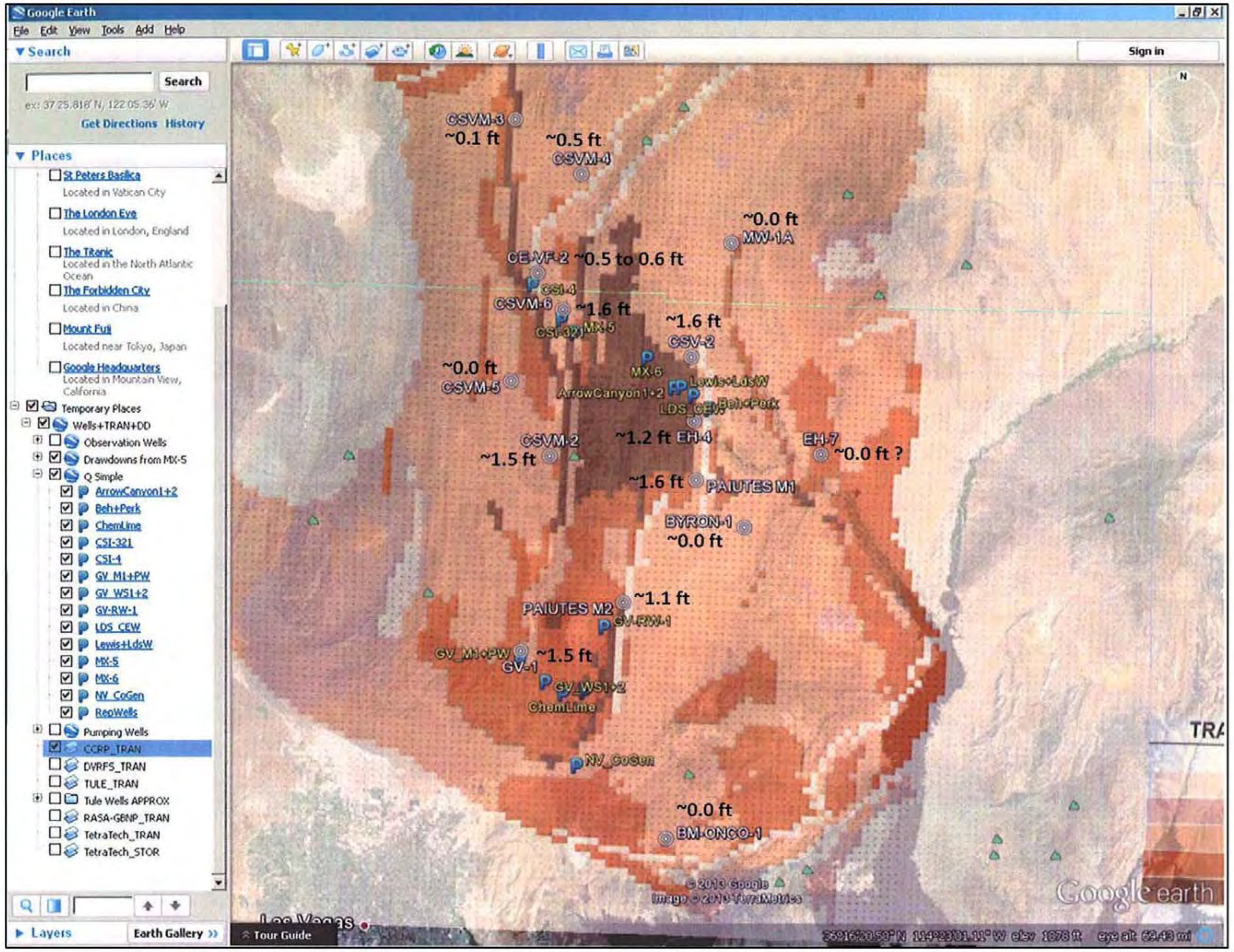
- basin-fill monitoring well MW-1A in Lower Meadow Valley Wash.

Moreover, no MX-5 induced drawdown appears to be present in the record of monitoring well EH-7 in Lower Moapa Valley (completed in carbonate rocks that are not part of the regional aquifer). However, the magnitude of MX-5 induced drawdown was substantial and nearly equal in most of the carbonate monitoring wells analyzed in the floor of CSV, the MRSA, Garnet Valley, and California Wash as of December 2012 (1.1. to 1.6 ft of a total 1.9 to 2.5 ft of observed water level change). Carbonate monitoring wells CSVM-4 and CSVM-3 in northern CSV were an exception to this otherwise remarkably uniform response as of the end of the test. Smaller components of MX-5 induced drawdown were estimated in CSVM-4 and CSVM-3 (about 0.5 and 0.1 ft, respectively).

We conclude that pumping at MX-5 in the carbonate-rock aquifer created drawdown of approximately equal magnitude throughout CSV (at least the floor of the valley), the MRSA, Hidden and Garnet valleys, and California Wash as of the end of the 2-year test. Given this result and the connectivity of this portion of the carbonate-rock aquifer based on low hydraulic gradients under pre-test conditions and the calibration of two groundwater flow models, we likewise conclude that carbonate pumping at other locations within this area has also created (and will create) drawdown of nearly equal magnitude throughout the identified area. Using the results of these SeriesSEE analyses, we have delineated a portion of the carbonate-rock aquifer in which pumping causes water level declines of nearly equal magnitude throughout this part of the aquifer (**Figure 1.16**), including the source of the Muddy River Springs and majority source of the Muddy River. We note that these conclusions are consistent with the distribution of total drawdown documented in carbonate monitoring wells as of the end of the 2-year test (**Figure 1.17**).

We note that this differentiation of pumping signals includes differentiating drawdown induced by MX-5 pumping in CSV from drawdown induced by pumping at the Arrow Canyon and basin fill wells in the MRSA, the CSI production wells in CSV, and production wells in Garnet Valley, the Black Mountains Area, and California Wash (the other major production wells listed in **Table A.1**). See **Appendix A.4** for a discussion of the extent to which drawdown due to pumping at locations other than MX-5 has been isolated as part of these analyses.

Due to the limited availability of observation wells in east-central to southern California Wash and the portion of the Black Mountains Area that lies between southern California Wash and the Overton Arm of Lake Mead, it was not possible to evaluate the potential for a hydraulic connection between the delineated area (including California Wash) and Rogers and Blue Point springs.



☐ St Peters Basilica
Located in Vatican City
☐ The London Eye
Located in London, England
☐ The Titanic
Located in the North Atlantic Ocean
☐ The Forbidden City
Located in China
☐ Mount Fuji
Located near Tokyo, Japan
☐ Google Headquarters
Located in Mountain View, California
- ☑ Temporary Places
  - ☑ Wells+TRAN+DD
    - ☐ Observation Wells
    - ☑ Drawdowns from MX-5
    - ☑ Q Simple
      - ☑ ArrowCanyon1+2
      - ☑ Beh+Perk
      - ☑ ChemLime
      - ☑ CSI-321
      - ☑ CSI-4
      - ☑ GV_M1+PW
      - ☑ GV_WS1+2
      - ☑ GV-RW-1
      - ☑ LDS_CEW
      - ☑ Lewis+LdsW
      - ☑ MX-5
      - ☑ MX-6
      - ☑ NV_CoGen
      - ☑ RepWells
    - ☐ Pumping Wells
  - ☑ CCRP_TRAN
  - ☐ DVRFS_TRAN
  - ☐ TULE_TRAN
  - ☐ Tule Wells APPROX
  - ☐ RASA-GBNP_TRAN
  - ☐ TetraTech_TRAN
  - ☐ TetraTech_STOR

Figure 1.15 MX-5 pumping-induced drawdown (ft) in monitoring wells within the Order 1169 Study Area based on preliminary SeriesSEE analyses performed using the method of Halford et al. (2012); base map is total transmissivity calibrated using the Central Carbonate-Rock Province (CCRP) Model developed by SNWA for the Clark, Lincoln, and White Pine Counties Groundwater Development Project.

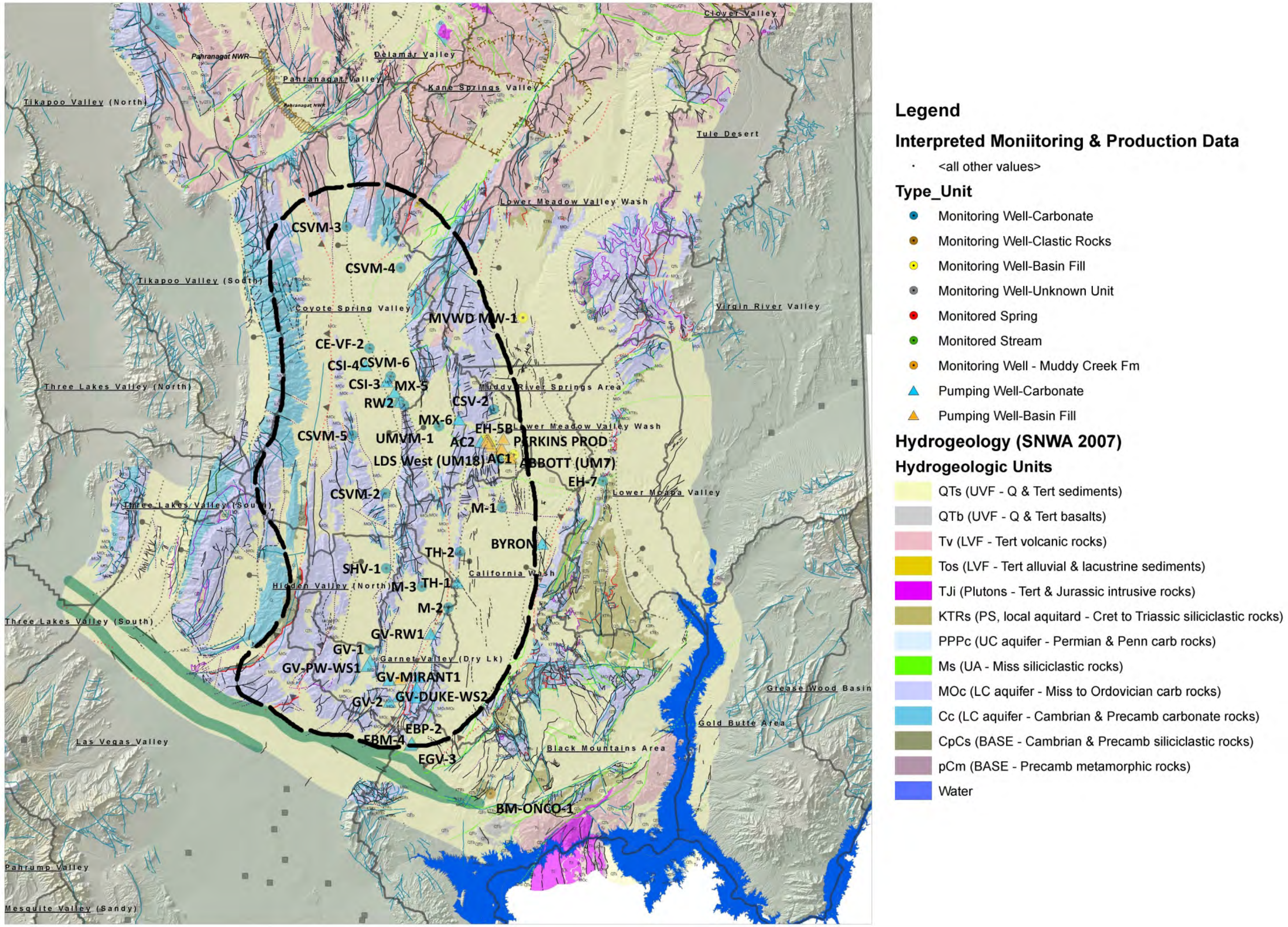


Figure 1.16. Map showing the approximate location of the portion of the carbonate-rock aquifer in which pumping results in water level declines of roughly equal magnitude everywhere else in this part of the aquifer and depletion of the Muddy River Springs. (Delineated area based on SeriesSEE analyses and generalized geologic considerations. Base is SNWA (2007a) Hydrogeologic Units.)

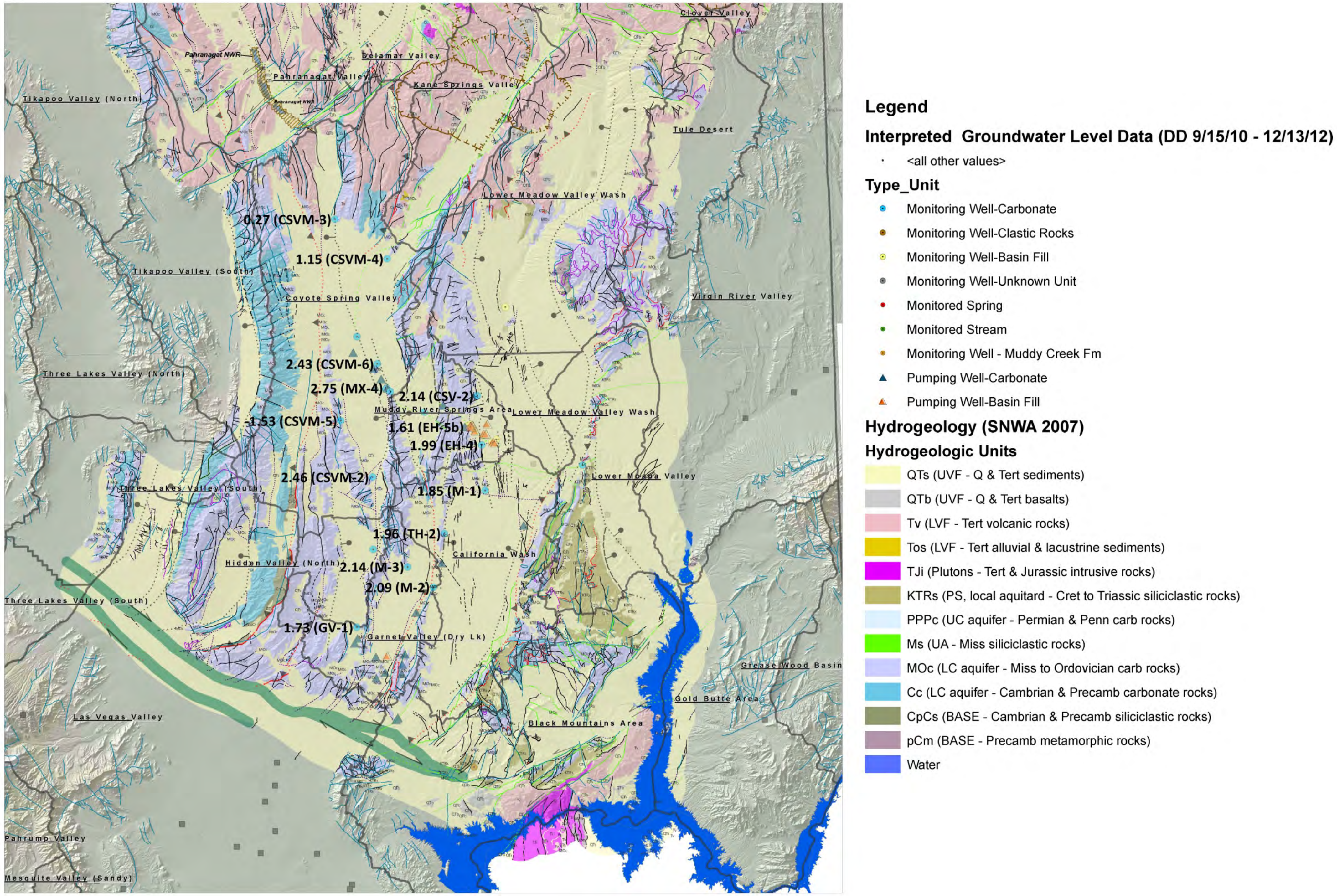


Figure 1.17. Total drawdown in the carbonate-rock aquifer due to all carbonate pumping during the Order 1169 test, September 15, 2010 to December 31, 2012; base is SNWA (2007) Hydrogeologic Units.

Conceptual Model of the Portion of the Carbonate-Rock Aquifer System Affecting the Muddy River Springs

We hypothesize that the response to MX-5 pumping observed during the Order 1169 pumping test was due to two factors:

1. a high degree of connectivity within the portion of the regional carbonate-rock aquifer underlying CSV, the MRSA, Hidden and Garnet valleys, and California Wash (the delineated area); and
2. relatively constant groundwater inflows to this portion of the carbonate-rock aquifer.

Based on the results of our SeriesSEE analyses and a range of other observations discussed in previous sections, a high degree of connectivity exists within the portion of the carbonate-rock aquifer underlying the delineated five-basin area (as discussed in the previous section). We additionally propose that groundwater inflows to this portion of the carbonate-rock aquifer are primarily limited to CSV and that these inflows are relatively constant.

Specifically, the magnitude of the head drop from Pahranagat Valley into CSV (or Delamar Valley to CSV) is on the order of 1,000 ft. As a result, no amount of pumping-induced drawdown in CSV or the other four basins can measurably increase the hydraulic gradient and the groundwater inflow across the northern boundaries of CSV into the delineated area. Interbasin groundwater flow into the portion of the carbonate-rock delineated in **Figure 1.16** is for all practical purposes constant, regardless of the magnitude of drawdown induced in CSV and the other basins by pumping.

Likewise, groundwater inflow to CSV and the other basins in the form of precipitation recharge is not only limited, but relatively constant from year to year compared to the overall water budget of this portion of the carbonate-rock aquifer. Consequently, the portion of the carbonate-rock aquifer delineated in **Figure 1.16** is effectively a high-transmissivity carbonate-rock reservoir with fixed inflows. Pumping anywhere in this portion of the carbonate-rock aquifer effectively lowers groundwater levels everywhere within ‘the reservoir’ by almost equal amounts in relatively short periods of time (consistent with the results of our SeriesSEE analyses and a range of other observations during the test).

Additionally, groundwater pumping must eventually be balanced by increased inflows, decreased natural outflows, or a combination thereof (Bredehoeft, 2007). Since groundwater inflows to this portion of the carbonate-rock aquifer are for all practical purposes constant, all pumping from the ‘reservoir’ must eventually be captured from natural discharge at a rate approaching 100 percent of the rate of pumping. Natural discharge within the delineated area, in turn, is limited to the Muddy River Springs, and the Muddy River and ET associated with phreatophytic vegetation in the MRSA and California Wash (DeMeo et al., 2008). Consequently, all pumping from this portion of the carbonate-rock aquifer must eventually be captured from the springs, river, and (or) ET in the MRSA and California Wash. Any carbonate pumping in excess of the current rate of natural discharge in the MRSA and California Wash will potentially result in capture from Rogers and Blue Point springs over longer periods of time and/or long-term declines in carbonate water levels throughout the five basins.

Capture of natural discharge in the MRSA has already occurred to some extent as a result of the Order 1169 pumping. We have documented a total reduction in spring discharge of about 1200 af during the pumping test (described in detail in the following section on impacts to springs). Unprecedented declines in carbonate water levels during the test were also accompanied by unprecedented declines in the discharge of the two highest-elevation warm springs in the MRSA, Pederson and Pederson East springs, as well as lesser reductions in discharge at the Warm Springs West gage (**Figures 1.4** and **1.5**) and several lower elevation warm springs in the MRSA (Jones, Baldwin, and the Plummer Unit springs).

Assessment of Pumping Captured from Groundwater Storage during the 2-Year Test

We estimate that a large portion of MX-5 pumping and some portion of the other carbonate pumping which occurred during the Order 1169 pumping test was likely captured from groundwater storage as of the end of the 2-year test, with only a fraction captured to date from natural discharge. The high-transmissivity carbonate-rock reservoir delineated in **Figure 1.16** is approximately 690,000 acres in area[6]. Based on SeriesSEE analyses, an average 1.4 ft of drawdown was induced in this portion of the carbonate-rock aquifer as of the end of the test in response to the withdrawal of 9,300 af from MX-5 (9/15/2010 to 12/13/2012). If the average storage coefficient for this portion of the carbonate-rock aquifer is 0.01, then the majority of groundwater pumped from MX-5 during the 2-year test was captured from groundwater storage. Likewise, carbonate water levels declined an average of 2.0 ft in the delineated area over the 2-year test period in response to the withdrawal of 19,900 ac-ft from all carbonate production wells. Again, if the average storage coefficient for this portion of the carbonate-rock aquifer is as great as 0.014, then the majority of carbonate pumping was captured from groundwater storage, rather than natural discharge, during the test.

We note that the magnitude of the storage coefficients implied by these simple volumetric calculations, approximately 0.01, is plausible based on estimates of storage coefficients for the carbonate-rock aquifer at other locations. Specifically, no storage coefficient estimates are available for this portion of the carbonate-rock aquifer based on the interpretation of pumping (aquifer) tests. No storage coefficient was estimated from a multi-well pumping test performed in carbonate well Arrow Canyon 1 in the MRSA in the 1990's (Buqo, 1994; after Belcher et al., 2001); and no storage coefficients could be estimated from 1986 single-well pumping tests conducted in carbonate wells CSV-2 in the MRSA or CE-VF-2 in CSV (USGS, 2013). However, an unconfined storage coefficient of 0.020 has been estimated from a multi-well pumping test in carbonate well 184W101 in Spring Valley (USGS, 2013); and a confined storage coefficient of 2.0E-04 to 9.0E-03 was estimated by the Southern Nevada Water Authority (SNWA 2009) from a multi-well pumping test in well 184W105 in Spring Valley.

Based on the available storage coefficient estimates for carbonate rocks elsewhere in Nevada, we conclude that the storage coefficient implied by our volumetric calculations for the delineated portion of the carbonate-rock aquifer, which data suggest is confined in some locations and unconfined in others,

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[6] Specifically, 693,100 acres is roughly the area delineated in Figure 1.16 less the most northerly portion of CSV where MX-5 induced drawdown as of the end of the 2-year test was less than the 1.1 to 1.6 ft estimated at nearly all other locations in the identified area.

is plausible and that the bulk of carbonate pumping during the test was captured from groundwater storage. As such, only a fraction of the pumping was captured from natural discharge as of the end of the test. We expect the full impacts of the Order 1169 pumping test, most of which have not yet been realized, to include capture of spring and stream discharge, followed by ET, in the MRSA and California Wash in an amount that approaches the rate of MX-5 pumping imposed during the test. Moreover, about three-quarters of drawdown observed in the carbonate-rock aquifer within the five identified basins was attributable to MX-5 pumping as of the end of the test based on SeriesSEE analyses. We interpret this to mean that the remaining quarter or more of drawdown was attributable to other pumping. That is, the carbonate-rock aquifer system, specifically the portion underlying the delineated area, had not reached equilibrium with respect to pumping at one or more production wells predating MX-5 as of the end of the test. As a consequence, we expect the full impacts of the test to include the capture of an additional increment of natural discharge associated with continued pumping at some number of existing carbonate production wells (wells predating MX-5) within the Study Area.

Limitations of the Test and Unresolved Questions

The only significant limitation of the Order 1169 pumping test was that two years was not sufficient to observe the transition from the capture of pumping from groundwater storage to the capture of pumping from natural discharge. As a result, the full impacts of the level of pumping during the test on spring and stream discharges were not observed during the 2-year test.

The time required to transition from a state where pumped water is supplied from groundwater storage (reductions in groundwater levels) to the capture of spring/stream discharge and evapotranspiration is unknown. The time for this transition to occur may be so long that by the time a critical reduction in spring flow is identified (e.g., based on a reduction in flow at the Warm Springs West gage), the ensuing recovery in groundwater levels may not occur fast enough to protect spring discharge and biological resources in the MRSA.

Additionally, available information is not sufficient to evaluate the potential for a hydraulic connection between the delineated high-transmissivity portion of the carbonate-rock aquifer (CSV, the MRSA, Hidden and Garnet Valleys, and California Wash) and Rogers and Blue Point springs; nor is it sufficient to determine whether MX-5 induced drawdown in California Wash propagated through the MRSA, through Hidden and Garnet valleys, or both.

Conclusions for Impacts to Groundwater

Based on our SeriesSEE analyses, we have delineated a portion of the carbonate-rock aquifer underlying CSV, the MRSA, Hidden and Garnet valleys, and California Wash, a subset of the overall Order 1169 Study Area, in which pumping causes water level declines of nearly equal magnitude throughout this part of the aquifer over relatively short periods of time (i.e., the 2-year test period or less). The results of our SeriesSEE analyses confirm that the 'signature' seen in groundwater level hydrographs for carbonate monitoring wells in these five basins was indeed due to MX-5 pumping. The area delineated using

SeriesSEE analyses is also consistent with distance-drawdown hydrographs for the carbonate-rock aquifer constructed using data collected during the test.

Based on this result and considerations related to the nature of groundwater inflows to CSV, we hypothesize that this portion of the carbonate-rock aquifer acts as a high-transmissivity (high-diffusivity) 'reservoir' with fixed inflows. As a consequence, pumping anywhere in this portion of the carbonate-rock aquifer effectively lowers groundwater levels everywhere in 'the reservoir' by nearly equal amounts (consistent with the results of our SeriesSEE analyses and a range of other observations). As an additional consequence, all pumping from the 'reservoir' must eventually be captured from the Muddy River Springs, Muddy River, and (or) ET associated with phreatophytic vegetation in the MRSA and California Wash, the only forms of natural discharge in the delineated five-basin area, at a rate that approaches 100 percent of the rate of pumping. Any carbonate pumping in the area that exceeds the current rate of natural discharge in the MRSA and California Wash will potentially result in capture from Rogers and Blue Point springs over longer periods of time and (or) long-term declines in groundwater levels.

We estimate that the bulk of MX-5 pumping, as well as some portion of other carbonate pumping that occurred during the test, was likely captured from groundwater storage (a lowering of groundwater levels) based on volumetric calculations, which suggests that only a fraction of the water pumped was captured from natural discharge as of the end of the test. This is confirmed by our estimate of the decline in spring flows that occurred during the test in the MRSA (discussed in detail later in this section) which represents a fraction of the average rate of MX-5 pumping.

If pumping in the carbonate-rock aquifer continues in the delineated area at the rate it occurred during the test, we expect additional declines in spring and stream flows to occur in the MRSA and California Wash in an amount that approaches the average rate of MX-5 pumping, plus an additional increment of capture associated with the continuation of other carbonate pumping in the area. Increasing the rate of carbonate pumping in the delineated area over the level that occurred during the test will result in further capture of spring and stream flows and (or) ET in the MRSA and California Wash in an amount that approaches 100 percent of the increase in the rate of pumping.

Finally, we note that the impacts of the Order 1169 pumping test, both observed and anticipated, are the result of pumping approximately one-third of the 16,300 afy currently permitted in CSV[7] and that the applications pending under Order 1169 potentially represent a substantial increase in those rights. This suggests that water is not available for the pending applications in CSV, in part or whole, or for applications pending in the MRSA, Hidden or Garnet valleys, or California Wash under the Order, as discussed in the Availability section of this report.

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[7] The annual-mean rate of pumping in CSV during the test, 5,378 afy, divided by the currently permitted rights in CSV, 16,300 afy.

Impacts to Springs

This portion of the report presents our interpretation of the impacts of the Order 1169 pumping test on springs and discharge in the MRSA. We begin by describing the theoretical relationship between groundwater levels in the carbonate rock aquifer and regional spring discharge. We hypothesize that changes in spring discharge will be proportional to the changes in hydraulic head differential at each individual spring and that the higher elevation springs with the smallest hydraulic head will be the most sensitive to the drawdown observed during the pumping test. To validate this hypothesis, we examine the observed changes in discharge at several springs and flow monitoring sites in the system in relation to spring water surface elevation, groundwater level decline, and the estimated changes in hydraulic head differential at the springs. We also discuss other factors affecting groundwater levels and spring discharge during the pumping test including precipitation, fire effects, and land use changes in the area.

Theoretical Groundwater Level/Spring Discharge Relationships

It is well established that spring discharge in the MRSA emanates from the regional carbonate-rock aquifer (Eakin 1966; Prudic et al., 1993; Thomas et al., 1996). The regional carbonate-rock aquifer is confined and the potentiometric surface of the aquifer is greater than the land surface elevation of the springs. This hydraulic head differential causes groundwater in the carbonate rock aquifer to rise to the land surface, along fissures and fractures that occur in the area, and flow as spring discharge. We assume that the flow at any spring is governed by Darcy's Law, which states that flow through a porous medium is proportional to the hydraulic head differential or hydraulic gradient (Fetter, 1994). The greater the difference between the water surface elevation at the spring and the hydraulic head of the aquifer, the greater the spring discharge, other factors being constant.

The high transmissivity of the carbonate rock aquifer in the CSV-MSRA corridor creates a consistent and fairly uniform potentiometric surface beneath the landscape with little variation in hydraulic head in the aquifer. The difference in land surface elevations between MX-4 in CSV and the springs in MRSA, some 15 miles to the east, is about 350-450 feet, but the difference in the potentiometric surface of the regional aquifer between carbonate monitoring wells MX-4 in CSV and EH-4 in MRSA is only about 5-6 feet. The high transmissivity and associated low hydraulic gradient results in a fairly uniform potentiometric surface elevation across the MRSA. However, the elevations of springpools in the area vary by more than 70 feet (Beck et al., 2006). This potentially leads to a large range of hydraulic head differential between the individual springs in the MRSA. Higher elevation springs have a much smaller hydraulic head differential than lower elevation springs. This concept is illustrated in **Figure 1.18**.

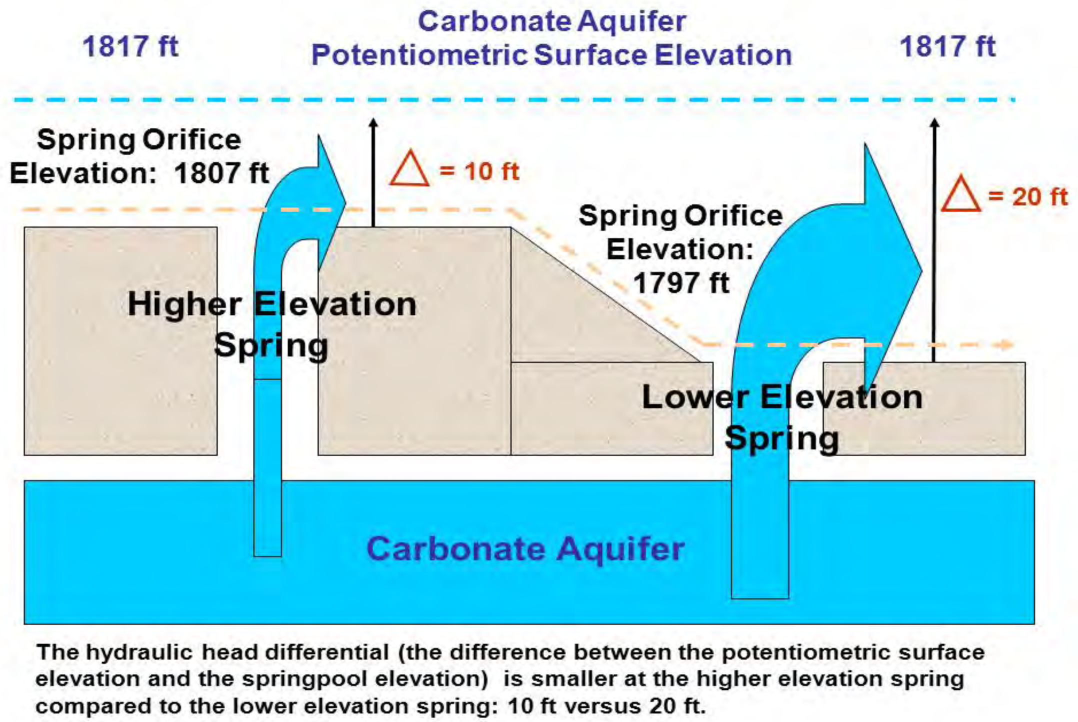

Figure 1.18. Theoretical head differential at springs of *different* elevation, assuming a uniform potentiometric surface in the regional carbonate-rock aquifer.

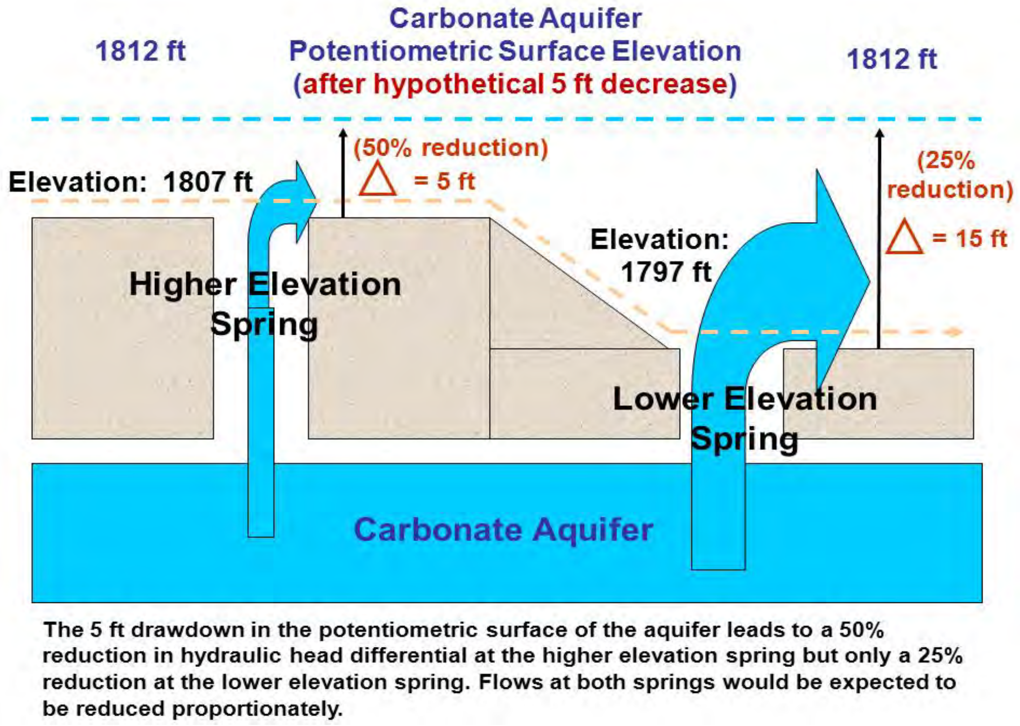

Figure 1.19. Theoretical effects of a uniform drawdown on head differential and spring discharge at higher and lower elevation springs.

Groundwater pumping leads to the development of a drawdown cone around the pumping center. As the drawdown cone extends to the springs, the hydraulic head differential at the springs will be reduced. Darcy's Law states that a reduction in the hydraulic head differential will result in a proportional decrease in flow rate, all other factors being constant. If, for example, a lowering of the potentiometric surface leads to a 25% decrease in the hydraulic head differential at a spring, one would expect a similar percentage reduction in flow at that spring. It follows that the springs in the system with the smallest hydraulic head differential, i.e., the highest elevation springs, will be relatively more sensitive to a uniform decline in the potentiometric surface of the carbonate rock aquifer resulting from groundwater pumping. This concept is illustrated in **Figure 1.19**.

Data Sources and Data Quality

The data we used in our analyses, including the source, type, and frequency of the data; period of record and site history; monitoring agency or organization; quality of the data; and location and physical characteristics of the site will be discussed in this section. **Figure 1.20** shows the location of all the monitoring sites described here. For surface water monitoring sites, we found it convenient to distinguish between spring monitoring sites (those sites located directly at the springpool outflows) and flow monitoring sites (those sites located some distance downstream of the springpools). All data presented here, along with the graphical and statistical analyses, are appended as data files to this report.

There are two carbonate monitoring wells in the MRSA near the Refuge: EH-4 and EH-5b (**Figures 1.1 and 1.20**). Both wells are monitored by Nevada Energy and have periodic measurements since 1986, with continuous data available since 1997. The water level elevations and trends at both monitoring wells are very similar and highly correlated (see **Figure 1.2** and the appended data file: Order 1169 EH4 Data_NDWR_Dec 2012.xlsx, for a comparison of the two wells). Because the data from EH-4 are less erratic and more complete, and the well is physically located closer to the Refuge, we use EH-4 data here and assume that the water level in EH-4 is representative of the elevation of the potentiometric surface in the regional carbonate-rock aquifer in the MRSA. There is some uncertainty associated with this assumption; the hydraulic head at the springs themselves may differ from that represented by water levels at EH-4. The springs are physically located some distance from EH-4 and the aquifer depth at which the springs are sourced may not correspond with the depth of the well opening at EH-4. Nevertheless, the EH-4 data were used to develop relationships between carbonate water levels and discharge at various sites in the MRSA.

We also used periodic measurements of shallow groundwater levels from October 2009 through December 2012 in nine monitoring wells located in the MRSA. These data are collected and reported by the Southern Nevada Water Authority (SNWA).

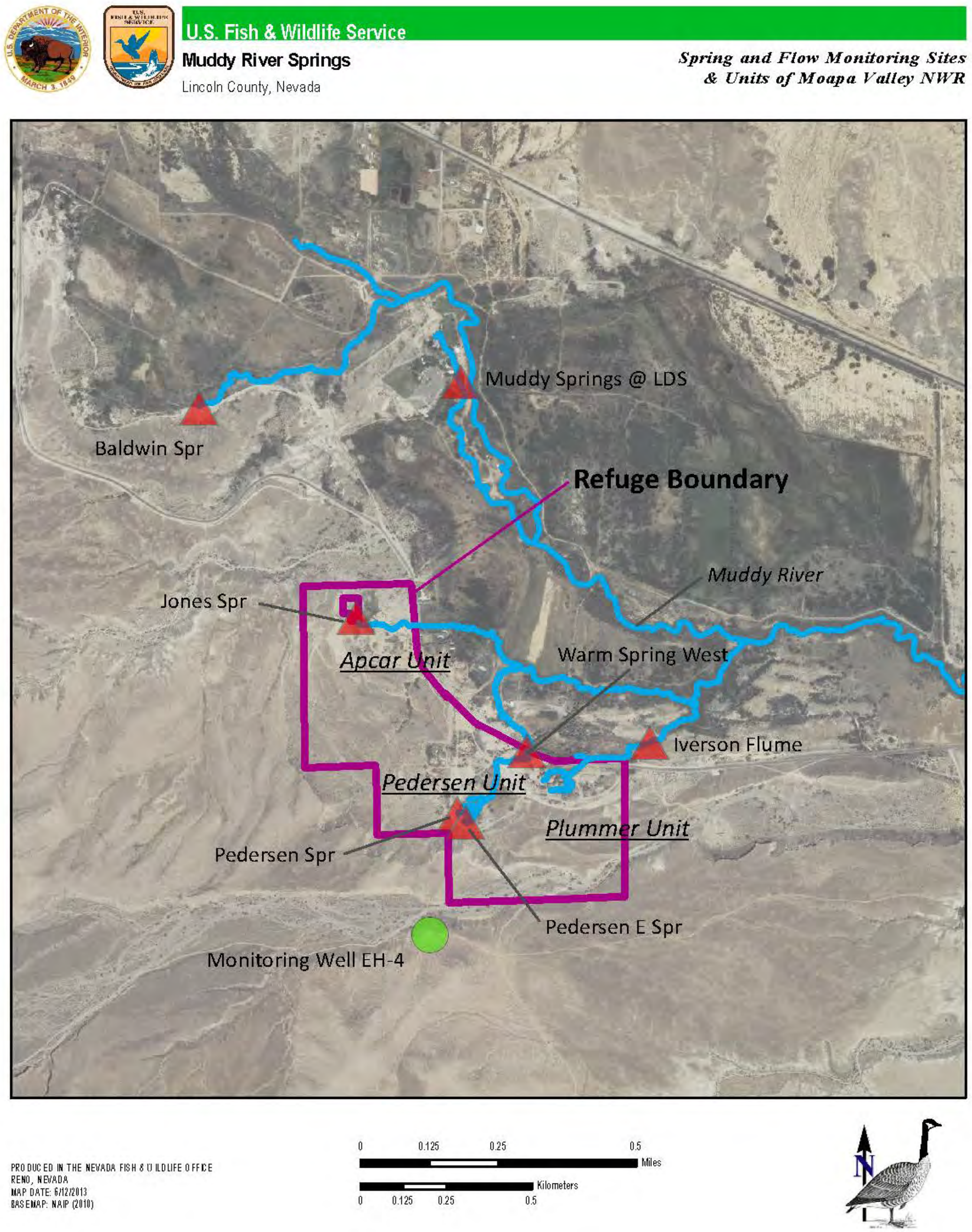

Figure 1.20. Map showing the locations of spring and flow monitoring sites; the boundary and three units of the Moapa Valley NWR; as well as the EH-4 carbonate monitoring well, all discussed in this section of the report.

The Moapa Valley NWR consists of three units: the Pedersen[8] Unit, the Plummer Unit, and the Apcar Unit (**Figure 1.20**). The springs on the Pedersen Unit are the highest elevation springs in the MRSA. Given the expected sensitivity of the higher elevation springs and the importance of the Warm Springs West, we mainly focus our analyses on this area. There are three continuously monitored USGS sites on the Pedersen Unit: Pederson Spring (USGS Site No. 09415910), Pederson East Spring (USGS Site No. 09415908), and Warm Springs West (USGS Site No. 09415920). Pederson Spring and Pederson East Spring are two spring monitoring sites that measure the outflows from the springpools. Both springs have historically averaged about 0.2 cfs until recently. Warm Springs West is a flow monitoring site that measures the combined discharge from diffuse groundwater seepage and five major spring groups located about 0.1-0.2 miles upstream on the Pedersen Unit of the Refuge.

Pederson Spring (USGS Site No. 09415910) has been monitored continuously by the USGS with a v-notch weir since 1986, with data gaps from 1994 to 1996 and 2003 to 2004. The v-notch weir readings are converted to flow using an independent rating developed by the USGS for the site. Finalized flow data are available through February 21, 2013 at this site. The early record is variable and may have been affected by poor check measurements, diversions from the springpool, a major fire at the site in 1994, leakage under the weir, and other factors. In April 2004, the old v-notch weir was replaced with a new v-notch weir because of leakage around the old weir. Ratings for the new weir were adapted by USGS in October 2004 and again in April 2010. The gap in the record from February 2003 to April 2004 is due to questions about leakage and accuracy of the old weir during this period. The relationship of spring discharge to EH-4 water levels is significantly different ($p=0.0000$) for the old weir and the new weir, in terms of slope and intercept (see appended data file: USGS 09415910_Pederson Sprs nr Moapa_all data_1985-2013.xlsx). This suggests that measurements from the two periods may not be comparable. For this reason, we only use the record from the new weir since 2004 when considering the relationship of Pederson springflow to EH-4 water levels.

Pedersen East Spring (USGS Site No. 09415908) has been monitored continuously since 2002 with a v-notch weir. The v-notch weir readings are converted to flow using an independent rating developed by the USGS for the site. New ratings were adapted by USGS in October 2002 and again in April 2010. Finalized flow data are available through February 21, 2013 at this site. Pedersen East Spring is the highest elevation spring in the Pedersen East Spring group but there are several other springs in the spring group that are comparable in flow. The combined flow of the Pederson East Spring group, which includes Pederson East spring, has been measured periodically with a current meter by the USGS, as discussed below.

Warm Springs West (USGS Site No. 09415920) has been monitored continuously with a flume since 1985. Flume readings are converted to discharge using the theoretical stage-discharge relationship of the flume. Finalized flow data are available through February 20, 2013 at this site. Unmetered irrigation diversions on the Refuge upstream of the site during the first half of the record resulted in

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[8] There are two different spellings of this name: Pedersen with an "e" at the end is the correct spelling of the landowner's last name. Pederson with an "o" at the end is an incorrect spelling of the landowner's name, but was adopted by the USGS for the spring and stream names. We will use both spellings here, in context.

measurements that were quite variable throughout the period. The variability in flows was greatly reduced once these diversions were discontinued after 1999 (**Figure 1.21**). For this reason, we only use the measurement record after 1999 when considering the relationship of Warm Springs West discharge to EH-4 water levels.

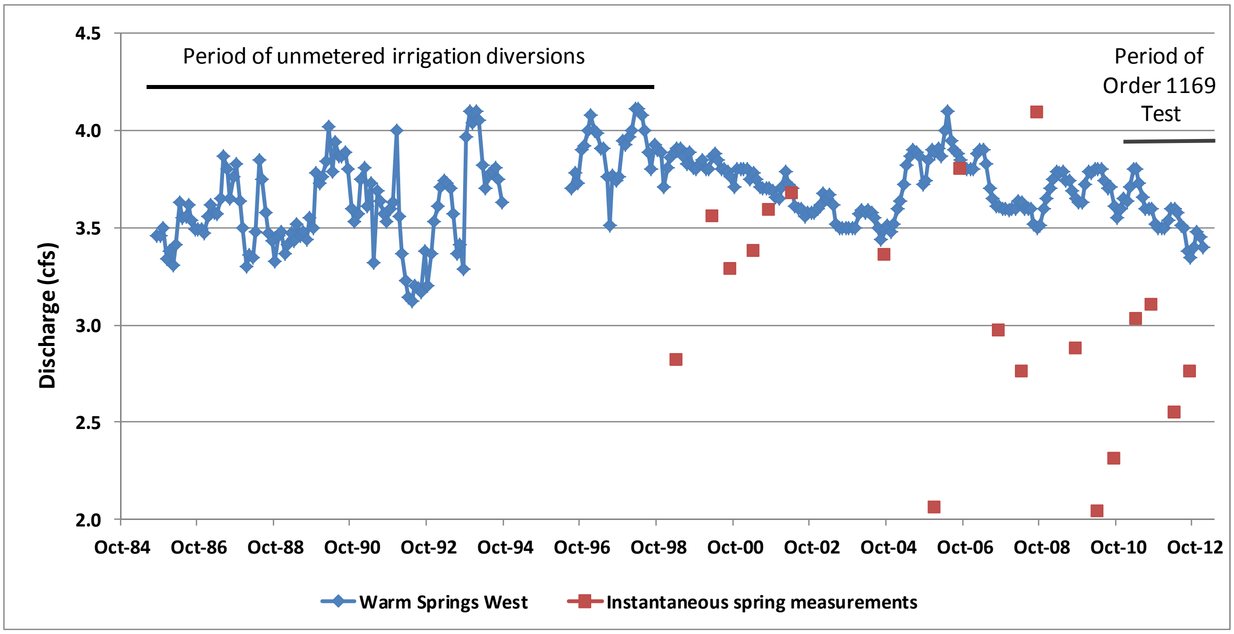

Figure 1.21. Monthly flows at the Warm Springs West gage (USGS No. 09415920) from 1985 to 2012 and the sum of instantaneous measurements collected upstream of the gage by USGS at M-11, M-12, M-13, M-19, and Pederson Spring twice a year from 1999 to 2012.

The Warm Springs West gage captures the discharge produced from Pederson and Pederson East Springs, in addition to several other smaller springs and diffuse groundwater seepage occurring upstream of the gage. The majority of flow at the gage is produced by four major spring groups (M-11, M-12, M-13, and M-19) that are larger and downstream of the Pederson and Pederson East springs. The USGS has been collecting synoptic measurements of spring discharge at these spring groups with a current meter or SonTek FlowTracker about twice a year (usually spring and fall) since 1999. The sum of the instantaneous measurements from these sites and the concurrent flow from Pederson Spring on the same date (which is not captured by any of the synoptic measurements), is shown in **Figure 1.21**. The outflow channels at these four spring groups (M-11, M-12, M-13, and M-19) are small, shallow, and narrow and are difficult to measure, resulting in much more variability than the v-notch weir or flume measurements.

The sum of these periodic measurements (**Figure 1.21**), which include all spring discharge contributing to the Warm Springs West gage, is usually less than the flow measured at the Warm Springs West gage located about 0.1 miles downstream. The remaining flow at the gage is assumed to come from diffuse groundwater seepage into the channel, upstream of the gage. Reportedly, USGS and FWS biologists have observed cool-water inputs in the lower part of the stream, just upstream of the Warm Springs West gage, while snorkeling during fish surveys.

Other USGS sites examined and discussed in this report include three USGS flow monitoring sites: the Warm Springs confluence at Iverson flume (USGS Site No. 09415927), the Muddy Springs at LDS Farm nr Moapa (USGS Site No. 09415900) and the Muddy River nr Moapa (USGS Site No. 09416000). The Iverson flume is located off the Refuge, about 0.25 miles downstream of the Plummer Unit springs, and therefore measures a combination of carbonate springflow, rainfall runoff, and diffuse groundwater seepage emanating upstream of the gage. From October 2001 through October 2008, the Iverson Flume gage measured the combined outflows of the Pedersen and Plummer Units of the Refuge. However, in October 2008, the outflow from the Pedersen Unit, downstream of Warm Springs West, was disconnected from the Plummer outflow stream and restored to a historical stream channel. The post-restoration average flow at the Iverson Flume gage is about half of the pre-restoration average since the Pederson outflow stream is no longer captured in the measurements. We only use the measurement record during the pumping test when considering the relationship of Iverson flume discharge to EH-4 water levels. Finalized flow data are available through September 2012.

In addition to the springs on the Plummer Unit, there is at least one large spring downstream of the Refuge boundary that contributes flow to the Iverson Flume gage. The USGS has collected periodic measurements of the outflow from the Plummer Unit at the Refuge boundary (USGS Warm Spring East, Site No. 364236114424301), upstream of this spring and the Iverson Flume gage. The nine measurements from 2008 through 2012 range from 2.13 cfs to 2.79 cfs and average 2.53 cfs, a little over half the post-restoration flow measured at the Iverson Flume gage since 2008. So the contribution from the large downstream spring and any other spring discharge and shallow groundwater seepage in the reach between the Refuge and the gage is considerable.

The Muddy Springs at LDS Farm nr Moapa (USGS Site No. 09415900) measures the spring discharge from the largest and lowest elevation spring in the MRSA. The spring, which had been used to maintain two swimming pools on the LDS property, has a continuous record of flow from 1985 to the present. According to the USGS site description, the site is located 0.1 miles downstream of the LDS pools and measurements at the site are affected by irrigation and recreation diversions for the pools upstream. The two large pools and the recreational facility have not been operated since they burned in the July 2010 fire, just prior to the pumping test. Finalized flow data are available through September 2012 for this site.

The Muddy River near Moapa site (USGS Site No. 09416000) measures the discharge in the Muddy River, just downstream of the MRSA. This site also has a continuous record of flow from 1985 to the present. The site measures a combination of carbonate spring discharge, shallow groundwater discharge, irrigation return flow, and rainfall runoff. We did attempt to relate discharge at the Muddy River site to carbonate water levels in EH-4 due to the influence of these other factors. Finalized flow data are available through September 2012 for this site.

We also consider data from two other spring monitoring sites in the MRSA: the daily total natural spring discharge at Jones Spring and Baldwin Spring, collected and reported by MVWD for the period August 2010 to December 2012 and available on the NDWR Order 1169 webpage http://water.nv.gov/mapping/order1169/. Both sites are located very close to the carbonate spring source and therefore, will primarily measure spring discharge from the regional carbonate springs only. The time series plot of discharge at both of these sites shows some questionable measurements during short periods of the pumping test (see appended data file: MVWD_data_Baldwin_Jones_daily_monthly 2010-2012.xlsx). We assumed there were problems with these values and we excluded data from these periods in developing the relationships between discharge and carbonate water levels during the pumping test at these sites. There was little difference in regression slopes with and without the excluded data. The appended datafile for these sites provides comparisons of the regression results.

Methods

For this section of the report, we consider monthly data for the period of the Order 1169 pumping test, which is considered to be from October 2010 to December 2012, the first and last complete months of the test. We focus on the period of the pumping test primarily but look at longer periods as well, depending on the site and the availability of data.

For the spring and flow monitoring sites, we conducted graphical and statistical analyses. We examined the relationship between discharge and climate graphically. We examined the relationship between discharge and pumping statistically, by correlating monthly discharge with monthly carbonate water levels in EH-4 for the period of the pumping test and for longer periods, where data are available. We calculated the slope and r^2 values for these relationships and estimate the maximum, minimum, and change in discharge observed during the pumping test. Because there is variability in the actual field discharge measurements, we used the regression equations from the discharge/EH-4 water level relationship to estimate discharge at a given carbonate water level.

For each site, we estimated the maximum, minimum, and change in the hydraulic head differential during the pumping test by computing the difference between the water surface elevation at the spring(s) contributing to the site and the carbonate water levels observed in EH-4 during the test. We then compared our estimates of the relative changes in hydraulic head differential during the pumping test, expressed as a percent, with the relative changes in discharge observed at each site, also expressed as a percent. Our assumption, as discussed above, is that relative changes in head differential and discharge should be approximately equal. Using the drawdown rate that we determined for EH-4 during the pumping test and the discharge/water level relationships, we estimate when discharges at key spring and flow monitoring sites will reach certain points of interest, assuming the level of pumping, drawdown, and decline in flow continue at the rate observed during the test. Lastly, we finish this part of the report with a discussion of some of the other factors that may have affected water levels and discharges during the period of the pumping test.

Results and Discussion

Pedersen Unit

Figures 1.22 and **1.23** show spring discharge at the three continuous surface water monitoring sites on the Pedersen Unit of the Refuge, along with water year precipitation in NV Climate Division 4. Springflow measurements are more variable than groundwater level measurements. Note that the discharge scale for the Warm Springs West gauge only extends from 3.0 to 4.2, while that for the Pederson gauges extend from 0.0 to 0.35. Thus the variability in the Pederson flows are proportionally larger than those for Warm Springs West. The seasonal cycles and trends in flows since 2000 generally mirror the carbonate water levels, decreasing from 2000 through 2004 due to increased carbonate pumping, increasing in 2005-2006 in response to the 2005 wet year, and declining overall during the 2-year pumping test. As with the groundwater levels, the lowest spring flows in the record at all of these sites occur during 2012, near the end of the pumping test despite the wet year in 2011. However, as can be seen on the figures, not all the spring measurement sites show the same degree of response to groundwater level declines, mainly because of differences in spring elevations, as discussed above. Next, we examine those individual responses in more detail, by considering relationships between discharge and carbonate water levels in EH-4.

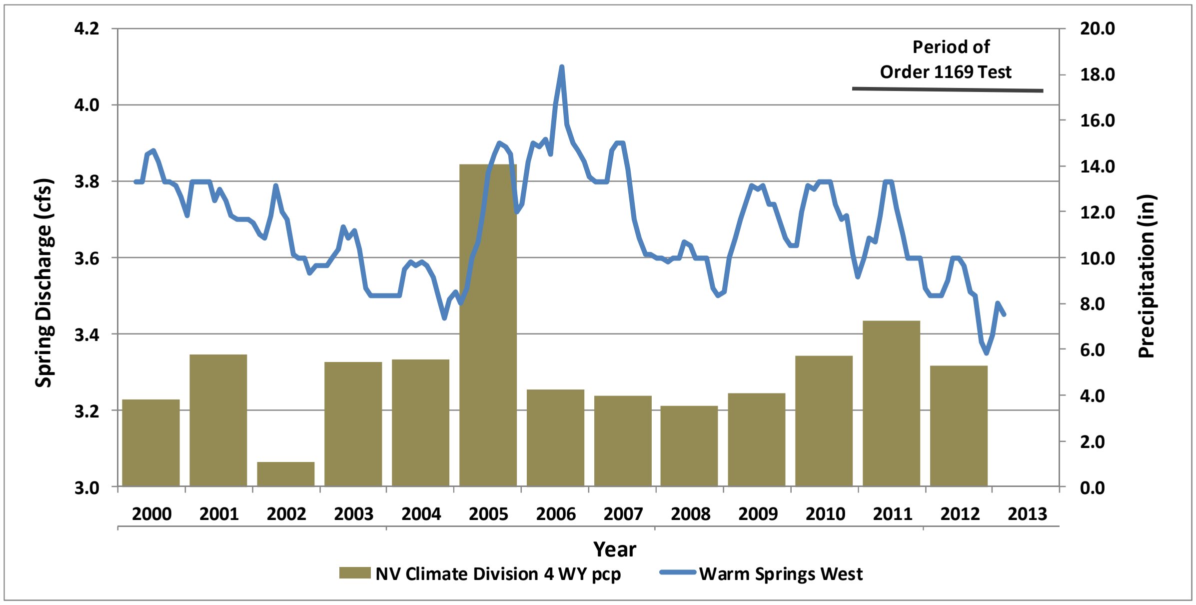

Figure 1.22. Monthly flows at the USGS Warm Springs West gage (USGS No. 09415920) and Nevada Climate Division 4 water year precipitation (centered on April of each water year) for the period Jan 2000 to Dec 2012.

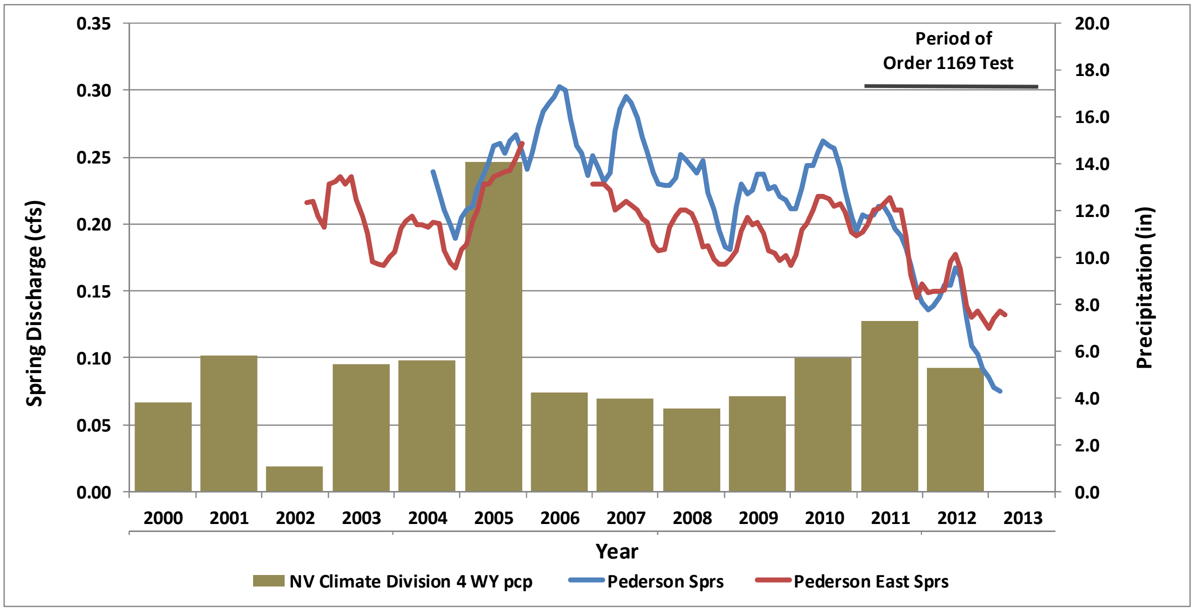

Figure 1.23. Monthly flows at the USGS Pederson Spring gage (USGS No. 09415910), Pederson East Spring gage (USGS No. 09415908), and Nevada Climate Division 4 water year precipitation (centered on April of each water year) for the period Jan 2000 to Dec 2012.

The first spring considered is the Pederson Spring, the highest elevation spring in the area (the gage datum or zero point of flow is 1810.99 ft). During the pumping test, the flows at Pederson Spring declined from a maximum of 0.22 cfs to 0.08 cfs (a 0.14 cfs or 63% reduction total from the maximum flow observed during the pumping test, **Figure 1.24**). The correlation between spring discharge and water level for EH-4 is very high (r^2 = 0.98 during the pumping test and r^2 = 0.93 for the entire 2004-2012 record). The slope of the discharge-water level relationship over the pumping test equates to -0.062 cfs (-28%) per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline in the EH-4 water level, Pederson Spring loses about 0.06 cfs of discharge (about 28% relative to the maximum discharge observed during the pumping test). The next question we address is: “Is this reasonable and close to what we expect for this site?”

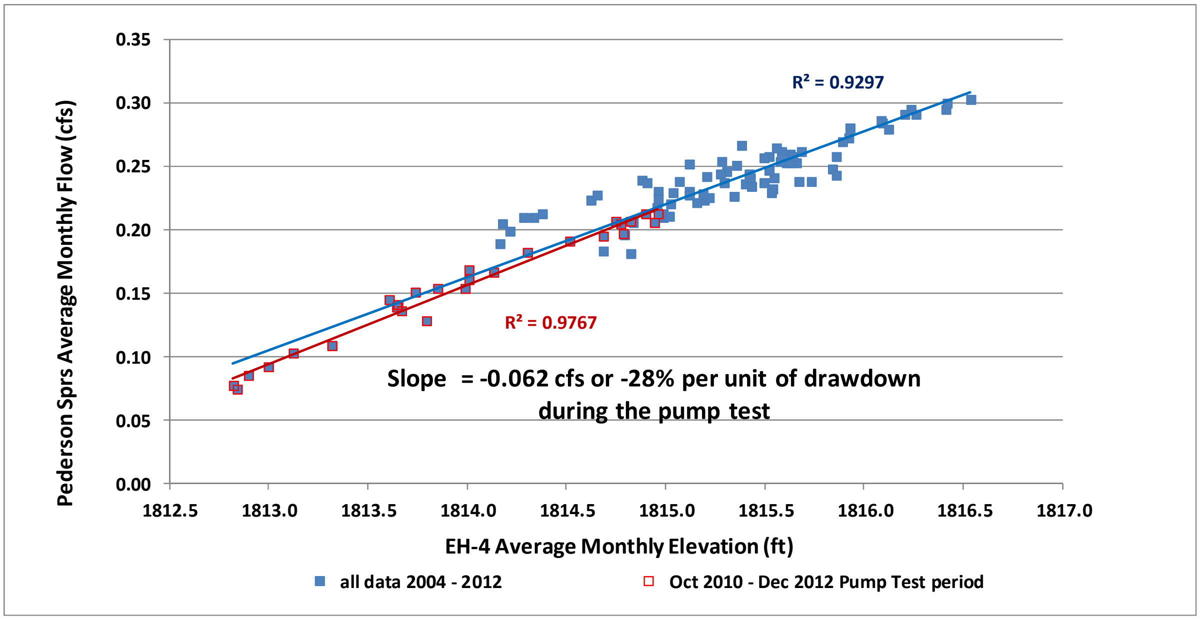

Figure 1.24. Monthly flows at Pederson Spring versus monthly carbonate water level elevations in EH-4 for the period May 2004 to Dec 2012.

The maximum and minimum monthly EH-4 carbonate water level elevations observed from October 2010 to December 2012 were 1815 ft and 1812.8 ft, respectively. At the maximum groundwater level elevation, Pederson Spring, with a water surface elevation of 1811 ft, had a hydraulic head differential of 4.0 ft (the “head differential” being estimated as the difference between EH-4 water level elevation and the spring water surface elevation). At the minimum EH-4 water level elevation observed during the pumping test, 1812.8 ft, the “head differential” is only 1.8 ft. Based on these two estimates, there is a predicted 25% decrease in hydraulic head differential per unit foot of drawdown, or a total reduction in head differential of 55% (assuming the maximum head of 4.0 ft represents 100%). Under the assumption that flow is proportionate to head, we should expect a similar percentage decline in flow. As shown above, there was a 28% decrease in flow per unit foot of drawdown or about 63% over the 2.2 foot range of carbonate water levels observed during the pumping test. The observed decline is very close to the independent estimate. The spring appears to be behaving in response to the decline in carbonate water levels and head differential as expected.

The x-intercept of the discharge/water level regression for the period of the pumping test is 1811.5 ft (**Figure 1.24**). This is the predicted carbonate water level elevation at which the spring discharge goes to zero (the spring dries up), based on the relationship between spring discharge and EH-4 levels. It differs from the estimated spring water surface elevation, perhaps because of the errors associated with the assumption that the water level in EH-4 represents the hydraulic head at the springs. Anyway, if the current rate of drawdown in EH-4 (0.92 ft/year) continues, the spring will stop flowing in about 1.5 years.

Next, we consider Pederson East Spring, which is the second highest elevation spring in the area, with a gage datum or zero point of flow of 1807.7 ft. During the pumping test, the flows at Pederson East Spring ranged from 0.22 cfs to 0.12 cfs (a 0.10 cfs or 45% reduction in total discharge, **Figure 1.25**). The correlation between spring discharge and EH-4 water level for Pederson East Spring is high during the pumping test but poorer for the entire period of record (r^2 = 0.92 during the pumping test and r^2 = 0.59 for the entire record). The reason for the poorer correlation over the entire record is not clear but it may indicate some changes or problems in the earlier flow record at the site. The slope of the relationship over the pumping test equates to -0.043 cfs (-21%) per unit foot of drawdown in the carbonate-rock aquifer. This means that for every one foot decline observed in the EH-4 water level, Pederson East Spring loses about 0.04 cfs (or about 21% per unit foot of drawdown). This is less than Pederson Spring, as expected, since Pederson East Spring is slightly lower in elevation and has a greater hydraulic head differential, and therefore, should be less sensitive to drawdown (see **Figure 1.19**).

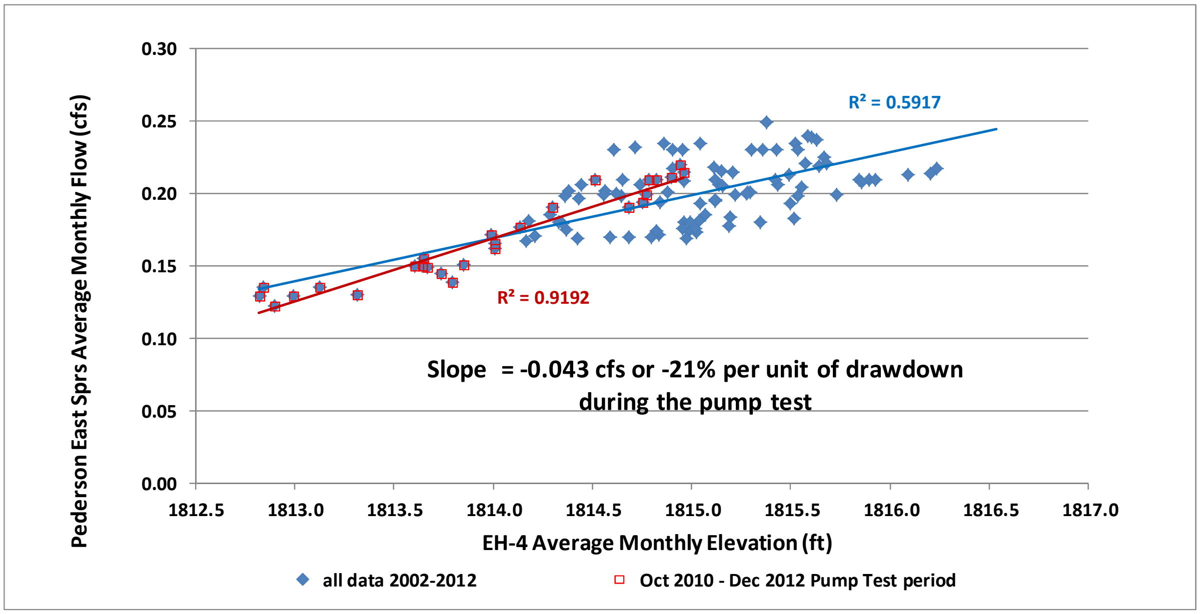

Figure 1.25. Average monthly flows at Pederson East Spring versus carbonate water level elevations in EH-4 for the period June 2002 to Dec 2012.

At 1815 ft., the maximum EH-4 carbonate water level elevation observed during the pumping test, Pederson East Spring has a hydraulic head differential of 7.3 ft (based on a water surface elevation of 1807.7 ft). At 1812.8 ft., the minimum EH-4 elevation observed, the “head differential” is 5.1 ft, which represents a 30% reduction in head from the maximum EH-4 water level elevation during the test. For every unit foot of drawdown, we expect about a 14% decrease in hydraulic head differential and flow. As shown above, the observed decline in flow was greater than this, about 21% per unit of drawdown or about 45% over the range of carbonate water levels. Nevertheless, the estimated and observed reductions are less than at Pederson Spring, and the Pederson East Spring discharge appears to be less sensitive to drawdown, as expected.

The x-intercept of the regression for the period of the pumping test is 1810.1 ft (**Figure 1.25**). This is the predicted carbonate water level elevation at which the spring discharge will go to zero. As with Pederson Spring, the elevation of the x-intercept of the regression differs from the water surface elevation of the spring, perhaps because of errors associated with the assumption that EH-4 exactly represents the hydraulic head at the spring. If the current rate of drawdown in EH-4 (0.92 ft/year) continues, the spring will stop flowing in about 2.5 to 3 years.

The relationship of Warm Springs West flow to carbonate water levels in EH-4 is shown in **Figure 1.26**. The correlation between discharge and water level for Warm Springs West is fairly high during the pumping test and for the entire period of record (r^2 = 0.79 during the pumping test and r^2 = 0.70 for the entire record). We may expect a poorer correlation between discharge and carbonate water levels at this site compared to the other two spring sites because the site is downstream of the major springs and may be responsive to shallow basin-fill aquifer water levels and rainfall runoff, as well as carbonate-rock aquifer water levels.

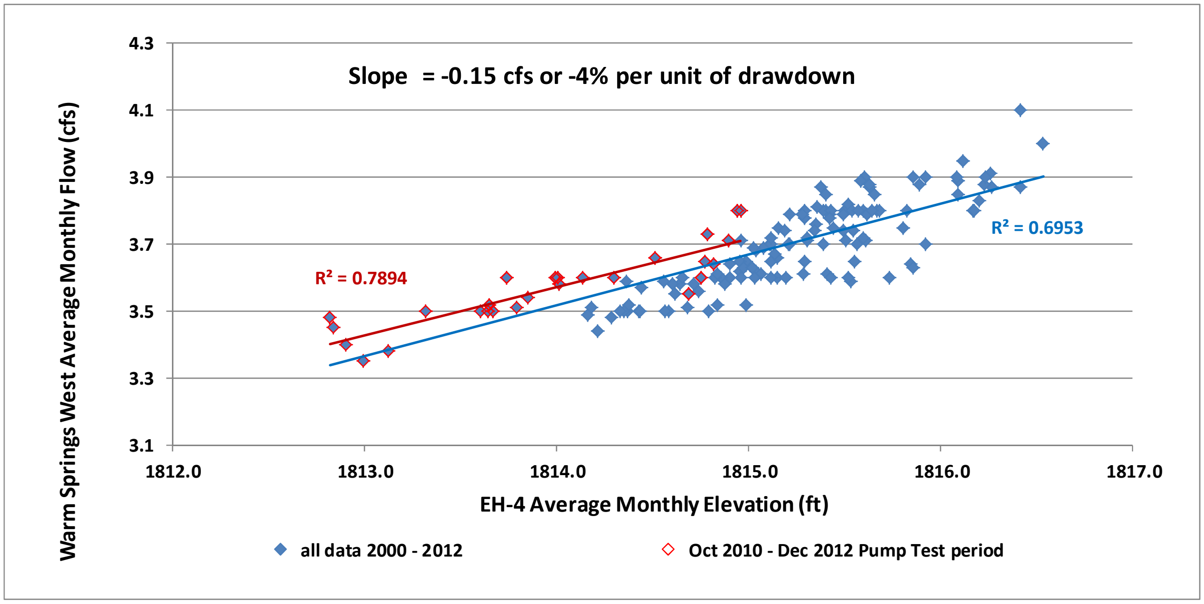

Figure 1.26. Average monthly flows at Warm Springs West versus carbonate water level elevations in EH-4 for the period Jan 2000 to Dec 2012.

During the pumping test, Warm Springs West declined from an average flow of 3.72 cfs, at a carbonate water level elevation of 1815.0 ft, to an average flow of 3.40 cfs, at a water level elevation of 1812.8 ft. The total decline equates to about 0.32 cfs (9%) or about a 4% decrease from the pre-test flow rate per unit foot of drawdown. The total decline, 0.32 cfs, is 0.09 cfs greater than the sum of the declines (0.13+0.10=0.23 cfs) observed in the Pederson and Pederson East Springs, located upstream of the gage. Note that there appears to be little or no decline in flow during the first year of the pumping test at the Warm Springs West gage; most of the decline is observed in the second year (see **Figure 1.22**). We believe that higher precipitation during the first year of the pumping test may have increased shallow groundwater seepage upstream of the gage and countered some of the effects of pumping.

Next, we compare the observed decline with the estimates of the expected decline at the Warm Springs West gage, given the range of carbonate water levels at EH-4 observed during the pumping test. Since the Warm Springs West gage measures the combined discharge from a number of individual springs, estimating the hydraulic head differential at the site is more involved. The majority of flow at the Warm Springs West gage is accounted for with measurements at Pederson Spring and the four major spring groups measured by the USGS twice a year: Spring 19, Spring 13, Spring 12, and Spring 11. (The discharge at Pederson East Spring is included in the measurement at Spring 19). Beck et al. (2006) provides information on the approximate elevation of these different spring groups. Using these approximate elevations, we estimated the reduction in head differential at each spring group and applied this reduction to the average flow, available from the periodic measurements from each of the spring groups (M-19, M-11, M-12, M-13).

The approximate elevations, average flows, estimated head differentials, and estimated reductions in head for each spring or spring group are shown in **Table 1.2**. Because the periodic flow measurements at the spring groups are so variable, we used the measurements from September 2007 to September 2010 (a period when EH-4 elevations averaged 1815.2 ft, see **Figure 1.2** and **1.3**) to calculate the average flow at each of the four spring groups prior to the start of the pumping test. The total discharge at all four measurement sites, along with flows at Pederson Spring, averaged 2.88 cfs for this period (these measurements are plotted **Figure 1.21**). The average of the daily flows at the Warm Springs West gage on concurrent dates for the same period is 3.65 cfs. Approximately 80% of the flow at the Warm Springs West gage is accounted for with the spring measurements during the 2007 to 2010 period.

Using the maximum and minimum carbonate water levels observed at EH-4 during the pumping test, (1815 ft to 1812.8 ft), the proportional reductions in head differential at the five spring groups are 55% at Pederson Spring and 9% to 17% at the other four spring groups. Multiplying the estimated proportional reduction in head differential by the average flow from 2007-2010 at each of the five spring groups shows that the contribution of the springs should have been reduced in total by about 0.5 cfs during the pumping test. Applying a similar reduction in flow at the Warm Springs West gage means the flow during the pumping test should have declined by about 0.5 cfs or 14% in total. The observed decline during the pumping test was slightly less than this, about 0.32 cfs or about 9% in total. Nevertheless, the relative decline at Warms Springs West is considerably less than at Pederson and Pederson East Springs, as expected based on the lower elevations of the other springs.

Plummer Unit, Apcar Unit, and other MRSA Sites

Next, we examine the observed and/or expected reductions in discharge at springs on the Plummer and Apcar Units and elsewhere in the MRSA, given the changes in carbonate water levels observed during the pumping test. Springs in all of these areas are lower in elevation than the springs on the Pederson Unit, so they are expected to be less sensitive to declines in carbonate water levels.

Table 1.2. Periodic measurements and characteristics for the major spring groups on the Pedersen Unit.

Spring or spring group	Water surface elev (ft)	Estimated head differential (ft) at EH-4 = 1815 ft	Average flow (cfs) 2007-2010	Estimated reduction during pumping test (%)	Estimated flow in Dec 2012
Pederson Spring	1811.0	4	0.23	55%	0.10
M-19 (this site includes the discharge from Pederson East Spring)	1802.0	13	0.86	17%	0.71
M-13	1799.5	15.5	0.69	14%	0.59
M-12	1798.5	16.5	0.31	13%	0.27
M-11	1791.5	23.5	0.79	9%	0.72
Total of all springs			2.88		2.40
Warm Springs West (average on same dates)			3.65		*3.17**

This is the estimated flow, applying the reduction that should have been observed at the Warm Springs West gage during the pumping test. As shown above in* ***Figure 1.28**, the flow at Warm Springs West during the pumping test ranged from 3.72 cfs at 1815 ft to 3.40 cfs at 1812.8 ft.*

Monthly flows at the USGS Iverson gage along with water year precipitation in NV Climate Division 4 are shown in **Figure 1.27** for the period October 2008 to December 2012, the period following the restoration of the Pederson channel. Flows were fairly stable during the first part of the pumping test but decreased slightly during the last part of the pumping test. The timing of the decline is similar to Warm Springs West and the flows at this site may have been influenced by the 2011 wet year as well.

The variability and increase in flows observed in 2008-09 may be a response to the restoration itself. The Plummer stream bank at the site of the old Pederson confluence was reconstructed and “shored up” as part of the restoration. There was likely a temporary increase in channel losses along this section of the channel after the restoration. As the reconstructed stream bank became saturated and sealed itself, channel losses would have declined, resulting in an increase in flows measured downstream at the Iverson flume. We have observed a similar response (a period of high initial channel losses followed by recovering flows) with stream restoration work at Ash Meadows NWR. Since this increase is believed to be an artifact of the restoration work, we didn’t attempt to correlate discharge with carbonate water levels prior to the pumping test.

The relationship of Iverson Flume flows to carbonate water levels in EH-4 during the pumping test is shown in **Figure 1.28**. The relationship is poor (r^2=0.42) but this is not surprising since the site is located a considerable distance from the springs (about 0.25 miles downstream) and measurements may be responsive to shallow basin-fill aquifer water levels and rainfall runoff, as well as carbonate-rock aquifer water levels. Discharge measurements at the Iverson Flume gage ranged from an average of 4.64 cfs to 4.38 cfs during the pumping test (finalized data are available only through Sept 2012). This is a decline of 0.13 cfs (2.7%) per unit foot of drawdown and 0.25 cfs (5%) over the first two years of the pumping test. Extrapolating this rate of decline through December 2012 gives a total decrease in discharge of 0.28 cfs or 6% during the pumping test.

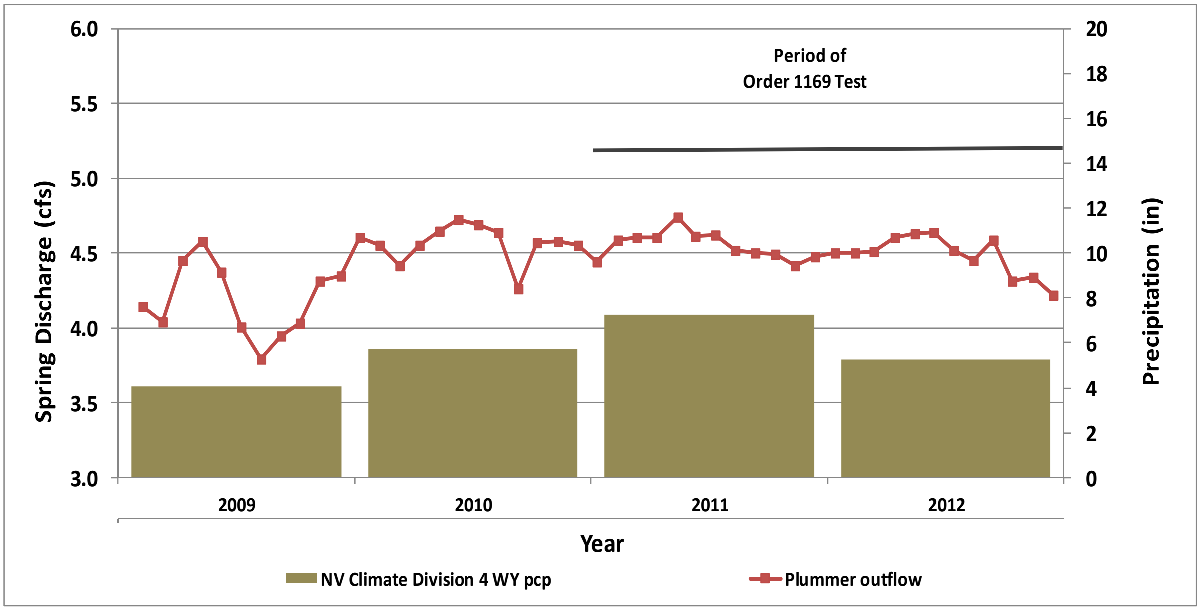

Figure 1.27. Monthly flows at the USGS Iverson Flume gage (USGS No. 09415927) for the period Oct 2008 to Sept 2012 and Nevada Climate Division 4 water year precipitation (centered on April of each water year) for the same period.

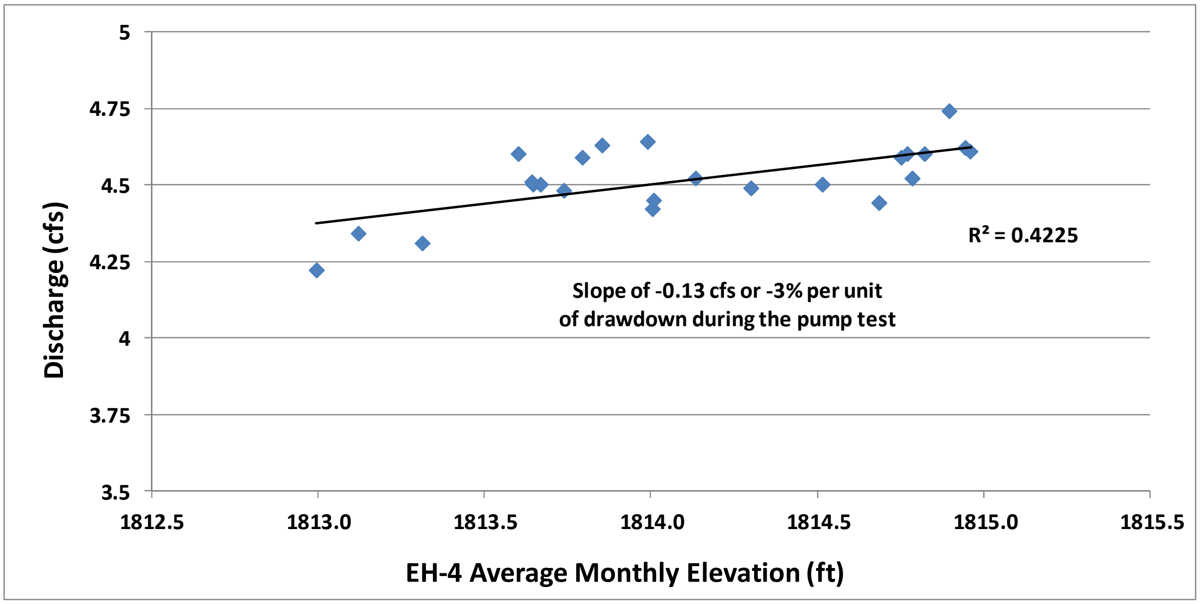

Figure 1.28. Average monthly flows at the Iverson Flume versus carbonate water level elevations in EH-4 for the period Oct 2010 to Sept 2012.

The springs contributing to the Plummer stream outflow are much lower in elevation than those on the Pederson Unit. Beck et al. (2006) give the elevations of USGS sites M-15, M-16, and M-20 (all measuring springs on the Plummer Unit) as 1749.2, 1757.2, and 1749.8 ft, respectively. This means there was 58 to 66 ft of head differential or more at these springs at the start of the pumping test. The spring(s) downstream of the Refuge are even lower in elevation and less sensitive to drawdown, but they contribute close to half of the discharge measured at the Iverson Flume gage. Applying the 2.2 ft decline of carbonate water levels observed during the pumping test indicates the head differential at the Plummer Unit springs was reduced by 3% to 4%. The observed decline of 6% for the pumping test is slightly greater than what is estimated for the Plummer Unit, although the discharge/water level relationship is poor and the regression slope estimate has a large uncertainty in it.

The time series plots of daily total natural discharge at Jones and Baldwin Springs for the period of the pumping test is shown in the appended data file for these two sites. The relationship of the monthly total natural discharge at both springs to monthly carbonate water levels in EH-4 is shown in **Figure 1.29**. At Jones Spring, the correlation is very high during the pumping test ($r^2 = 0.90$). For the period of the pumping test, Jones Spring declined from an average flow of 1.61 cfs, at a carbonate water level elevation of 1815.0 ft, to an average flow of 1.55 cfs, at a water level elevation of 1812.8 ft. This is a decline of 0.027 cfs (1.7%) per unit foot of drawdown or about 0.06 cfs (4%) in total.

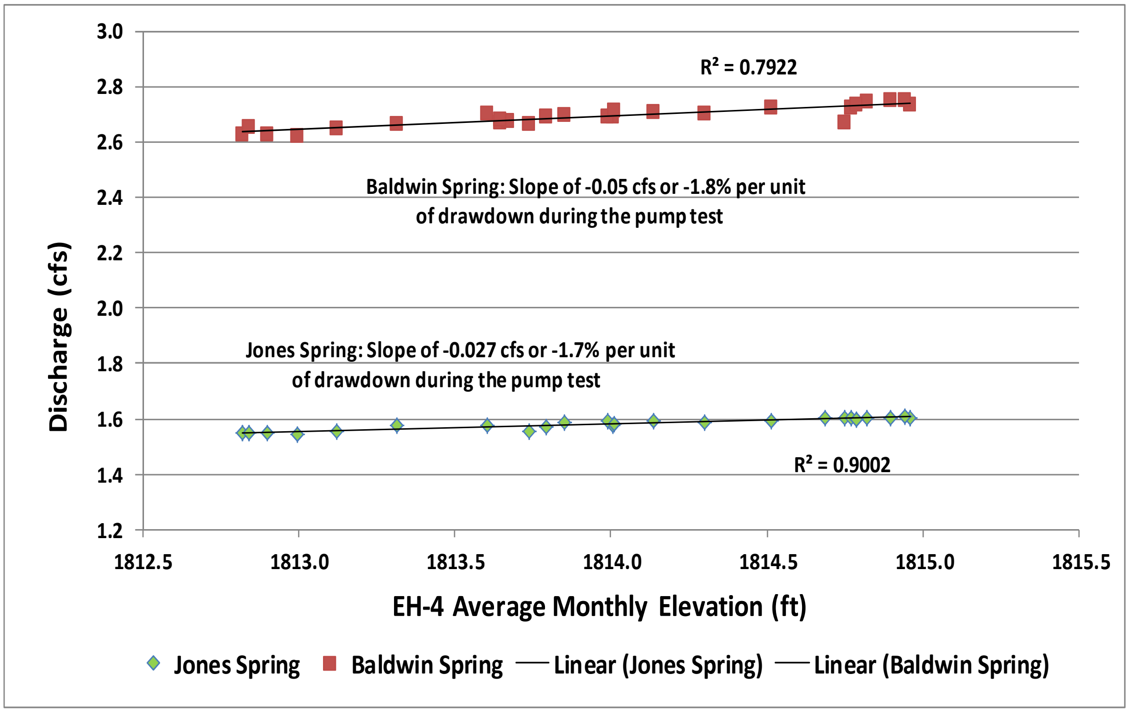

Figure 1.29. Average monthly flows at the Jones Spring and Baldwin Spring versus carbonate water level elevations in EH-4 for the period Oct 2010 to Dec 2012 (excluding Oct-Dec 2011 at Jones Spring and Oct 2010 at Baldwin Spring as discussed in Data Sources and Data Quality).

Beck et al. (2006) gives the elevation of a benchmark located 140 ft northwest of the Jones Spring pumphouse as 1775.72 ft. The actual spring elevation is unknown but assuming the springhead is the same elevation, the estimated hydraulic head differential is 39 feet at the spring at the start of the pumping test. A 2.2 ft drawdown in carbonate water levels represents a 6% decrease in the total head differential at the spring. Based on this, we would expect a 6% decrease in flow during the pumping test. The observed decline in flow of 4% during the pumping test is slightly less than this.
At Baldwin Spring, the correlation between total natural discharge and carbonate water levels in EH-4 is fairly high for the period of the pumping test (r^2 = 0.79, **Figure 1.29**). During the pumping test, Baldwin Springs discharge declined from an average flow of 2.74 cfs, at a carbonate water level elevation of 1815.0 ft, to an average flow of 2.63 cfs, at a water level elevation of 1812.8 ft. This is a decline of 0.05 cfs (1.8%) per unit of drawdown or about 0.11 cfs or 4% in total.

The elevation of a benchmark 100 feet east of the pumphouse at Baldwin Spring is 1775.68 ft (Beck et al., 2006). This is almost equal to the benchmark elevation for Jones Spring above. As with Jones Spring, the actual spring elevation is unknown, but assuming the springhead is the same elevation, then the elevation and head differential is the same as Jones Spring. The 2.2 ft decrease in carbonate water levels observed at EH-4 during the pumping test should result in a predicted decrease of 0.16 cfs (6%) in total. The observed decline of 4% total is slightly less than this (**Figure 1.29**). It is interesting to note that relative declines in flow observed at Jones Spring and Baldwin Spring are equal, although the absolute flows are almost double at Baldwin Spring. Based on the hypothesized relationship discussed above, the relative declines are expected to be equal, given the similarity in spring elevations.

The time series plot of discharge at the Muddy Springs at LDS Farm gage and the Muddy River nr Moapa gage are presented in **Figure 1.30** for January 2000 to September 2012, along with water year precipitation in NV Climate Division 4. Muddy Springs is the largest and lowest elevation spring in the MRSA, with an average flow of 7.6 cfs since 2000 and a water surface elevation of 1745.34 ft (Beck et al. 2006). With an estimated hydraulic head differential of 70 ft, this spring is expected to be the least sensitive to drawdown of any of the springs in the MRSA. Reportedly, according to the USGS, the site is not responsive to precipitation, unlike other flow monitoring sites in the area. This can be seen in the time series plot in the appended data file (USGS 09415900_Muddy Sprs at LDS Farm nr Moapa NV_all data_1985-2012.xlsx), which shows a lack of any clear wet year response, including 2005.

Muddy Spring flows are inversely correlated with carbonate water levels in EH-4 (r^2 = 0.45) during the pumping test, increasing with decreasing carbonate water levels, in contrast to all the other sites (see appended data file). This means there is a slight increase in flow during the pumping test. The correlation is very poor and the residuals with time show a major positive deviation in the second year of the pumping test, indicating a step change in the relationship due to some other factor. The most likely factor is the fact that the two large pools were drained and the recreational facility was essentially abandoned sometime after the fire that occurred in July 2010.

Flows at the Muddy River nr Moapa site show lots of variability and also a slight increasing trend in recent years (**Figure 1.30**). As discussed below, this site is likely responding to several factors including wetter than normal precipitation in 2011, fire effects, and land use changes and restoration activities in the MRSA. We did not attempt to correlate Muddy River flows to carbonate water levels.

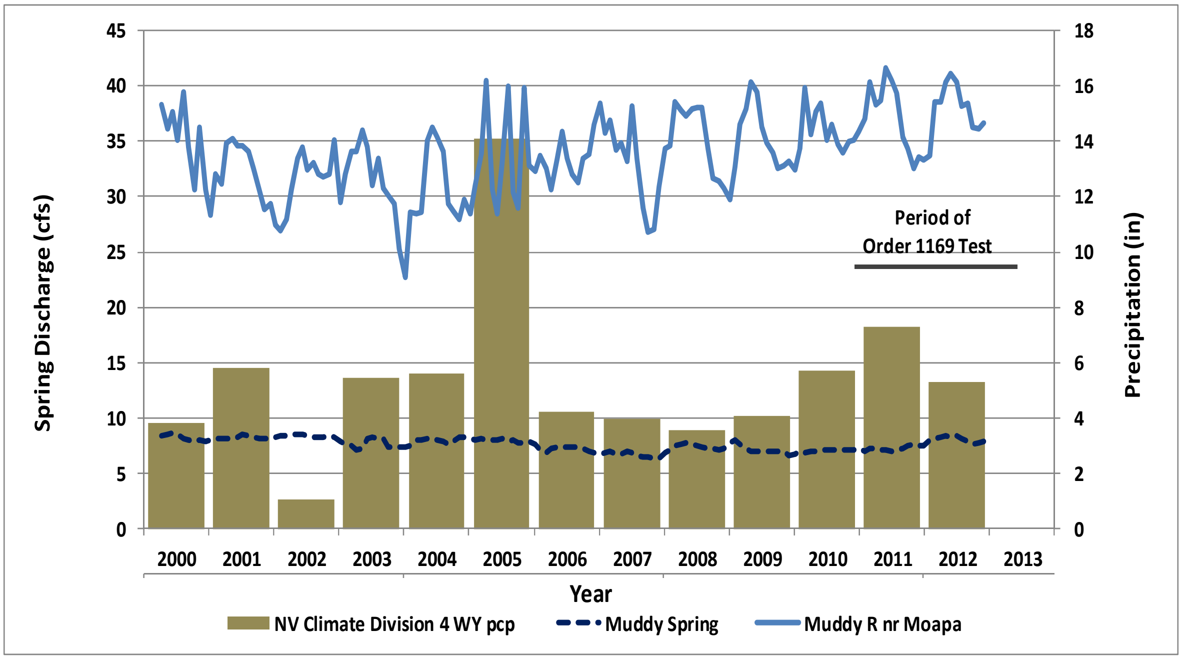

Figure 1.30. Monthly flows at the USGS Muddy Springs at LDS Farm nr Moapa (USGS Site No. 09415900) and the Muddy River near Moapa (USGS Site No. 09416000) for the period Jan 2000 to Sept 2012 and Nevada Climate Division 4 water year precipitation (centered on April of each water year) for the same period.

Other Factors Affecting Spring Discharge and Water Levels

Carbonate water levels and spring discharge in the MRSA are responding to several factors simultaneously and some of these factors cause opposing responses. The major factors that affect water levels and spring discharge in the area are precipitation and carbonate pumping (see the multiple regression presented earlier and Mayer and Congdon, 2008). The influence of precipitation and the wet year in water year 2011, which started in October 2010 at the same time as the pumping test, likely mitigated some of the response to pumping at Warm Springs West gage and the Iverson Flume gage (**Figure 1.22** and **1.27**). Neither flow gage appears to show declines in response to pumping until the 2nd year of the pumping test. The wet year may also be related to recent increases observed at Muddy Springs and the Muddy River gages, although other factors are likely involved as well.

One other factor could be the fire on July 1, 2010 in the MRSA that burned 600 acres, adjacent to the Refuge (**Figure 1.31**). The fire, which occurred just three months prior to the start of the pumping test, destroyed vegetation and resulted in a reduction in ET and an instantaneous increase in shallow water levels in the area of the burn (Christi Emery, SNWA, personal comm. related to a poster presented at the Nevada Water Resources Association 2013 annual conference). Huntington et al. (2013), in Figures 11, 13, and 14, present ET and precipitation in the MRSA from calendar years 2001 to 2012. While precipitation in CY 2005 and CY 2010 were about equal, ET in CY 2010 was much less than in CY 2005, likely because the fire burned much of the vegetation in the area. Figures 11 and 13 indicate that ET stayed low in CY 2011 and CY 2012, after the fire, as well. Precipitation and groundwater discharge that was not lost to ET probably made its way to the river, resulting in higher streamflows in the river. The burned area also included the pool and recreational facility upstream of the Muddy Springs gage, which may be partly responsible for the increase in flows observed at that site.

Figure 1.31. Aerial photo of burned area in the MRSA from the fire that occurred on July 1, 2010, just prior to the pumping test. The extent of the burned area is estimated to be about 600 acres. The view is looking to the southeast.

The ongoing removal of palm trees and tamarisk and the retirement of irrigated lands in the area over the last several years are also important land use changes that are contributing factors. All of these factors are expected to reduce ET and increase shallow water levels and flows in the MRSA. A recent report by DRI (Huntington et al., 2013) estimated that ET in the MRSA has declined about 600 to 900 af over the period 2001-2012. Three of the four SNWA monitoring wells located near the Refuge (Lower Pederson MW1, Stone Cabin MW2, and Francis Taylor) show increasing shallow aquifer levels during the period of the pumping test (see appended file: SNWA shallow monitoring wells_MRSA_periodic meas 2009-2012.xlsx). Because the shallow basin-fill aquifer likely contributes to flow at all the flow monitoring sites (sites located downstream of springs, including the Warm Springs West gage, the Iverson Flume gage, the Muddy Springs gage, and the Muddy River gage), the discharge at these gages may have been affected as well. We propose that while carbonate water levels and spring discharge were decreasing in response to increased carbonate pumping during the pumping test, some of these other factors may have contributed to increases in flows.

Conclusions for Impacts to Springs

Table 1.3 summarizes the results from the analyses. Pederson Spring, Pederson East Spring, Apcar Spring, and Baldwin Spring are all spring monitoring sites that are located at the outflows of springs and only measure regional spring discharge. These spring monitoring sites show the highest correlations with carbonate water levels in EH-4. All four sites showed declines during the pumping test and the relative declines were proportional to the estimated reduction in hydraulic head differential at each spring. Pederson and Pederson East Springs, the highest elevation springs, showed observed declines of 62% and 45%, respectively, during the pumping test. These springs are the most sensitive to groundwater pumping because they have the smallest hydraulic head differential. The Apcar and Baldwin springs, approximately equal in elevation and both lower than Pederson or Pederson East springs, showed observed declines of 4% during the pumping test. Predicted declines in flow, based on changes in head differential, are similar to the observed declines in flow at each spring (see **Table 1.3**). The system is responding to pumping impacts and drawdown as hypothesized (see **Figures 1.18 and 1.19**).

Other flow monitoring sites (sites located some distance from spring sources), such as Warm Springs West and the Iverson flume, were not as highly correlated with carbonate water levels in EH-4. Nevertheless, these sites still showed declines during the pumping test and the declines were approximately proportionate to the expected reductions in head differentials at the springs contributing to the sites. Warms Springs West and the Iverson gage declined about 9% and 6%, respectively, during the pumping test.

Two other flow monitoring sites, the Muddy Springs at LDS Farm and the Muddy River nr Moapa, showed increases in flow during the pumping test. The Muddy Springs is the lowest elevation spring in the MRSA and is therefore least affected by drawdown. Increasing flows at this site during the pumping test may be a result of upstream effects from the fire that led to changes in the operation of the pool and recreational facility. Other factors may have contributed to flow increases at both of these sites as well including 1) the high precipitation during the first year of the pumping test; 2) the fire and loss of vegetation in July 2010 just prior to the pumping test; and 3) the ongoing removal of tamarisk and palm trees and the retirement of irrigation lands in the area. These factors may have ameliorated or obscured some of the pumping impacts at these gages.

The total sum of the reductions in discharge during the period of the pumping test is 0.77 cfs or about 1250 af. This is about 13% of the total MX-5 pumping in CSV during the test and only about 6% of the total volume of carbonate pumping (19,914 af) during the test in CSV, MRSA, Garnet Valley, Hidden Valley and California Wash. As carbonate pumping continues, carbonate water levels will decrease further and the volume of groundwater discharge captured through reduced springflow and ET will increase until the system reaches a new equilibrium and the pumping rate equals the captured discharge rate (Bredehoeft, 2007; Bredehoeft and Durbin, 2009).

With respect to spring discharge impacts, if the current rate of pumping, drawdown, and decline in discharge observed during the test continues in the near-term, Pederson Spring, the highest elevation and most sensitive spring in the MRSA, will reach zero discharge in about 1.5 years. Pederson East Spring, the second most sensitive spring, will reach zero discharge in about 2.5 to 3 years. We note again that the annual carbonate pumping rate in CSV during the test was only about one-third of the total appropriated volume in that basin.

Table 1.3. Summary of Results for Impacts to Spring Discharge

Site name	Type of site	Site elevation (mean sea level)	Correlation with EH-4 carbonate water levels (r^2) during the pumping test	Relative changes in observed discharge during the pumping test (% per foot of drawdown)	Total change predicted during the pumping test (cfs) (based on estimated head changes)	Total change observed during the pumping test (cfs) (based in observed changes in flow)
Pederson Spr	Spring Monitoring	1811	0.98	-28%	0.12	0.13
Pederson East Spr	Spring Monitoring	1807.7	0.92	-20%	0.07	0.10
Warm Springs West (includes Ped Spr and Ped East Springs)	Flow Monitoring	1792 to 1811	0.79	-4%	0.50	0.32
Jones Spr	Spring Monitoring	1776	0.90	-2%	0.06	0.06
Baldwin Spr	Spring Monitoring	1776	0.79	-2%	0.11	0.11
Iverson Flume	Flow Monitoring	1749 to 1757	0.42	-3%	0.16	0.28
Muddy Springs	Flow Monitoring	1745	0.45	+7%		
Total Reduction in Discharge					0.83	0.77*

**Sum of Warm Springs West, Iverson Flume, Jones, Baldwin (the Warm Springs West gage includes Pederson and Pederson East Springs). The sum of predicted changes in flow at these four gages is very close to the observed sum, but that is mainly because of compensating errors at the two flow monitoring gages: Warm Springs West and Iverson Flume. We didn't predict changes in flow at Muddy Springs due to the influence of other factors at that gage.*

Section 2 – Modeling of Groundwater Pursuant to the Pending Applications

Modeling Simulations of Pumping Impacts to Groundwater and Springs

In this section of the report, we use a numerical groundwater flow model developed by Tetra-Tech (2012a) to evaluate the impacts to groundwater levels and springs discharge from various pumping scenarios. We also use the model to simulate the recovery of the system if the MX-5 pumping had ceased after the pumping test was completed in December 2012.

Tetra Tech Groundwater Flow Model

On behalf of three Department of the Interior bureaus (the US Fish and Wildlife Service, National Park Service, and Bureau of Land Management), Tetra Tech (2012a) prepared a three-dimensional model of groundwater flow of part of the Colorado River Flow System. This model is intended to provide information on the long-term effects of existing and future groundwater use on the groundwater system, which includes resources that are the responsibility of these three bureaus.

The model domain includes all basins in which groundwater right applications are pending under Order 1169. The model simulates groundwater flow in the regional carbonate-rock aquifer system that is the source of the Muddy River Springs, Muddy River, and likely contributes to warm springs of Lake Mead National Recreation Area. Tetra Tech Model Version 1.0 (described in detail in Tetra Tech 2012a) is a three dimensional, 18-layer groundwater flow model developed using MODFLOW-2000, a widely used finite difference groundwater flow code developed by the U.S. Geological Survey, calibrated over the following time frames:

- Transient groundwater level and spring and stream discharge measurements, 1949 to 1987, representing a 39-year period of basin-fill pumping in the MRSA. Initial conditions were established by running the model to steady state under pre-pumping conditions.

- Transient groundwater level and spring and stream discharge measurements, October 2008 to December 2011, including the first year of the 2-year Order 1169 pumping test. Calibration focused on CSV and the MRSA.

Simulations of the Potential Effects of Pumping the Pending Applications

A series of pumping simulations were performed using the Tetra Tech Model Version 1.0 to estimate the effects of pumping various subsets of existing rights and pending applications within the model domain, including pending applications held in abeyance under Order 1169 (Tetra Tech 2012b). These pumping scenarios included:

- Scenario 1 – Current locations and rates of pumping;
- Scenario 2 – All existing groundwater rights, pumped and unpumped;
- Scenario 3 – All existing groundwater rights, plus all large[9] pending applications filed through 1989
- Scenario 4 – All existing groundwater rights, plus all large pending applications filed through 1994;
- Scenario 5 – All existing groundwater rights, plus all large pending applications filed through 1999;
- Scenario 6 – All existing groundwater rights, plus all large pending applications filed through 2004; and
- Scenario 7 – All existing groundwater rights, plus all large pending applications filed through 2009.

Tetra Tech (2012b) includes a series of figures showing time-series of simulated groundwater levels and spring/stream discharges and contour maps of simulated drawdown for each of the above pumping scenarios. Contour maps provided in Tetra Tech (2012b) depict simulated drawdown of the water table at a series of elapsed times since the end of 2011 (end of the last calibration run). Time axes for simulated time-series hydrographs depict time elapsed since the end of 2011. The discussion presented below will focus on the simulation results for Scenarios 1, 2 and 3 as they pertain to CSV and the MRSA.

Figure 2.1 (Figure 3.1-2a of TetraTech 2012b) shows the simulated spring discharge in the MRSA for Scenario 1, which evaluates the long-term pumping impacts resulting from a continuation of the current locations and rates of pumping. The model predicts that the discharge from the springs will decline as the existing pumping captures flow from the springs. Discharge from the Pederson spring is predicted to cease after nearly 500 years, but is nearly dry after 200 years. If all existing permitted water rights (used and unused) were pumped (Scenario 2), the model-predicted declines are more significant (**Figure 2.2**, or Figure 3.2.2a from Tetra Tech 2012b), with the Pederson and Cardy Lamb springs predicted to cease flowing in 30 and 60 years, respectively. Finally, **Figure 2.3** (Figure 3.3-2a of Tetra Tech 2012b) shows the simulated spring discharge in the MRSA for Scenario 3, which evaluates the long-term impacts resulting from pumping all existing permitted water rights (used and unused) and all large pending applications in the area filed through 1989, including SNWA's pending water rights in CSV. Under this simulation, the model predicted declines are more significant than under Scenario 2, indicating that the discharge from all of the major springs in the MRSA will cease flowing within 10 years (Pederson Spring) to 150 years (Muddy and Plummer springs). Declines in flow from the springs will affect the flow in the Muddy River downstream from the springs, and impact downstream water users. The following section compares the modeled and observed effects of the Order 1169 pumping using a longer dataset than available for calibrating the model. This analysis found that the model under-simulates the effects of the pumping. Thus, springs will dry up quicker than estimated by the model.

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[9] 'Large' pending groundwater right applications refers to applications for 1,000 or more acre-feet per year (Tetra Tech, 2012b).

Post-Audit of Second Year of the Order 1169 Test

A post-audit analysis of the Tetra Tech model (Tetra Tech 2013) was performed, using data collected during 2012, the last year of the test. Calibration of the model was based in part on the observed responses to pumping of the carbonate-rock aquifer in Coyote Spring Valley (CSV) over the first part of the Order 1169 test, during the period September 2010 through December 2011. Data are now available on the effects of pumping in CSV through December 2012. The first part of this section is designed to determine how well the modeling results agree with the water-level drawdown and spring discharge data collected in 2012. The model was not re-calibrated to the more recent information. The results can be used to estimate whether the model over predicts or under predicts the effects of pumping in CSV. The conclusions of this evaluation should only be applied to the effects of pumping in CSV, and not from other Hydrographic Areas.

The post-audit simulation was performed with the long-term model described in Tetra Tech (2012a), modified to include an additional 12 months of pumping to cover the period January 1, 2012 through December 31, 2012. Details are provided in Tetra Tech (2013). In addition, the model simulation time was extended an additional 15 years (2013 to 2027) to evaluate the time required for the groundwater system to recover from the effects of Order 1169 pumping. These changes and the results are discussed later in this section. Briefly, the Multinode Well package dataset in the model was modified by incorporating the reported monthly pumping volumes into additional monthly stress period records. If reported values were not available for a well during 2012, the average of the monthly pumping for the previous three-year period was used for the applicable month in 2012, under the assumption that water needs in 2012 were similar to those in recent years. Other data sets were extended as well, and the changes are described in Tetra Tech (2013).

Figure 2.4 (Figure 2-3 of Tetra Tech 2013) shows the simulated and observed water-level changes, for selected wells. The addition of another year of MX-5 pumping to the simulation, and the comparison of simulated and observed drawdown, makes it evident that the model under-simulates the amount of drawdown that is being caused by pumping of the carbonate-rock aquifer. Tetra Tech (2012a, p. 45) had noted that the model does not simulate short-term (seasonal) variability in some areas where it is observed, and suggested that adjustment of carbonate transmissivity and storage parameters may improve the model fit to observed changes in water levels. Additionally, it was unclear, based on simulating pumping through 2011, whether the model under-simulated the amount of drawdown (i.e., calculated less drawdown than occurred) caused by pumping at MX-5. The current results clearly indicate that the model under-simulates the amount, and probably the extent and timing, of drawdown. For example, at CSVM-6 (located about 3 miles north of MX-5), the simulated drawdown is approximately 0.6 feet, while the observed is up to 2.4 feet. At CSVM-2 and CSV-3, approximately eight to ten miles south of MX-5, the measured drawdowns were up to 2 feet, but the simulated values are less than 0.5 feet. In California Wash, the observed drawdown was also about 2 feet (Paiute M-1 and Paiute M-3) but the simulated drawdown is 0.3 feet or less.

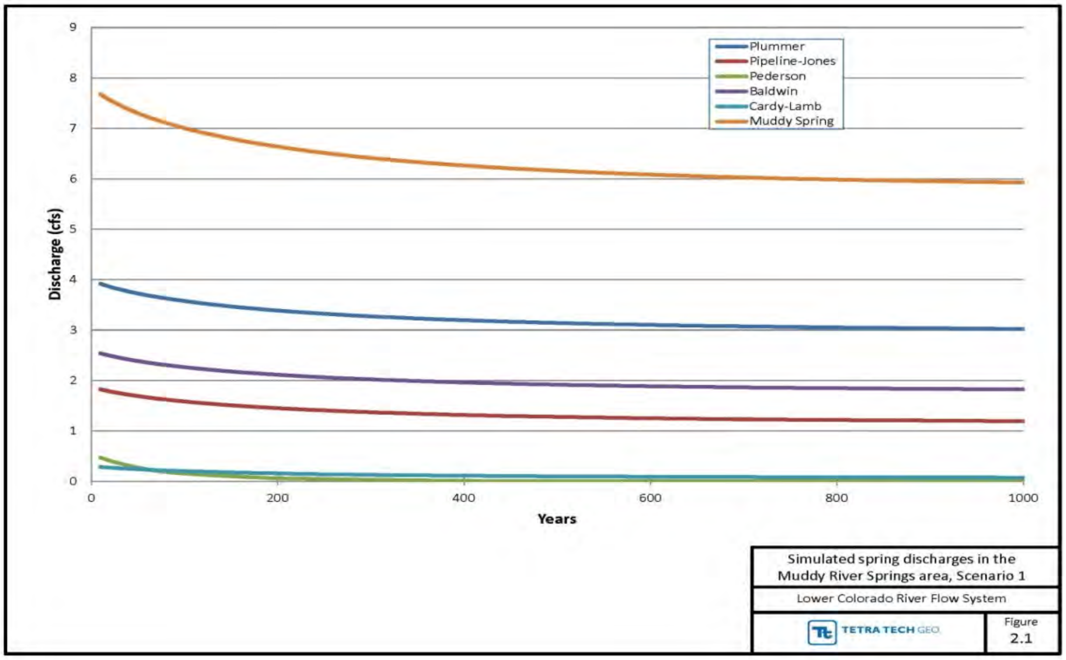


Figure 2.1. Simulated spring discharges in the Muddy River Springs area, Scenario 1.

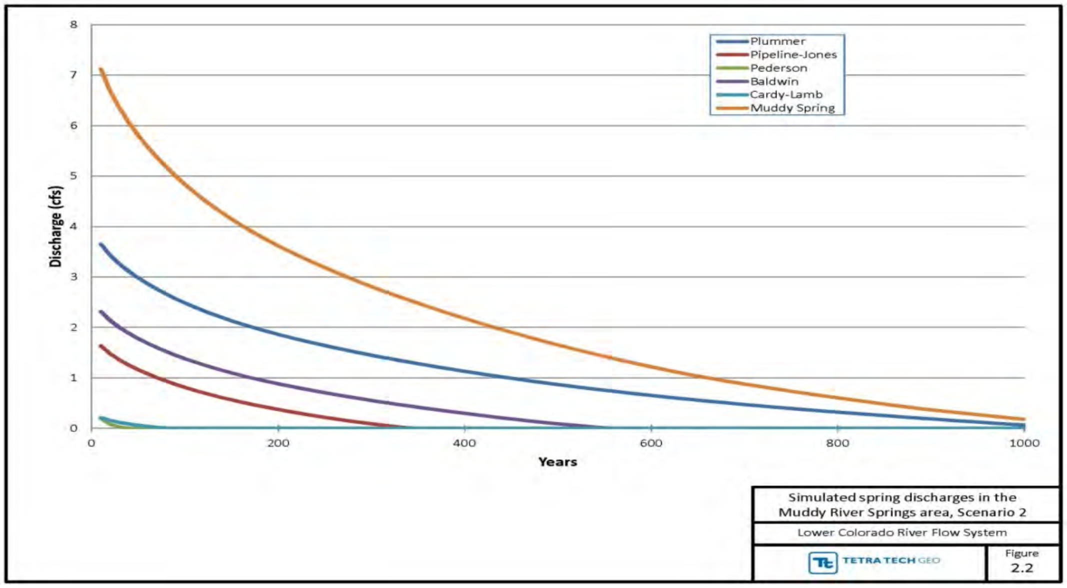


Figure 2.2. Simulated spring discharges in the Muddy River Springs area, Scenario 2.

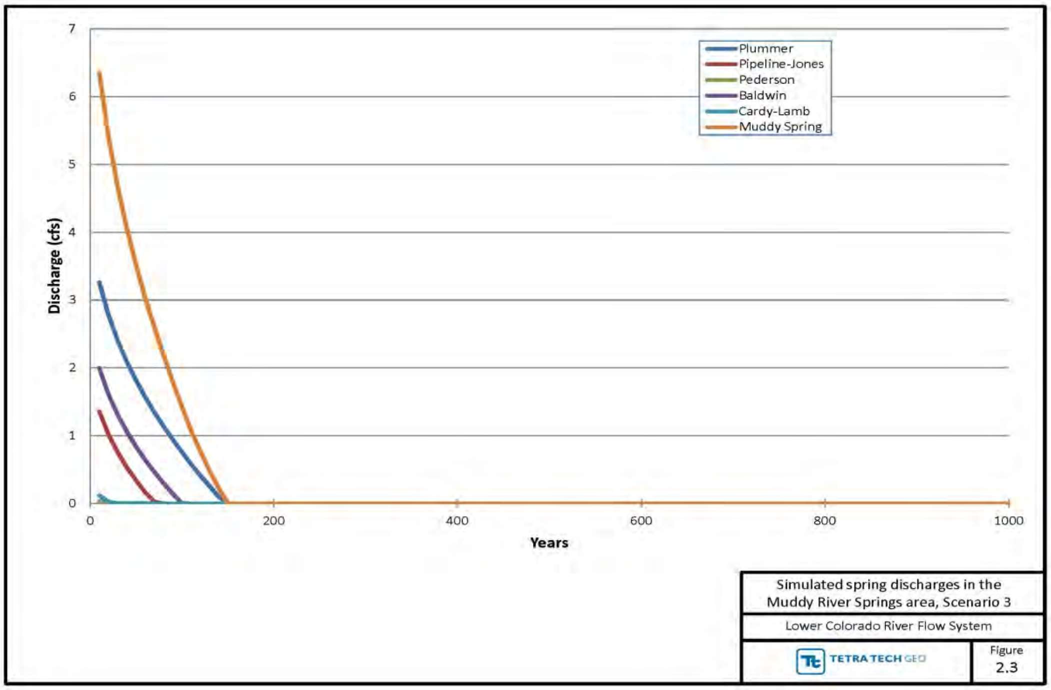


Figure 2.3. Simulated spring discharges in the Muddy River Springs area, Scenario 3.

Figure 2.5 (Figure 2-4 of Tetra Tech 2013) shows the observed and simulated discharge rates from the springs. In general, the model simulates very little change in the discharges, while there are small observed declines in the measured values during the test period. The increases in observed discharge at Muddy Spring are believed to have been caused by anthropogenic changes near the spring and/or the 2010 fire which occurred in the immediate area. The limited simulated impact on the discharge is caused, in part, by the under-simulation of drawdown.

Maps of the simulated drawdown caused by pumping of MX-5 were developed by first simulating the effects of all existing pumping (including MX-5), then simulating the effects of all existing pumping except MX-5, and subtracting the simulated water levels of the second run from those of the first run. The result is a dataset with the simulated drawdown caused by pumping of MX-5. This approach was used to eliminate possible effects that might be caused by non-linear boundary conditions, and isolates the effects of MX-5 pumping.

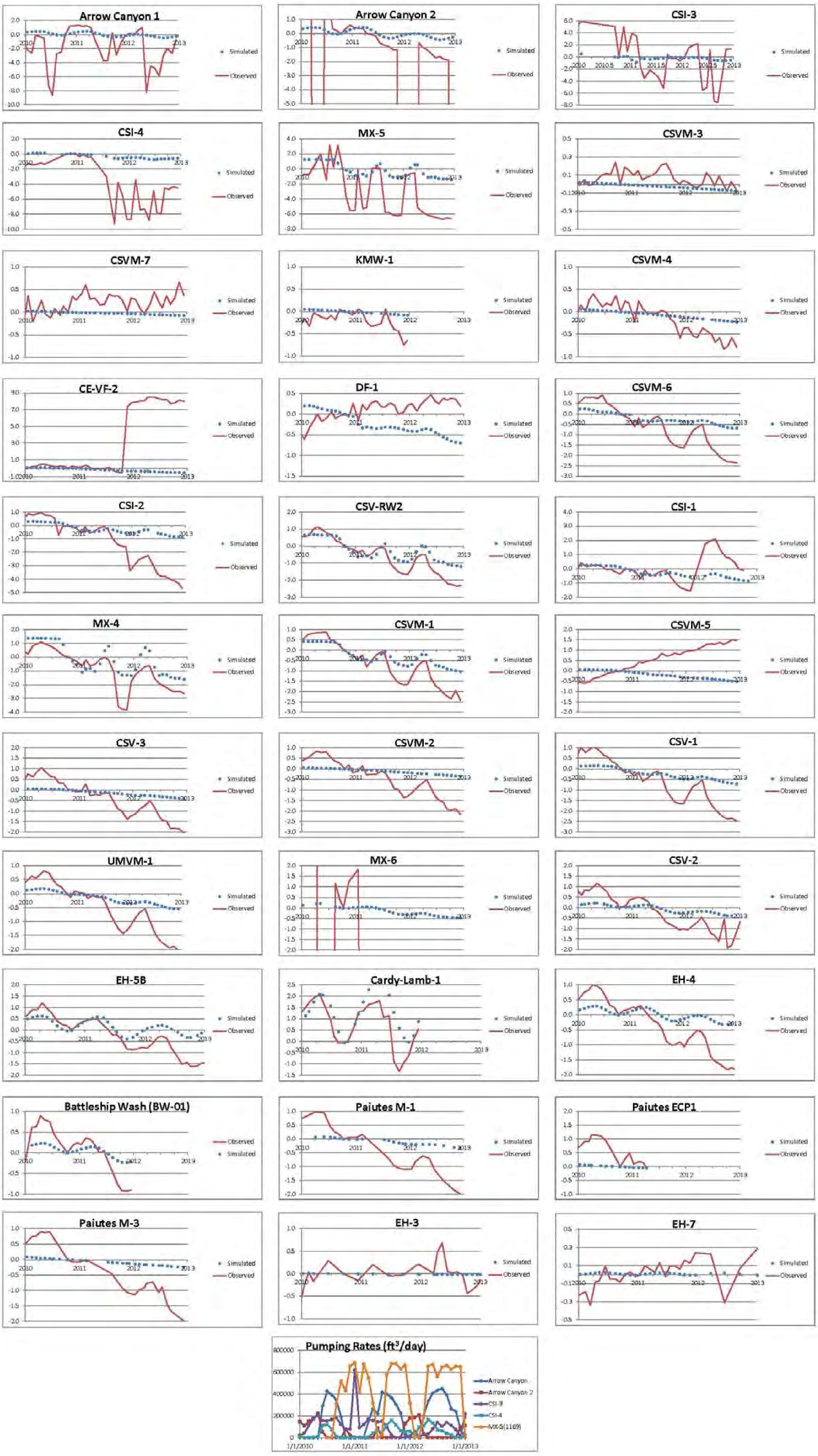


Figure 2.4. Comparison of simulated and observed drawdown in selected wells, 2010 - 2012.

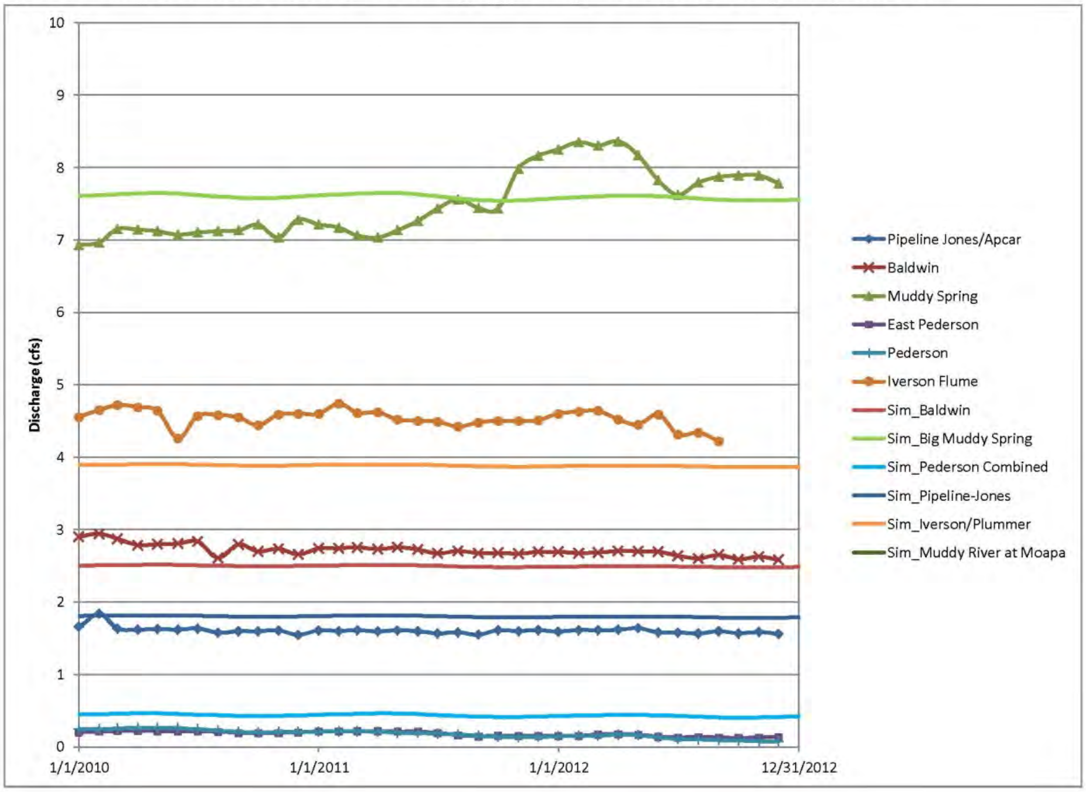


Figure 2.5. Comparison of observed and simulated spring discharge, Muddy River Springs Area, 2010 - 2012.

Figure 2.6 (Figure 2-5 of Tetra Tech 2013) shows the simulated drawdown in model layer 5 caused by MX-5 pumping as part of the Order 1169 test at three different times. The leftmost panel shows the simulated effects at the end of December 2011, while the central panel shows the simulated effects of an additional year of pumping. The rightmost panel is discussed further below under the recovery discussion. Layer 5 is the model layer with the greatest drawdown at the location of MX-5. **Figure 2.7** (Figure 2-6 of Tetra Tech 2013) is a similar set of maps, for model layer 11. This layer has the greatest extent of drawdown.

In the time interval between the end of 2011 and the end of 2012, pumping continued from MX-5, and the extent of simulated drawdown increased in all directions. The amount of drawdown near MX-5 also increases, in both layer 5 and 11. The area of drawdown has begun to extend more in a north-south direction, reflecting the geology. To the north, the area of simulated drawdown greater than 0.1 feet has reached Kane Spring Valley. To the south, it has reached the central part of Garnet Valley and nearly all of Hidden Valley.

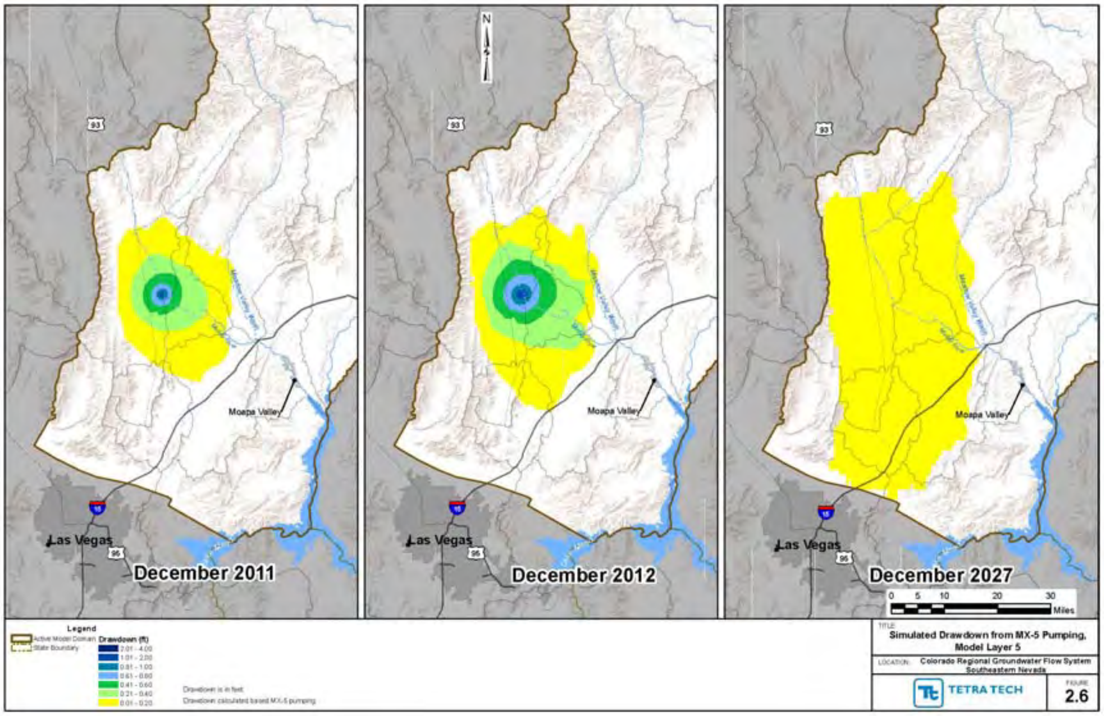


Figure 2.6. Simulated drawdown from MX-5 pumping, Model layer 5.

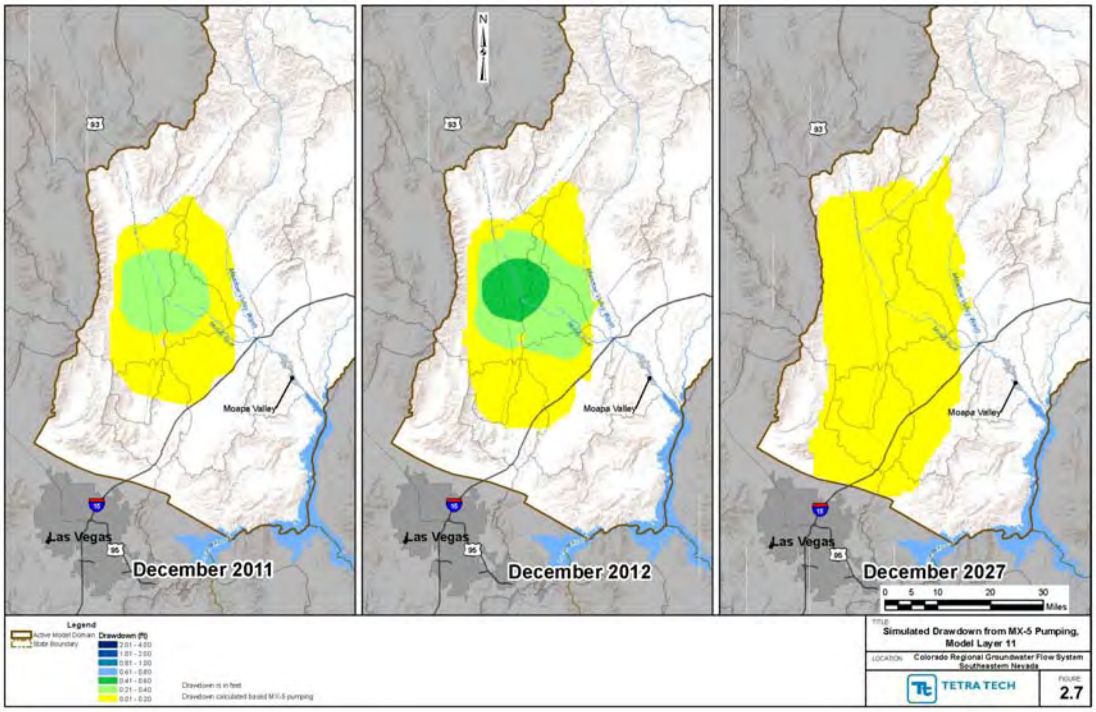


Figure 2.7. Simulated drawdown from MX-5 pumping, Model layer 11.

As noted above, the model under-simulates the drawdown caused by the Order 1169 pumping of MX-5 through the end of 2012. Thus, the amount of drawdown depicted on these maps is less than has been observed. Similarly, the simulated effect of this pumping on the discharge from springs in the Muddy River Springs area is too small. These results indicate that additional calibration of the model using the more recent data would be beneficial. In the interim, the predictive results presented in Tetra Tech (2012b) that pertain to pumping from the carbonate rocks in Coyote Spring Valley should be viewed as conservative. Specifically, the carbonate water levels that drive the discharge from the springs in the Muddy River Springs area will decline more quickly than simulated, and the flows from the springs and in the Muddy River will decline more quickly.

The model was also used to evaluate what is likely to happen if pumping in CSV were to be reduced. One management option for protecting the stream and spring environments in the Muddy River Springs area would be to reduce or curtail pumping rates if water levels declined to a threshold value. However, it is unknown whether a reduction in the pumping rate would cause an “immediate” recovery of water levels and spring flow throughout the Muddy River Springs area, or if drawdown and water-discharge would continue to decline for some time, and by how much. The second part of this section evaluates the likely effects, using cessation of pumping in MX-5 at the end of the Order 1169 test as the imposed change in pumping stress.

The model was run using monthly stress periods for a 15-year period (2013 to 2027), in which no pumping was assumed to occur from MX-5, but other pumping was assumed to occur at the average of the rates reported for 2010, 2011 and 2012.

Simulated drawdown at several wells is shown on **Figure 2.8** (Figure 3-1 in Tetra Tech 2013). The water levels show the effects of MX-5 pumping superimposed on a general downward trend. The effect of stopping MX-5 pumping is very evident in wells close to MX-5 (MX-4, CSV-RW2, CSVM-1, UMVW-1, MX-6) and easily discernible in more distant wells (DF-1, CSVM-6, CSVM-5, CSV-3, CSVM-2, CSV-1). The effect is also present (as observable changes in slope) in the simulated responses of Arrow Canyon, Arrow Canyon 2, KMW-1, CSVM-4, CE-VF-2, CSI-2, CSI-1, CSV-2, EH-5B, EH-4, BW-01, Paiutes M-1 and Paiutes M-3.

The time required for recovery is a function of the distance from MX-5 and the criterion used to define when recovery is complete. **Figure 2.9a** through **2.9d** (Figures 3-2a, 3-2c, 3-2d and 3-2h in Tetra Tech 2013) show the simulated drawdown and recovery responses as a result of starting and stopping MX-5 pumping. For example, at MX-4 (**Figure 2.9a**), about 75% of the drawdown is recovered very quickly, but after 15 years, the recovery is about 90% complete. At MX-6 (**Figure 2.9b**), the simulated recovery is about 75% complete after 15 years. At EH-4 (**Figure 2.9c**), located near Pederson Spring in the MRSA, the maximum drawdown is simulated as occurring several months after cessation of MX-5 pumping, and the recovery is about 70% complete after 15 years. In areas that are much further away, recovery is simulated as not beginning until after 15 years since pumping ceased at MX-5. Although the simulated drawdown at CSVM-3 (**Figure 2.9d**) is only 0.03 feet after the 28 months of MX-5 pumping and 15 years of recovery, the drawdown is continuing to increase.

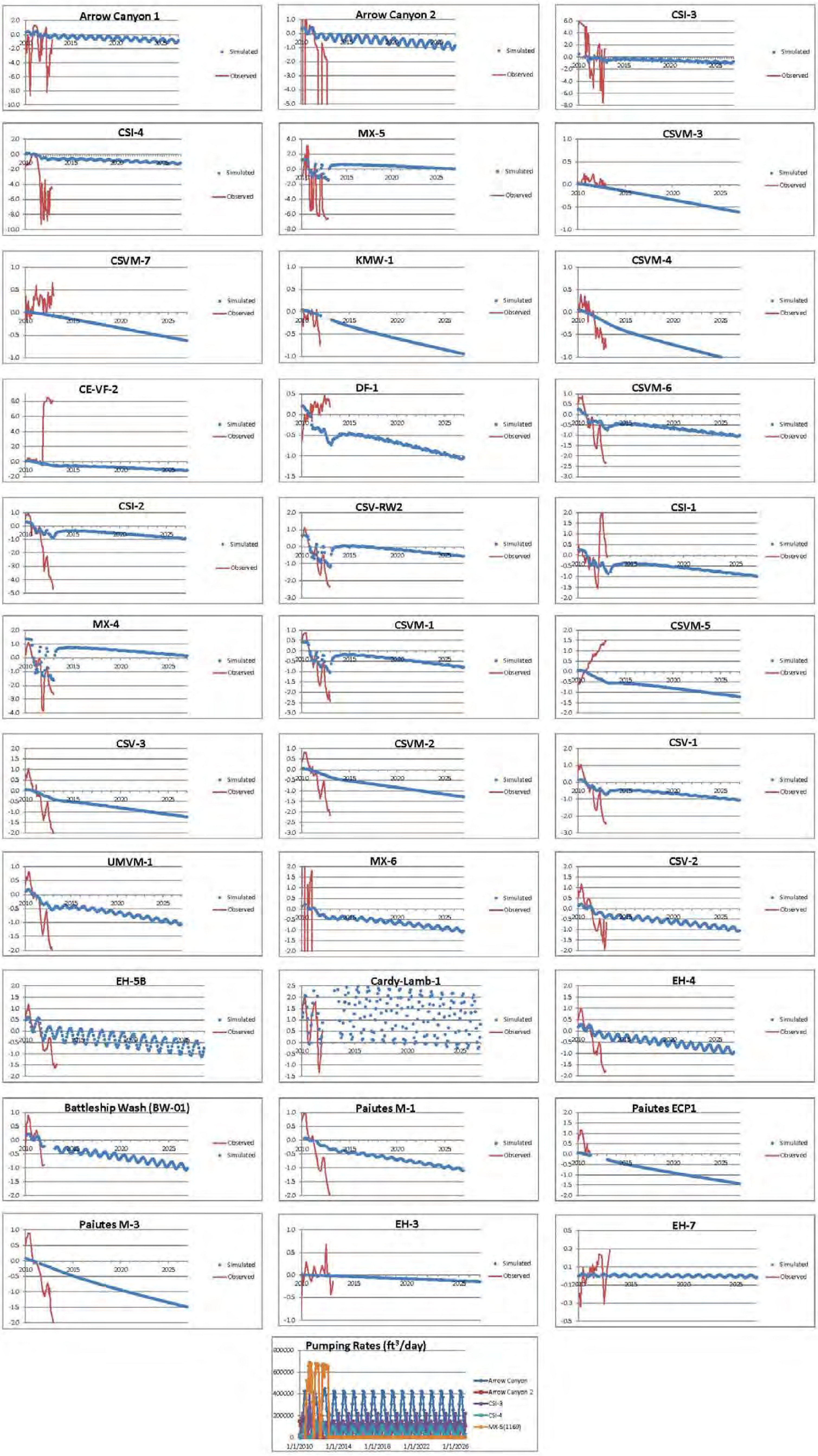
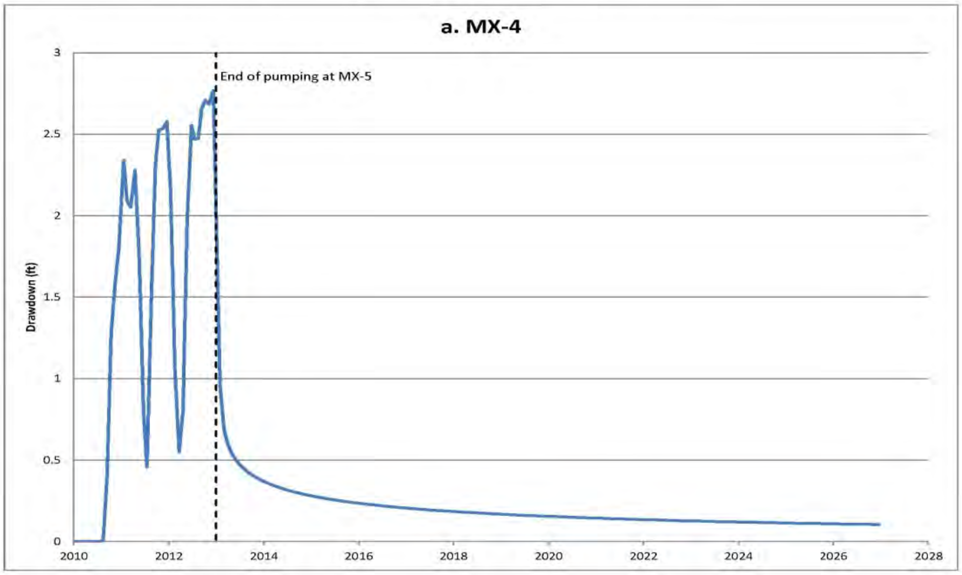
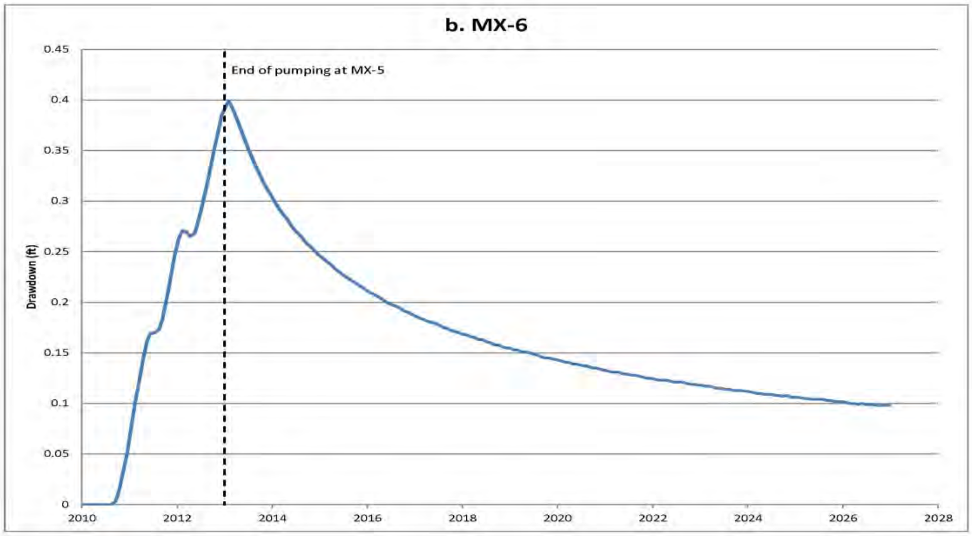
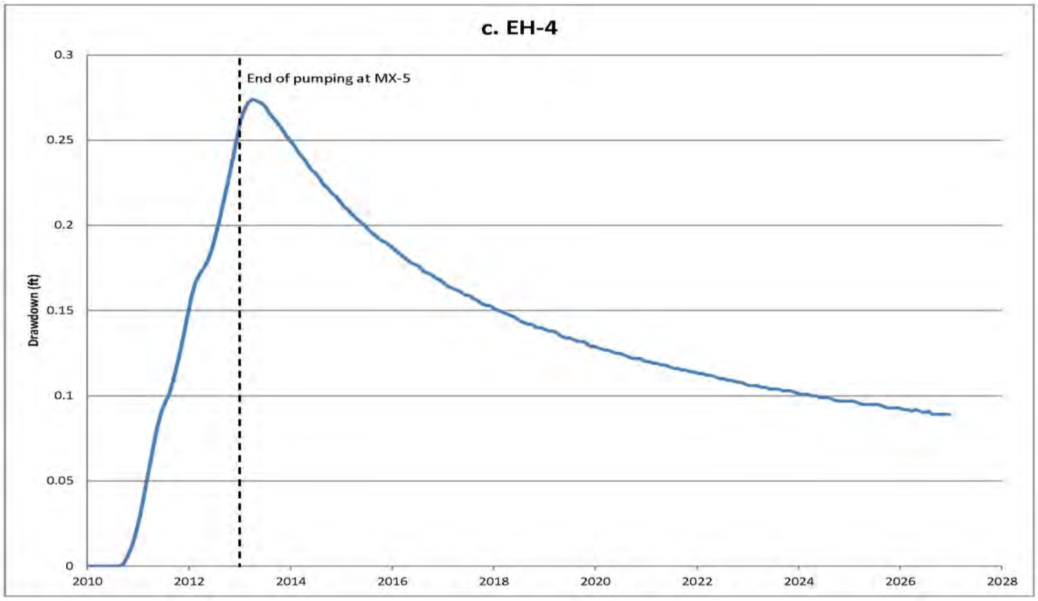


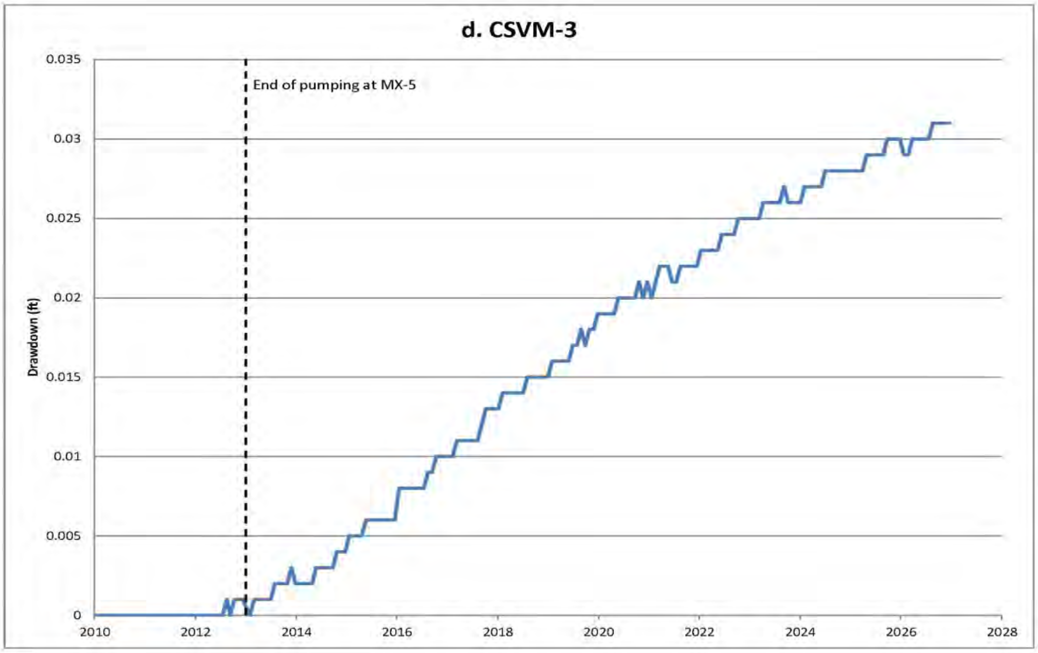
Figure 2.8. Simulation of water levels in selected wells, 2010 - 2012.

Figure 2.9. Simulated drawdown and recovery caused by pumping of MX-5 at selected wells.






c. EH-4
End of pumping at MX-5
Drawdown (ft)
0.3
0.25
0.2
0.15
0.1
0.05
0
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028


d. CSVM-3
End of pumping at MX-5
Drawdown (ft)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028

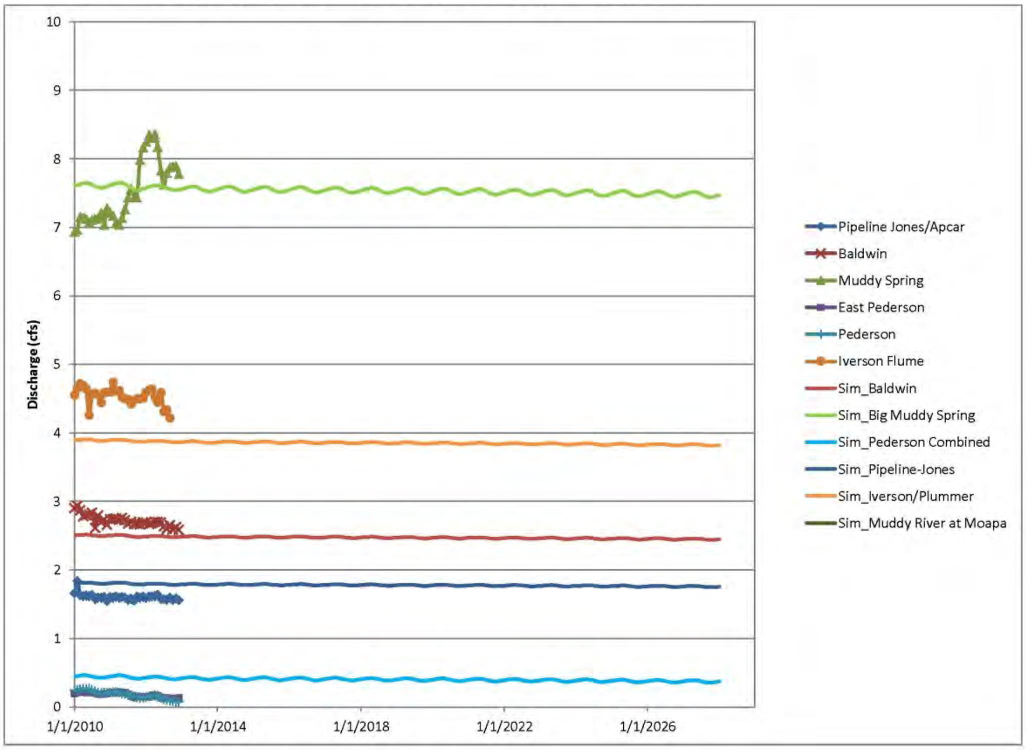


Figure 2.10. Simulated spring discharge rates, Muddy River Springs Area, 2010 - 2027.

Because the model simulates that the effects from the pumping are both smaller than and less widespread than observed, the model also would be expected to predict that changes in water levels occur slower than observed. Thus, the recovery would also be expected to occur quicker than predicted by the model.

Since there was no easily observable decrease in the simulated spring discharge, no easily observable increase in simulated spring flow should occur after MX-5 pumping is stopped. However, a plot of simulated discharge (**Figure 2.10**) shows a minor decrease in flow. For example, the decline simulated for Baldwin Spring is less than 2% of the flow in 2010.

The rightmost panel in **Figures 2.6** and **2.7** shows the simulated drawdown after 15 years of recovery. Recovery near MX-5 is nearly complete (recovery was about 90% at MX-4). However, the area with at least 0.01 feet of drawdown continued to increase, and has reached the western and southern model boundaries in layer 11. While the simulated drawdown in these areas is small, the simulation demonstrates that although drawdown has nearly recovered near the pumping well, impacts in other areas may be continuing to increase a decade or more after pumping has stopped. Although the model under-predicts the amount of drawdown, the area that was simulated as being affected by pumping of MX-5 is quite similar in extent to that determined from the SeriesSEE evaluation of the data. This becomes apparent in the results from the 15-year recovery period, whereas the SeriesSEE evaluation found that the effects were evident at the end of the Order 1169 test.

There are two significant conclusions from the recovery simulation:

1. Except in the immediate vicinity of MX-5, recovery from the effects of the 28-month pumping of MX-5 will take longer than 28 months, and may take substantially longer to occur depending on the location. Near the Muddy River Springs, approximately one-third of the simulated drawdown remains after 15 years of recovery.
2. The model predicts that the drawdown in Coyote Spring Valley and the Muddy River Springs area caused by MX-5 pumping is superimposed on a slower decline of water levels that is likely largely caused by pumping of carbonate-rock aquifer water from Arrow Canyon and Arrow Canyon 2. However, in the recovery simulation, carbonate pumping from wells in Garnet and the western part of the Black Mountains Hydrographic Area was also included in the recovery simulation and may be responsible for part of the slower observed decline in simulated water levels in the vicinity of MX-5.

Conclusions from Post-Audit Simulation

Results of the post-audit simulation indicate that the model under-simulates the amount (i.e., calculates less effect) of drawdown and reduction of spring discharge than has actually occurred as a result of MX-5 pumping. The observed drawdown is more widespread, and of greater magnitude, than simulated. The model simulates that the discharge from springs is not affected to a measureable amount, but the real effects are measureable. Thus, predictions that have been made with the model that evaluate the effects of pumping in Coyote Spring Valley should be considered to be conservative. The impacts from pumping would be larger and more widespread than simulated.

This evaluation also indicates that simulated recovery of water levels and springflow from the 28-month Order 1169 pump test will occur over years, and in the Muddy River Springs area, that recovery will be approximately 70% complete after 15 years. In areas that are “distant” from MX-5, drawdown may still be increasing 15 years after pumping of MX-5 is stopped. If pumping at MX-5 were to occur for longer than 28 months, the rate of recovery can be expected to be slower.

Conclusions from Modeling on the Availability of Groundwater Pursuant to the Pending Applications

The model simulation results presented in Tetra Tech (2012b) had indicated that continuation of the current pumping (including MX-5) into the future would cause slow decreases in discharge from springs in the Muddy River Springs Area, but that if all existing water rights (used and unused) and pending water rights in CSV (including SNWA’s pending water rights applications) were fully pumped, there would be major impacts on spring discharge (and the dependent flow in the Muddy River) within 10 to 150 years. However, the post-audit of the model clearly indicates that the model under-simulates the effects of pumping from the carbonate-rock aquifer. The timeframes predicted by the model for causing impacts to the springs are much too long. The evaluation of the spring flow data presented in Section 1 of this report indicates that if pumping from MX-5 were continued at the recent rates, Pederson Spring would dry up in years, not decades. Thus, the long-term modeling predictions presented in Tetra Tech

(2012b) should be considered to be very conservative. Changes will occur more quickly than presented in that report.

The modeling simulation results provide additional evidence that it is unlikely that the carbonate-rock aquifer can support increases in the pumping rates, without having significant impacts on spring discharge rates. Further, the recovery simulation indicates that the pumping will impact water levels, and thus spring discharge rates, for extended periods of time. Continued monitoring of water levels and spring discharge rates is needed, even if groundwater production does not occur at rates greater than the pre-Order 1169 test rates.

Section 3 - Pumping Test Results and Groundwater Availability

In this section of the report, we review the water budget and perennial yield information for the five-basin area identified in our groundwater analysis. We also summarize portions of recent rulings by the State Engineer related to the concept of perennial yield, especially as it applies to hydrologically-connected basins.

In determining the amount of water available for appropriation, the State Engineer is required to determine that there is unappropriated water available at the proposed source of supply, that the proposed use not conflict with existing water rights, and that the proposed use not prove detrimental to the public interest. The most important information from the pumping test, relevant to these three considerations, has to do with the comparison of the volume of water that was pumped during the pumping test with the volume of water currently appropriated in CSV. The pumping test removed an average of 5,400 afy in CSV over the two-year period of the test. This is only one-third of the 16,300 afy of groundwater that is already appropriated through existing water right permits in CSV (see Order 1169) (NSE, 2002a). The monitoring results from the pumping test clearly show that it is not possible to pump even this reduced volume of groundwater from CSV, at least in the area of MX-5 and the CSI wells, without affecting spring discharge in the MRSA. Furthermore, the results indicate carbonate pumping at any location within the five hydrologically-connected basins in this area (southern CSV, MRSA, Hidden Valley, Garnet Valley, and California Wash) will lower groundwater levels uniformly throughout these basins within relatively short time periods and will eventually capture spring discharge in the MRSA.

Our analyses of spring impacts suggests that if the pumping and drawdown were to continue at the current rate for another 1.5 to 3 years, upper elevation springs will dry up. The pumping test provides evidence that pumping of 5,400 afy of groundwater could be challenging over the long-term without creating adverse impacts to springs, Federal resources dependent on them, and downstream water rights. With respect to the question of whether groundwater is available for appropriation or not, our analysis as presented in this report suggests the answer is no.

Water Budget Analysis

The approach the State Engineer has used in determining water availability for appropriation is to evaluate the water budget information for a basin. The evaluation of water budgets in hydrographic basins in Nevada can be difficult because several components, including recharge from precipitation and interbasin groundwater flow, cannot be directly observed. Usually there are ranges of estimates for these components that are inferred from supporting hydrologic, geologic, and geochemical data. Several competing water budgets for CSV were presented in testimony and evidence at the 2001 protest hearings on the pending water right applications. A more recent water budget modeling effort (SNWA, 2007b) revisited the water budget for CSV but the range of estimates remains essentially unchanged. The information from the 2001 protest hearings, as summarized in Order 1169 (NSE, 2002a, pp 5-6), indicates that there is a maximum of 50,000 afy of groundwater inflow into CSV and a maximum of 53,000 afy of groundwater that flows out of the basin. The extra 3,000 afy of groundwater outflow is the estimate of net recharge from local precipitation in CSV. Of the 53,000 afy of subsurface outflow from CSV, 37,000 afy flows southeast and discharges at the MRSA as spring discharge and ET. This discharge in the MRSA is already fully appropriated through the 1920 decree, as identified in Order 1169 (NSE, 2002a), and therefore not available for appropriation. According to the January 21, 1920, Order of Determination and the March 11, 1920, Further and Supplemental Order of Determination of the Nevada State Engineer, there is no water available for appropriation in the Muddy River, its headwaters, sources of supply, and tributaries (Muddy Valley Irrigation Company, 1938).

That leaves a maximum of 16,000 afy of additional subsurface outflow that may bypass the MRSA and may be available for appropriation. More recently, the State Engineer has questioned and rejected the existence of 8,600 afy of outflow from CSV to Hidden Valley as proposed by SNWA (see Ruling 6167, pp 65-67) (NSE, 2012d), which appears to reduce the estimates of CSV outflow and available water in the basin further. The 16,300 afy of existing water right permits in CSV, as identified in Order 1169, equals or exceeds even the highest estimates of the remaining subsurface outflow from CSV, as acknowledged in Order 1169 (NSE, 2002a, p 6). From a water budget perspective, it appears there is no groundwater available for appropriation in CSV and our interpretation of the pumping test results does not suggest otherwise.

Order 1169 also states that “an unknown quantity of water may be available from storage but it is not known if any of this water could be pumped without unreasonable and irreversible impacts” (NSE, 2002a, p 5). The pumping test provided some information relevant to this issue too. To date, almost all of the water pumped has been removed from storage. Although the pumped volume during the test represents only a small portion (one-third) of the total existing water right permits in CSV, impacts to springs in the MRSA have been observed already, particularly those at the highest elevations. Those impacts are expected to increase if the current rate of pumping continues, as more of the natural spring discharge is captured by pumping in CSV and elsewhere. These effects will only be magnified if more of the existing water rights in CSV are put to beneficial use, which makes mitigating these impacts challenging. Based on the results of the pumping test, it does not seem possible to remove groundwater from storage without reducing carbonate water levels and impacting springflows. With respect to the question of whether groundwater is available for appropriation or not, our analysis as presented in this report suggests the answer is no.

Perennial Yield Analysis

The State Engineer has relied on the concept of perennial yield to assess whether there is unappropriated water available in a basin. Perennial yield is defined as the maximum amount of groundwater that can be salvaged each year over the long term without depleting the groundwater reservoir. Perennial yield is ultimately limited to the maximum amount of natural discharge that can be “salvaged for beneficial use.” In a number of rulings, the State Engineer states that the perennial yield cannot be greater than, and in some cases may be less than, the natural recharge of a basin, which is defined as the combination of subsurface inflow and the fraction of local precipitation that contributes to groundwater.

The "salvaged" water referred to above has historically been viewed as the volume of groundwater that is discharged as ET through phreatophytes. "Salvaging" that water means that this groundwater is captured through pumping before it is discharged as ET through plants. In CSV, as in several other basins in the area, there is no phreatophyte vegetation and no groundwater ET to "salvage" (DeMeo et al. 2008). All groundwater in CSV is predominantly discharged as interbasin subsurface outflow to the MRSA and possibly in lesser amounts to other downstream basins as well. The perennial yield of basins like CSV, where there is no ET, is limited to the some portion of the interbasin outflow.

In applying the perennial yield concept to hydrologically-connected basins, the State Engineer has acknowledged that he has to manage basins comprehensively rather than individually. If the interbasin flow into or out of a basin is already appropriated in an upstream or downstream basin, that water is not available for appropriation in the individual basin. The State Engineer notes this in several rulings, including Ruling 5986 (NSE, 2009) on the Tule Desert Hydrographic Basin, which states:

> "The amount of subsurface discharge that can be captured is highly variable and uncertain. Perennial yields for these basins have historically been set at one-half of the subsurface discharge. However, when conditions are such that there is subsurface flow through several basins, there is a potential for double accounting and over appropriating the resource if the perennial yield of each basin is equal to one half of the subsurface outflow, and basin subsurface inflows are not adjusted accordingly. Therefore, allowances and adjustments are required to the perennial yields of basins in these flow systems so that over appropriation does not occur."

In Ruling 6167 (NSE, 2012d) on the Delamar Valley hydrographic basin, the State Engineer states:

> "It is also well known that regional groundwater flow systems hydrologically connect many of these basins and make management on the hydrologic basin-scale complex, and often dependent on prior management/appropriation decisions. In these cases, the State Engineer must determine from which basin the groundwater should be counted as available. If the interbasin flow is appropriated in one basin, it is not available for appropriation in an adjacent basin."

In other words, the same water cannot be "double-counted" or "double-appropriated." As demonstrated with the water budget analysis above, there are 53,300 afy of existing water right permits for the subsurface outflow from CSV, 16,300 afy in CSV and 37,000 afy downgradient in the MRSA. This volume of appropriated water is equal to even the most optimistic estimates of subsurface outflow from CSV. In addition, because the area is hydrologically-connected, we believe that the existing water rights in all five basins must be considered in any appropriation decision.

While considering the hydrologic connectivity of basins, the State Engineer also must consider the time scale of any potential impacts. In Ruling 6167 (NSE, 2012d) again, he states:

> "At the same time, it is important to consider the time frames and geologic uncertainties involved. Withdrawals upgradient may or may not affect downgradient users within a reasonable time frame. The State Engineer has found that if no measureable impacts to existing

> rights occur within hundreds of years, then the statutory requirement of not conflicting with existing rights is satisfied. "

Our analyses of impacts to spring discharge from the pumping test show that measureable impacts from the existing level of pumping are observed on the scale of months to years rather than hundreds of years.

Finally, with respect to the perennial yield of CSV, it has to be noted that some portion of the interbasin inflow to CSV from two tributary basins adjacent to CSV (Delamar, Kane Springs) has been appropriated already, but not developed. Ruling 5712 (NSE, 2007) appropriated 1,000 afy in Kane Springs Valley and Ruling 6167 (NSE, 2012d) appropriated 6,100 afy in Delamar Valley. Both of these appropriations will eventually reduce the interbasin inflow to CSV if and when they are developed. The State Engineer has recognized that prior appropriation of upgradient interbasin flow is an issue that must be considered (see Rulings 5465, 5621, and 6144-6167) (NSE, 2005; NSE, 2006; NSE, 2012a; NSE, 2012b; NSE, 2012c; NSE, 2012d). With respect to Dry Lake and Delamar Valley basins, Ruling 6167 (NSE, 2012d) states:

> "By discounting any subsurface inflow from up-gradient basins that is already appropriated, systematic double counting can be eliminated. These controls on the regional flow system allow groundwater to be available in every basin for beneficial use."

It seems prudent to follow the same approach here and discount the subsurface inflow already appropriated. This means the amount of groundwater already allocated in CSV may even be greater than the actual available water, given the constraints with existing appropriations upgradient and downgradient of CSV. There is no information from recent studies or from our interpretation of the pumping test results to suggest that there is additional groundwater available in the basin. The fact that the pumping to date in CSV represents only one-third of the existing water rights permitted in CSV and that our analysis of spring impacts suggests that even this small level of pumping could lead to unreasonable and possibly irreversible impacts in the next few years confirms what is indicated by the analyses of water budgets and perennial yield – there is no additional groundwater available for appropriation.

Section 4 - Public Interest Considerations and Federal Groundwater-Dependent Resources

This section of the report provides an overview of public interest considerations related to the availability of groundwater for appropriation pursuant to the applications held in abeyance by Order 1169. We focus our discussion on the potential impacts of decreased spring discharge and groundwater levels on resources that the U.S. Fish and Wildlife Service (Service or USFWS), NPS, and BLM hold in trust for the public. As stated earlier, the State Engineer is required to establish that a proposed groundwater use will not prove detrimental to the public interest when determining the amount of groundwater available for appropriation. The State Engineer has considered the protection of threatened and endangered species as well as sensitive species and related environmental values when determining whether water is available for appropriation.[10]

In Nevada, all surface water and groundwater (NRS 533.025), as well as non-domesticated wildlife in its natural habitat (NRS 501.100), is considered a public resource. The State is trustee of these resources, managing them for the benefit of the citizens of Nevada and the United States. Several species that occur in the MRSA are protected under State of Nevada statute, including but not limited to the Moapa dace (*Moapa coriacea*), which is classified as endangered (NAC 503.065.2); the Moapa speckled dace (*Rhinichthys osculus moapae*) and the Muddy River population of the Virgin River chub (*Gila seminuda*), which are both classified as sensitive fishes (NAC 503.067); and many species of migratory birds, including the southwestern willow flycatcher (*Empidonax traillii extimus*), which is classified by the State of Nevada as endangered (NAC 503.050). Some of these species are also federally protected under the Endangered Species Act (ESA) of 1973, as amended (16 U.S.C. 1531 *et seq*.).

Below, we focus our discussion on two resources in the MRSA managed by the Service, which are also of interest to the State of Nevada and the other federal agencies: the Moapa Valley National Wildlife Refuge (NWR; Refuge), including the fish and wildlife found there; and the Moapa dace, which is an endangered fish that has been federally protected since March 11, 1967 (USFWS, 1967). This is followed by a discussion of NPS and BLM water and groundwater-dependent resources. The existence and/or biotic integrity of these resources depend on thermal spring discharge from the carbonate-rock aquifer in the MRSA.

USFWS Moapa Valley National Wildlife Refuge

Moapa Valley NWR was established on September 10, 1979, to secure and protect habitat for the endangered Moapa dace. The purpose or mission of Moapa Valley NWR is derived from the Endangered Species Act of 1973, as amended: "...to conserve (A) fish or wildlife which are listed as endangered species or threatened species...or (B) plants..." (16 USC Sec. 1534) (USFWS, 2009). The Refuge and its resources are held in trust for the public and managed by the Service. Moapa Valley NWR comprises

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[10] See Ruling 3784 (February 14, 1994) (Lahontan cutthroat trout), Ruling 4683 (November 24, 1998) (Cui-ui and Lahontan cutthroat trout) and Ruling 6164 (March 22, 2012) (wildlife, wetlands and fisheries).

multiple, adjacent but visually distinct units – the Plummer Unit, the Pedersen Unit, and the Apcar Unit (see **Figure 1.20**) – purchased by the Service from various, willing sellers from 1979 to 2006.

Moapa Valley NWR is managed for two primary goals (USFWS, 2009):

Goal 1. Protect and restore, when possible, healthy populations of endemic and special status species, such as the endangered Moapa dace, within the Muddy River headwaters.

Goal 2. Provide local communities and others with opportunities to enjoy and learn about the resources of Moapa Valley NWR and participate in its restoration.

Most of Moapa Valley NWR was previously held by private landowners and used as several resorts with swimming pools and other developed features. These alterations have been removed and the habitat improved since 1979, with significant efforts and funding from the Southern Nevada Public Land Management Act (SNPLMA) focused on restoration at the Refuge from 2004 through 2012. Public use facilities were added in 2008 on the Plummer unit of the Refuge and opened to the public in 2009. Opportunities for the public at the Refuge include wildlife observation, photography, hiking, environmental education and outreach programs, and volunteer events. Visitors primarily come from the local communities of Moapa, Overton and Logandale, as well as Mesquite and Las Vegas (including some tourists). These efforts have occurred in support of the aforementioned goals to protect and restore habitat for endemic and special status species, as well as provide opportunities for visitors.

In support of the purpose of Moapa Valley NWR to secure and protect habitat for the endangered Moapa dace, the Service has two water rights that have been certificated by the Nevada State Engineer. One of these is a non-consumptive right for 3.5 cfs of spring flow as measured at the Warm Springs West flume for the maintenance of habitat of the Moapa dace and other wildlife purposes (Permit No. 56668, Certificate No. 15097 issued subject to the terms of Permit No. 56668). The other is for approximately 0.25 cfs from a well (Permit No. 27216, Certificate No. 12758 issued subject to the terms of Permit No. 22738, Certificate No. 8331). Surface water from the springs on Moapa Valley NWR also supports adjudicated rights downstream from the Refuge. Use of these surface water rights downstream does not generally affect the Refuge. In November 2008, the Service also applied for non-consumptive, in-stream flow rights to be used for wildlife on the Apcar and Plummer spring systems. These water right applications are being held in abeyance until the completion of the pumping test under Order 1169.

Moapa Valley NWR contains part of the unique system of thermal springs in the MRSA, including the springs and uppermost streams of Plummer, Pederson, and Apcar/Jones. These springs and streams provide aquatic and riparian habitats that support sensitive birds, amphibians, bats, and other fish in addition to the Moapa dace, including the endemic Moapa White River springfish (*Crenichthys baileyi moapae*) and the State protected Moapa speckled dace. The MRSA provides habitat for a unique assemblage of aquatic species including ten native thermophiles dependent upon the warm springs and streams for survival. Besides the dace and springfish, the system supports four endemic invertebrates found nowhere else in the world – the Moapa naucorid (*Limnocoris moapaensis*), Moapa riffle beetle (*Microcylloepus moapus*), Moapa pebblesnail (*Pyrgulopsis avernalis*), and Moapa Warm Springs riffle beetle (*Stenelmis moapa*). The upland areas on Moapa Valley NWR support a variety of birds, small mammals and reptiles, including the threatened Mojave desert tortoise (*Gopherus agassizii*).

The species and resources that depend on the aquatic and riparian habitats in the MRSA do not recognize and stay within the boundaries of the Moapa Valley NWR. Other adjacent and nearby lands also contain springs, streams, and wetlands that provide important protection for the resources in the MRSA that are held in trust for the public. Specifically, the Warm Springs Natural Area provides habitat that is critical to protect the ten native aquatic species, and numerous birds, amphibians, bats and reptiles observed in the MRSA. The aquatic and riparian habitats on these lands sustain 28 Nevada State sensitive or federally listed species, including important tributary streams and the main-stem river for the endangered Moapa dace, nesting habitat for the endangered southwestern willow flycatcher, and habitat for Nevada’s largest breeding population of vermilion flycatcher (*Pyrocephalus rubinus*) (SNWA, 2011). The Warm Springs Natural Area was acquired with public federal funds by the Southern Nevada Water Authority to “develop a natural area” that “will provide controlled public access to enjoy the abundant natural resources, will include interpretation of the resources and Threatened and Endangered species located on the site, and will include measures to preserve and protect those resources” (SNWA, 2011). Further downstream on the main-stem Muddy River, additional aquatic and riparian species depend on the water and associated habitat that occurs along public lands managed by the Bureau of Land Management, State of Nevada (Overton Wildlife Management Area), and National Park Service.

The Moapa Dace and its Vulnerability to Environmental Stressors

The endangered Moapa dace is endemic to the headwaters of the Muddy River system where it is estimated to have occupied 25 springs and about 16 km (10 mi) of stream habitat in the early 20th century (Ono et al., 1983). Currently, the dace population is constrained to three thermal spring complexes and their respective springbrooks (Pederson, Plummer, and Apcar/Jones), including their confluence upstream of the Muddy River, an area that is roughly 20% of its historic distribution. The majority of the dace population is found on the Moapa Valley NWR and the Southern Nevada Water Authority’s Warm Springs Natural Area. Habitat alterations, the introduction of nonnative fishes, and water withdrawals over the last century have restricted the dace’s distribution within the Muddy River system and resulted in severe population declines.

The status of the species has fluctuated over the last 20 years, with a couple of significant population increases and decreases during this period. Snorkel surveys conducted each February (1994 to present) throughout the upper Muddy River system show that Moapa dace counts have ranged from a high of 3,825 individuals in February 1994 to a low of approximately 460 individuals in February of 2008 and 2009, prior to onset of the Order 1169 pumping test. One significant decline is attributed to the invasion of nonnative blue tilapia (*Oreochromis aurea*) where the dace population decreased from 3,825 individuals in 1994 to 1,565 individuals in 1997. Between 1999 and 2007, surveys yielded between 900 and 1,300 individuals. In 2008, the dace population again experienced a drastic decline in numbers, falling to its lowest known level of 459 individuals (a 60% decline from the previous year). The cause of this population crash remains unknown. From 2009 through early 2012, dace numbers slowly increased. Most recently (February 2013), surveyors counted 1,226 fish, an 88% increase over February 2012 survey results. We attribute this latest population increase to recent habitat restoration activities on the Moapa Valley NWR and the Warm Springs Natural Area, including removal of nonnative palm trees from stream channels, planting of native vegetation, improving stream velocities, and channel reconfiguration. Specifically, the lower Pederson Springbrook was re-routed closer to its historical alignment with a new channel created in October 2008. This reach has generally supported increasing numbers of Moapa dace since its creation and the largest number of dace of any reach in recent surveys (August 2012 and February 2013). Most of the upper and lower reaches of the Apcar/Jones Springbrook have also been restored and the dace population has increased in this area as well.

While the status of the Moapa dace has improved over the last couple of years presumably due to habitat restoration, the Service continues to be concerned about long-term persistence of the species. The different life stages of the Moapa dace are dependent upon thermal springs, springbrooks, and the main-stem Muddy River for survival (Scoppettone et al., 1992), but the availability of these habitat types continues to be limited by system alterations and the presence of nonnative fish. For example, the largest spring in the MRSA remains unavailable to the dace for spawning and use by early life stages due to recreational development (swimming pools, chlorination, and water diversion), and the North Fork, South Fork, Muddy Creek, and the Muddy River main-stem do not currently support Moapa dace. The dace's restricted range and small population size makes it vulnerable to extirpation from existing threats (e.g., nonnative fishes, water withdrawals), catastrophic events, or stochastic variation in demographic rates or in the environment. For example, wildfire in the MRSA is a continuing threat that could be catastrophic to the Moapa dace. In 1994, a fire nearly wiped out the dace population. A more recent (July 2010) fire, while burning about 600 acres including occupied dace habitat, did not spread to the Moapa Valley NWR where 75% of the dace population sought refuge. Thus, maintaining or increasing available spring and springbrook habitat on the refuge and adjacent areas– which in part can be achieved by ensuring adequate flows– will likely reduce extinction risk and increase the dace's ability to recover quickly from disturbances (i.e., increase its resiliency).

For these reasons, the Moapa dace remains highly vulnerable to habitat changes such as those that could result from reductions in spring discharge due to groundwater pumping in the MRSA or adjacent hydrographic basins. Reductions in springflow could affect essential dace habitat features, such as substrate composition and water depth, velocity, and temperature (Hatten et al., 2013). Life history attributes and behavior (e.g., ability to effectively drift feed, fish size and thus fecundity) could also be affected by reduced water volumes and velocities resulting from diminished springflow, and interactions between native and nonnative fishes (e.g., predation and competition) could be exacerbated as habitat diversity and complexity is reduced due to decreased flows. In particular, the dace is vulnerable to habitat changes in spawning areas because of its reliance on thermal spring discharge to create conditions conducive to successful reproduction (stable water temperatures between 30 and 32 °C, such as that found near and downstream of spring heads) and survival of early life stages (larvae are found exclusively in the upper reaches of these spring-fed tributaries) (Scoppettone et al., 1992).

As just described, the entire Moapa dace population is currently found within the Pederson, Plummer, and Apcar/Jones springbrooks, and the springs that contribute flow to these streams provide important habitat for spawning and early life stages. Therefore, maintaining adequate spring and streamflow in these springbrooks is extremely important to survival of the Moapa dace. The hydrologic analysis presented in this report demonstrates that the springs in the MRSA do not show the same degree of response to groundwater level declines, mainly because of differences in spring elevation. Pederson and Pederson East springs are at a higher elevation than the other MRSA springs and appear to be the most sensitive to declines in carbonate water levels from groundwater pumping. If the current rate of drawdown continues in carbonate monitoring well EH-4, these two higher-elevation springs will cease to flow in 1.5 to 3 years. This does not mean that streamflow in Pederson Springbrook will cease within this timeframe because 4 other major spring groups that are at lower elevation and are less sensitive to groundwater level declines (referred to in this report as spring groups M-11, M-12, M-13, and M-19) contribute a large proportion of total flow to this springbrook. During the Order 1169 pumping test, average monthly flow at Warm Springs West gage on Pederson Springbrook (which measures the combined discharge from Pederson Spring and the other 4 major spring groups) declined by 9 percent. Spring and streamflow reductions during this period were less for Plummer and Apcar/Jones, as expected due to the lower elevation of the springs contributing flow to these springbrooks. We estimated a 6% flow reduction at the Iverson Flume on Plummer Springbrook (with a slightly lower reduction in flow [3-4%] for the contributing springs) and a 4% decline in flow at Jones Spring (which feeds the Apcar stream) during the pumping test.

Based on this, we now address the question “What are the potential impacts to Moapa dace habitat and the dace population if additional groundwater is appropriated in the MRSA and adjacent hydrographic basins?” To answer this, we looked to a recent study conducted by Hatten et al. (2013), in which the authors developed a set of habitat models for the dace and conducted hydraulic simulations with a two-dimensional hydrodynamic model to estimate the extent of dace habitat over a range of flows (plus or minus 30% of base flow, in 10% increments). Using results from this study, we first considered potential impacts to dace habitat based on observed or estimated impacts to spring and streamflow during the Order 1169 pumping test. Because only one-third of the total appropriated volume in CSV was pumped during the Order 1169 pumping test, we anticipate greater impacts to dace habitat if appropriated rights are fully developed and/or additional groundwater is allocated and developed.

The habitat-flow simulations conducted by Hatten et al. (2013) consistently showed that reduced springflows produced less Moapa dace habitat in the Pederson, Plummer, and Apcar springbrooks. Additionally, the simulations showed that Plummer Springbrook appears to be the most sensitive to reductions in flow (i.e., greatest potential habitat loss for any given flow reduction), followed by Pederson and then Apcar. Based on Hatten et al. (2013), a 9% decline in flow in the Pederson

Springbrook (such as observed during the pumping test) would result in a small (<5%) reduction in dace habitat. Similarly, Apcar/Jones springbrook is predicted to have a <5% reduction in habitat from baseline conditions if flows decline by amounts observed at Jones Spring during the pumping test. On the other hand, Moapa dace habitat within Plummer Springbrook appears to be very sensitive to flow reductions. While a 6% reduction in base flow in this stream (the estimated decrease during the pumping test) was not specifically modeled by Hatten et al. (2013), their study predicted a rather large (20%) reduction in dace habitat within this stream in response to a 10% decrease in base flow. We assume a somewhat lower amount of habitat loss for a 6% decrease in flow, but a greater impact if all existing permitted groundwater rights in CSV are developed (as this would represent three times the amount of pumping that occurred under the pumping test). Given the species' limited distribution, habitat losses of this amount could prove significant. We note that the above estimates of habitat loss for all three springbrooks do not take into account the potential offsetting of pumping impacts with recent habitat restoration activities or other conservation measures.

We assume that a reduction in habitat, if it were to occur, would be followed by a decline in Moapa dace numbers since population size of many endangered species is thought to be limited by the amount of suitable habitat available to them (Williams et al., 2002). Over the last five years, the majority (up to 90%) of the dace population counted during fish surveys in the MRSA has been in the Pederson and Plummer springbrooks. Thus, habitat loss within these streams is expected to adversely affect the overall dace population. Additionally, dace only spawn in the Pederson, Plummer, and Apcar/Jones spring systems, while no dace are found in the other two major spring systems (Baldwin and Muddy Spring). Reduction and/or cessation of thermal spring discharge within the three occupied springbrooks, particularly Pederson and Plummer, would reduce the amount of spawning habitat (i.e., waters at the appropriate temperature for spawning), thereby affecting the dace's ability to successfully reproduce and reducing fecundity and overall population numbers. This could have negative implications for survival and/or recovery of the species.

To conclude, we remain concerned about the Moapa dace's ability to persist long-term despite recent population growth. Its numbers are still lower than historic estimates (Scoppettone et al., 1992; USFWS survey data); it is restricted to a small geographic area that is but a fraction of its historic range; it has very specific habitat requirements, particularly for spawning and early life stages, which makes it vulnerable to changes in the environment; and it is exposed to numerous stressors with limited opportunities to move away from the ensuing effects, such as habitat degradation. These are characteristics that make a species highly vulnerable to extinction (Williams et al., 2005; Burkhead 2012). Moapa dace numbers increased during the pumping test period, but we attribute this to recent habitat restoration in the MRSA, which appears likely to have offset impacts to habitat caused by pumping-induced flow reductions, although this has not been substantiated. However, we caution that restoration of physical habitat (e.g., reconfiguration of stream channels, removal of nonnative plants, and planting of native vegetation) will only go so far towards maintaining or improving the dace's status if the anthropogenic stressors that lead to habitat degradation are not also addressed (Hilderbrand et al., 2005; Christian-Smith and Merenlender, 2010). These fish depend on thermal spring discharge to create and maintain important habitat characteristics, and this species is thought to be more sensitive to flow reduction than some other fish species inhabiting the Muddy River system (Hatten et al., 2013). If additional groundwater is appropriated in CSV, the MRSA, and adjacent areas, spring discharge and streamflow could be lowered to the point that physical habitat restoration will not be an effective or possible mitigation option.

Aquatic species such as the Moapa dace have evolved life history strategies primarily in response to the natural flow regime of the systems they inhabit (see Bunn and Arthington, 2002). Altering this flow regime could affect crucial drivers of dace population dynamics, such as the resources needed for spawning, juvenile growth, recruitment, feeding, and other behaviors. Given the dace's sensitivity to flow reduction, and the potential consequences of habitat loss for a species with an extremely limited distribution, we recommend that no additional water be appropriated in CSV and adjacent hydrographic basins.

NPS and BLM Groundwater-Dependent Resources

Several important warm springs are located in the Overton Arm area of Lake Mead National Recreation Area (Lake Mead NRA), which is administered by the NPS. These springs include Rogers, Blue Point, Corral, and Scirpus springs, and other smaller, unnamed springs. Discharge from these springs provides water for riparian vegetation and wildlife habitat, and sustains a recreational amenity enjoyed by many park visitors.

The United States has federal reserved water rights for all of the springs within Lake Mead NRA. The United States also has a state appropriative water right to Rogers Spring (Certificate No. 4476).

The relict leopard frog (*Lithobates onca ;* formerly classified as *Rana onca*), previously believed extinct, has been found at Rogers, Corral, and Blue Point Springs. In 2002, the species was petitioned for listing as endangered under the ESA. The Service subsequently found that listing is warranted, but development of a proposed listing regulation is precluded by other higher priority listings. It remains on the Service's candidate species list. Although not an endangered or threatened species, a herd of approximately 150 of Nevada's official state animal – the desert bighorn sheep - also use these springs in the northern part of Lake Mead NRA.

The likely source of the water discharging from these springs is the regional carbonate-rock aquifer system. Therefore, the withdrawal of groundwater from this aquifer system upgradient of these springs would most likely affect their rates of discharge. Although the Order 1169 pumping test period was too short to be able to identify the effects of upgradient groundwater withdrawals on these springs, geologic, hydrologic, and hydro-geochemical evidence indicates that these springs likely are vulnerable to depletion of discharge from longer-term and/or cumulative carbonate pumping in the five hydrologically connected basins discussed in earlier sections of this report.

The BLM also has several trust resources in the area as well. Both the Moapa dace and the Moapa speckled dace occur in parts of the Muddy River that are managed by the BLM Southern Nevada District Office. Both species are BLM Special Status Species, a category that includes 1) species listed or proposed for listing under the ESA and 2) BLM-designated Sensitive Species - species requiring special management consideration to promote their conservation and reduce the likelihood and need for future listing under the ESA. Sensitive species are designated by the BLM State Director. Many of the species protected by the Service and the State of Nevada are on BLM's State Sensitive Species List. This list includes the Moapa Warm Springs riffle beetle, the Moapa pebblesnail, and the Moapa Valley pryg (*Pyrgulopsis carinifera*), some of which are referred to in this report by the Service.

Further, the BLM is a member of the Biological Action Committee for the Muddy River working to conserve and recover the rare aquatic species listed in this report. As part of these efforts, BLM used SNPLMA funding to design and construct three fish barriers on the Muddy River to prevent the upstream migration of nonnative species from the Virgin River. The barriers also segmented the river into sections that can be treated in order to remove the nonnatives. The fish barrier design includes the ability to remove the center sections and allow for connectivity after the each segment is clear of nonnative fish. The approximate cost for the construction of the barriers was $600,000. BLM has also contributed additional funding for the removal of nonnative fish species. In addition, the BLM has partnered with the Service and the Walton Foundation to conduct restoration projects on the Muddy River to benefit the southwestern willow flycatcher by increasing potential foraging habitat, which is also groundwater dependent.

Conclusions from Public Interest Considerations

Our view continues to be that groundwater should be developed in a manner that will avoid impacts to groundwater-dependent public resources to the extent possible; or, if such impacts cannot be avoided, to minimize those impacts to groundwater-dependent resources, including the natural resources and public facilities at the Moapa Valley NWR, Lake Mead NRA, and on other lands, as well as the endangered Moapa dace and other federally or State-protected and sensitive species that inhabit (some exclusively) these areas. Appropriating additional groundwater within CSV, the MRSA, and adjacent hydrographic basins (Hidden and Garnet valleys and California Wash) would likely prove detrimental to the public interest given that these resources and lands rely on thermal spring discharge from the carbonate-rock aquifer.

Section 5 - Overall Report Conclusions

In 2002, the Nevada State Engineer issued Order 1169, which stated that all pending and new water right applications in the carbonate-rock aquifer in Coyote Spring Valley (Basin 210), Black Mountains Area (Basin 215), Garnet Valley (Basin 216), Hidden Valley (Basin 217), the Muddy River Springs Area, a.k.a. Upper Moapa Valley (Basin 219), and Lower Moapa Valley (Basin 220) would be held in abeyance pending further study (NSE, 2002a). California Wash (Basin 218) was later added to the list through Ruling 5115 (NSE, 2002b). The applications were held in abeyance so that the State Engineer could collect more information on the effects of groundwater pumping from the carbonate-rock aquifer prior to making a determination on pending water right applications in the listed basins. The order called for a study covering a "*5-year minimum period of time during which at least 50% of the water rights then currently permitted in the Coyote Springs Valley groundwater basin are pumped for at least two consecutive years.*"

The Order 1169 Study officially started on November 15, 2010 and was finished on December 31, 2012. Carbonate pumping in CSV, which averaged about 2,000 afy from 2006 to 2009, more than doubled to 5,400 afy during the pumping test. Groundwater pumping in adjacent basins remained relatively unchanged from previous years during the period of the pumping test. The volume of pumping in CSV during the test was approximately one-third of the groundwater rights currently permitted in that basin.

The U.S. Fish and Wildlife Service, National Park Service, and Bureau of Land Management prepared this report in response to the State Engineer's request for information related to the pumping test. The report addresses the three questions posed by the Nevada State Engineer in Order 1169A (NSE, 2012e):

- What information was obtained from the pumping study/test?
- What were the impacts of pumping under the pumping test?
- What is the availability of water pursuant to the pending applications?

The main findings of this report are:

- The effects of pumping MX-5 are readily apparent in water-level data from the carbonate-rock aquifer over a 1,100 square mile area that is hydrologically-connected and encompasses five hydrographic basins: Coyote Spring Valley, the Muddy River Springs Area, Hidden Valley, Garnet Valley, and California Wash. There is no scientific justification for managing groundwater production from the carbonate-rock aquifer separately in these five hydrographic basins.
- The results indicate carbonate pumping at any location within the five hydrologically-connected basins in this area (southern CSV, MRSA, Hidden Valley, Garnet Valley, and California Wash) will lower groundwater levels nearly uniformly throughout these basins within relatively short time periods and will eventually capture from the Muddy River Springs, Muddy River, and (or) ET associated with phreatophytic vegetation in the MRSA and California Wash, the only forms of natural discharge in this area, at a rate that approaches 100 percent of the pumping.

- An evaluation of the discharge from springs in the Muddy River Springs area indicates that pumping of MX-5 has caused observable reduction in the discharge from the higher elevation springs, and that the observed capture of the spring discharge was 10 to 20% of the rate at which MX-5 was pumped. Thus, during the duration of the Order 1169 test, most of the water was being produced from storage (i.e., from the release of water caused by the reduction in water levels). Drawdown in the carbonate-rock aquifer was continuing to increase at the time the test was officially ended (December 31, 2012), and therefore the capture of discharge at the springs was also continuing to increase. If pumping of MX-5 continues at the same rate as during the test, discharge from the Pederson spring would likely cease in about 1.5 years and discharge from Pederson East spring would likely cease in about 2.5 to 3 years. Continued pumping would cause other springs to decline or dry up as well until the declines in spring discharge and ET equal the volume of pumping.
- The model developed by Tetra Tech in 2012 underestimates the magnitude of groundwater-level changes and the amount of time for them to be developed, but matches well the area that will be affected by pumping from the carbonate-rock aquifer. Thus, the predicted effects of pumping from the carbonate-rock aquifer are very conservative, and the springs will be impacted considerably sooner than the model predicts, under the pumping scenarios simulated.
- Our analysis of water budgets and perennial yield information suggests that there is no available water in CSV or any of the other four hydrologic basins discussed above. The fact that the pumping in CSV during the test was only one-third of the existing water rights permitted in CSV and that our analysis of spring impacts suggests that even this small level of pumping could lead to unreasonable and possibly irreversible impacts confirms this finding.
- The ecosystem around the Muddy River Springs area is dependent on the discharge from the springs. The Moapa dace is dependent on the higher temperature discharges. Additionally, the flow in the Muddy River is dependent on the discharge from the carbonate-rock aquifer. Pumping of the carbonate-rock aquifer will reduce the streamflow and impact downstream water rights holders. The Muddy River is fully adjudicated. Therefore, there is no water available for water right applications pending under Order 1169 within the five basins described above.

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Appendix A

Well specifications and supplemental groundwater level, drawdown, and production hydrographs

Table A.1 Specifications for Wells Utilized in Groundwater Analyses, Section 1.

Basin_name	Well	Well Type	Agency	UTM E 11N NAD83 (m)	UTM N 11N NAD83 (m)	MP Elev NAVD88 (ft)	Completion Unit^{*1}	Perforations (ft bgs)	Frequency WL Monitoring	Record
Lower Meadow Valley Wash	MVWD MW-1	Monitoring	MVWD	707,906	4,087,860	1992.16	F	144 - 200	Monthly	Monthly: Aug-10 - Dec-12
Coyote Spring V	CE-VF-2	Monitoring	SNWA	683,007	4,082,892	2468.35	C	---	Continuous	Intermittent: 8/13/98 - 10/1/04 Daily: 8/13/03 - 12/11/12
Coyote Spring V	CSVM-1	Monitoring	SNWA	688,602	4,073,793	2160.6	F	320 - 1020	Continuous	Intermittent: 3/20/03 - 5/28/03 Daily: 7/10/03 - 12/13/12
Coyote Spring V	CSVM-2	Monitoring	SNWA	685,625	4,059,370	2572.74	C	720 - 1380	Continuous	Intermittent: 3/5/03 - 7/23/03 Daily: 10/14/04 - 12/11/12
Coyote Spring V	CSVM-3	Monitoring	SNWA	679,319	4,102,600	2650.68	C	380 - 1180	Continuous	Intermittent: 7/15/03 - 7/23/03 Daily: 8/14/03 - 12/11/12
Coyote Spring V	CSVM-4	Monitoring	SNWA	688,086	4,095,971	2842.38	C	800 - 1580	Continuous	Intermittent: 7/10/03 Daily: 8/13/03 - 12/11/12
Coyote Spring V	CSVM-5	Monitoring	SNWA	680,295	4,068,774	3130.70	C	1020 - 1760	Continuous	Intermittent: 2/18/03 - 7/10/03 Daily: 8/13/03 - 12/11/12
Coyote Spring V	CSVM-6	Monitoring	SNWA	686,453	4,078,333	2251.66	C	420 - 1160	Continuous	Intermittent: 3/28/03 - 7/15/03 Daily: 7/23/03 - 12/13/12
Coyote Spring V	MX-4	Monitoring	SNWA/USGS	688,003	4,074,277	2174.98 (NWIS); 2177.02 (SNWA)	C	50 - 669	Continuous	Intermittent: 10/16/98 - 12/10/12
Coyote Spring V	CSI-1	Production	CSI (reported by SNWA)	686,043	4,074,459	2278.05	C	520 - 880	Continuous	Monthly: Jan-05 - Dec12 Daily: 1/1/10 - 12/31/12
Coyote Spring V	CSI-2	Production	CSI (reported by SNWA)	687,083	4,075,781	2208.95	C	525 - 1006	Continuous	Monthly: Jan-05 - Dec12 Daily: 1/1/10 - 12/31/12
Coyote Spring V	CSI-3	Production	CSI (reported by SNWA)	685,813	4,077,531	2334.51	C	571 - 1132	Monthly/Cont.	Monthly: Jan-06 - Dec12 Daily: 1/1/10 - 12/31/12
Coyote Spring V	CSI-4	Production	CSI (reported by SNWA)	682,366	4,080,185	2511.40	C	844 - 1373	Monthly/Cont.	Monthly: Jan-06 - Dec12 Daily: 1/1/10 - 12/31/12
Coyote Spring V	RW2	Production	NV Energy	687,862	4,074,082	2200.06	C	460 - 700	Continuous	Monthly: Jan-10 - Dec12 Daily: 8/1/10 - 12/31/12
Coyote Spring V	MX-5	Production	SNWA	688,084	4,074,219	2176.13	C	121 - 628	Continuous	Monthly: Apr-08 - Dec12 Daily: 1/1/10 - 12/31/12
Black Mountains Area	BM-ONCO-1	Monitoring	SNWA	702,650	4,010,748	2055.83	Clastic	440 - 1280	Quarterly	Intermittent: 5/21/02 - 11/19/12
Black Mountains Area	EBP-2	Production	NV Cogen.	689,628	4,018,599		C	755 - 1241	Monthly	Monthly: Jan-00 - Dec-12
Black Mountains Area	EGV-3	Production	NV Cogen.	689,858	4,018,999		C	702 - 955	Monthly	Monthly: Jan-00 - Dec-12
Black Mountains Area	EBM-4	Production	NV Cogen.	689,784	4,018,826		C	608 - 1129	Monthly	Monthly: Jan-00 - Dec-12

Garnet V	GV-1	Monitoring	SNWA	682,983	4,034,143	2691.14	C	1040 - 1380	Continuous	Intermittent: 6/18/02 - 11/07/02 Daily: 12/14/02 - 12/13/12
Garnet V	GV-DUKE-WS1	Production	NV Energy	686,197	4,029,178	2243.50	C	537 - 685	Monthly	Monthly: Jan-02 - Dec-12 Daily: 8/1/10 - 12/31/12
Garnet V	GV-DUKE-WS2	Production	NV Energy	686,185	4,029,177	2246.72	C	877 - 1944	Monthly	Monthly: Jan-02 - Dec-12 Daily: 8/1/10 - 12/31/12
Garnet V	GV-MIRANT1	Production	NV Energy	683,115	4,032,318	2567.87	C	1197 - 1979	Monthly	Monthly: May-2 - Dec-12 Daily: 1/1/10 - 12/31/12
Garnet V	GV-PW-WS1	Production	NV Energy	682,654	4,031,460	2532.29	C	1240 - 1980	Monthly	Monthly: Jan-02 - Dec-12
Garnet V	GV-RW1	Production	NV Energy	692,928	4,036,645	2069.20	C	553 - 833	Quarterly	Monthly: Jan-01 - Dec-12 Daily: 8/1/10 - 12/31/12
Garnet V	Chem Lime Old	Production	Chemical Lime Co.	687,941	4,029,333	---	F	350 - 500	Monthly	Monthly: Jan-01 - Dec-12
Garnet V	Chem Lime New	Production	Chemical Lime Co.	687,748	4,026,563	---	C	540 - 840	Monthly	Monthly: Jan-01 - Dec-12
Garnet V	GV-2	Production	Dry Lake Water Co.	686,226	4,025,690	2424	C	852 - 1232	Monthly	Monthly: Jan-08 - Dec-12
Garnet V	Republic Well #1	Production	Republic Env. Tech.	---	---	---	C	---	Monthly	Quarterly: Mar-07 - Mar-10; Monthly Apr-10 - Dec-12
Garnet V	Republic Well #2	Production	Republic Env. Tech.	690,674	4,027,890	---	C	883 - 963	Monthly	Quarterly: Mar-07 - Mar-10; Monthly Apr-10 - Dec-12
Garnet V	Republic Well #5	Production	Republic Env. Tech.	691,053	4,029,626	---	C	460 - 700	Monthly	Quarterly: Mar-07 - Mar-10; Monthly Apr-10 - Dec-12
Garnet V	Republic Well #6	Production	Republic Env. Tech.	690,552	4,026,318	---	C	900 - 1150	Monthly	Quarterly: Mar-07 - Mar-10; Monthly Apr-10 - Dec-12
Garnet V	M-3	Monitoring	MBPI	691,536	4,044,302	2235	C	630 - 670	Continuous	Intermittent: 12/6/00 - 11/13/10 Daily: 1/1/11 - 12/31/12
Hidden V	SHV-1	Monitoring	SNWA/USGS	685,751	4,047,256	2650.32	C	45 - 920	Continuous	Intermittent: 5/29/98 - 12/11/12
California Wash	ECP-1	Production	MBPI	696,729	4,046,590	2230.05	C	600 - 1125	Continuous	Monthly: Jan-09 - Dec-12
California Wash	ECP-2	Production	MBPI	696,723	4,046,742	---	C	55 - 1228	Quarterly	Monthly: Jan-09 - Dec-12
California Wash	ECP-3	Production	MBPI	696,714	4,046,984	---	C	74 - 1500	Quarterly	Monthly: Jan-09 - Dec-12
California Wash	M-1	Monitoring	MBPI	704,517	4,057,109	1895.69	C	360 - 400	Continuous	Intermittent: 12/6/00 - 11/13/10 Daily: 1/1/11 - 12/31/12
California Wash	M-2	Monitoring	MBPI	695,836	4,040,876	2108.5	C	640 - 680	Continuous	Intermittent: 12/6/00 - 11/13/10 Daily: 1/1/11 - 12/31/12
California Wash	TH-2	Monitoring	MBPI	697,684	4,049,916	2338.09	C	TD 1198	Continuous	Intermittent: 12/6/00 - 11/13/10 Daily: 1/1/11 - 12/31/12

California Wash	TH-1	Production	MBPI	697,233	4,044,981	2205.95	C	TD 1100	Daily	Monthly: Jan-09 - Dec-12
California Wash	BYRON	Monitoring	SNWA	710,994	4,051,282	1903.06	C	780 - 1095	Monthly	Intermittent: 7/5/10 - 12/13/12
MRSA	CSV-2	Monitoring	SNWA/USGS	703,217	4,072,967	2188.68	C	---	Continuous	(NWIS) Daily: 2/6/91 - 4/24/13
MRSA	EH-4	Monitoring	NV Energy	703,929	4,064,736	1933.93	C	TD 285	Continuous	Intermittent: 1/23/87 - 9/8/10 Daily: 9/15/10 - 12/17/12
MRSA	EH-5B	Monitoring	NV Energy	701,569	4,067,619	1844.80	C	TD 264	Continuous	Intermittent: 1/23/87 - 9/8/10 Daily: 9/15/10 - 12/17/12
MRSA	UMVM-1	Monitoring	SNWA	694,305	4,070,248	2061.88	C	960 - 1760	Continuous	Intermittent: 7/15/03 Daily: 7/23/03 - 12/13/12
MRSA	ARROW CANYON1	Production	MVWD	701,104	4,067,755	1861.45	C	205 - 565	Continuous	Monthly: Jan-00 - Dec-12 Daily: 8/1/10 - 12/31/12
MRSA	ARROW CANYON 2	Production	MVWD	701,103	4,067,768	1863.29	C	480 - 742	Continuous	Monthly: Jan-05 - Dec-12 Daily: 8/1/10 - 12/31/12
MRSA	MX-6	Production	MVWD	697,482	4,071,381	2278.11	C	325 - 937	Monthly	Monthly: Jan-00 - Dec-12 Daily: 8/1/10 - 12/31/12
MRSA	LDS Central	Production	NV Energy	704,114	4,066,544	1762.78	F	25 - 50	Monthly	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	LDS East	Production	NV Energy	704,479	4,066,594	1753.13	F	17 - 77	Monthly	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	LDS West	Production	NV Energy	702,746	4,067,083	1807.80	F	---	Monthly	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Lewis 1	Production	NV Energy	702,182	4,068,043	1828.71	F	---	4 months (production only)	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Lewis 2	Production	NV Energy	702,339	4,067,921	1826.04	F	---	Continuous	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Lewis 3	Production	NV Energy	701,956	4,068,021	---	F	---	4 months (production only)	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Lewis 4	Production	NV Energy	702,028	4,067,620	---	F	---	4 months (production only)	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Lewis 5	Production	NV Energy	702,196	4,067,485	---	F	---	4 months (production only)	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	Behmer	Production	NV Energy	706,031	4,065,080	---	F	0 - 115	4 months (production only)	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
MRSA	PERKINS PRODUCTION	Production	NV Energy	705,693	4,065,206	2274.60	F	25 - 125	Monthly	Monthly: Jan-00 - Dec-12 Daily: 1/1/11 - 12/31/12
Lower Moapa V	EH-7	Monitoring	NV Energy	720,660	4,060,990	---	C	---	Continuous	Intermittent: 1/23/87 - 1/4/13

Appendix A.2 – Additional groundwater level and production hydrographs as a function of time

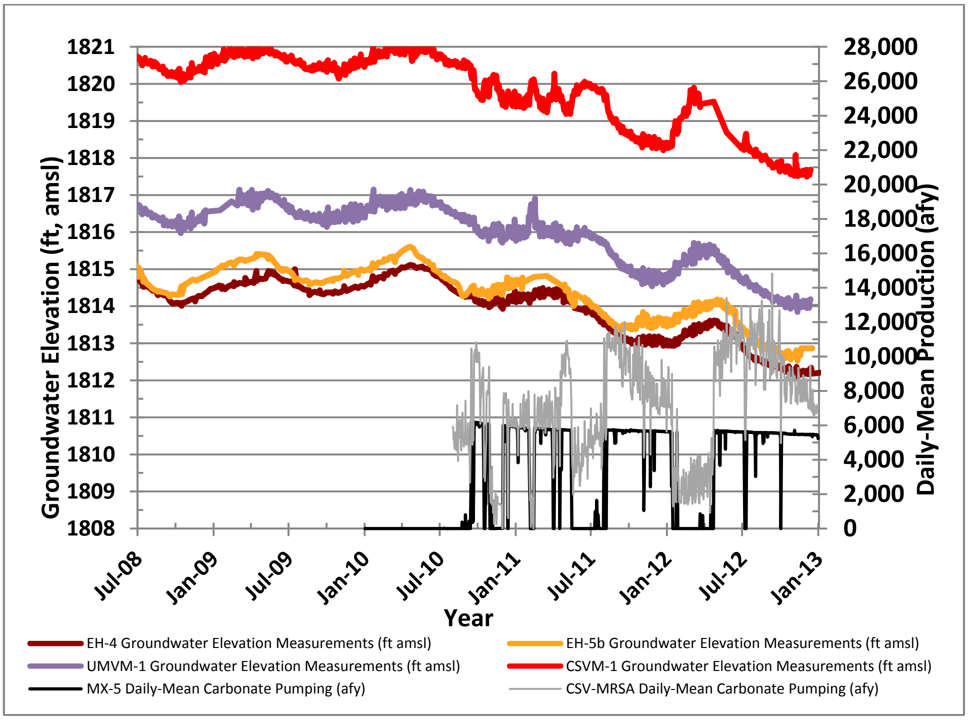


Figure A.2-1. Groundwater elevations in carbonate monitoring wells CSVM-1 in CSV and UMVM-1, EH-5b, and EH-4 in the MRSA EH-4, July 2008 to December 2012, and daily-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from August 2010 to December 2012.

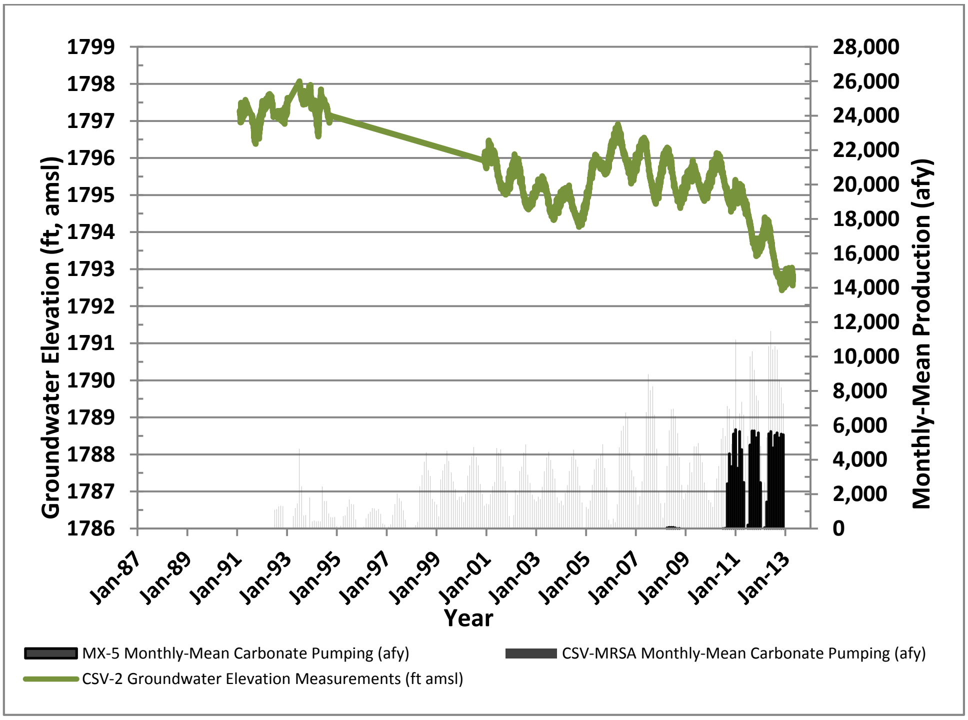


Figure A.2-2. Groundwater elevation in carbonate monitoring well CSV-2 in the MRSA and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

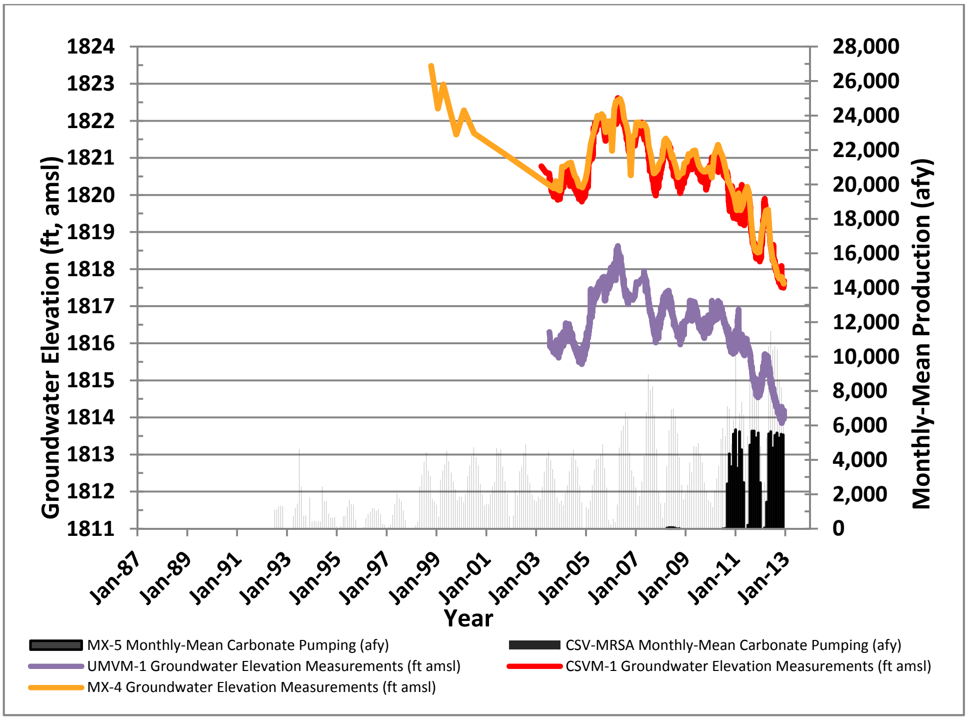


Figure A.2-3. Groundwater elevations in carbonate monitoring well UMVM-1 in the MRSA and CSVM-1 and MX-4 in the CSV and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

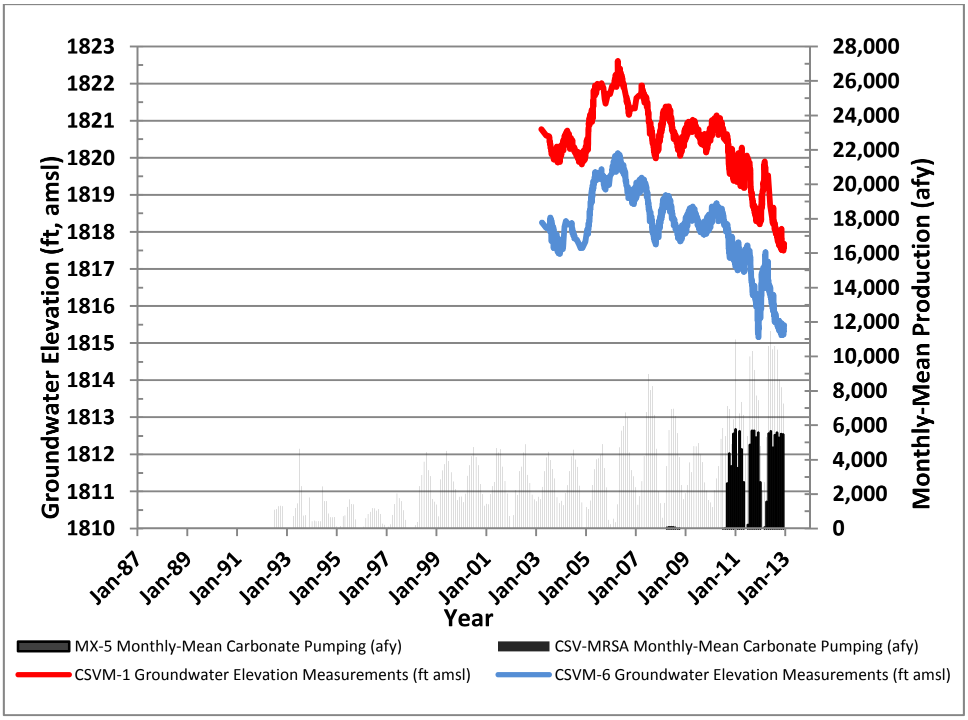


Figure A.2-4. Groundwater elevations in carbonate monitoring well CSVM-1 and CSVM-6 in the CSV and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

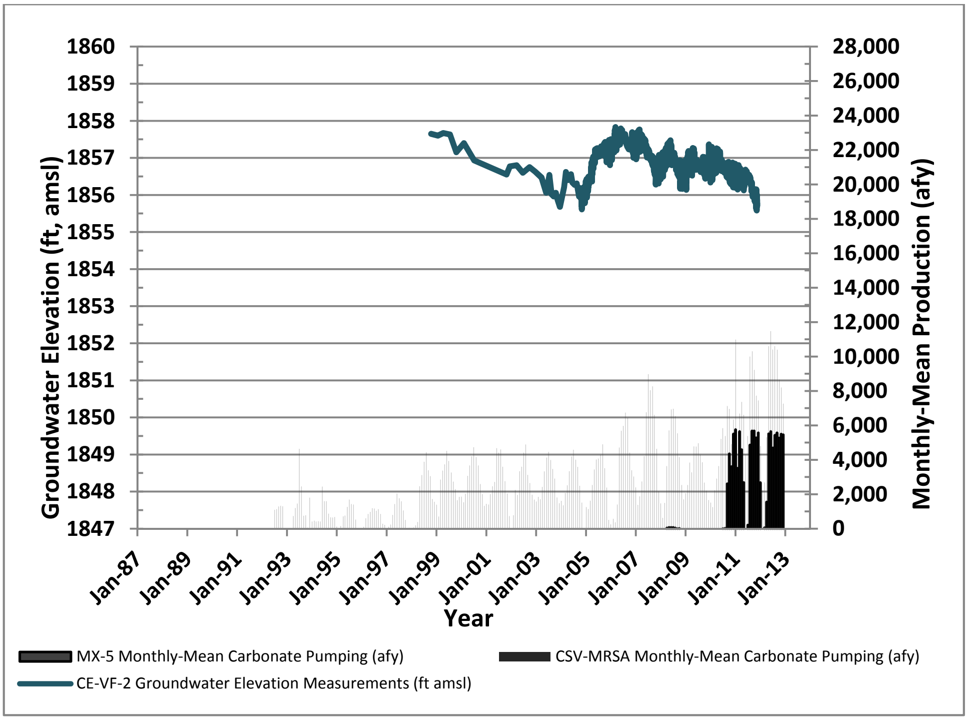


Figure A.2-5. Groundwater elevations in carbonate monitoring well CE-VF-2 in the CSV and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

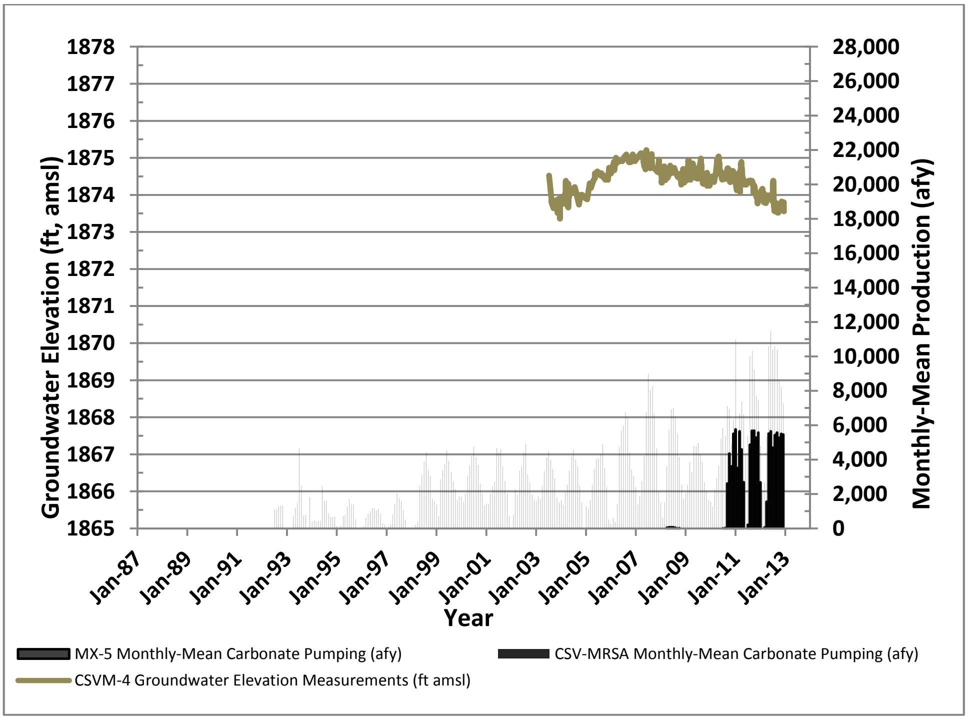


Figure A.2-6. Groundwater elevations in carbonate monitoring well CSVM-4 in the CSV and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

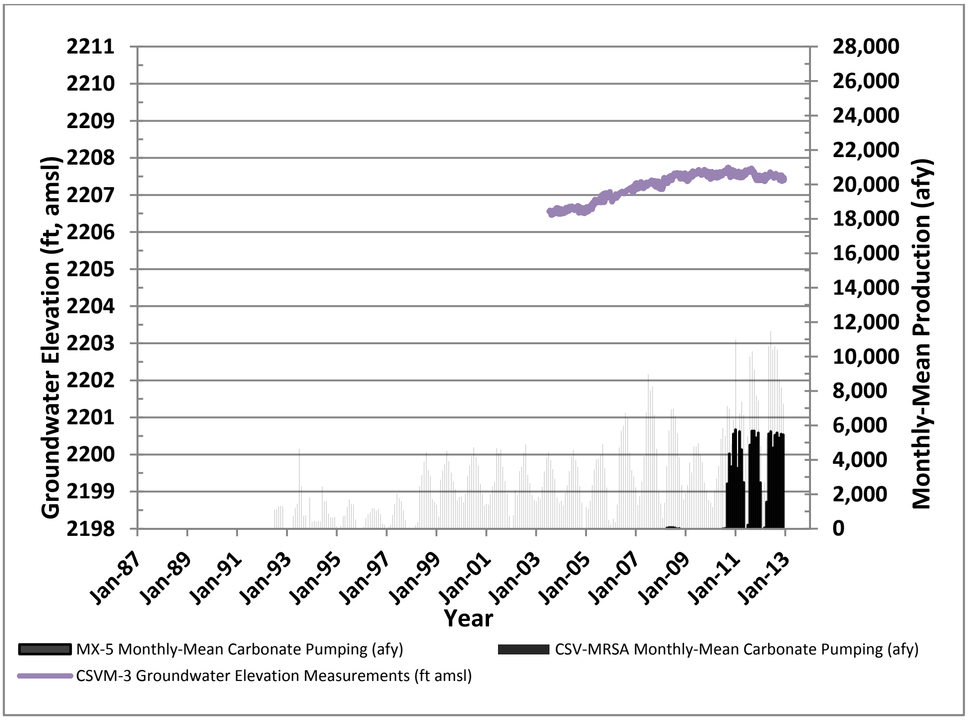


Figure A.2-7. Groundwater elevations in carbonate monitoring well CSVM-4 in the CSV and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

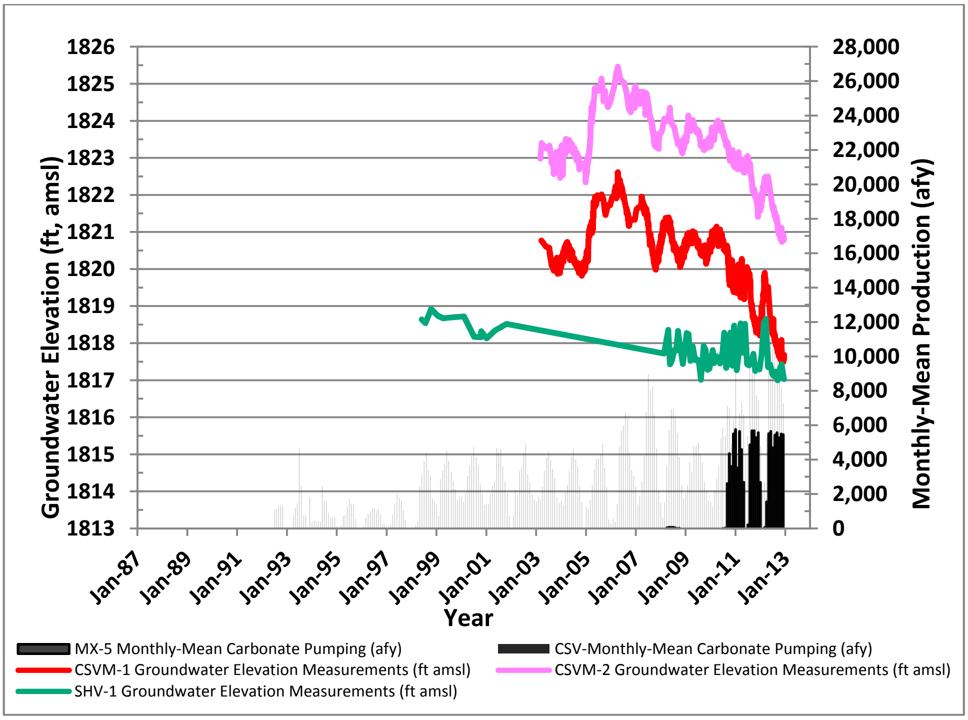


Figure A.2-8. Groundwater elevations in carbonate monitoring well CSVM-1 and CSVM-2 in the CSV and SHV-2 in Hidden Valley and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

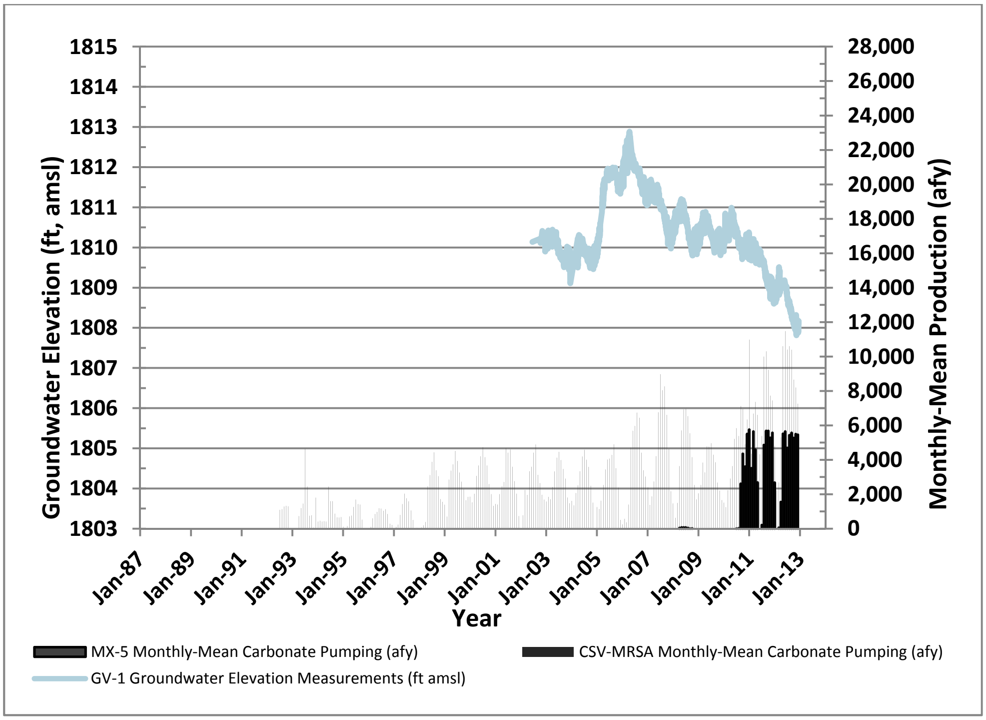


Figure A.2-9. Groundwater elevations in carbonate monitoring well GV-1 in Garnet Valley and monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area from 1987 to 2012.

Appendix A.3 – Additional drawdown and production hydrographs as a function of time

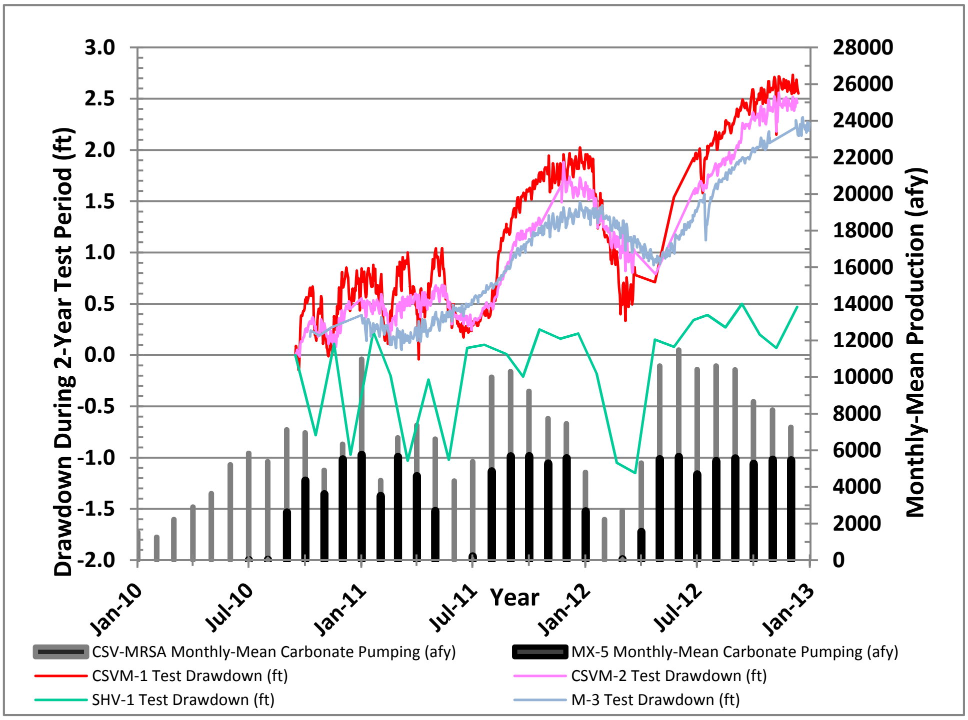


Figure A.3-1. Estimated drawdown in carbonate monitoring wells CSVM-1 and CSVM-2 in CSV, SHV-1 in Hidden Valley, and M-3 in Garnet Valley versus monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area, from September 15, 2010, to December 31, 2012, i.e., during the 2-year pumping test.

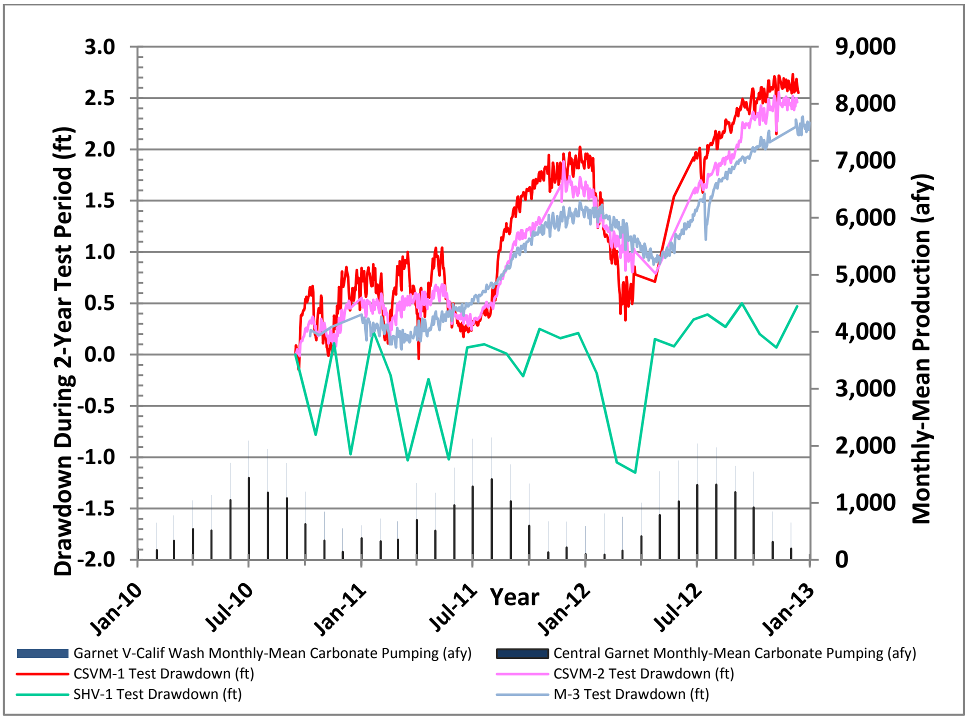


Figure A.3-2. Estimated drawdown in carbonate monitoring wells CSVM-1 and CSVM-2 in CSV, SHV-1 in Hidden Valley, and M-3 in Garnet Valley versus monthly-mean production rates in the carbonate-rock aquifer in central Garnet Valley and Garnet Valley and California Wash as a whole from 1987 to 2012.

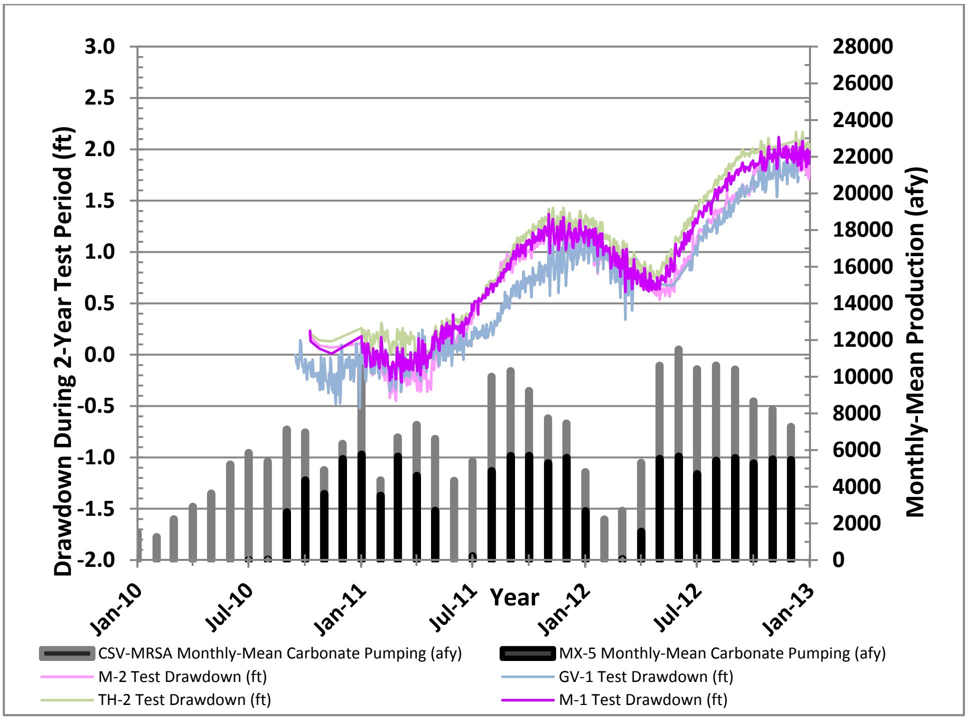


Figure A.3-3. Estimated drawdown in carbonate monitoring wells M-3, M-2, and GV-1 in Garnet Valley, and TH-2 and M-1 in California Wash versus monthly-mean production rates in the carbonate-rock aquifer at production well MX-5 and in the combined CSV and MRSA area, from September 15, 2010, to December 31, 2012, i.e., during the 2-year pumping test.

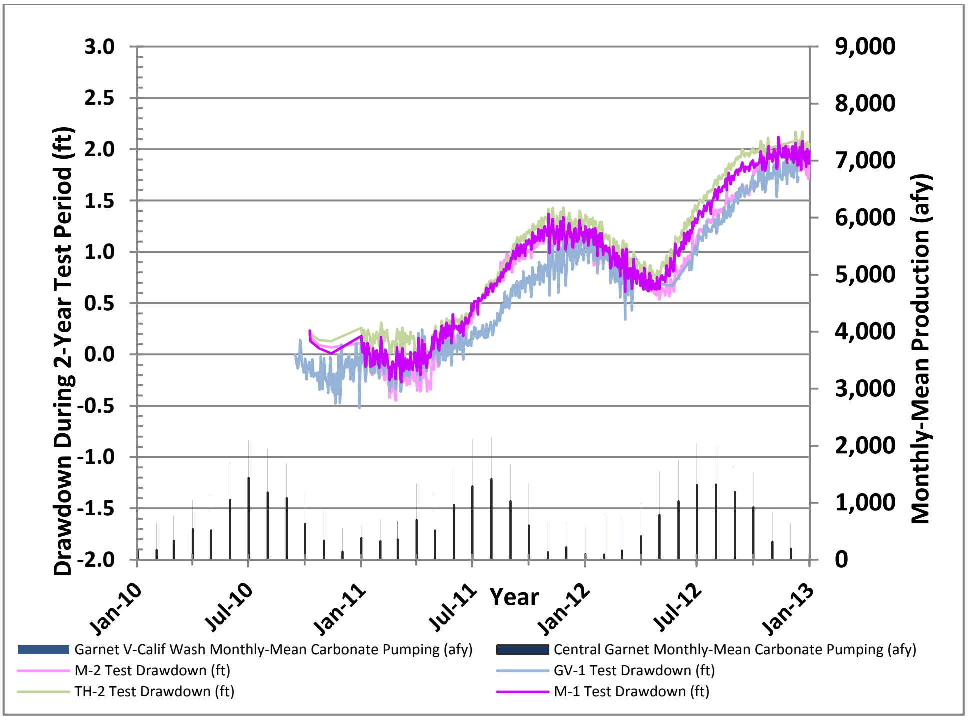


Figure A.3-4. Estimated drawdown in carbonate monitoring wells M-3, M-2, and GV-1 in Garnet Valley, and TH-2 and M-1 in California Wash versus monthly-mean production rates in the carbonate-rock aquifer in central Garnet Valley and Garnet Valley and California Wash as a whole from 1987 to 2012.

Appendix A.4 Results of SeriesSEE Evaluation of Drawdown, Order 1169 Pumping of MX-5

SeriesSEE (Halford and others, 2012) is a software package that uses multiple-regression techniques to remove “noise” caused by barometric pressure changes, earth tides, and pumping of other wells from a set of water-level measurements to facilitate interpretation. Because of the length of time for the Order 1169 test, and the much shorter wavelength and lower magnitude of barometric and earth-tide induced changes, no corrections for barometric and earth-tide changes were needed. The SeriesSEE approach uses Theis transforms to calculate the drawdown caused at a well of interest from pumping from another well or pumping center. These transforms are based on the standard Theis assumptions. In particular, each Theis transform used to calculate the drawdown assumes that the aquifer is homogeneous (using transmissivity and storage parameters specific to each pumping well/observation well pair), and infinite in extent. Superposition is used to incorporate the effects of monthly temporal changes in flow rates and the combined effects of multiple pumping wells.

A multiple-regression technique is used to estimate the transmissivity and storage parameters for each production well/observation well, minimizing the sum of squared differences between the measured and modeled drawdowns at the well of interest. The quality of the results from the multiple regression is determined by the available data, the applicability of the modeling equation (superposed Theis solutions), and the independence of the dependent variables, in this case the monthly pumping rates. If the pumping rates are highly correlated (i.e, the shapes of the rate versus time curves are very similar), the regression technique will not be successful in separating out the effects of pumping of the different wells. In other words, if all pumping schedules have similar seasonal variability, and do not vary year to year, the technique will be unable to differentiate the drawdown caused by different wells. There will be a tendency to “zero out” the effect of some wells and increase the effects caused by other wells. However, if the pumping schedules are not similar, the technique will be much more effective in differentiating the effects of the different wells. For example, if one well was pumped for a few months one year, and another well was pumped for a few months a different year, the technique would be very successful in differentiating the wells’ effects. In an area where there is existing groundwater production for different wells, the situation is more complicated than this example.

The area in which the Order 1169 test was performed is one in which there is existing seasonal pumping, and more constant pumping, from many wells. Fortunately, the Order 1169 test was conducted with collection of water-level data from many wells for a period of several years before the pumping of MX-5, followed by data collection during a more than two-year period of MX-5 pumping. Although there were some breaks in the pumping of MX-5, these breaks were short and not at the same time as the periods of low seasonal pumping of other wells. The pumping schedule for MX-5 was different from the schedules for other wells (thus, poorly correlated with other wells). It was therefore likely that the effects of MX-5 pumping could be differentiated.

Three examples of the SeriesSEE-evaluated drawdowns are provided in **Figures A.4-1, A.4-2, and A4-3**. **Figure A.4-1** shows the modeled drawdowns for observation well EH-4, located near many of the springs of concern. This figure includes several different plots. At the top is a plot of the measured and SeriesSEE-modeled drawdowns at EH-4. The modeled drawdown is the sum of the drawdowns calculated at the different pumping wells or groups of wells (some of which are not shown in these

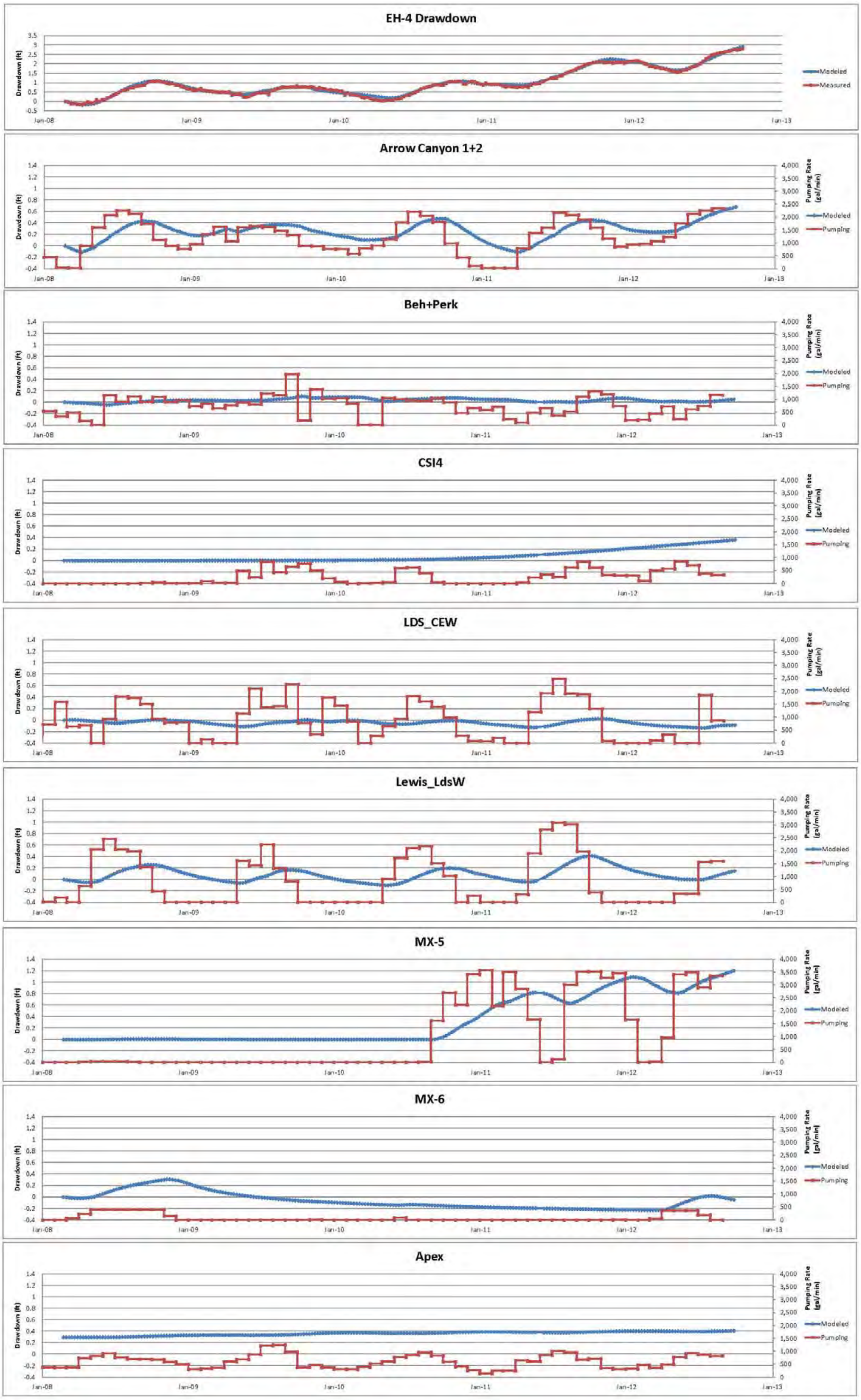


Figure A.4-1. SeriesSEE-estimated drawdown at EH-4, caused by pumping at selected wells.

figures). The other plots show monthly production (expressed in gpm) for selected different production wells or groups of pumping wells, and the modeled drawdown caused by that pumping. For example, the second plot from the top shows the measured monthly pumping and the model-simulated drawdown (at EH-4) for the Arrow Canyon wells. There is a seasonal variation in the pumping rate, and in the resultant model-simulated drawdown. There is also a several-month lag between the pumping and the simulated drawdown. The annual cycle has an amplitude of approximately 0.4 feet, and the total simulated drawdown of approximately 0.6 feet. Similar seasonal effects were simulated for the pumping labeled LDS_CEW (LDS Central and Eastern wells) and for Lewis_LDSW (Lewis wells and LDS West well). There were two short periods of pumping (in 2008 and 2012) from MX-6 and the simulated drawdown at EH-4 is apparent for each period. For pumping from some of the wells (e.g., CSI-4 and Beh+Perk (Behmer and Perkins)), the simulated drawdown is limited and smooth, a result of the transmissivity and storage parameters estimated for these wells for this particular analysis (drawdown at EH-4). The drawdown at MX-5 is notable on this figure, a result of the magnitude of the pumping, and its timing. As noted above, pumping did not occur during the early part of the analysis period (before October 2008), and there are two subsequent periods where pumping was stopped. The difference between the temporal pattern for MX-5 and the patterns for other wells allows SeriesSEE to successfully separate the effects of MX-5 pumping from other pumping.

The next figure (**Figure A.4-2**) shows the SeriesSEE results for well M2 on the Paiute Reservation in California Wash. The plot at the top shows that the regression was able to match the measured drawdown well. The results indicate that there are signals from the Arrow Canyon wells, Lewis_LdsW, MX-5, MX-6, and the Apex wells. Note that, although the rates and timing of production from LDS_CEW and Lewis_LdsW are similar, the regression model determined that the effects of the pumping from these wells were considerably different. This illustrates an important factor of this type of analysis, mentioned above. When two of the independent variables are similar (correlated), the regression approach may not be able to differentiate their contributions, and may cancel out effects of one of the variable (in this case, the effects of pumping from LDS_CEW). Note, however, that the timing and magnitude of pumping from MX-5 provided sufficient information to the regression process that the technique was able to differentiate the effects of this pumping.

The analysis of drawdown measured at CSVM-6 (**Figure A.4-3**) is an example of a SeriesSEE evaluation where there are some results that are hydrologically inconsistent, but where the approach was successful in differentiating the effects of MX-5 pumping. CSVM-6 is located northwest of MX-5, near CSI-3. The regression analysis indicated little drawdown from Arrow Canyon pumping, or pumping from the valley-fill wells in the Muddy River Springs area. It did indicate drawdown from CSI-4, which is nearby. The SeriesSEE model considers earlier pumping (pre-2008) and calculated that cessation of earlier pumping of CSI-3 caused recovery of water levels in CSVM-6 (not shown) during the period 2008 through 2012. To offset this drawdown, the model simulated over 2 feet of drawdown from pumping of MX-6, even the pumping from this well was limited. The estimated drawdown from many of these wells does not appear to be reasonable. In spite of these unrealistic results, the regression procedure was able to differentiate the effects of MX-5 pumping, and estimated a drawdown pattern from MX-5 pumping that is very similar to the other MX-5 patterns shown.

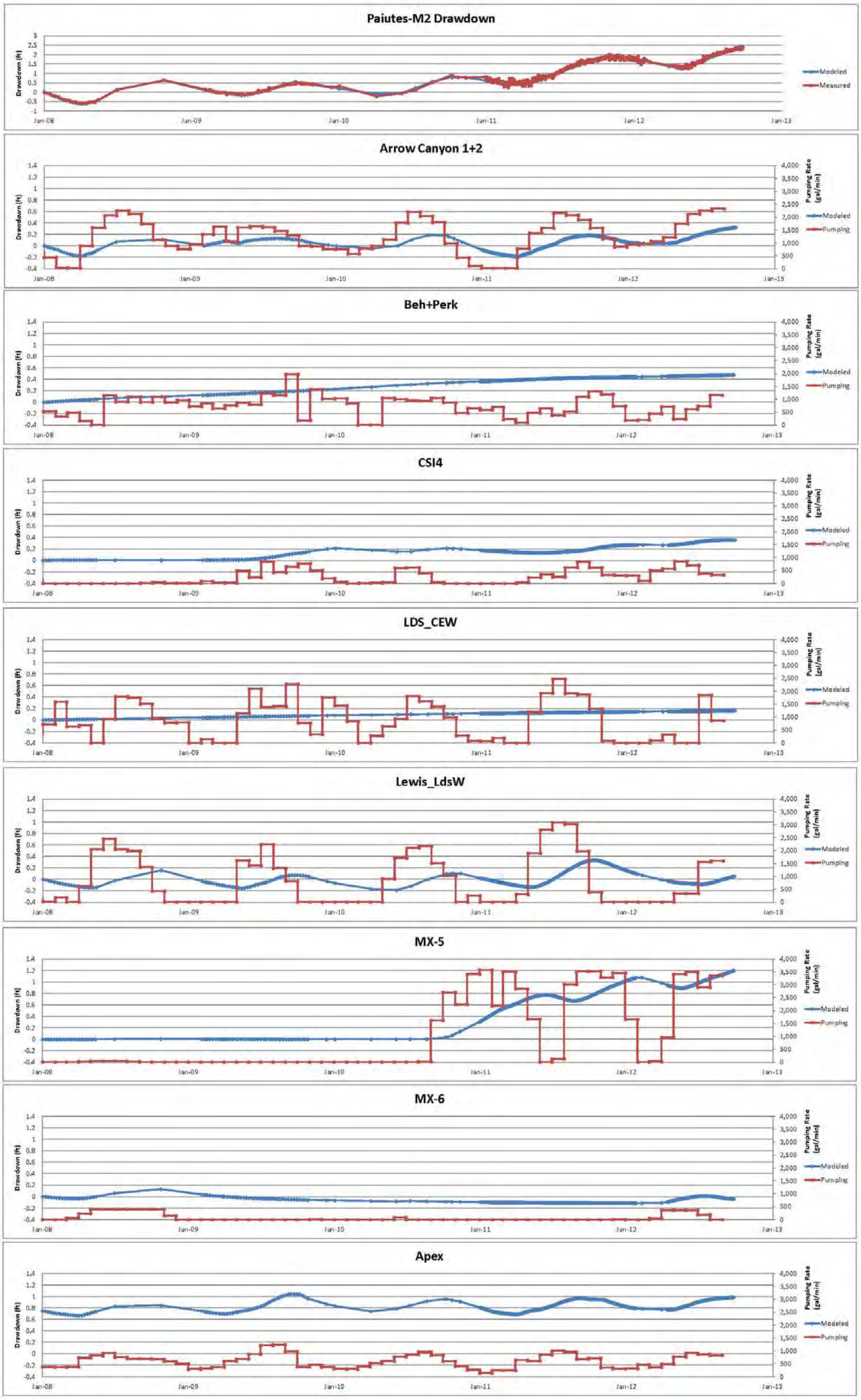


Figure A.4-2. SeriesSEE-estimated drawdown at Paiutes-M2, caused by pumping at selected wells.

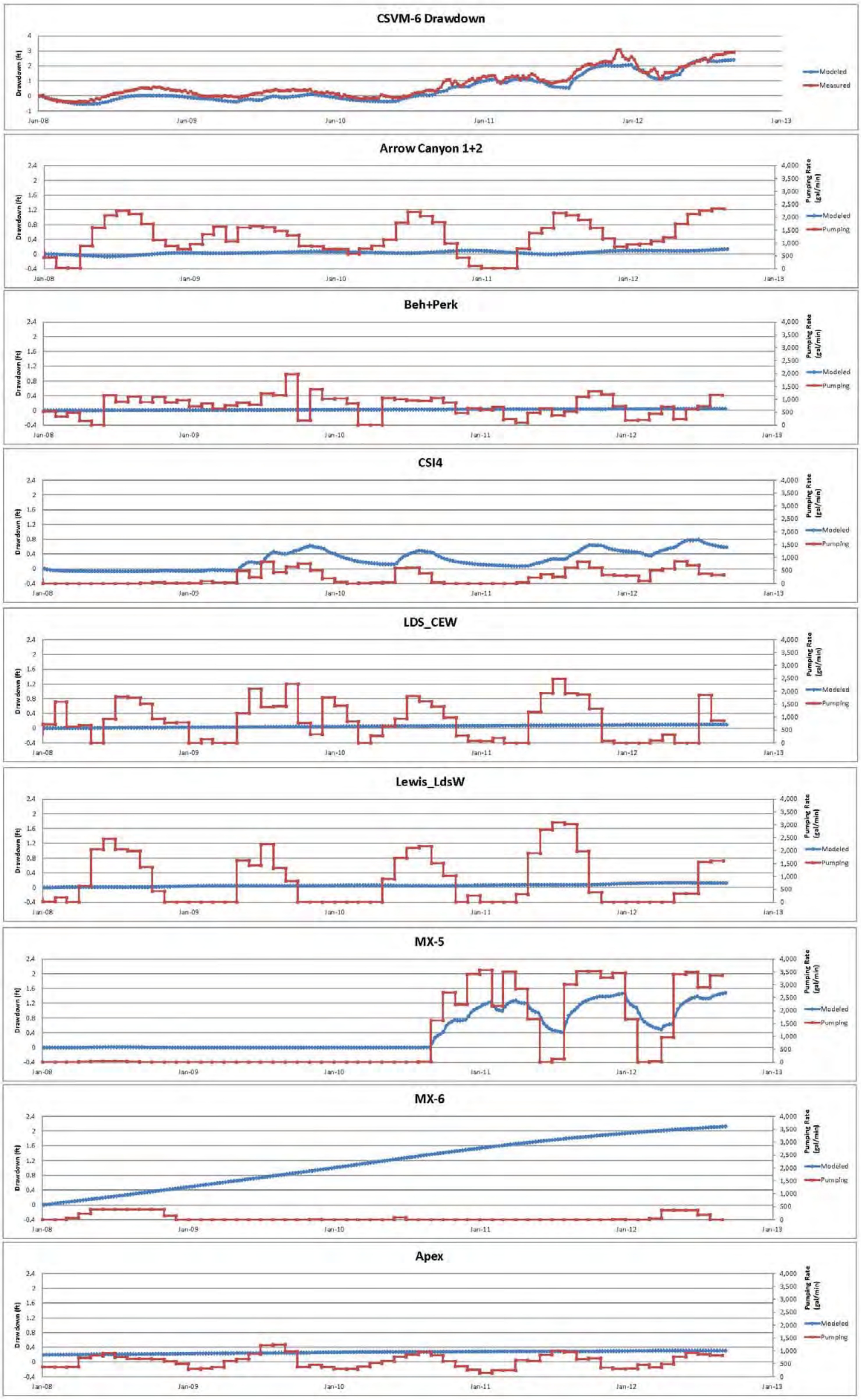
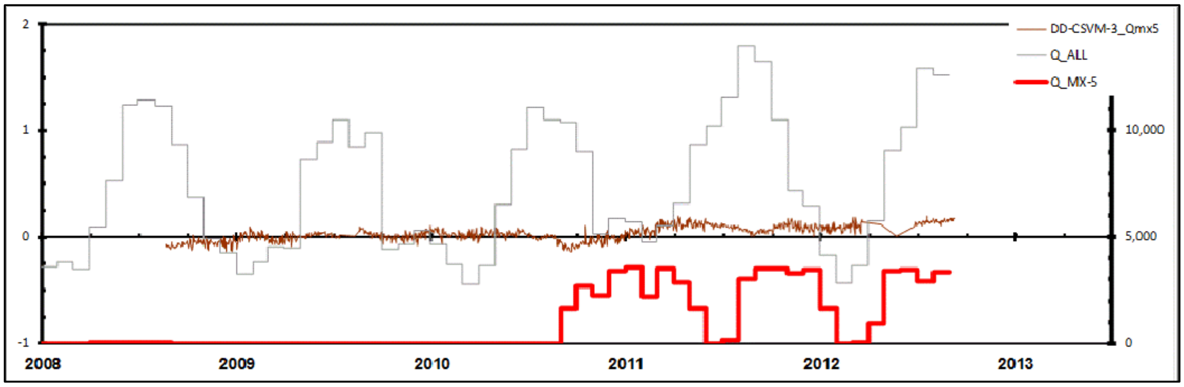


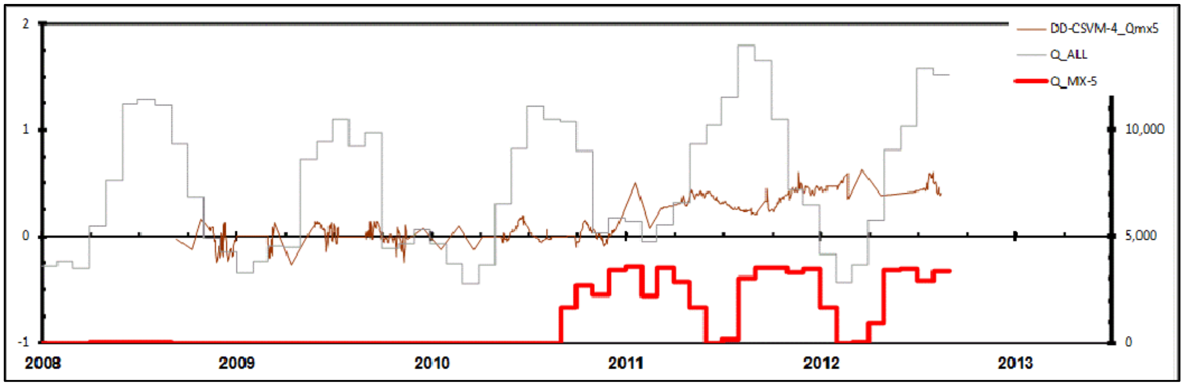
Figure A.4-3. SeriesSEE-estimated drawdown at CSVM-6, caused by pumping at selected wells.

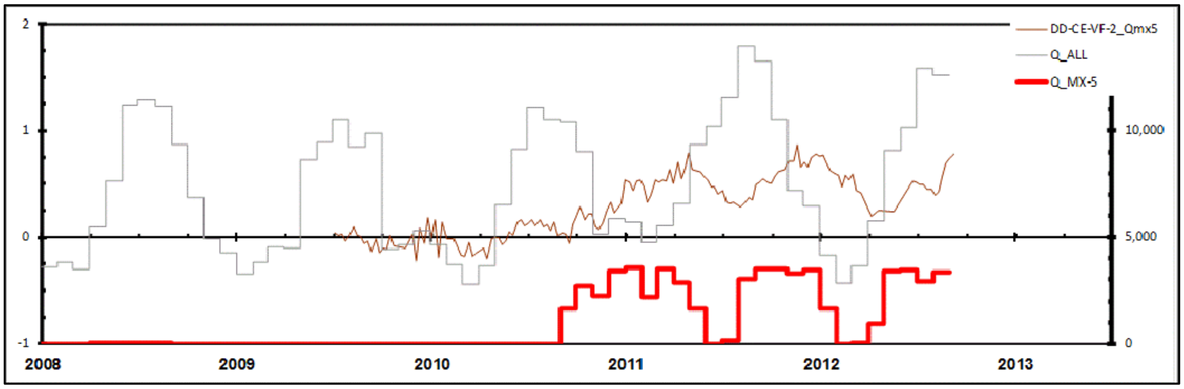
Evaluation of the results from other observation wells that were evaluated confirm these patterns. While the available data may not allow SeriesSEE to consistently identify the sources of the drawdown observed in the observations well (largely because of temporal correlation of pumping rates), SeriesSEE consistently identified drawdown caused by pumping of MX-5. The MX-5-caused drawdown patterns were similar in magnitude and shape. The ability of SeriesSEE to determine the drawdown caused by MX-5 is the result of the large magnitude and different temporal pattern of the MX-5 pumping.

The remainder of this Appendix provides SeriesSEE-determined drawdown caused by pumping of MX-5, added to the residuals of the regression (the differences between the measured and simulated drawdowns). This provides a visual comparison of the estimated drawdown with the residuals, and allows the viewer to decide whether the remaining noise (residuals) obscures the drawdown.

Appendix A.4-4 – Hydrographs of MX-5 pumping-induced drawdown estimated in monitoring wells within and outside of the Study Area, based on preliminary SeriesSEE analyses versus MX-5 pumping and total pumping within the Study Area, January 1, 2008 to December 13, 2012.



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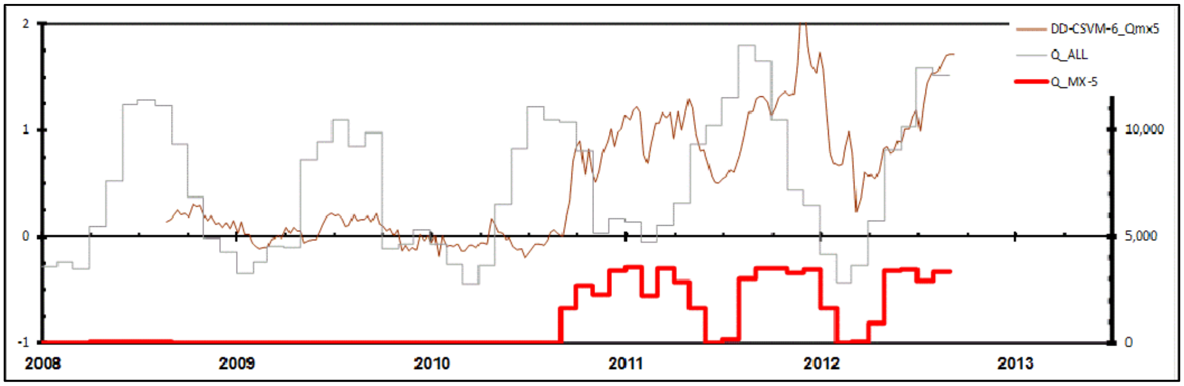
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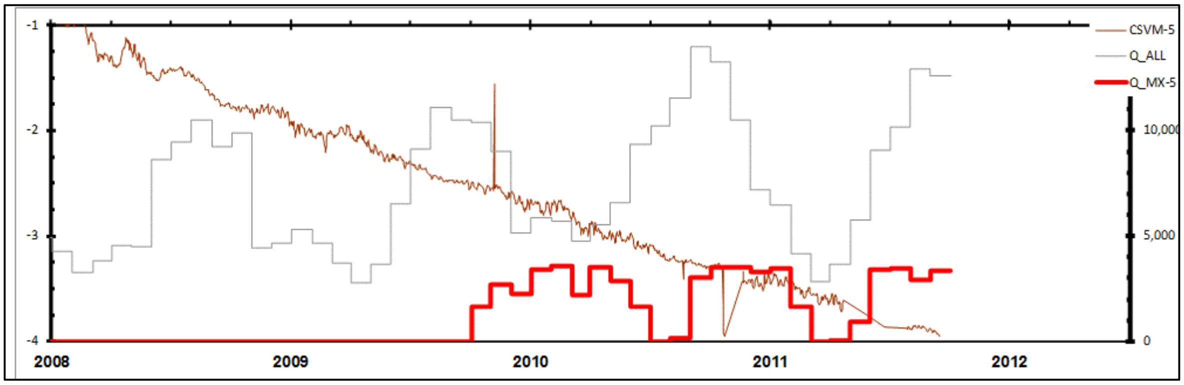
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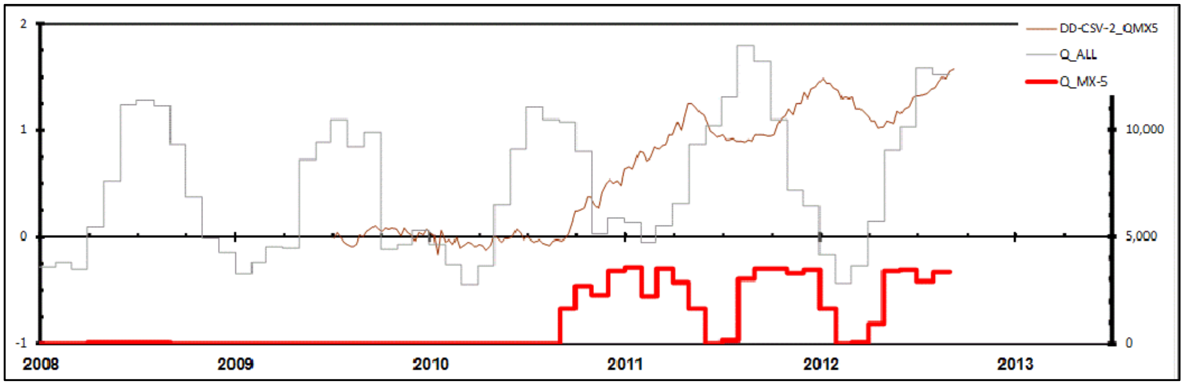
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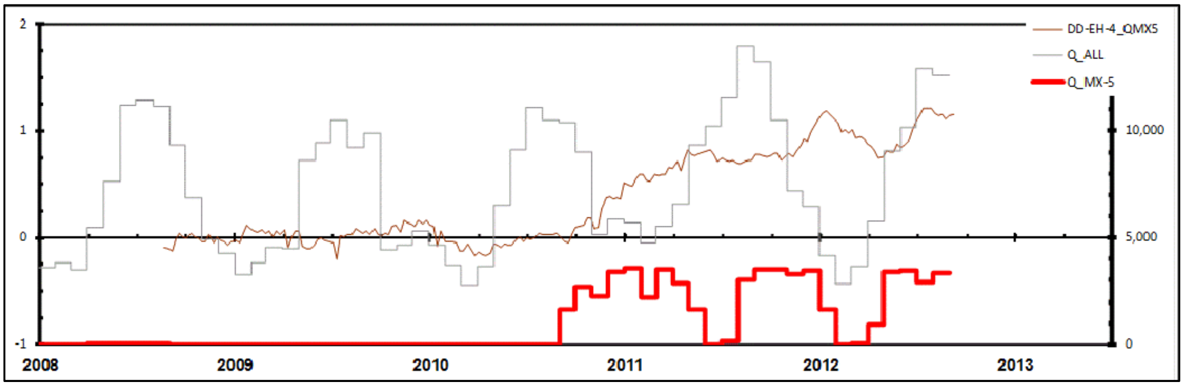
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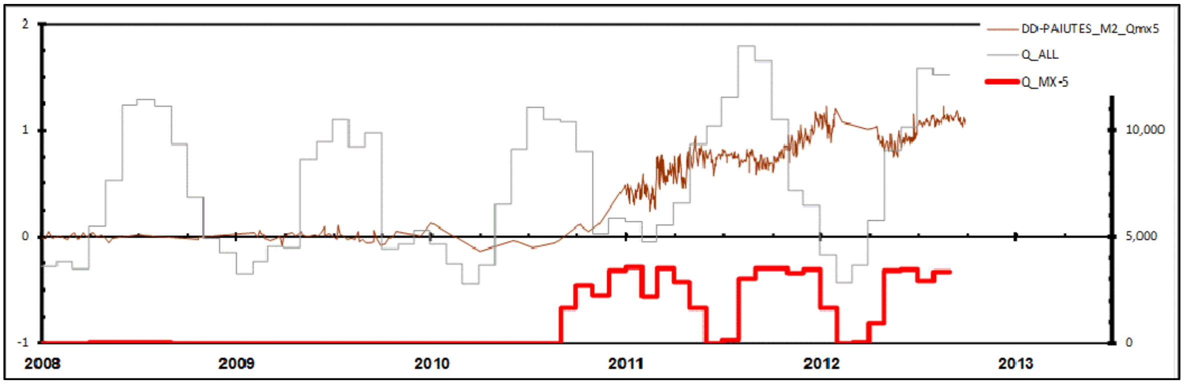
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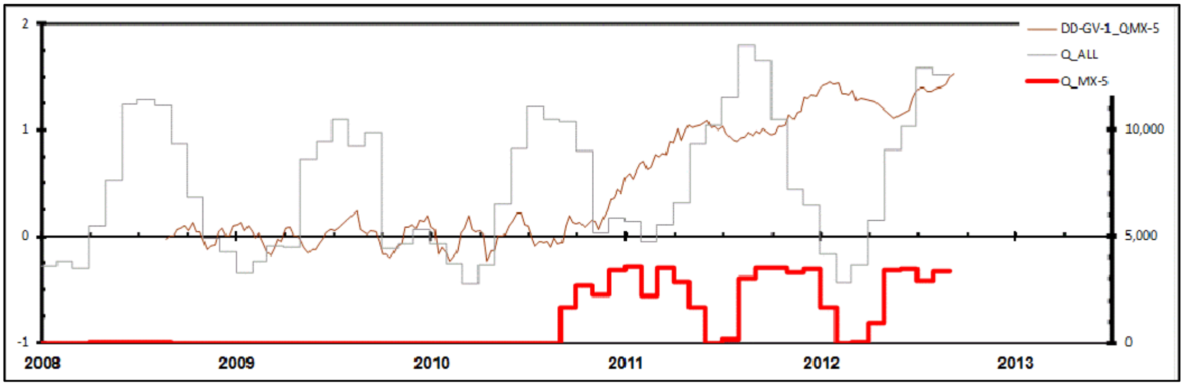
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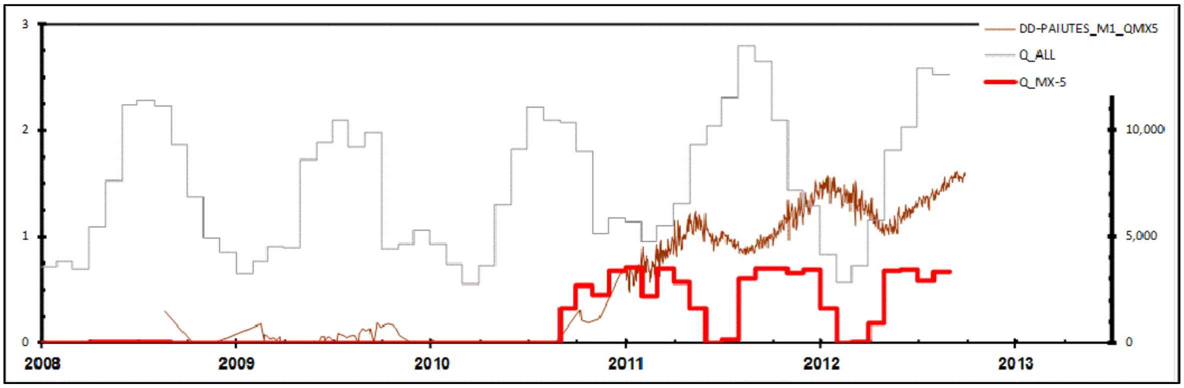
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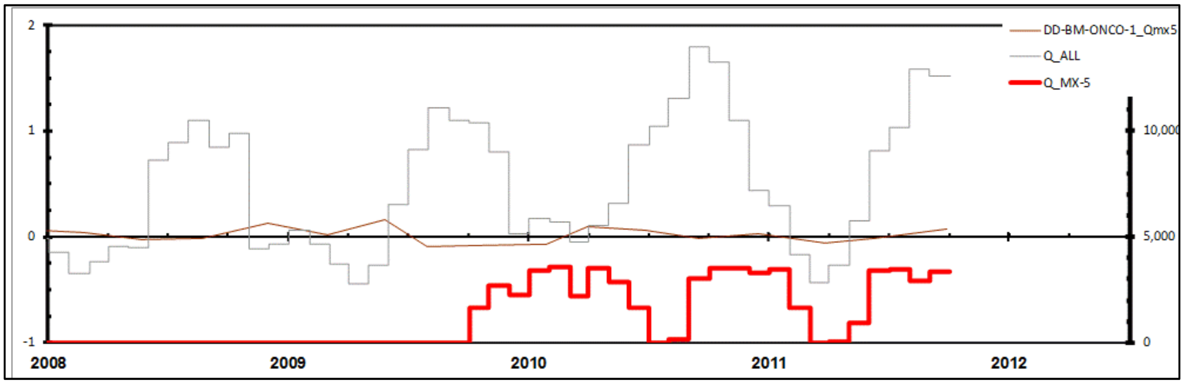
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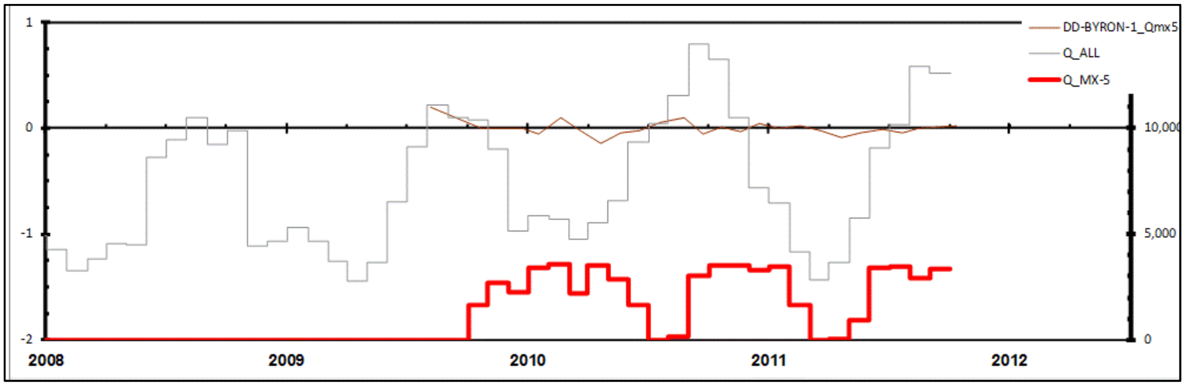
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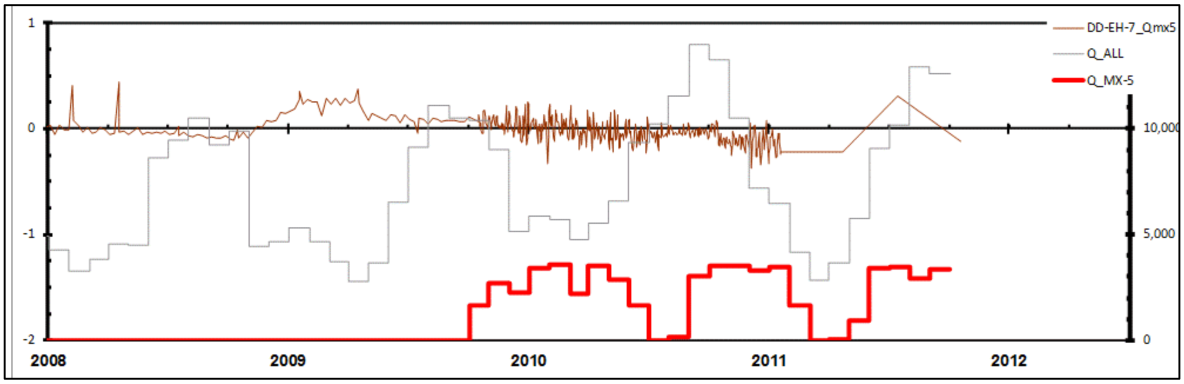
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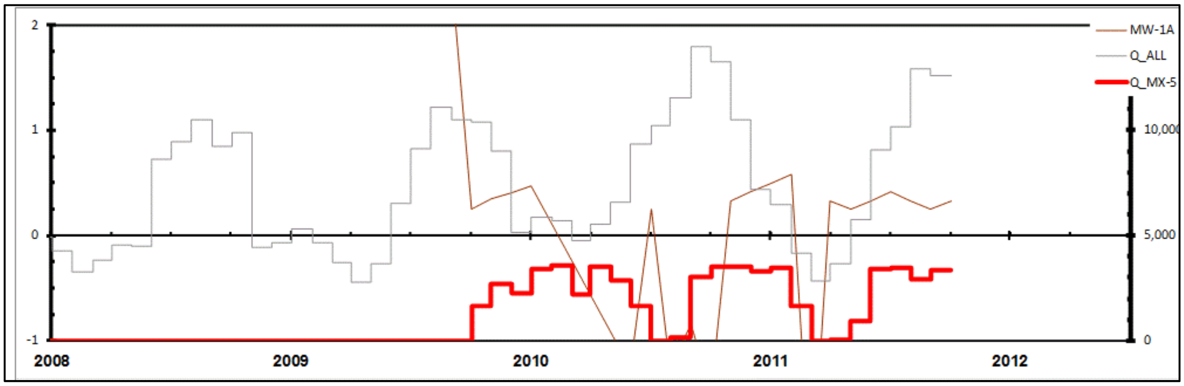
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Prepared in cooperation with the Southern Nevada Water Authority

Water-Surface Elevations, Discharge, and Water-Quality Data for Selected Sites in the Warm Springs Area near Moapa, Nevada

Open-FIle Report 2006–1311

U.S. Department of the Interior
U.S. Geological Survey

SE ROA 10996

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Conversion Factors, Datums, Discharge or Flow, Instantaneous Discharge, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
centimeter (cm)	0.10	millimeter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
square foot	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Conversion Factors, Datums, Discharge or Flow, Instantaneous Discharge, and Abbreviations and Acronyms—Continued

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83).

Discharge or Flow

The rate that matter passes through a cross section of a stream channel or other water body per unit of time. The term commonly refers to the volume of water (including, unless otherwise stated, any sediment or other constituents suspended or dissolved in the water) that passes a cross section in a stream channel, flume, weir, canal, pipeline, etc., within a given period of time (cubic feet per second).

Instantaneous Discharge

The discharge at a particular instant of time (see also “Discharge”).

Abbreviations and Acronyms

Abbreviations and Acronyms	Meaning
BM	bench mark
DGPS	Differential Global Positioning System
DRI	Desert Research Institute
FWS	U.S. Fish and Wildlife Service
GPS	global positioning system
LVVWD	Las Vegas Valley Water District
MVID	Muddy Valley Irrigation District
MVWD	Moapa Valley Water District
NDWR	Nevada Division of Water Resources
NGS	National Geodetic Survey
NPC	Nevada Power Company
NWIS	National Water Information System
OPUS	Online Positioning User Service
Reclamation	Bureau of Reclamation
RM	reference mark
RP	reference point
SNWA	Southern Nevada Water Authority
UNAES	University of Nevada Agricultural Experiment station
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

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Water-Surface Elevations, Discharge, and Water-Quality Data for Selected Sites in the Warm Springs Area near Moapa, Nevada

By David A. Beck, Roslyn Ryan, Ronald J. Veley, Donald P. Harper, and Daron J. Tanko

Abstract

The U.S. Geological Survey, in cooperation with Southern Nevada Water Authority and the Nevada Division of Water Resources, operates and maintains a surface-water monitoring network of 6 continuous-record stream-flow gaging stations and 11 partial-record stations in the Warm Springs area near Moapa, Nevada. Permanent land-surface bench marks were installed within the Warm Springs area by the Las Vegas Valley Water District, the Southern Nevada Water Authority, and the U.S. Geological Survey to determine water-surface elevations at all network monitoring sites. Vertical datum elevation and horizontal coordinates were established for all bench marks through a series of Differential Global Positioning System surveys. Optical theodolite surveys were made to transfer Differential Global Positioning System vertical datums to reference marks installed at each monitoring site. The surveys were completed in June 2004 and water-surface elevations were measured on August 17, 2004. Water-surface elevations ranged from 1,810.33 feet above North American Vertical Datum of 1988 at a stream-gaging station in the Pederson Springs area to 1,706.31 feet at a station on the Muddy River near Moapa.

Discharge and water-quality data were compiled for the Warm Springs area and include data provided by the U.S. Geological Survey, Nevada Division of Water Resources, U.S. Fish and Wildlife Service, Moapa Valley Water District, Desert Research Institute, and Converse Consultants. Historical and current hydrologic data-collection networks primarily are related to changes in land- and water-use activities in the Warm Springs area. These changes include declines in ranching and agricultural use, the exportation of water to other areas of Moapa Valley, and the creation of a national wildlife refuge. Water-surface elevations, discharge, and water-quality data compiled for the Warm Springs area will help identify (1) effects of changing vegetation within the former agricultural lands, (2) effects of restoration activities in the wildlife refuge, and (3) potential impacts of ground-water withdrawals.

Introduction

The Warm Springs area, located in the northwestern end of Moapa Valley, Nev., (fig. 1) consists of a network of springs and seeps that form the headwaters of the Muddy River. Over time, this area has been home to the Anasazi and the Southern Paiute Indian tribes, outlaws, prospectors, Mormon settlers, and others (Baxter and Haworth, 1996; U.S. Fish and Wildlife, 1991). The availability of water has provided past and current inhabitants with the resource necessary to sustain life in a desert setting. In addition, nearby entities, such as the Moapa River Indian Reservation, the Moapa Valley Water District (MVWD), and the Nevada Power Company (NPC), use water obtained from the area. The Warm Springs area is home to the Moapa Valley National Wildlife Refuge. The refuge was established in 1979 to protect and secure the riparian habitat of an endangered native minnow, the Moapa dace (*Moapa coriacea*) (U.S. Fish and Wildlife, 1991). A brief history of water-resources development in the Warm Springs area is included in Appendix A.

The Warm Springs area is located approximately 60 mi northeast of Las Vegas, which is one of the fastest growing metropolitan areas in the country. For more than 50 years, Las Vegas has used Lake Mead as its main source of drinking water. The ongoing growth of Las Vegas and the effects of the recent drought on the Colorado River have prompted water-resource managers to seek out and investigate additional sources of water. Presently (2006), the Nevada State Engineer is considering numerous applications to develop ground-water resources in basins adjacent to the upper Moapa Valley that would provide additional water to Las Vegas and Moapa Valley. It is not known what effects these proposed ground-water withdrawals will have on the riparian habitats and springs that form the Warm Springs area. Efforts are underway to acquire additional data to monitor for potential effects of these ground-water withdrawals.

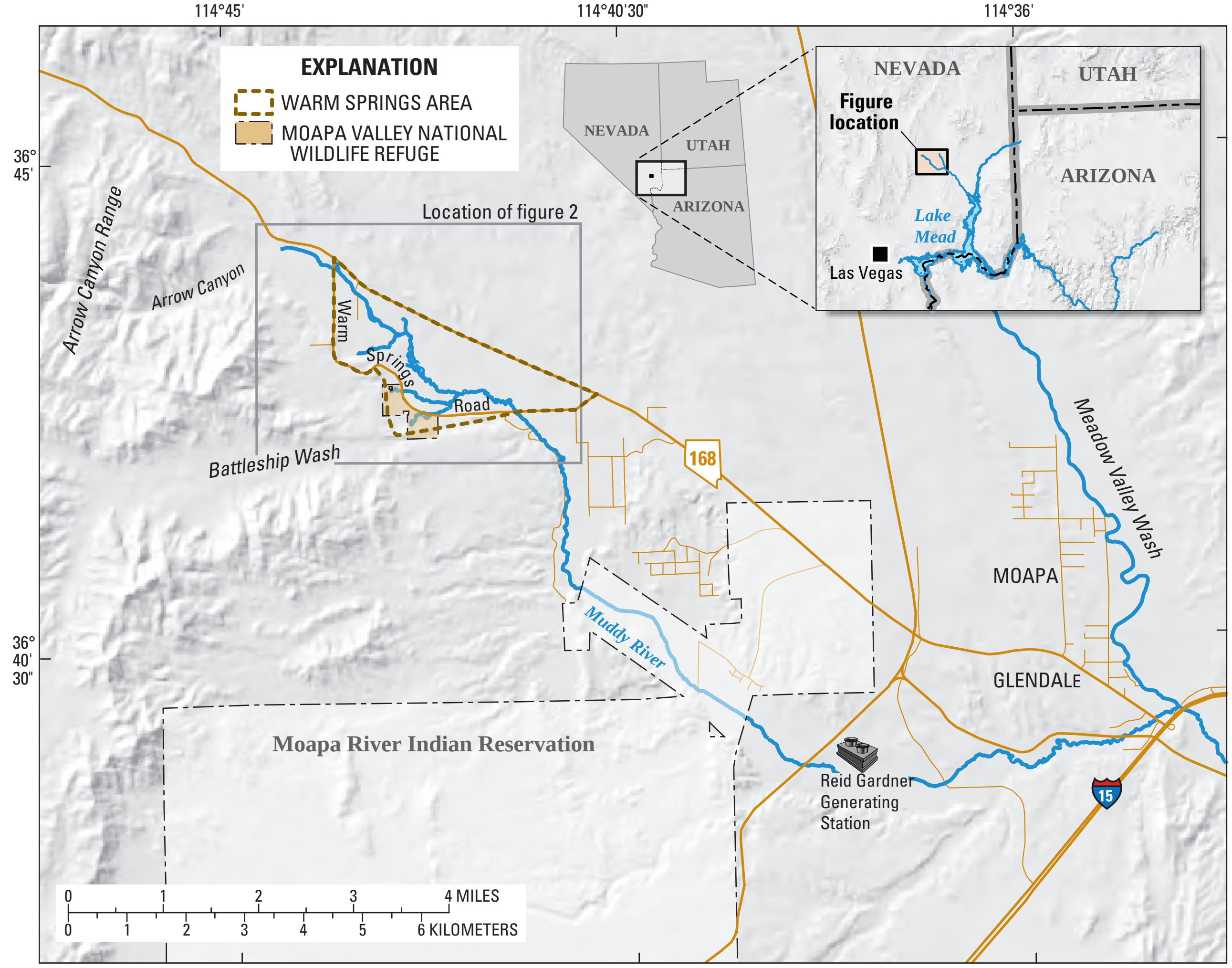

Figure 1. Location of study area and local features, Moapa Valley, Nevada.

As part of these efforts, the U.S. Geological Survey (USGS), in cooperation with the Southern Nevada Water Authority (SNWA), has completed a survey of water-surface elevations in the Warm Springs area. Bench marks (BMs), reference marks (RMs), reference points (RPs), and staff plates were established that will provide resource managers with tools to determine water-surface elevations at numerous monitoring sites in the area. These data will be used to assist in the efforts to determine what effects, if any, nearby ground-water withdrawals may have on the springs within the Warm Springs area.

Purpose and Scope

The primary purposes of this study are (1) to determine water-surface elevations in spring-fed pools and channels that currently are monitored by the USGS, and (2) to compile existing discharge and water-quality data within the Warm Springs area. For the purposes of this report, the Warm Springs area is defined as the area of the upper Moapa Valley upstream of the Muddy River Bridge at Warm Springs Road. The principle areas include the Muddy River flood plain and all the springs and seeps that are generally bounded by State Highway 168 and Warm Springs Road (fig. 2).

Permanent RMs and staff plates were installed near each of the hydrologic monitoring sites so that water-surface elevations could easily be obtained and related to land-surface datum. Land-surface datums used in this study were derived from permanent BMs established by the Las Vegas Valley Water District (LVVWD), SNWA, and USGS adjacent to the major spring groups and other monitoring sites. The elevations of these BMs were determined from a series of Differential Global Positioning System (DGPS) surveys. The elevations were transferred to the monitoring sites by optical theodolite surveys.

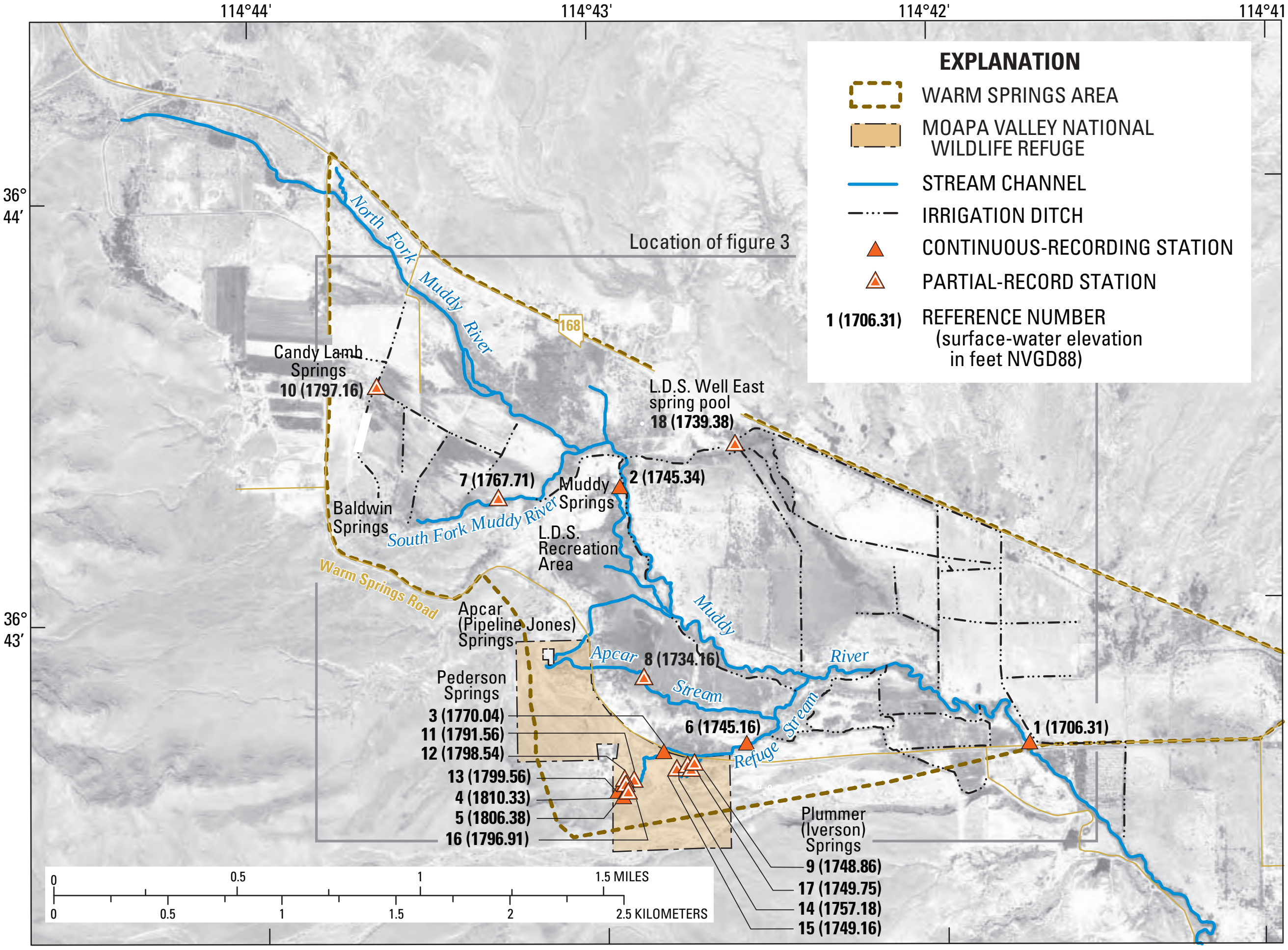

Figure 2. Location of major spring groups, U.S. Geological Survey monitoring stations, and water-surface elevations on August 17, 2004, in the Warm Springs area near Moapa, Nevada.

Existing discharge and water-quality data compiled for the Warm Springs area include data collected by the USGS and other agencies that manage, regulate, study, or use the water resources of the area. These data are included in this report, with measurements of water-surface elevations throughout the Warm Springs area made during this study, to support studies relating the condition of the springs to the regional ground-water flow system. Evaluation of the quality-assurance procedures for data collection by the other agencies is beyond the scope of this study. As a result, the USGS cannot verify the accuracy of the data provided.

As a supplement to data compilation, compendiums of water-resources development and data-collection networks are presented. Historical perspectives were based on (1) available data and references, (2) telephone interviews with many government and municipal officials, and (3) personal interviews with long-term residents within the Warm Springs area. Inclusion of the two compendiums in this report is intended to relate the historical development of the hydrologic monitoring network with land- and water-use changes in Moapa Valley.

Description of Study Area

The Warm Springs area, also known as the Muddy Springs area, is a network of springs and seeps that are located along the northeast slope of the Arrow Canyon Range (fig. 1). The area is bounded by Highway 168 to the north and northeast, Battleship Wash to the south, and Warm Springs Road to the west and southeast (fig. 1). There are six major spring groups within the study area that are generally aligned in a northwest-southeast direction: Cardy Lamb, Baldwin, Apcar, Muddy, Pederson, and Plummer (fig. 2). An unnamed spring area is located adjacent to Highway 168 near L.D.S. East well (fig 2, site 18); however, flow from this area discharges only intermittently.

The Warm Springs area is located near the southern boundary of the White River ground-water flow system (Prudic and others, 1995). Discharge from the springs and seeps of the Warm Springs area is believed to be the largest and most southerly outflow from this ground-water system (Eakin, 1966). The physiography of the study area is characterized by north-trending mountains to the west and a broad alluvial basin to the east. The topography consists of normal-faulted terrains that form complex, heterogeneous geologic settings with unique local and regional characteristics.

The primary aquifers in the area generally are made up of carbonate rocks of Paleozoic age and sedimentary rocks of Tertiary age. The carbonate rocks form complex aquifers whose extents and thicknesses are largely unknown. These aquifers interconnect with aquifers of other rock types and, where deformed or fractured, have the potential to transmit ground water (Prudic and others, 1995).

The climate of the area is semiarid to arid with approximately 5 in. of annual precipitation, low humidity, and high evapotranspiration rates (Eakin, 1966; Mozejko, 1981). Recharge to the ground-water system supplying the Warm Springs area is primarily from precipitation in the high mountain ranges in east-central Nevada (Eakin, 1966). Ground-water discharge within the Warm Springs area is from evaporation, transpiration by plants, and flow from the springs.

The discharge channels of springs in the area and the main stem of the Muddy River primarily are meandering and shallow and contain moderate amounts of fine silt and organic debris. Vegetation within and along the channel banks include cattails (*Typha* spp.), willows (*Salix* spp.), mesquite (*Prosopis* pubescens), reeds, and non-native palm trees (*Washingtonia filifera* and *Phoenix dactylifera*) and Tamarisk (*Tamarix* spp.). Aquatic plants such as algae, spike rush (*Eleocharis* spp.), water nymph (*Najas* spp.), watercress (*Nasturtium* spp.), pondweed (*Potamogeton* spp.), and non-native eel grass (*Vallisneria* spp.) are abundant in most spring pools and slack water areas (Mozejko, 1981; U.S. Fish and Wildlife Service, 1995).

The Warm Springs area is home to numerous birds, mammals, and reptiles, including quail (*Callipepla gambelii*), roadrunners (*Geococcyx californianus*), songbirds, shorebirds, cottontail rabbits (*Sylvilagus* spp.), coyotes (*Canis latrans*), foxes, spiny soft-shell turtles (*Amyda spinifera*), and snakes. In addition to the aforementioned endangered Moapa dace, several other species in the area's waterways are listed as sensitive. These include the Moapa White River springfish (*Crenichthys baileyi moapae*), Moapa pebblesnail (*Fluminicola avernalis*), and the Moapa Warm Spring riffle beetle (*Stenelmis moapa*) (U.S. Fish and Wildlife Service, 1991, 1995).

Water-Surface Elevations

The USGS, in cooperation with SNWA and Nevada Division of Water Resources (NDWR), operates and maintains a surface-water network of 6 continuous-record stream-gaging stations and 11 partial-record stations in the Warm Springs area near Moapa, Nev. (table 1). To determine the elevation of the water surface at each monitoring site, BMs, RMs, and RPs were established at strategic locations within the Warm Springs area. For this report, a BM is defined as a permanent marker that was installed in the ground or on a structure and that has an established elevation based on the North American Vertical Datum of 1988 (NAVD 88). The elevations of these markers were derived from survey-grade differential global positioning system (GPS) instrumentation. A RM is defined as a permanent marker installed in the ground or on a structure in the vicinity of a gaging station. The elevations of the RMs were determined by optical theodolite surveys from a nearby bench mark. A RP is a permanent marker installed on a structure at a gaging station that allows direct measurement of water-surface elevation using a graduated measuring tape or ruler. The elevation of the RP also is determined by optical theodolite survey from a nearby bench mark. The elevations of the RMs and RPs in this report also were based on the NAVD 88.

Water-surface elevations at each of the monitoring stations were determined by reading the water level (stage) at the staff plate installed at each site. The elevation of each staff plate was determined from optical theodolite survey using nearby reference marks as control. Because staff plates have their own scale, the elevation of a water surface is obtained by converting stage value to differential GPS elevation.

Bench Marks

Permanent land-surface BMs used for this study were established by the LVVWD, Stantec (on contract with SNWA), and the USGS. BMs consist of either brass plates, steel bolts, or rebar set in concrete structures or survey-grade earth anchors. Photographs and descriptions of selected BMs used for this study are included in Appendix B and table 2, respectively. The locations of these BMs were selected on the basis of the long-term stability of the area or of the structure a BM was installed on and the proximity of each BM to each of the monitoring sites. The location of each BM is shown in figure 3.

Table 1. Index to continuous-record and partial-record stream-gaging stations and miscellaneous sites in the Warm Springs area near Moapa, Nevada.

[Map site numbers for station locations are shown on figure 2. Latitude and longitude are shown in degrees, minutes, and seconds. **Abbreviations:** USGS, U.S. Geological Survey; NAD27, North American Vertical Datum of 1927; NV, Nevada; ft, foot]

Map site No.	USGS site identification	Station name	Coordinates NAD27		Period of record	Remarks
			Latitude	Longitude		
			Continuous-record stations			
1	09416000	Muddy River near Moapa, NV	36°42'40"	114°41'40"	July 1913 to September 1915 April 1916 to September 1918 June 1928 to October 1931 April to July 1932 October 1944 to September 2004	Gage at 10-ft Cipolletti weir
2	09415900	Muddy Springs at L.D.S. Farm near Moapa, NV	36°43'18"	114°42'53"	August 1985 to September 1994 June 1996 to September 2004	Gage at flume (3-ft throat)
3	09415920	Warm Springs West near Moapa, NV	36°42'41"	114°42'48"	August 1985 to September 1994 June 1996 to September 2004	Gage at flume (1-ft throat)
4	09415910	Pederson Spring near Moapa, NV	36°42'35"	114°42'54"	October 1985 to September 1994 June 1996 to September 2004	Gage at weir (45° v-notch)
5	09415908	Pederson East Springs near Moapa, NV	36°42'34"	114°42'56"	May 2002 to September 2004	Gage at weir (45° v-notch)
6	09415927	Warm Springs Confluence at Iverson Flume near Moapa, NV	36°42'41"	114°42'32"	October 2001 to September 2004	Gage at flume (3-ft throat)
			Partial-record stations			
7	09415875	Baldwin Springs near Moapa, NV	36°43'16"	114°43'14"	February 2001	Flume (3-ft throat)
8	09415940	Apcar Stream at Pipeline Jones Flume near Moapa, NV	36°42'51"	114°42'53"	February 2001	Flume (3-ft throat)
9	364236-114424301	Warm Springs East (Plummer Main)	36°42'36"	114°42'43"	August 1982 to September 2004	Near Eakin site #10 (Appendix D; fig. D1)
10	364327-114430801	Muddy River Springs 10 (M-10)	36°43'27"	114°43'08"	January 1986 to September 2004	Concrete irrigation channel near Eakin site #38 (Appendix D; fig. D1)
11	364235-114425201	Muddy River Springs 11 (M-11)	36°42'38"	114°42'52"	September 1963 March 1987 to September 2004	Downstream of Pederson Spring
12	364237-114425401	Muddy River Springs 12 (M-12)	36°42'37"	114°42'54"	March 1987 to September 2004	Downstream of Pederson Spring
13	364236-114425401	Muddy River Springs 13 (M-13)	36°42'36"	114°42'54"	January 1986 to September 2004	Downstream of Pederson Spring
14	364238-114424201	Muddy River Springs 16 (M-16)	36°42'38"	114°42'44"	March 1987 to September 2004	Plummer west (90° v-notch weir)
15	364238-114424401	Muddy River Springs 15 (M-15)	36°42’38"	114°42’42"	March 1987 to September 2004	Plummer central
16	364235-114425301	Muddy River Springs 19 (M-19)	36°42'35"	114°42'53"	April 1998 to September 2004	Downstream of Pederson East Spring
17	364238-114424301	Muddy River Springs 20 (M-20)	36°42'37"	114°42'40"	October 1994 to September 2004	Plummer east
			Miscellaneous sites			
18	364329 114423501	Unnamed spring pool at L.D.S. Well East near Moapa, NV	36°43'29"	114°42'35"	August 2004	100 ft east of well

Table 2. Elevation and location information for permanent land-surface bench marks in the Warm Springs area near Moapa, Nevada.

[Map site numbers for bench mark locations are shown on figure 3. Elevation Ortho height is referenced to the North American Vertical Datum of 1988. Latitude and longitude are shown in degrees, minutes, and seconds. **Occupation time:** time, in hours, Global Positioning System was set up over a bench mark. **Abbreviations:** NAD 83, North American Datum of 1983; OPUS, Online Positioning User Service; USGS, U.S. Geological Survey; LVVWD, Las Vegas Valley Water District]

Map site No.	Site name (as in OPUS)	Date	Surveyed by	Elevation Ortho height (feet)	Horizontal Coordinates NAD 83		Occupation time (hours)	Description
					Latitude	Longitude		
WSBM-1	Jones Spring Box	05-05-04	Stantec	1,775.72	36°42'54.57129"N	114°43'09.63383"W	3.17	5/8 inch rebar with no cap, about 140 ft northwest of pumphouse, about 6 ft west of overhead powerline.
WSMB-2	Pipeline Jones Flume	07-20-04	USGS	1,735.52	36°42'50.36476"N	114°42'52.30915"W	2.75	Brass tablet in concrete on northeast side of flume, about 0.2 mi northeast of Warm Spring Road.
WSBM-3	Baldwin Spring	05-05-04	Stantec	1,175.68	36°43'13.68711"N	114°43'25.45556"W	3.48	5/8 inch rebar with no cap, about 100 ft east of the pumphouse, about 3 ft north of dirt road, and about 3 ft west of wooden fence post.
WSBM-4	Warm Springs Road near Iverson Flume	05-07-04	Stantec	1,759.90	36°42'37.69617"N	114°42'37.73940"W	3.98	5/8 inch rebar and aluminum cap in concrete, about 70 ft south of Warm Springs Road and about 30 ft east of driveway to Wildlife Refuge.
WSBM-5	Iverson Flume	05-14-02	LVVWD	1,746.17	36°42'40.81624"N	114°42'34.73365"W	3.22	Brass tablet in concrete on south side of flume on Refuge Stream, about 500 ft north of Warm Springs Road.
WSBM-6	Pederson Spring	05-06-04	Stantec	1,821.98	36°42'32.62813"N	114°42'55.32668"W	2.22	5/8 inch rebar and aluminum cap in concrete, in Wildlife Refuge about 300 ft southeast of Pederson Spring pool and about 10 ft above dirt road.
WSBM-7	Warm Springs West	05-06-04	Stantec	1,776.93	36°42'40.77093"N	114°42’51.02381"W	4.15	5/8 inch rebar and alumin cap in concrete, about 1,000 ft west of entrance to Wildlife Refuge and about 40 ft south of Warm Springs Road.
WSBM-8	Plummer Springs	05-06-04	Stantec	1,750.70	36°42'38.89120"N	114°42’44.37060"W	3.43	5/8 inch rebar and alumin cap in concrete, about 550 ft west of entrance to Wildlife Refuge and about 20 ft south of Warm Springs Road.
WSBM-9	Moapa Gage	05-07-04	Stantec	1,715.83	36°42'39.75208"N	114°41'43.35654"W	4.55	5/8 inch rebar and aluminum cap, about 5 ft north and about 4 ft west of southeast fence corner of gaging station perimeter fence.
WSBM-10	L.D.S. Well East	05-16-02	LVVWD	1,752.61	36°43'22.98995"N	114°42'37.14737"W	2.15	Brass tablet in southwest corner of concrete well pad inside fenced area.
WSBM-11	L.D.S. Gage	05-14-02	LVVWD	1,747.51	36°43'15.35091"N	114°42'55.94820"W	3.43	Brass tablet in east concrete abutment, about 0.1 mi below Muddy Springs and 30 ft west of dirt road.
WSBM-12	Baldwin Flume	06-03-04	USGS	1,769.07	36°43'16.23194"N	114°43'17.43571"W	23.98	5/8 bolt in concrete on south concrete abutment about 40 ft north of dirt road.
WSBM-13	M-10	06-03-04	USGS	1,799.25	36°43'32.65049"N	114°43'38.58223"W	18.68	5/8 bolt in concrete on top of culvert over concrete irrigation ditch, about 0.25 mi east of Warm Springs Road and about 3 ft south of dirt road.

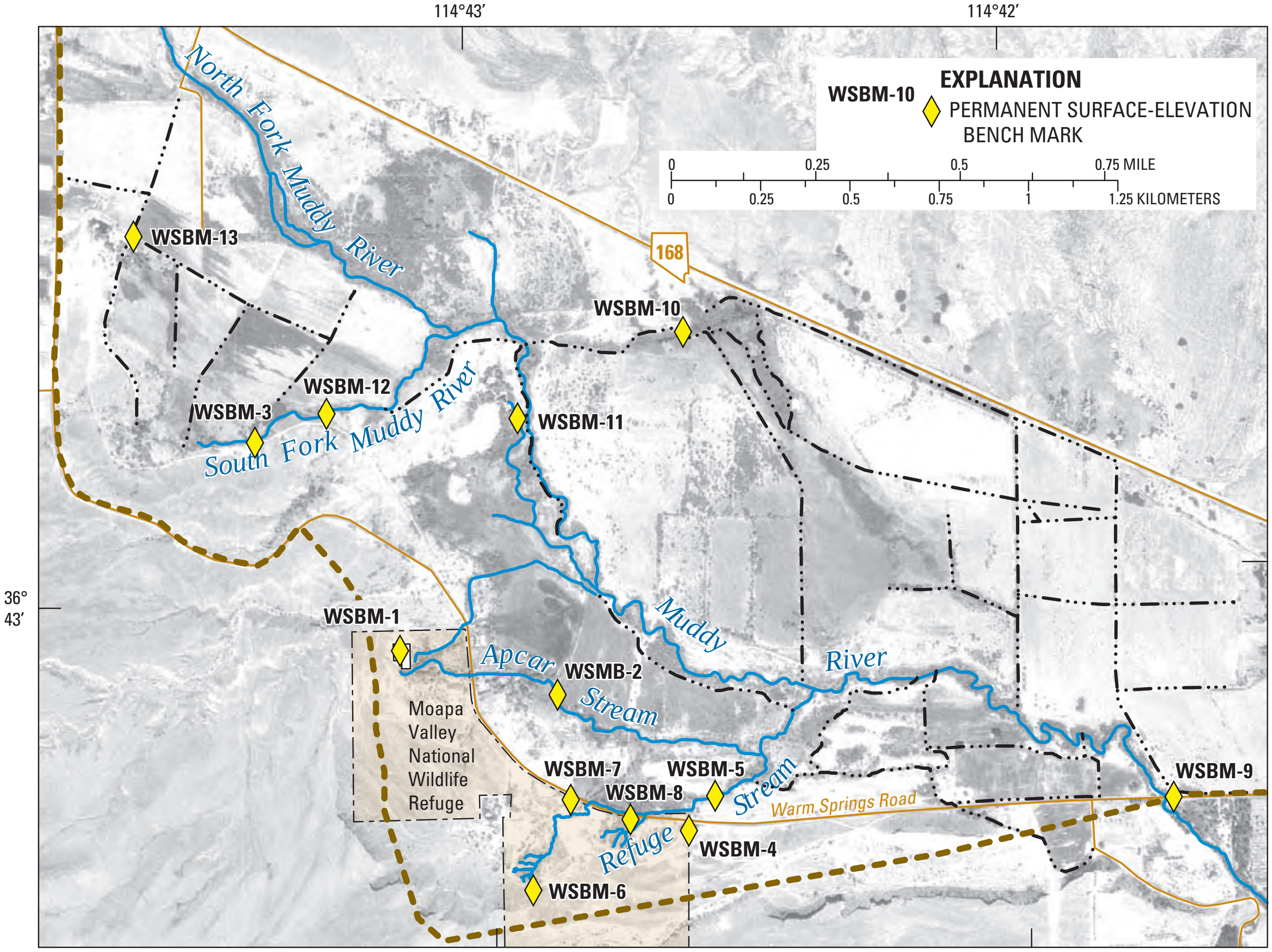

Figure 3. Location of permanent surface-elevation bench marks in the Warm Springs area near Moapa, Nevada.

Elevations and latitudes and longitudes for all the BMs in the study area were determined by applying DGPS surveying methods. The surveys consisted of setting up survey-grade DGPS equipment over each BM and processing the data through a National Geodetic Survey (NGS) web site. Equipment used by the LVVWD and Stantec and by the USGS for these surveys were the Trimble 5700™ and Ashtech ZExtreme™, respectively. According to manufacturer specifications, the relative accuracies of these units are 1 cm in the horizontal and 2 cm in the vertical.

The DGPS surveys of the study area ranged from just over 2 hours to almost 24 hours (table 2). When completed, the survey data were sent to the NGS Online Positioning User Service (OPUS) web site at http://www.ngs.noaa.gov/OPUS/. The GPS data files were then processed by OPUS using NGS computers and software to determine a BM positioning. The returned product, called the NGS OPUS Solution Report, lists the vertical datum, horizontal coordinates, and other related information. The accuracy of the OPUS corrected data is included with each individual sheet (Dave Doyle, National Geodetic Survey, oral commun., 2004). The vertical datum and horizontal coordinates for each BM are summarized in table 2. Copies of the OPUS Solution Reports are included in Appendix C.

BMs at Jones Spring Box (WSBM-1), Baldwin Spring (WSBM-3), and Warm Springs Road near Iverson flume (WSBM-4) are included in table 2 and figure 3 but were not used to determine RM elevations at USGS monitoring sites for this study. They are included in this report to document their location in the event other BMs are destroyed.

Reference Marks and Points

Following the installation and survey of the land-surface BMs in the Warm Springs area, permanent RMs or RPs were established at each of the current USGS monitoring sites. Existing or new RMs established at continuous-record stream gages typically included brass monuments or anchor bolts embedded in concrete-filled areas or on other stable structures adjacent to the site.

For the partial-record stations, staff plates were installed in the channel reaches where discharge measurements are periodically made. If there was no existing RM near the periodic site, fence posts were hammered into both banks of the channel. Where staff plates could not be installed, such as at site M-10, a RP with a 3/8-in. bolt was set into the vertical headwall of the culvert. The elevation of the water surface was then determined by measuring from the RP to the water surface using a graduated tape or ruler. Elevations and descriptions of the RMs and RPs for each site are given in table 3. Photographs of selected RMs and RPs are included in Appendix B for each site.

In addition to the RMs and RPs, optical theodolite surveys were done at each staff plate and at the top corners of each flume or weir. These additional points were surveyed to document the current conditions of existing structures and to help track changes that may occur in the future. This information also is included in table 3.

Optical theodolite surveys were used to transfer BM datum (NAVD 88) to the permanent RMs and RPs established at all the current monitoring sites. A detailed description of the concepts and procedures of optical theodolite surveying is given by Kennedy (1988). The identification number of the BM used for each survey is shown in table 3. The approximate locations of the BM relative to the USGS monitoring sites are shown in Appendix B.

The equipment used to complete the optical theodolite surveys included an engineer's automatic, or self-leveling, instrument and a "Frisco-style" aluminum rod. The precision and accuracy for each survey were in accordance with procedures described by Kennedy (1988).

Table 3. Elevations and descriptions of selected reference marks, points, and other features at continuous-recording and partial-record stations in the Warm Springs area near Moapa, Nevada.

[Map site numbers for station locations are shown on figure 2. **Reference mark-item:** RM-1, reference mark 1; RP-1, reference point 1; PZF, point of zero flow; F-1, top edge number 1 of a flume; W-1, top edge number 1 of a weir. **Land-surface benchmark used**: See table 1. **Abbreviations:** USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NV, Nevada; ft, foot]

Map site No.	USGS site identification No.	Station name	Date surveyed	Reference mark-item	Elevation NAD 83 (feet)	Land-surface benchmark used	Description
		Continuous-recording stations					
1	9416000	Muddy River near Moapa, NV	06-02-04	RM-1	1,709.68	WSBM-9	Top of eyebolt on top of left bank wingwall above staff plate.
				RM-5	1,717.23	WSBM-9	Top center of "I" beam on top of wall on left bank downstream of gage house.
				RM-6	1,717.67	WSBM-9	Top of 2-inch pipe at the northeast corner of gage house platform.
				RM-7	1,719.74	WSBM-9	Top of large bolt securing Nevada Power large white pipe along fence on left bank.
				RP-1	1,706.69	WSBM-9	Top of fence post at left edge of water below gage house.
				Staff plate	1,709.04	WSBM-9	Top of staff plate (3.34 ft).
2	9415900	Muddy Springs at L.D.S. Farm near Moapa, NV	06-03-04	RM-3	1,745.42	WSBM-11	Top of 2-inch PVC pipe at downstream right-bank concrete abutment wall.
				RM-4	1,747.25	WSBM-11	Center round of the "9" in "93" written in the concrete abutment on the right bank.
				RM-5	1,753.55	WSBM-11	Chiseled square in concrete slab on walkway to gage.
				RP-1	1,747.93	WSBM-11	Top of upstream right-bank edge of flume.
				RP-2	1,746.97	WSBM-11	Nail in staff-plate backboard.
				PZF	1,744.93	WSBM-11	Bottom of upstream end of flume.
				F-1	1,748.04	WSBM-11	Downstream right-bank top edge of flume.
				F-2	1,748.13	WSBM-11	Upstream right-bank top edge of flume.
				F-3	1,748.06	WSBM-11	Downstream left-bank top edge of flume.
				F-4	1,748.11	WSBM-11	Upstream left-bank top edge of flume.
3	9415920	Warm Springs West near Moapa, NV	06-03-04	RM-1	1,772.94	WSBM-7	Painted circle on rock wall above gage.
				RM-3	1,770.78	WSBM-7	Upstream streamward corner of concrete pad on left bank (no mark).
				PZF	1,769.12	WSBM-7	Bottom of upstream end of flume.
				F-1	1,772.30	WSBM-7	Upstream left-bank top edge of flume.
				F-2	1,772.31	WSBM-7	Downstream left-bank top edge of flume.
				F-3	1,772.33	WSBM-7	Downstream right-bank top edge of flume.
				F-4	1,772.27	WSBM-7	Upstream right-bank top edge of flume.
				Staff plate	1,772.13	WSBM-7	Top of staff plate (3.00 ft).

Table 3. Elevations and descriptions of selected reference marks, points, and other features at continuous-recording and partial-record stations in the Warm Springs area near Moapa, Nevada.—Continued

[Map site numbers for station locations are shown on figure 2. **Reference mark-item:** RM-1, reference mark 1; RP-1, reference point 1; PZF, point of zero flow; F-1, top edge number 1 of a flume; W-1, top edge number 1 of a weir. **Land-surface benchmark used**: See table 1. **Abbreviations:** USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NV, Nevada; ft, foot]

Map site No.	USGS site identification No.	Station name	Date surveyed	Reference mark-item	Elevation NAD 83 (feet)	Land-surface benchmark used	Description
Continuous-recording stations–Continued							
4	9415910	Pederson Spring near Moapa, NV	06-09--04	RM-4	1,809.32	WSBM-6	Brass tablet in concrete in cylinder in ground, about 40 ft northwest of spring pool.
				RM-5	1,814.04	WSBM-6	Brass tablet in concrete in cylinder in ground, about 45 ft east of spring pool.
				RM-6	1,810.95	WSBM-6	Top of anchor bolt on left bank (west) concrete wall.
				PZF	1,809.82	WSBM-6	Notch apex of weir plate.
				Staff plate	1,812.22	WSBM-6	Top of staff plate (6.74 ft).
5	9415908	Pederson East Spring near Moapa, NV	06-09-04	RM-2	1,807.73	WSBM-6	Top of anchor bolt on west side of spring pool that anchors steel supports for gage house.
				RM-3	1,807.62	WSBM-6	Brass tablet on top of upstream end of left-bank concrete wall.
				RP-1	1,807.25	WSBM-6	Nail in staff plate backboard on left bank weir wall.
				PZF	1,806.04	WSBM-6	Notch apex of weir plate.
				Staff plate	1,807.59	WSBM-6	Top of staff plate (6.74 ft).
6	9415927	Warm Springs Confluence at Iverson Flume near Moapa, NV	06-03-04	RM-2	1,747.50	WSBM-5	“X” on the L bracket.
				RM-3	1,746.58	WSBM-5	Top of 1–2-inch concrete anchor bolt on left bank.
				RP-1	1,747.89	WSBM-5	Top of upstream staff plate (10.14 ft).
				RP-2	1,747.89	WSBM-5	Top of downstream staff plate (10.14 ft).
				PZF	1,744.45	WSBM-5	Bottom of upstream end of flume.
				F-1	1,747.65	WSBM-5	Upstream right-bank top edge of flume.
				F-2	1,747.63	WSBM-5	Upstream left-bank top edge of flume.
				F-3	1,747.59	WSBM-5	Downstream left-bank top edge of flume.
				F-4	1,747.60	WSBM-5	Downstream right bank top edge of flume.
Partial-record stations							
7	9415875	Baldwin Springs near Moapa, NV	06-02-04	RM-1	1,769.04	WSBM-12	3–8-inch bolt in middle of concrete abutment on left bank.
				RM-2	1,771.83	WSBM-12	Top of fence post, 10 feet south of flume.
				RM-3	1,776.62	WSBM-12	Top edge of 3–8 inch lag bolt set horizontal in railroad-tie fence post, about 40 ft south of flume.
				PZF	1,767.42	WSBM-12	Bottom of upstream end of flume.
				F-1	1,770.61	WSBM-12	Upstream left-bank top edge of flume.
				F-2	1,770.58	WSBM-12	Upstream right-bank top edge of flume.
				F-3	1,770.57	WSBM-12	Downstream left-bank top edge of flume.
				F-4	1,770.59	WSBM-12	Downstream right-bank top edge of flume.
				Staff plate	1,769.31	WSBM-12	Top of staff plate (27.14 ft).
8	9415940	Apcar Stream at Pipeline Jones Flume near Moapa, NV	07-20-04	RM-1	1,735.19	WSBM-2	5–8-inch bolt in downstream end of concrete abutment on right bank.
				RM-2	1,735.33	WSBM-2	5–8-inch bolt in upstream end of concrete abutment on right bank.
				PZF	1,733.48	WSBM-2	Bottom of upstream end of flume.
				F-1	1,736.47	WSBM-2	Upstream left-bank top edge of flume.
				F-2	1,736.49	WSBM-2	Upstream right-bank top edge of flume.
				F-3	1,736.51	WSBM-2	Downstream left-bank top edge of flume.
				F-4	1,736.49	WSBM-2	Downstream right-bank top edge of flume.
				Staff plate	1,736.79	WSBM-2	Top of staff plate (3.34 ft).

Table 3. Elevations and descriptions of selected reference marks, points, and other features at continuous-recording and partial-record stations in the Warm Springs area near Moapa, Nevada.—Continued

[Map site numbers for station locations are shown on figure 2. **Reference mark-item:** RM-1, reference mark 1; RP-1, reference point 1; PZF, point of zero flow; F-1, top edge number 1 of a flume; W-1, top edge number 1 of a weir. **Land-surface benchmark used**: See table 1. **Abbreviations:** USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NV, Nevada; ft, foot]

Map site No.	USGS site identification No.	Station name	Date surveyed	Reference mark-item	Elevation NAD 83 (feet)	Land-surface benchmark used	Description
			Partial-record stations–Continued				
9	364236-114424301	Warm Springs East (Plummer Main)	06-10-04	RM-1	1,751.08	WSBM-8	Top of well casing on right bank of Plummer Main, about 15 ft southwest of gage.
				Staff plate	1,749.17	WSBM-8	Top of staff plate (3.34 ft).
10	364327-114430801	Muddy River Springs 10 (M-10)	06-03-04	RM-1	1,799.46	WSBM-13	3-8-inch bolt on top of concrete culvert, about 15 ft northwest of bench mark.
				RM-2	1,800.51	WSBM-13	Nail in south side of telephone pole, about 15 ft northwest of bench mark.
				RP-1	1,798.38	WSBM-13	3-8-inch bolt in east face of concrete culvert.
				RP-2	1,799.12	WSBM-13	3-8-inch bolt in north face of concrete culvert, about 15 ft northwest of bench mark.
11	364235-114425201	Muddy River Springs 11 (M-11)	06-09-04	RM-1	1,795.09	WSBM-6	Top of fence post on left bank.
				RM-2	1,795.09	WSBM-6	Top of fence post on right bank.
				Staff plate	1,794.10	WSBM-6	Top of staff plate (27.14 ft).
12	364237-114425401	Muddy River Springs 12 (M-12)	06-09-04	RM-1	1,801.76	WSBM-6	Top of fence post on left bank.
				RM-2	1,801.49	WSBM-6	Top of fence post on right bank.
				Staff plate	1,801.22	WSBM-6	Top of staff plate (27.14 ft).
13	364236-114425401	Muddy River Springs 13 (M-13)	06-09-04	RM-1	1,802.83	WSBM-6	Top of fence post on left bank.
				RM-2	1,804.33	WSBM-6	Top of fence post on right bank.
				Staff plate	1,801.91	WSBM-6	Top of staff plate (27.14 ft).
14	364238-114424201	Muddy River Springs 16 (Plummer West)	06-10-04	RM-1	1,758.08	WSBM-8	Top of 1-inch pipe in left bank, about 20 ft northeast of weir.
				W-1	1,757.37	WSBM-8	Top of left-bank end of weir.
				W-2	1,757.37	WSBM-8	Top of right-bank end of weir.
				Staff plate	1,757.79	WSBM-8	Top of staff plate (2.00 ft).
15	364238-114424401	Muddy River Springs 15 (Plummer Central)	06-10-04	RM-1	1,753.55	WSBM-8	Top of fence post in concrete wall, about 10 ft northwest of staff plate.
				Staff plate	1,751.24	WSBM-8	Top of staff plate (27.14 ft).
16	364235-114425301	Muddy River Springs 19 (M-19)	06-09-04	RM-1	1,800.88	WSBM-6	Top of fence post on left bank.
				RM-2	1,800.96	WSBM-6	Top of fence post on right bank.
				Staff plate	1,799.51	WSBM-6	Top of staff plate (27.14 ft).
17	364238-114424301	Muddy River Springs 20 (Plummer East)	06-10-04	RM-1	1,751.08	WSBM-8	Top of well casing on right bank of Plummer Main, about 15 ft southwest of staff plate.
				Staff plate	1,751.84	WSBM-8	Top of staff plate (27.14 ft).

Quality Assurance

To ensure the accuracy of BM datums and coordinates, OPUS Solutions for each DGPS survey were run using the NGS GEOID configuration (1999 and 2003) for computing orthometric heights. In addition, three of the BMs—Jones Spring Box, Baldwin Spring, and L.D.S. gage were resurveyed by one of the other agencies. OPUS solution reports for these three sites are included in Appendix C.

LVVWD and Stantec surveyed Jones Spring Box at Apcar on February 6, 2004, and Baldwin springs near the pump house on May 5, 2004. Differences between the Jones Spring Box surveys were 2 cm in the vertical (orthometric height) and 3 mm in the north horizontal (UTM coordinate).

Differences between the Baldwin Spring surveys were 1.4 cm in the vertical, 5 mm in the north horizontal, and 4 mm in the east horizontal (see OPUS reports, Appendix C).

Muddy Spring gage at L.D.S. Farm was surveyed by LVVWD and USGS on May 14, 2002, and June 2, 2004, respectively. Differences between the two surveys were 5 mm in the vertical, 2.1 cm in the north horizontal, and 5 mm in the east horizontal.

To ensure the accuracy of each optical theodolite survey, a series of operational checks were made on the instruments and rods. Visual inspections of equipment were made daily when in use, and peg tests were done to determine if instruments were in proper adjustment. A two-peg test was made before and after each series of levels. A complete description of the two-peg test procedure is given in a report by Kennedy (1988). At the same time the surveying instrument was peg-tested, the rod was checked by comparing it against an engineer's ruler.

Water-Surface Elevations

On August 17, 2004, water levels were obtained from the staff plates at all the USGS monitoring sites. The only exception was the water level at an unnamed spring-fed pool near well L.D.S Well East (fig. 2). The water-surface elevation of the pool which is located about 100 ft east of the well was measured using the optical theodolite survey for the BM at the well. In early July 2004, flow was observed to be discharging from several pools in the area and flowing into the Muddy River. By August 17, 2004, most of the pools had completely dried up and water no longer discharged from the area. On October 1, 2004, water was observed to be emanating from the surveyed well pond and other nearby pools and discharging to the Muddy River.

The elevation of each water surface was adjusted to NAVD 88 using the results of the differential stadia surveys. The location and water-level elevations of the readings made on August 17, 2004, are shown on figure 2 and included in table 4.

Table 4. Water-surface elevations measured on August 17, 2004, at continuous-recording and partial-record stations and miscellaneous sites in the Warm Springs area near Moapa, Nevada.

[Map site numbers for station locations are shown on figure 2. **Abbreviations:** USGS, U.S. Geological Survey; NAD83, North American Vertical Datum of 1983; NV, Nevada; ft, foot]

Map site No.	USGS site identification No.	Station name	Staff plate reading (feet)	Surface-water elevation NAD83 (feet)
		Continuous-recording stations		
1	09416000	Muddy River near Moapa, NV	0.61	1,706.31
2	09415900	Muddy Springs at L.D.S. Farm near Moapa, NV	.69	1,745.34
3	09415920	Warm Springs West near Moapa, NV	.91	1,770.04
4	09415910	Pederson Spring near Moapa, NV	4.85	1,810.33
5	09415908	Pederson East Spring near Moapa, NV	5.54	1,806.38
6	09415927	Warm Springs Confluence at Iverson Flume near Moapa, NV	7.62	1,745.16
		Partial-record stations		
7	09415875	Baldwin Springs Flume near Moapa, NV	25.54	1,767.71
8	09415940	Apcar Stream at Pipeline-Jones Flume near Moapa, NV	.71	1,734.16
9	364236114424301	Warm Springs East (Plummer Main)	3.03	1,748.86
10	364327114430801	Muddy River Springs 10 (M-10)	[1]1.22	1,797.16
11	364235114425201	Muddy River Springs 11 (M-11)	24.60	1,791.56
12	364237114425401	Muddy River Springs 12 (M-12)	24.46	1,798.54
13	364236114425401	Muddy River Springs 13 (M-13)	24.80	1,799.56
14	364238114424201	Muddy River Springs 16 (Plummer West)	1.40	1,757.18
15	364238114424401	Muddy River Springs (Plummer Central)	25.06	1,749.16
16	364235114425301	Muddy River Springs 19 (M-19)	24.55	1,796.91
17	364238114424301	Muddy River Springs 20 (M-20)	25.05	1,749.75
		Miscellaneous sites		
18		Unnamed spring pool at L.D.S. East Well near Moapa, NV		[2]1,739.38

[1] Reading is the distance from the reference point (RP) down to the water surface in the channel.

[2] Determined by optical theodolite survey from bench mark WSBM-10.

Discharge and Water-Quality Data

History of Data Collection

In July 1913, the first continuous-record stream-gaging station was established in the Warm Springs area by the Muddy Valley Irrigation District (MVID). The gage was constructed near its current location just upstream from the culvert at Warm Springs Road (site number 1, fig. 2). Gage-height record and discharge measurements were collected by the MVID from July 1913 to September 1915 and from April 1916 to September 1918. These records were furnished to the USGS; the monthly mean discharges were subsequently published in USGS Water Supply Paper 1049 (1947). The gage was reactivated in June 1928 by the University of Nevada Agricultural Experiment Station. Daily mean gage height and monthly runoff were furnished to the USGS from June 1928 to October 1931 and from April 1932 to July 1932. Monthly mean discharges for these periods also were published in Water Supply Paper 1049 (U.S. Geological Survey, 1947). The U.S. Bureau of Reclamation (Reclamation) reactivated the gage in October 1944 and constructed the 10-ft concrete Cipolletti weir (Appendix B, fig. B2). Reclamation collected continuous streamflow data until October 1948 when operation of the gage was turned over to the USGS. Daily mean discharges from 1944 to 1948 were computed by Reclamation and reviewed by the USGS. Daily mean discharges from 1944 to 1952 were subsequently published in Water Supply Paper 1243 (U.S. Geological Survey, 1954). Since 1952, the USGS has continued to operate and maintain the gage. Daily mean discharges for water years 1953 to 1960 were published annually in Water Supply Papers 1283 (1953), 1393 (1955), 1443 (1956), 1513 (1957), 1563 (1958), 1633 (1959), and 1713 (1960). For water years 1961 to 2004, the data were published in the USGS, Nevada District annual data report series (U.S. Geological Survey, Nevada District annual data reports, 1962–2004). A water year is the 12 month period from October 1 to September 30.

To analyze the gaging-station record as a means of characterizing spring discharges, a series of discharge measurements and estimates were made by the USGS at 40 sites in the Warm Springs area during September 10–12, 1963 (Eakin, 1964). As only a sketch map of these sites was available, a field reconnaissance was made during June 2004 to verify the location of each site and to obtain accurate coordinates. The coordinates, sketch map, and discharge and specific conductance data for these sites are included in Appendix D.

By the mid-1960s, the NPC withdrew ground water from wells in the northwest corner of the Warm Springs area as water supply for the Reid Gardner Generating Station about 3 mi downstream (fig. 1). In February 1966, NPC filed application with the Nevada State Engineer to pump additional water from these wells. In an agreement with the Muddy Valley Irrigation Company, NPC agreed to fund several "non-recording type weirs" on the major springs in the Warm Springs area. As part of the agreement, these hydraulic structures were to be under the jurisdiction of the State Engineer who would then measure the water levels on a periodic basis (Testolin and others, 1993). During August and September 1967, nine steel Parshall flumes were installed by the Desert Research Institute (DRI) under the direct supervision of the Nevada Division of Water Resources (NDWR). The nine flumes were installed at the following springs: Pipeline Jones, Flowing Well (Willow), Baldwin House Spring #1 (South), Baldwin House #2 (North), Baldwin Cuts, Baldwin Channel, Muddy (Big), Iverson, and Pederson. The locations, throat dimensions, and water-level data for eight of the nine flumes are included in Appendix B; water-level data were not available for the Flowing Well (Willow). Because flow rates were not included with the data provided by NDWR, discharges were computed for each water-level measurement using standard rating equations, from Leupold and Stevens (1987) for the reported size of each Parshall flume. Graphs and tables of the discharges for the period of record for each site are included in Appendix B. All the original nine flumes installed in 1967 have either been replaced or removed. The locations of the two Baldwin House Spring flumes near Cardy Lamb Springs and the Flowing Well (Willow) Flume could not be verified during this study; therefore, their exact locations are unknown.

Although not mentioned in Testolin and others (1993), NDWR reported an additional Parshall flume, Big Wash Flume, that was installed in October 1967 on the North Fork Muddy River about 500 ft upstream of the confluence with South Fork Muddy River (fig. 2). Water-level readings from 1967 to 1984 for this site were provided by NDWR and are included in Appendix B, table B2. The flume washed out sometime after 1984 and currently is upside down on the south bank of the river (Appendix B, fig. B6). The flume dimensions, as reported by NDWR, were verified in the field, and discharges were computed for the periodic gage-height readings using the standard rating for a 3-ft Parshall flume (Leupold and Stevens, 1987). A graph and table of the computed discharges for Big Wash Flume are included in Appendix B (fig. B7, table B2).

Beginning October 1, 1977, records of flow for the Muddy River Power Diversion, about 100 ft upstream of the USGS stream-gaging station at Warm Springs Road, Moapa (Appendix B, fig. B1) were provided by NPC to the USGS. Monthly mean discharges were published in the USGS Nevada District annual data reports for water years 1977 through 1985. Daily mean discharges were retrieved from the USGS National Water Information System (NWIS) database and are included in Appendix B (fig. B8, table B3). Annual mean daily discharge from the diversion for the period of record was 3.45 ft^3/s.

In 1978, a new flume, reported by NDWR as the Garden Ditch Flume, was installed on the north spring tributary just inside the entrance gate to Apcar (Pipeline Jones) Springs

(Appendix B, fig. B1). It is uncertain who installed the flume; however, field reconnaissance of the area in September 2004 indicated that the flume had been removed. The dimensions of the flume were obtained from a DRI report prepared for NPC as part of an evaluation of all flumes in the Warm Springs area (Wert and Pohlmann, 1992). Periodic water-level readings at this site through June 1992 also were provided by NDWR. Water levels, along with a graph and table of the computed discharges, are included in Appendix B (fig. B49, table B36).

In 1982, the USGS, in cooperation with local, State, and Federal agencies, began making periodic discharge measurements in the Warm Springs area as part of a long-term effort to characterize regional spring flow. By 1985, discharge measurements were being made at Warm Springs West (site 3, fig. 2), Muddy Springs at L.D.S. Farm (site 2, fig. 2), at Warm Springs East (site 9, fig. 2), and at Big Wash flume (fig. B5). The number of USGS periodic measurement sites continued to expand during the 1980s and 1990s and currently includes 11 partial-record stations (table 1). Graphs and tables of all discharge measurements made through September 2004 for all the sites are included in Appendix B.

In August 1985, the USGS, in cooperation with LVVWD and NDWR, installed continuous-stage recorders at the flumes at Warm Springs West and Muddy Springs at L.D.S Farm to document daily fluctuations in spring discharges. Daily mean discharges were computed for the spring flows at these gages and published in the USGS, Nevada District, annual data reports (1985–2004). Both stations are still operated and maintained by the USGS. Graphs and tables of daily mean discharges for the period of record for Warm Springs West and Muddy Springs at L.D.S Farm are included in Appendix B (fig. B42 and table B31, and fig. B46 and table B34, respectively).

In October 1986, the USGS, in cooperation with LVVWD and NDWR, installed an aluminum weir and continuous-stage recorder on the Pederson Springs pool (site 4, fig. 2). The purpose of this gage was to collect daily discharge data near the outlet of one of the major springs in the Moapa Valley National Wildlife Refuge. By early 2004, most of the palm trees surrounding the spring had been removed by the U.S. Fish and Wildlife Services (FWS), and in April 2004, a new weir was installed because water was leaking around the weir and the gage was not measuring flows accurately. Graphs and tables of daily mean discharges for the period of record are included in Appendix B (fig. B30, table B20).

By the early 1990s, only 5 of the original 10 flumes installed in 1967 were still being measured. Gage-height readings for Baldwin House #1 and #2 flumes stopped in June 1980, presumably because of construction of the L.D.S. pond at Cardy Lamb Springs (site 10, fig. 2). Readings at the Baldwin Cuts flume ended in August 1985 which was about 11 years after the MVWD began diverting flow from Baldwin Springs. Garden Ditch flume, mentioned in a report by DRI (Wert and Pohlmann, 1992), was reported to be in fair working condition in 1992; however, readings stopped after June 1992.

As conditions of the remaining flumes had significantly deteriorated, NPC contracted DRI in 1992 to evaluate the performance of each flume (Wert and Pohlmann, 1992). DRI recommended replacing the old steel flumes at Baldwin Springs Channel, Pipeline Jones, Pederson (Warm Springs West), Iverson, and Muddy (Big) Springs with new stainless-steel flumes that would be more resistive to the corrosive springflows. The DRI report by Wert and Pohlmann (1992), also discussed an “L.D.S Pool flume” which was described as downstream of the pond at Cardy Lamb Spring: Replacement of this flume was not recommended by DRI because flow was controlled by the pond, which was being used as storage for irrigation.

During the summer of 1993, NDWR replaced the five remaining flumes and continued to make periodic water-level measurements at each site. These periodic measurements are included in the flume records provided by NDWR and are given in Appendix B (figs. B42, B46, B53, B63, B66 and tables B30, B33, B41, B49, B50).

In April 1997, Converse Consultants, on contract to NPC, began making quarterly field measurements of temperature and specific conductance at 18 spring and surface-water sites within the Warm Springs area. The spring and surface-water sampling is part of a comprehensive hydrologic-monitoring program that Converse Consultants manages in the Warm Springs area and vicinity. Converse Consultants submits an annual report to NPC summarizing all surface-water, ground-water, water-quality, and water-use data collected or compiled (Converse Consultants, 2004). The location of each spring sampling site, plus data graphs and tables, are included in Appendix B (figs. B9, B18 to B26, B32, B44, B48, B50, B51, B54, B55, B57, B61, B68, B70, B71 to B74 and tables B10 to B17, B21, B32, B37, B38, B42, B48, B52 to B55).

In December 1997, MVWD began collecting water samples from the pump houses at Baldwin and Apcar (Pipeline Jones) Springs. Samples are collected at these sites annually and are analyzed for major ions and selected dissolved constituents. Analyses of the water samples for 1997 through 2004 for the Baldwin and Apcar Springs are included in Appendix B (tables B39 and B43, respectively).

On June 1, 1998, FWS installed a staff gage and steel weir at the spring on the Plummer West tributary, one of the three tributaries of the Plummer Springs Group (Appendix B, fig. B9). This site, referred to as station M-16 by the USGS, has been measured by the USGS since 1987. The staff gage was read several times a month by FWS from 1998 to 2002. Discharges were computed by applying the standard rating for a 90-degree v-notch weir (Rantz and others, 1982). Data collected at this site are given in Appendix B (tables B7 and B8). On October 26, 1998, FWS began making periodic discharge measurements in Plummer Main tributary (Appendix B, fig. B9). This site, also referred to as Warm Springs East, has been measured by the USGS since 1982. Periodic discharge measurements at this site were made by FWS using either a pygmy current meter or a Marsh-

McBirney velocity meter. Several measurements were made each year until the site was discontinued on May 30, 2001. Graphs and tables of discharge data for the Warm Springs East site are included in Appendix B (fig. B10, tables B4 and B5).

On February 6 and 7, 2001, a series of discharge measurements were made within the Warm Springs area as part of a seepage study for the Muddy River. Discharge and water-quality data were collected by USGS, SNWA, FWS, and NDWR at 14 sites, including the 5 NDWR flumes and the 9 sites measured in September 1963 (Beck and Wilson, 2006). Location information and data collected at these sites are included in Appendix E.

A continuous-stage recorder was installed by the USGS, in cooperation with SNWA, at the Iverson flume on Refuge Stream on October 1, 2001 (fig. B65). At the time the gage was installed, flow was backed up at the flume because of palm trees and other debris blocking flow downstream. The stage-discharge relation for this station was developed and is maintained using current-meter measurements of discharge. A graph and tables of computed and daily mean discharges through September 2004 are included in Appendix B (fig. B66, tables B50 and B51)

By 2002, all the palm trees that surrounded the former recreational pool at Pederson East Spring in the Moapa Valley National Wildlife Refuge had been removed by FWS. On May 10, 2002, the USGS, in cooperation with SNWA and FWS, installed a recording gage with weir control. A graph and table of the daily mean discharges collected through September 2004 are included in Appendix B (fig. B27, table B18).

Water-quality samples were collected in 2004 by DRI at Pederson East Spring, M-13, Baldwin Springs, and Muddy Springs at L.D.S Farm. Field measurements of temperature, pH, specific conductance, and dissolved oxygen were made and water samples were collected and analyzed for major ions and stable hydrogen and oxygen isotopes. Tables summarizing the field and laboratory results for each site are included in Appendix B (tables B19, B26, B35, and B44).

U.S. Geological Survey Monitoring Stations

Site identification numbers were assigned to each USGS monitoring station in this report, whether continuous or partial-record site. For all continuous-record and some partial-record sites, these numbers range from 8 to 10 digits and are designated in order of downstream direction along a main stream. For example, the complete 8-digit number for station 09416000 (Muddy River near Moapa) includes a 2-digit part number (09), plus the 6-digit downstream order number (416000). The part number refers to an area, the boundaries of which coincide with specified natural drainage boundaries. Records in this report are for sites in Part 09, the Colorado River Basin. When a station is added between two consecutively numbered stations, an additional digit is added to the upstream station number.

Most of the partial-record gaging stations in this report have site identification numbers based on the grid system of latitude and longitude. These numbers consist of 15 digits and provide a general geographic location and a unique number for each site. The first 6 digits denote the degrees, minutes, and seconds of latitude; the next 7 digits denote degrees, minutes, and seconds of longitude. The last two digits are sequential numbers for sites within a 1-second grid. For example, the site at Warm Springs East has a complete 15-digit number of 364236114424301. This site is located at 36 degrees, 42 minutes, 36 seconds latitude and 114 degrees, 42 minutes, 43 seconds longitude. It is the first station recorded in that 1-second grid. The description of geographic locations of a station may be refined, but the unique identification number remains unchanged.

Continuous-Record Stream-Gaging Stations

A continuous-record stream-gaging station is a site where data are collected with sufficient frequency to define daily mean values and variations within a day. Continuous-record gaging stations are equipped with instrumentation that records the gage height (stage) for the stream at selected frequencies, typically 15-minute intervals. These stage recordings are stored by a data logger and then later downloaded or transmitted into the USGS NWIS database. Discharge measurements are made at selected intervals, usually every 6 to 8 weeks. These data, together with supplemental information, are used to compute daily discharges (Rantz and others, 1982). The locations of the six continuous-record gaging stations currently operated within the Warm Springs area by the USGS, in cooperation with SNWA, are shown in figure 2. The sites also are listed in table 1 and include the following: Muddy River near Moapa (09416000), Muddy Springs at L.D.S. Farm near Moapa (09415900), Warm Springs West near Moapa (09415920), Pederson Spring near Moapa (09415910), Pederson East Springs near Moapa (09415908), and Warm Springs Confluence at Iverson Flume near Moapa (09415927). Site information, photographs, and graphs and tables for daily mean discharge for the period of record for these sites are included in Appendix B.

Partial-Record Stream-Gaging Stations

A partial-record stream-gaging station is a site where stage, discharge, or other hydrologic measurements are made one or more times during a year but at a frequency insufficient to develop a daily record. There is no instrumentation recording gage height at these sites. Measurements of gage height and corresponding discharge are done manually by field personnel. The USGS currently monitors 11 partial-record gaging stations in the Warm Springs area. These sites typically are visited and measured every 6 months. Eight of the 11 stations are within two of the major spring groups, Pederson and Plummer. The locations of all partial-record gaging stations are shown in figure 2 and given in table 1. Sites in the Pederson Spring Group include: Station 364235114425201 (M-11), Station 364237114425401 (M-12), Station 364236114425401 (M-13), Station 364235114425301 (M-19). Sites in the Plummer Spring Group include: Warm Springs East (364236114424301), Muddy River Springs 16 (364238114424201or M-16), 364238114424401 (M-15 or Plummer Central), and Muddy River Springs 20 (364238114424301). Other partial-record sites include Muddy River Springs M-10 (364327114430801), Baldwin Springs near Moapa (09415875), and Apcar Stream at Pipeline Jones flume near Moapa (09415940). Site information, photographs, and graphs and tables of discharge measurements for the period of record for these sites are included in Appendix B.

Summary

The U.S. Geological Survey (USGS), in cooperation with Southern Nevada Water Authority and Nevada Division of Water Resources (NDWR), operates and maintains a surface-water network of 6 continuous-record stream-gaging stations and 11 partial-record stations in the Warm Springs area near Moapa, Nevada. Permanent land-surface bench marks were installed in the Warm Springs area by the Las Vegas Valley Water District, the Southern Nevada Water Authority, and the USGS to determine water-surface elevations at these gaging-stations. Vertical datum elevations and horizontal coordinates were established for all bench marks through a series of Differential Global Positioning System (DGPS) surveys. DGPS vertical datums were transferred to reference marks and points installed at each monitoring site using optical theodolite surveys. All surveys were completed by June 2004, and water-surface elevations were measured on August 17, 2004. Water-surface elevations ranged from 1,810.33 ft at Pederson Spring to 1,706.31 ft at Muddy River near Moapa.

All USGS discharge and water-quality data published through September 30, 2004, for the Warm Springs area were compiled for this study. Additional discharge and water-quality data were provided by other agencies that manage, regulate, study, or use the water resources of the area. Periodic water-level readings for 10 flumes were provided by NDWR. U.S. Fish and Wildlife Service provided discharge data for springs within the Moapa Valley National Wildlife Refuge. Additional water-quality data were provided by the Moapa Valley Water District (MVWD), Desert Research Institute (DRI), and Converse Consultants.

Chronologies of water-resources development and hydrologic data collection are included in this report to illustrate the relation of the hydrologic monitoring network with historical and contemporary land- and water-use changes in the Warm Springs area. Prior to 1950, the Warm Springs area consisted of a few ranches that derived their water from individual springs or wells. From the 1950s to the late 1960s, most of the small ranches eventually merged into one working ranch with large land areas watered by an intricate network of irrigation ditches. Recreational facilities were established to take advantage of the warm spring waters for year-round aquatic and outdoor activities. The first exportation of water from springs in the study area was for supply to a nearby power plant and to growing communities to the south. As a result of these activities, flumes were installed near the major spring groups to monitor effects of water withdrawals and diversions.

Toward the late 1970s, environmental concerns resulted in the creation of the Moapa Valley National Wildlife Refuge that eventually terminated two of the three recreational developments. Additional hydrologic monitoring was started to characterize the water resources within the refuge for the protection and management of the Moapa dace. During the 1980s, additional ground-water and surface-water sources were tapped to meet the growing capacity of the powerplant. To provide better monitoring of the effects of water withdrawals, additional gages were installed and existing flumes were upgraded. In the 1990s, the wildlife refuge was expanded and additional monitoring sites were established.

In the past 4 years, two new recording gages were installed and major improvements were made to an existing site. With the completion of the water-surface surveys and the compilation of discharge and water quality data, this upgraded network will help identify potential effects on the water resources as a result of (1) changes in vegetation within the former agricultural lands, (2) changes within the Wildlife Refuge due to restoration activities, (3) continued withdrawal of ground water within the valley, and (4) potential withdrawals of ground water from adjacent basins.

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Appendix A. History of Water-Resources Development within the Warm Springs Area Near Moapa, Nevada

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History of Water Resources Development

The Warm Springs area has a rich history of farming, ranching, and recreation. The first known dwellers within the area were the Anasazi and the Southern Paiute Indians (Baxter and Haworth, 1996). Little is known about the Anasazi in southern Nevada. By the early 1800s, the Paiutes had sizable populations along the Muddy and Virgin Rivers (Holt, Ronald, accessed July 22, 2004 http://www.onlineutah.com/paiutehistory.shtml). Although most of these riverine and desert groups were primarily foragers and hunters, the Paiutes were known to also have irrigated crops, such as corn, squash, melons, and wheat, along the banks of the Muddy River (Mozejko, 1981). In addition to using the river as a source of irrigation and drinking supply, the Paiutes also used it for ceremonial rites, which are still practiced today within the Moapa Paiute Indian Reservation (Phil Swain, Moapa Band of Paiutes, oral commun., 2004).

From the 1870s to the early 1880s, Warm Springs was cohabited by Indians, outlaws, and prospectors. The first known ranch in the Warm Springs area was started in 1871 with several cattle and horses rustled by a fugitive bank robber from Texas. He built a rock house just north of the current Church of the Latter Day Saints (L.D.S.) Recreation Area (Baxter and Haworth, 1996). He called the ranch Stone Cabin Springs and worked it until his death in 1882.

The first Mormon settlers arrived in the Warm Springs area in 1889 and cleared and irrigated about 30 acres to grow alfalfa and cotton. Although several other ranches subsequently sprang up in the area, the longest worked ranch was the Home Ranch, which began about 1910. It was located north of Warm Springs Road, across from the Pederson Spring area. From 1910 to 1950, the Home Ranch changed ownership frequently but continued to be used primarily for farming and ranching. The largest parcel of land irrigated during this period was about 60 acres (Baxter and Haworth, 1996). By the 1940s, several of the larger springs in the area had gained popularity with locals and visitors for camping, swimming, and bathing (Jim Haworth, local resident, oral commun., 2004).

In 1950, Francis Taylor acquired the Home Ranch and changed the name to Warm Springs Ranch. Taylor eventually expanded the size of the ranch to about 1,200 acres, which was used, in part, to experiment with different pasture grasses and to breed cattle suitable for the desert environment (Baxter and Haworth, 1996). A large mansion that still exists and bears his name (fig. A1) was built adjacent to a large spring-fed pool (Muddy Springs) that is the source of flow discharging from the current L.D.S. Recreation Area. During the 1950s and early 1960s, large amounts of water were diverted from the springs when a network of approximately 6.5 miles of irrigation ditches, mostly concrete (fig. A2), were installed throughout the valley (Jim Haworth, local resident, oral commun., 2004). Only a few of these irrigation ditches are in use today as most have been abandoned or are unusable (fig. A2).

At the same time that the Warm Springs Ranch was expanding under Taylor's proprietorship, the 1950s ushered in two private recreational developments. The first was called the 7-12 Warm Springs Resort, which was located in the area currently known as the Pederson Springs area; it consisted of trailer parking, two swimming pools, a snack bar, and residential housing. The small pool (fig. A3) was filled directly by discharge from a spring below the pool, and the larger pool (fig. A4) was filled by diverting discharge from a spring. The second development became known as the Desert Oasis Warm Springs Resort, which encompassed most of the area currently called the Plummer Springs area but also included the former pool which is now known as Pederson East Spring (fig. A5). By the 1990s, the Desert Oasis Warm Springs Resort had developed into a private time-share/spa that ultimately included trailer parking, a spa, a swimming pool, ponds, a 5,000-ft^2 mansion, and a water slide (figs. A6, A7, and A8).

In 1954, the Moapa Valley Water Company and the Overton Water District entered into a joint agreement to pump water from the Warm Springs area to residential, business, and dairy establishments to the south (Hafner, 1967). A small spring on a hillside on Francis Taylor's ranch was selected for a pump house and developed to create a discharge of about 2 ft^3/s. In 1960, the pump house was installed on what is now called the Apcar (Pipeline Jones) Springs (fig. A9). Water (1 ft^3/s) and land (1 acre) at the spring were donated to the Moapa Valley Water Company by Francis Taylor (Baxter and Haworth, 1996). Frederick Apcar subsequently purchased approximately 45 acres of land surrounding the spring and used the area primarily for his own private recreation. Apcar enlarged and concreted one of the springs and constructed a large swimming pool (fig. A9; Baxter and Haworth, 1996). A new pump house was constructed at Apcar Springs during the summer of 2004 by the Moapa Valley Water District (fig. A9).

In the mid-1960s, a coal-fired powerplant (Reid Gardner Generating Station) was constructed along the east bank of the Muddy River about 3 mi southeast of the Warm Springs area (fig. 1). Water required for plant operations initially was obtained from the Muddy River near the plant and from several wells owned by Clarvid Lewis located in the northwest corner of Warm Springs area (Richard Willer, Nevada Power Company, oral commun., 2004). By the early 1970s, the NPC constructed a diversion and pumping station along the north bank of the Muddy River about 100 ft upstream of the USGS stream-gaging station at Warm Springs Road (fig. A10). Water is pumped directly from the river and transmitted by pipeline to the powerplant.

In 1968, shortly after the death of Francis Taylor, Howard Hughes, having seen the Warm Springs area during a test flight, purchased the entire Warm Springs Ranch. Although Hughes owned the Ranch for nearly 8 years, he reportedly never set foot on it (Baxter and Haworth, 1996). By the early to mid-1970s, water diverted for irrigation for ranch operations reached its maximum (Jim Haworth, local resident, oral commun., 2004). Water demand, however, continued to grow in the rest of Moapa Valley, and in 1974 the MVWD installed a pump house at Baldwin Springs (fig. A11). This pump house is still operating; however, the amount of water withdrawn, 6.5 acre-ft during 2003 (Converse Consultants, 2004), is significantly less than the amount pumped from Apcar Springs.

In 1978, 2 years after the death of Howard Hughes, the Warm Springs Ranch was purchased by the L.D.S. Church. After a couple of years, the cattle operation started to decline, and the church planted fruit and nut trees, hoping to develop the ranch as a welfare farm (Gary Holt, L.D.S. Recreation Area, oral commun., 2004). The experimental welfare farm was unsuccessful, and by the mid-1980s the Church had leased most of its water rights to NPC and sold off all but about 73 acres of the Ranch. The remaining church property, which kept the name of the Warm Springs Ranch (fig. A12) was subsequently developed into a recreational center for L.D.S. Stakes in southern Nevada. The area is now called the L.D.S. Recreational Area and includes a large swimming pool (fig. A12), campgrounds, and the renovated Francis Taylor mansion (fig. A1). The mansion survived a fire in 1987 that destroyed many of the old Warm Springs Ranch homes, barns, and corrals. The spring-fed pond is still used for swimming, and the large swimming pool is periodically filled with water from the spring-fed pond. The L.D.S. Recreation Area hosts numerous group outings and uses ground water pumped from a private well to support on-site residential and campground facilities.

In 1979, approximately 90 acres of land that included most of the 7-12 Warm Springs Resort and a small part of the Desert Oasis Warm Springs Resort was deemed by the Federal government as habitat for the endangered Moapa dace (*Moapa coriacea*). The property was purchased by the government and was designated as the Moapa Valley National Wildlife Refuge. The U.S. Fish and Wildlife Service (FWS) assumed custody of the refuge and began a long-term restoration program.

Development of another recreational area on L.D.S. church property was attempted in the early 1980s at the northwest end of the valley. Although the development reportedly was built by Lee Earl (Richard Pedersen, local resident, oral commun., 2004), the area has been called Cardy Lamb (Scoppettone and others, 1987). A large concrete pond and a bathhouse were built about 400 ft east of Warm Springs Road (fig. A13). The pond was built over one of the springs that had previously supplied irrigation water through the original concrete-ditch network to fields east of the area. The facility never materialized and the property eventually was sold (Richard Pedersen, oral commun., 2004). Water from the pond is used by the current owner to irrigate several nearby fields for livestock grazing. An underground drainage pipe connects the pond to the irrigation ditches.

In the early 1980s, NPC significantly increased the capacity of the Reid Gardner Generating Station. Although additional water was available from their Meadow Valley wells, the quality of the water was poor; consequently the company began purchasing water rights from the L.D.S. Church and other private owners in the Warm Springs area (Richard Willer, Nevada Power Company, oral commun., 2004). Currently, NPC pumps water from about 12 wells and 1 surface-water diversion from the Muddy River near Moapa (another intake pump was installed in 1999) in the Warm Springs area.

By 1986, most of the existing 7-12 Warm Springs Resort recreational facilities within the initial refuge boundary had been removed. These included the trailer hookups, swimming pools, and snackbar. The current conditions of the areas where the two swimming pools had been located are shown in figures A3 and A4. The Desert Oasis Warm Springs Resort continued to operate until a fire swept through the area in 1994. After the fire, the resort essentially remained unused until 1997 when the property was purchased by Del Webb and turned over to the FWS to be incorporated as part of the Moapa Valley National Wildlife Refuge (Amy Sprunger-Allworth, U.S. Fish and Wildlife Service, oral commun., 2004).

In 2001, the Federal government purchased the 45 acres adjacent to Apcar Spring and incorporated that property as part of the wildlife refuge. By spring 2002, the FWS had removed the former recreational pool at Pederson East Spring and many of the palm trees within the Pederson Spring Group (fig. A5) and had began restoration projects in the Plummer and Apcar Spring areas.

Farming and ranching continues today within the Warm Springs area, but land usage has dropped significantly since its peak in the mid-1970s. The set of aerial photographs in figure A14 depict the difference in the amount of acreage irrigated during 1976 and 2003. Estimated acreage irrigated in 1976 was about 600 acres compared with about 100 acres in 2003.

A. **View of the mansion during the mid-1970s. Photograph from Baxter (1996).**

B. **View of the mansion in July 2004. Photographed by D. Beck.**

Figure A1. Francis Taylor mansion, built in the 1950s in the Warm Springs area near Moapa, Nevada.

A. **Concrete irrigation ditch east of Cardy Lamb Swimming Pond.**

B. **Former concrete irrigation ditch south of Cardy Lamb Swimming Pond that has been completely filled in with dirt.**

Figure A2. Concrete irrigation ditches near Cardy Lamb Swimming Pond in the Warm Springs area near Moapa, Nevada. Both views photographed in June 2004 by D. Beck.

A. Former 7-12 Warm Springs Resort small swimming pool during the 1950s. Photograph courtesy of R. & L. Pederson.

B. Same area after small swimming pool, trailer hookups, and palm trees were removed by the U.S. Fish and Wildlife Service. Photographed in June 2004 by D. Beck.

Figure A3. Former Warm Springs Resort small swimming pool, Warm Springs area near Moapa, Nevada.

A. **Former 7-12 Warm Springs Resort large swimming pool during the 1960s. Photograph courtesy of R.& L. Pederson.**

B. **Same area after large swimming pool, bathhouse, and snackbar were removed by the U.S. Fish and Wildlife Service. Photographed in June 2004 by D. Beck.**

Figure A4. Former Warm Springs Resort large swimming pool, Warm Springs area near Moapa, Nevada.

A. **View in April 2000 of the spring and site of the former recreational pool.**

B. **Same view in July 2004 after the pool structure and palm trees had been removed. Photograph by D. Beck.**

Figure A5. Pederson East Spring in the Moapa Valley National Wildlife Refuge near Moapa, Nevada.

A. **View of the mansion and spring area.**

B. **View of the mansion and parking area.**

Figure A6. Former Desert Oasis Warm Springs Resort in the Warm Springs area near Moapa, Nevada. Both views photographed in July 2004 by D. Beck.

A. **Spring-fed swimming pool.**

B. **Remains of a water slide and pool.**

Figure A7. Recreational facilities of the former Desert Oasis Warm Springs Resort in the Warm Springs area near Moapa, Nevada. Both views photographed in July 2004 by D. Beck.

Figure A8. View of the spa and mansion at the former Desert Oasis Warm Springs resort in the Warm Springs area near Moapa, Nevada. Photographed in July 2004 by D. Beck.

A. **View of Moapa Valley Water District's old (right) and new (left) pump houses in the foreground.**

B. **View of former swimming pool built by Frederick Apcar around 1980.**

Figure A9. View of Apcar (Pipeline Jones) Springs in the Warm Springs area near Moapa, Nevada. Both views photographed in June 2004 by D. Beck.

Figure A10. View looking downstream at Nevada Power Company water diversion and pumping station on the Muddy River, in the Warm Springs area near Moapa, Nevada. The diversion is about 100 feet upstream of the U.S. Geological Survey streamflow-gaging station at Warm Springs Road. Photographed in February 2004 by D. Beck.

Figure A11. View of the Baldwin Springs area and the Moapa Valley Water District pump house in the Warm Springs area near Moapa, Nevada. Photographed in June 2004 by D. Beck.

A. **Entrance to the recreation area.**

B. **Swimming pool in the recreation area.**

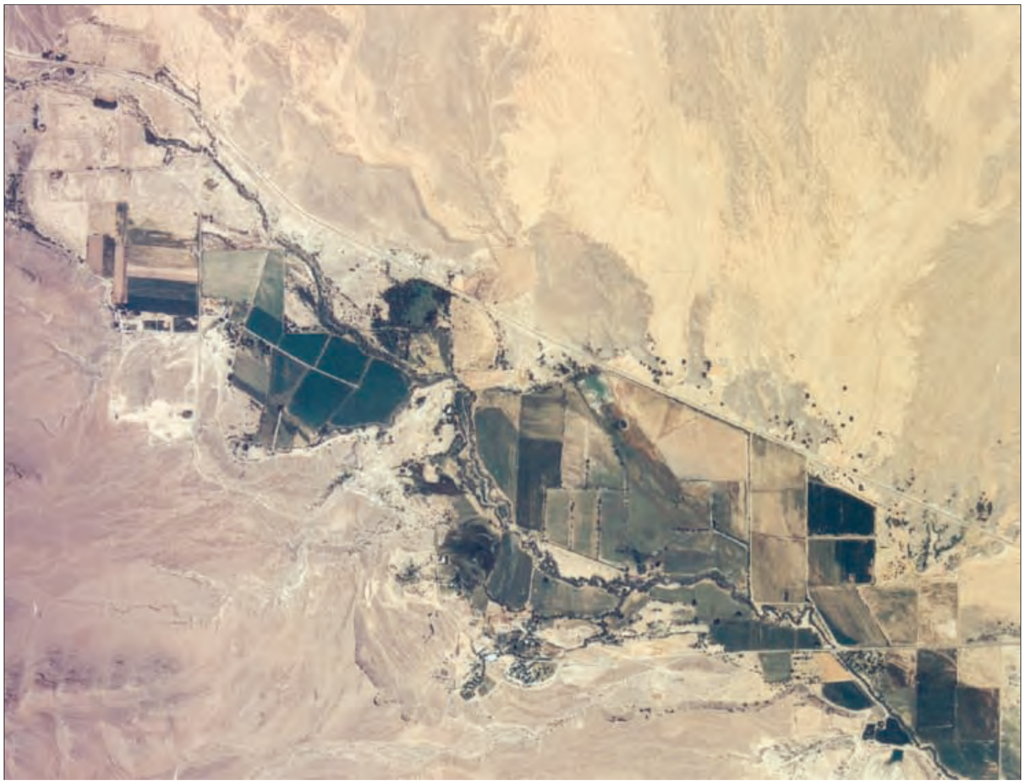
Figure A12. Church of the Latter Day Saints Recreational Area in the Warm Springs area near Moapa, Nevada. Both views photographed in June 2004 by D. Beck.

A. **View of spring-fed pond and bathhouse, with pond nearly drained. Photographed in June 2004. Photographed in June 2004 by D. Beck.**

B. **View of pond when fully filled. Photographed in September 2004 by D. Beck.**

Figure A13. Church of the Latter Day Saints Recreation Area at Cardy Lamb Springs, in the Warm Springs area, near Moapa, Nevada.

1976



2003

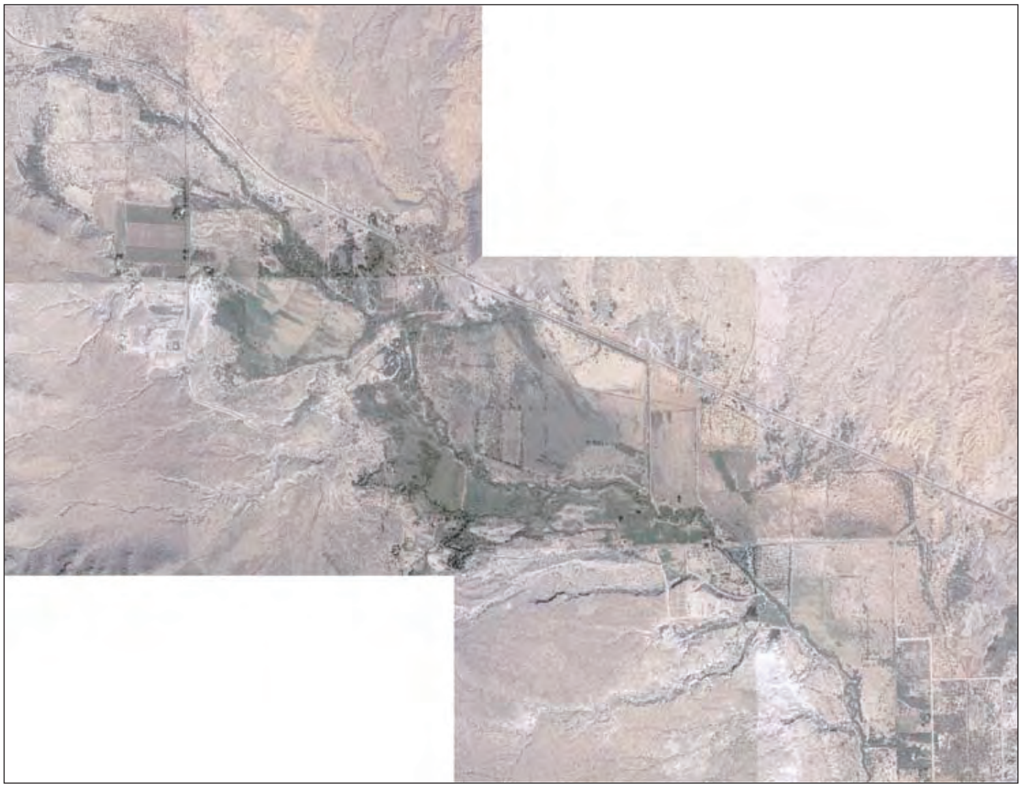


Figure A14. Irrigated acreage in the Warm Springs area near Moapa, Nevada, in 1976 and 2003.

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Appendix B. Water-Level, Discharge, and Water-Quality Data for Selected Monitoring Sites Within the Warm Springs Area Near Moapa, Nevada

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Muddy River

The following sites are included within this section:

09416000 Muddy River near Moapa, Nevada (1913–2004)
Big Wash Flume near Moapa, Nevada (1967–84)
09415950 Muddy River Power Diversion near Moapa, Nevada (1978–85)

09416000 Muddy River near Moapa, Nevada

The stream-gage at Muddy River near Moapa originally was established by the Muddy Valley Irrigation District (MVID) on July 1, 1913, at its present location upstream of Warm Springs Road (fig. B1). Water-level record and discharge measurements were collected by the MVID from July 1913 to September 1915 and from April 1916 to September 1918. The gage was reactivated in June of 1928 by the University of Nevada Agricultural Experiment Station (UNAES). Daily mean gage height and monthly discharge were collected by the UNAES from June 1928 to October 1931 and from April 1932 to July 1932. The Bureau of Reclamation (Reclamation) reactivated the gage October 21, 1944, and collected continuous streamflow data until October 1, 1948, when the operation of the gage became the responsibility of the U.S. Geological Survey. Flow is diverted about 100 ft upstream of the gage by the Nevada Power Company for use at the Reid Gardner Generating Station about 3 mi downstream of the gage (fig. 1). The hydraulic control for this site is the 10-ft concrete Cipolletti weir, which was installed by the USBR in 1944 just upstream from the Warm Springs Road crossing (fig. B2).

Daily mean discharges for the period of record are plotted on figure B3 and listed in table B1. Photographs of the bench and reference marks established for this gage on June 2, 2004, are shown in figure B4.

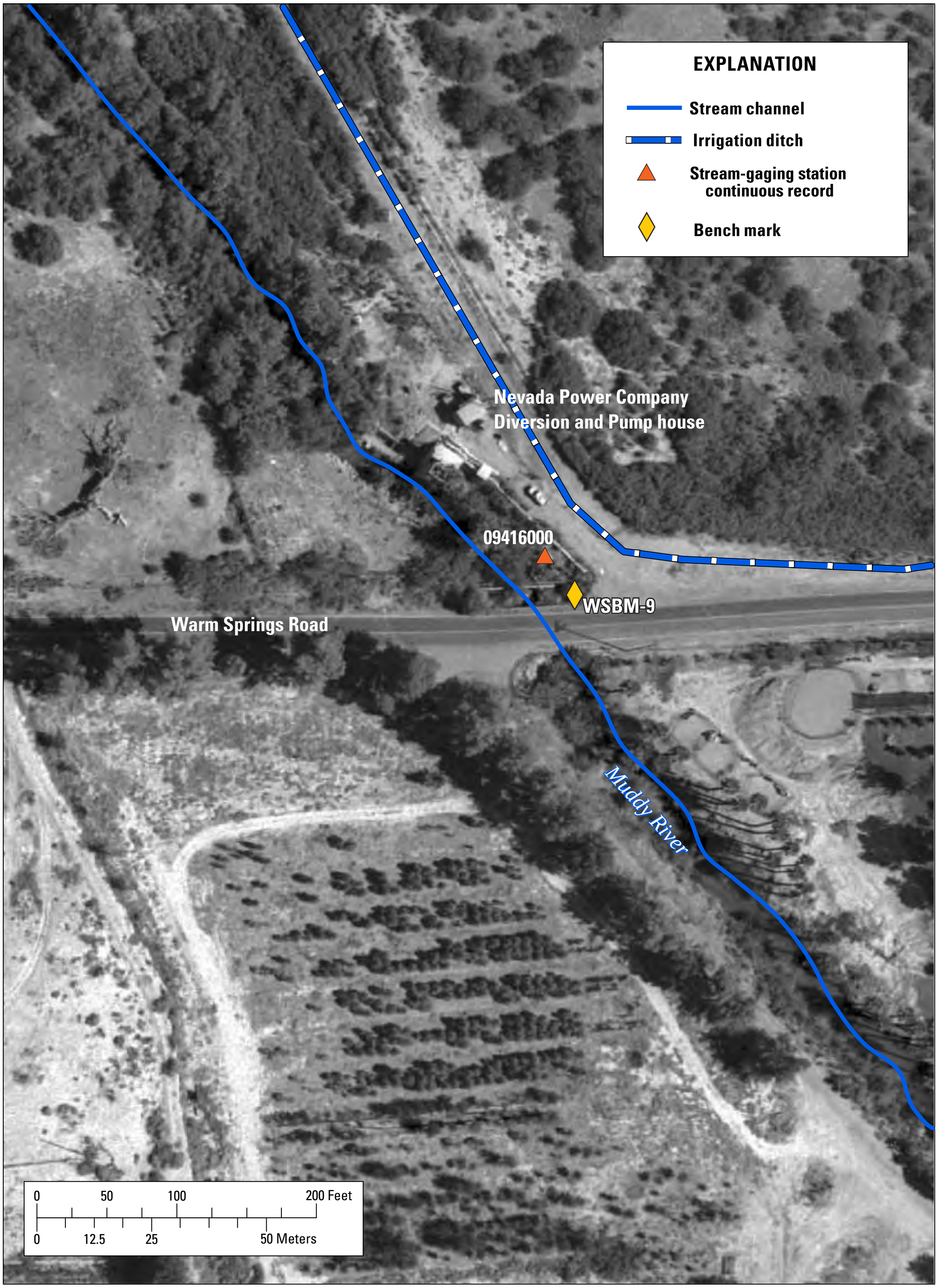

Figure B1. Location of Muddy River stream-gaging station (09416000), bench mark WSBM-9, and Nevada Power Company's diversion and pump house in the Warm Springs area near Moapa, Nevada.

Figure B2. View looking downstream of the Cipolletti weir upstream of Warm Springs Road at the Muddy River stream-gaging station (09416000) in the Warm Springs area near Moapa, Nevada. Photographed in June 2004 by D. Beck.

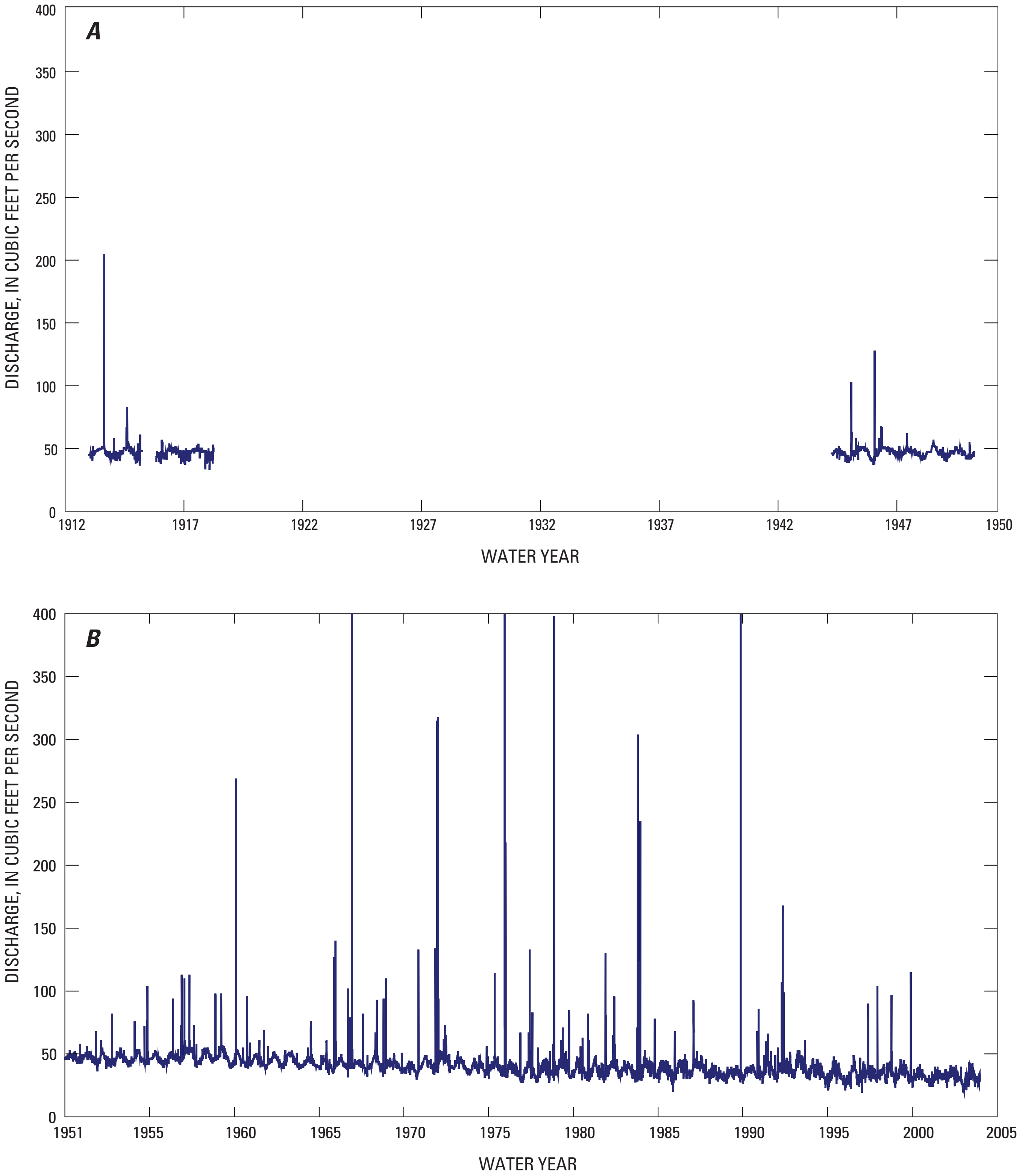

Figure B3. Daily mean discharges for stream-gaging station 09416000, Muddy River near Moapa, Nevada, for (*A*) water years 1913–15, 1916–18, and 1944–47, and (*B*) water years 1951–2004.

Table B1. Daily mean discharges for continuous-recording stream-gaging station 09416000 Muddy River near Moapa, Nevada, water years 1913–2004.

Table B1 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

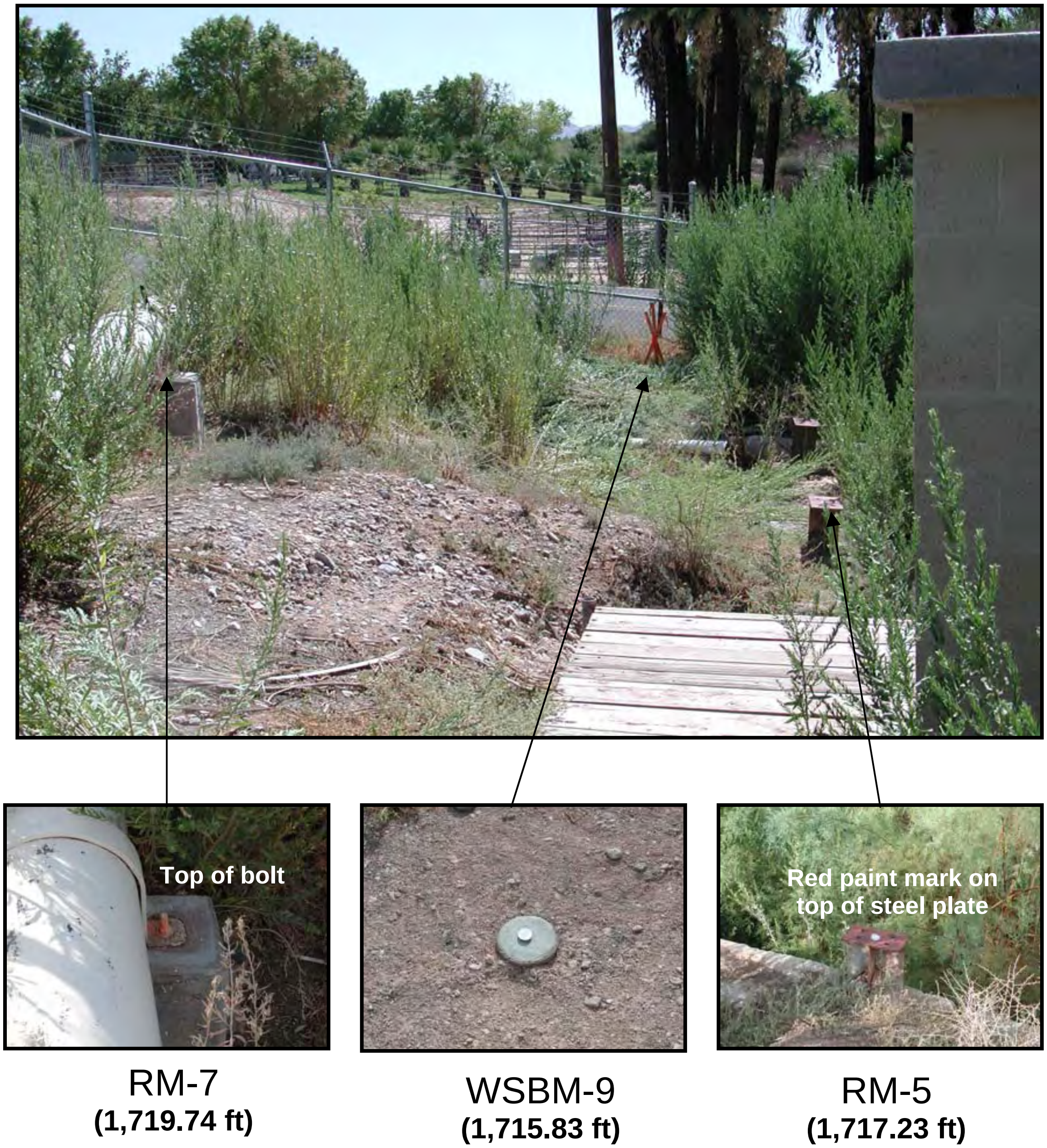

Figure B4. Location and elevation of bench mark WSBM-9 and reference marks RM-5 and RM-7 at streamgaging station 09416000, Muddy River near Moapa, Nevada, June 2, 2004, elevation in feet above NGVD 88. Photographed by D. Beck.

Big Wash Flume near Moapa, Nevada

A 3-ft Parshall flume was installed on Big Wash (North Fork Muddy River) on October 11, 1967, by the Nevada Division of Water Resources (NDWR). The flume was located approximately 500 ft upstream of the confluence with South Fork Muddy River (fig. B5). The source of water in the river originates from springs and seeps located in the uppermost northwest drainage of the Warm Springs area.

Data provided by NDWR show that water levels in the flume were generally measured monthly from October 11, 1967 to July 18, 1984. Several gaps occur in the record, the largest two occurring from March 1969 to February 1974 and from May 1981 to March 1984. Information provided by NDWR did not indicate whether a new flume had been installed after any of these gaps, but the information did note that a 3-ft flume was in use for the entire period of record. The former flume site was visited by the U.S. Geological Survey on September 16, 2004, and a 3-ft steel Parshall flume was observed upside down on the south bank of the river (fig. B6).

As only water-level measurements were provided by NDWR, discharge rates were computed using a standard rating equation for the 3-ft Parshall flume (Leupold and Stevens, 1987). A plot of the computed discharges from October 1967 to July 1984 is shown in figure B7. A complete listing of the water-level measurements and computed discharges are included in table B2. Discharges computed from October 1967 to March 1969 are substantially less than the computed discharges for the remainder of the period. Although flow may have been bypassing the flume at that time, documentation was unavailable to verify it.

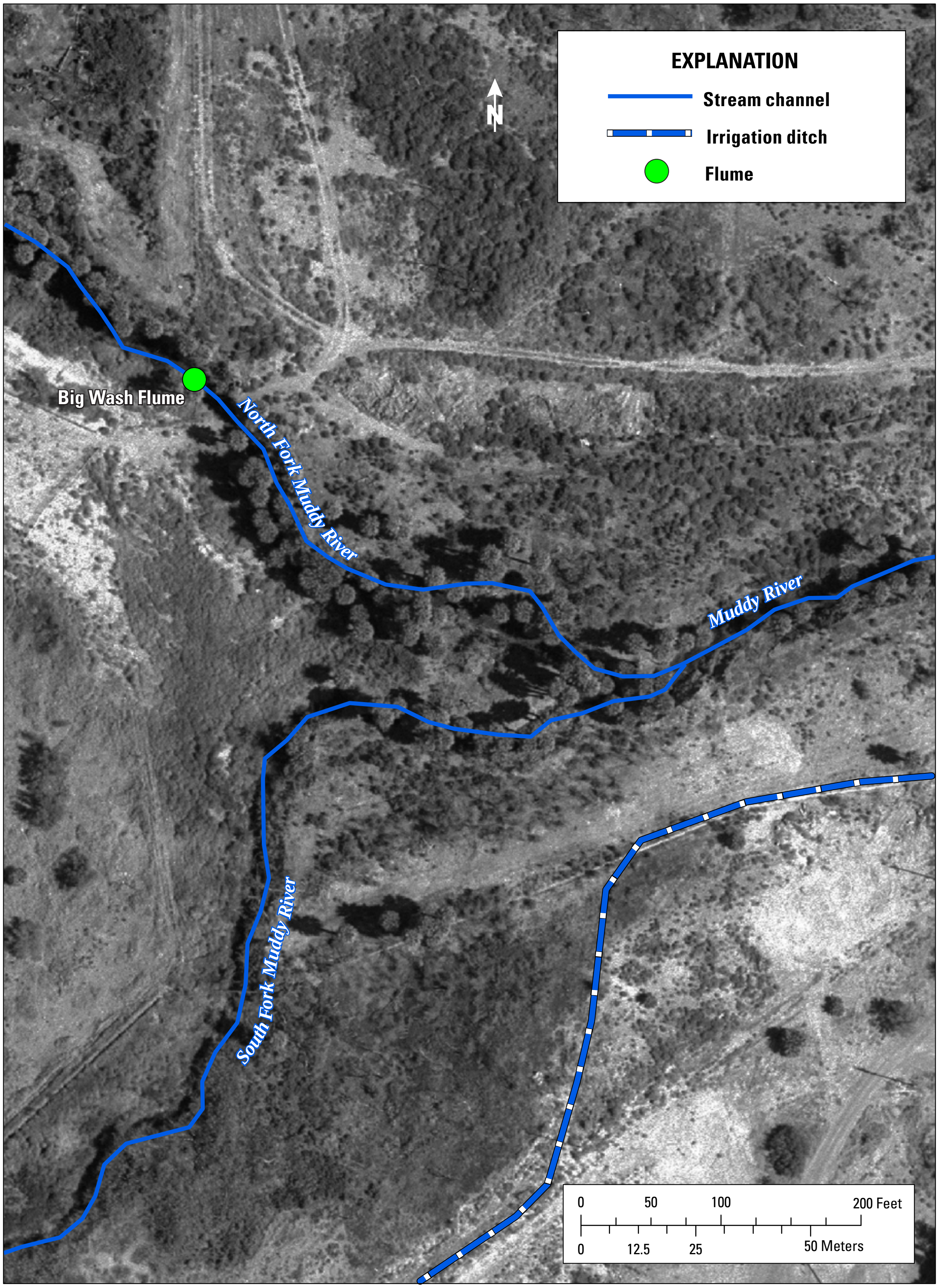

Figure B5. Location of former Big Wash flume site on the North Fork Muddy River in the Warm Springs area near Moapa, Nevada.

Figure B6. Former Big Wash flume on right bank of North Fork Muddy River in the Warm Springs area, near Moapa, Nevada. The flume is about 500 feet upstream of confluence with South Fork Muddy River. Photographed in September 2004 by D. Beck.

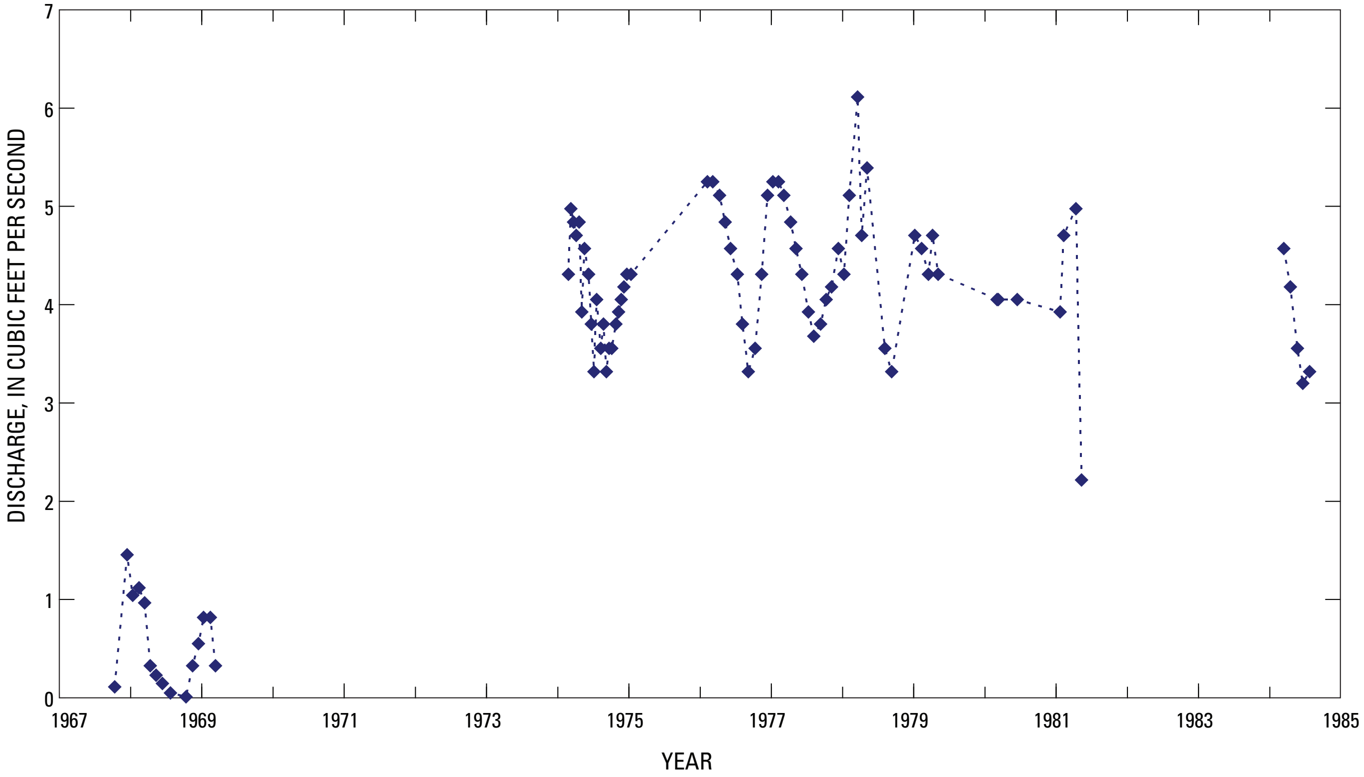

Figure B7. Instantaneous discharges for the Big Wash flume in the Warm Springs area near Moapa, Nevada, 1967–69, 1974–81, and 1984.

Table B2. Water levels and instantaneous discharges for Big Wash flume, near Moapa, Nevada, 1967–84.

Table B2 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

09415950 Muddy River Power Diversion and Pump House near Moapa, Nevada

In the early 1970s, the Nevada Power Company (NPC) constructed a diversion and pump house along the north bank of the Muddy River approximately 100 ft upstream of the U.S. Geological Survey (USGS) stream-gaging station at Warm Springs Road (fig. B1). Water is pumped directly from the stream and transmitted through a pipeline to the Reid Gardner Generating Station (fig. 1) about 3 mi southeast of the gage. The NPC provided the USGS with pumpage data from October 1, 1977, to September 30, 1985. Daily mean discharges for the period were computed and published in the USGS, Nevada District, annual data report series between water years1978 and 1986). See figure B8 and table B3 for a graph and a table, respectively, of the daily mean discharges. Annual mean daily discharge from the diversion for water years 1978 to 1985 was 3.45 ft^3/s.

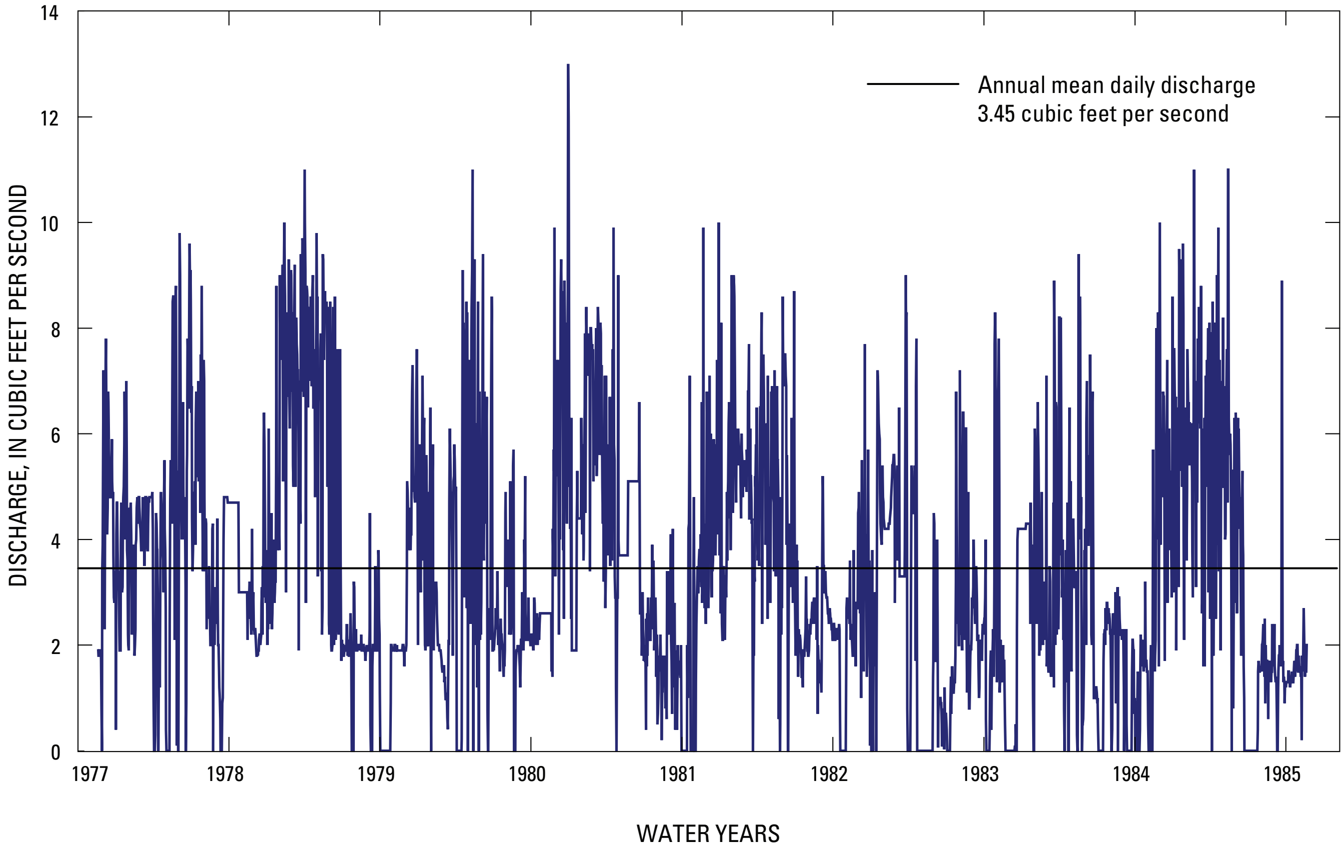

Figure B8. Daily mean discharges for the Muddy River power diversion in the Warm Springs area, near Moapa, Nevada, water years 1978–85. Pumping data was provided to U.S. Geological Survey by Nevada Power Company.

Table B3. Daily mean discharges for the Muddy River Power Diversion near Moapa, Nevada (09415950), water years 1978–85.

Table B3 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Plummer Springs Group

The following sites are included within this section:

364236114424301 Warm Springs East (Plummer Main) near Moapa, Nevada (1982–2004)
364238114424401 Muddy River Springs 15 (M-15) near Moapa, Nevada (1987–2004)
364238114424201 Muddy River Springs 16 (M-16) near Moapa, Nevada (1987–2004)
364238114424301 Muddy River Springs 20 (M-20) near Moapa, Nevada (1994–2004)
Converse Consultant Water-Quality Site S1a (1997–2004)
Converse Consultant Water-Quality SIte S1b (1997–2004)
Converse Consultant Water-Quality Site S34 (1997–2004)
Converse Consultant Water-Quality Site S42 (1997–2004)
Converse Consultant Water-Quality Site S43 (1997–2004)
Converse Consultant Water-Quality Site-S44 (1997–2004)
Converse Consultant Water-Quality Site-S44a (1997–2004)
Converse Consultant Water-Quality Site S56 (1997–2004)

364236114424301 Warm Springs East (Plummer Main) near Moapa, Nevada

The partial-record stream-gaging station at Warm Springs East was established by the U.S. Geological Survey (USGS) on August 2, 1982, and is located about 70 ft downstream of the confluence with Plummer East tributary and about 180 ft upstream of Warm Springs Road (fig. B9). Flow in Warm Springs East is the combined discharge from all springs and seeps on that part of the Moapa Valley National Wildlife Refuge, formerly known as the Desert Oasis Warm Springs Resort. Periodic discharge measurements have been made by the USGS since 1982. Discharge measurements for the period of record are plotted in figure B10 and listed in table B4.

In October 1998, the U.S. Fish and Wildlife Service (FWS) installed a staff plate in the channel and made periodic discharge measurements through May 2002. The FWS discharge measurements are also plotted on figure B10 and are listed in table B5.

Photographs of the staff plate and bench mark, and of the reference mark established by the USGS at the Warm Springs East stream-gaging station on June 10, 2004, are shown in figure B11.

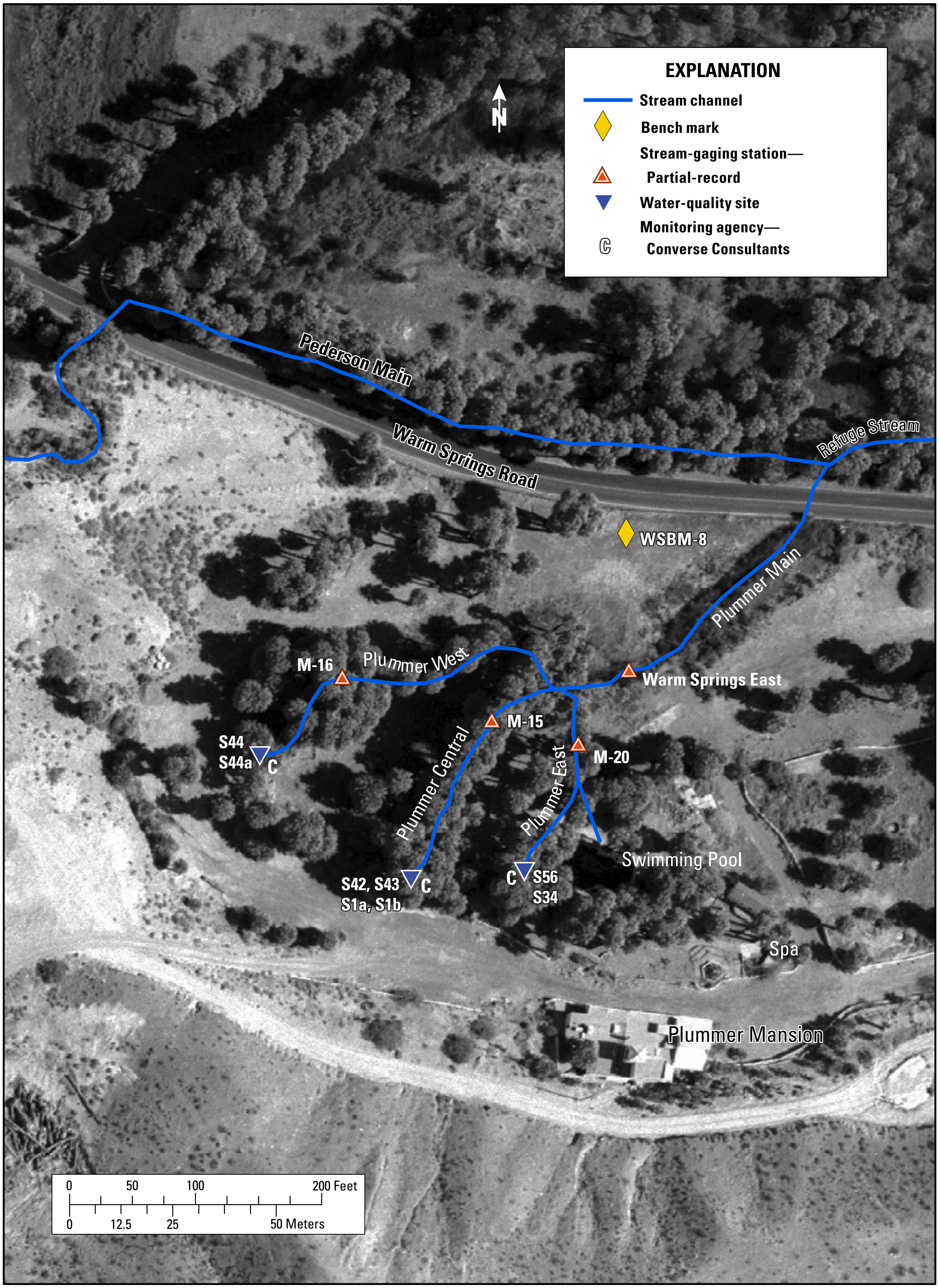

Figure B9. Location of Plummer Springs Group stream-gaging station, monitoring sites, and bench mark WSBM-8 in the Warm Springs area near Moapa, Nevada.

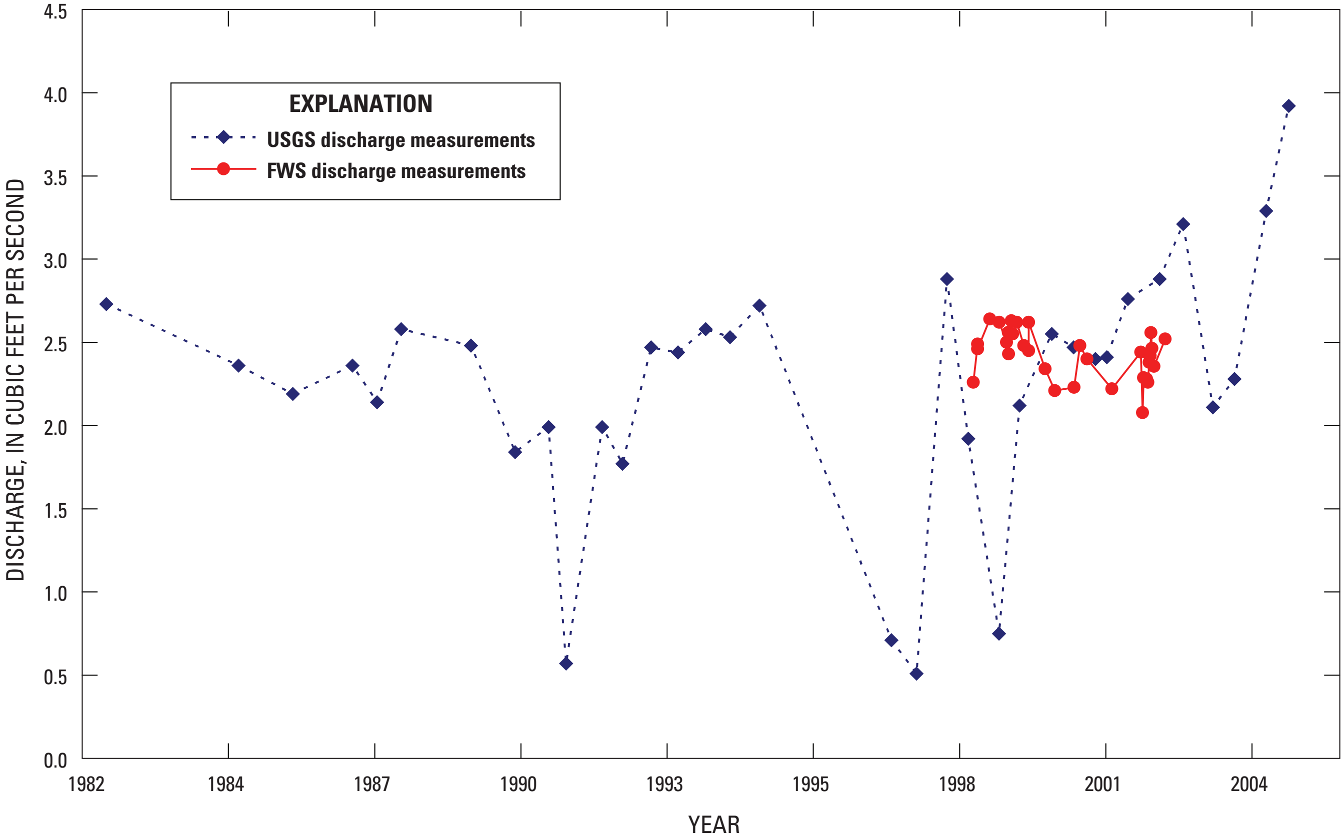

Figure B10. Periodic discharge measurements for partial-record stream-gaging station 364236114424301 Warm Springs East (Plummer Main) near Moapa, Nevada, 1982–2004. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) database, accessed 2005 at http://waterdata.usgs.gov and U.S. Fish and Wildlife Service (FWS).

Table B4. Periodic discharge measurements for partial-record stream-gaging station 364236114424301 Warm Springs East (Plummer Main) near Moapa, Nevada, 1982–2004.

[Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov]

Table B4 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B5. Periodic discharge measurements for partial-record stream-gaging station 364236114424301 Warm Springs East (Plummer Main) near Moapa, Nevada, 1998–2002.

[Data provided by U.S. Fish and Wildlife Service]

Table B5 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Warm Springs East
RM-1 (1,751.08 ft)

WSBM-8
(1,750.70 ft)

Figure B11. Location of bench mark WSBM-8 and reference mark RM-1 for stream-gaging station 364236114424301 Warm Springs East near Moapa, Nevada. Photographed June 10, 2004 by D. Beck. Elevation bench and reference marks in feet above NAVD 88.

364238114424401 Muddy River Springs 15 (M-15) near Moapa, Nevada

The partial-record gaging station at Muddy River Springs 15 (M-15) was established by the U.S. Geological Survey (USGS) on March 12, 1987, and is about 40 ft upstream of the confluence with the Plummer West tributary (fig. B9). Discharge at Muddy River Springs 15 originates upstream from several springs just west of a large swimming pool that was installed by the former Desert Oasis Warm Springs Resort. The area is now part of the Moapa Valley National Wildlife Refuge managed by the U.S. Fish and Wildlife Service (FWS). The FWS removed many of the former resort's recreational facilities and currently is restoring the springs. Periodic discharge measurements have been made by the USGS since 1987. Discharge measurements for the period of record are plotted in figure B12 and listed in table B6.

Photographs of the staff plate and reference mark established for the Muddy River Springs 15 monitoring site on June 10, 2004, are included in figure B13.

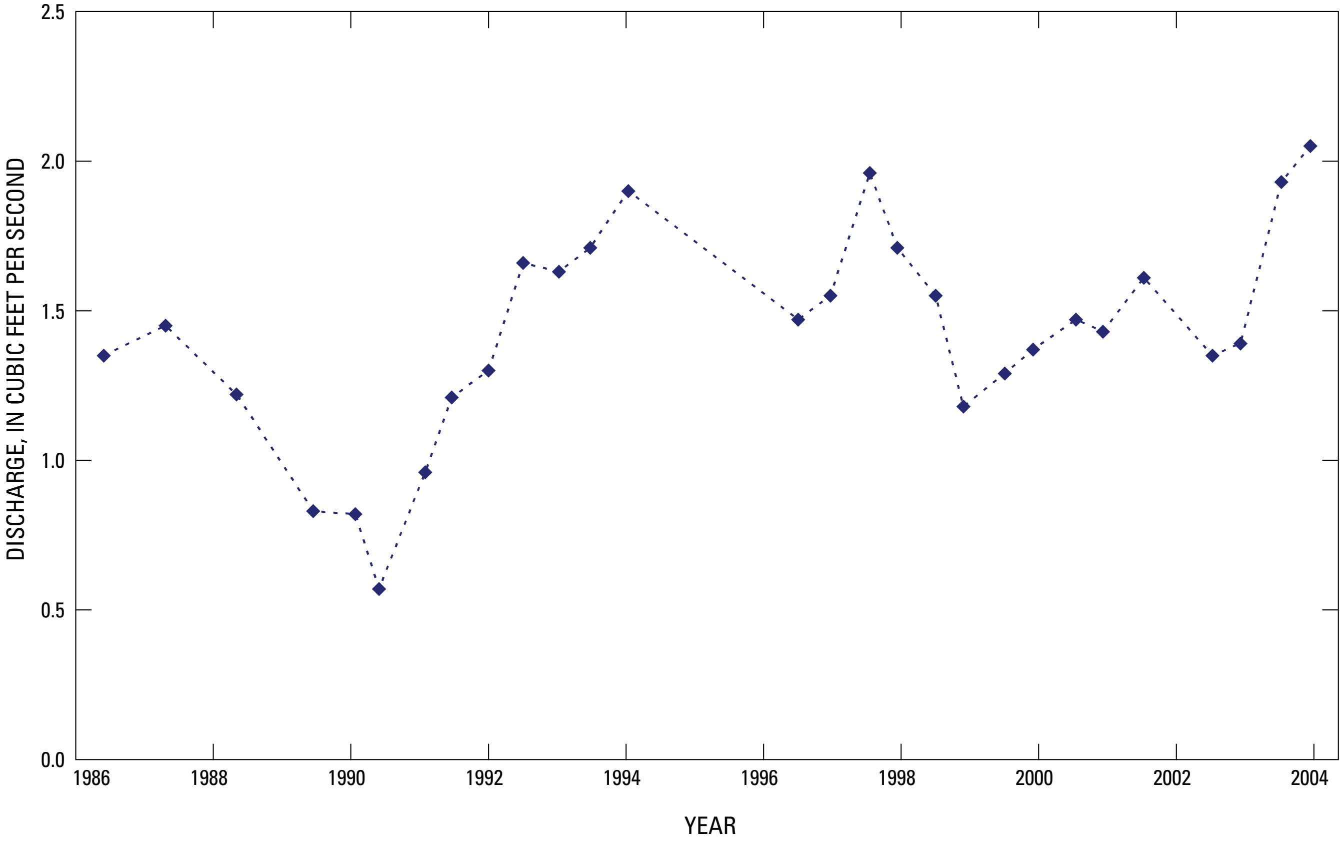

Figure B12. Periodic discharge measurements for partial-record stream-gaging station 364238114424401, Muddy River Springs 15 (M-15) near Moapa, Nevada, 1987–2004. Data from U.S. Geological Survey National Water Information System (NWIS) database, accessed 2005 at http://waterdata.usgs.gov.

Table B6. Periodic discharge measurements for partial-record stream-gaging station 364238114424401 Muddy River Springs 15 (M-15) near Moapa, Nevada, 1987–2004.

Table B6 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Pond upstream of M-15

Figure B13. Location of staff plate and reference mark (RM-1) at station 364238114424401 Muddy River Springs 15 (M-15) near Moapa, Nevada, and view of upstream pond. Photographed June 10, 2004 by D. Beck.

364238114424201 Muddy River Springs 16 (M-16) near Moapa, Nevada

The partial-record gaging station at Muddy River Springs 16 (M-16) was established by the U.S. Geological Survey (USGS) on March 12, 1987, and is about 225 ft upstream of the confluence with the Plummer Central tributary (fig. B9). Discharge at Muddy River Springs 16 originates from a spring-fed pond just upstream of the gage. The area around the spring had previously been developed for trailers and recreational vehicles by the former Desert Oasis Warm Springs Resort. The area is now part of the Moapa Valley National Wildlife Refuge. U.S. Fish and Wildlife Service (FWS) has removed many of the resort's facilities and is currently restoring the springs. Periodic discharge measurements have been made by the USGS since 1987. Discharge measurements for the period of record are plotted in figure B14 and listed in table B7.

In March 1998, the FWS installed a 90-degree v-notch weir and staff plate in the channel. From 1998 to January 2002, FWS made periodic water-level measurements at the weir as well as two measurements of discharge. Discharges for the water-level measurements were computed using a standard weir rating (Rantz, 1982) and are plotted in figure B14. The computed and manual discharge measurements are listed in table B8.

Photographs of the FWS weir and staff plate and of the USGS reference mark established on June 10, 2004, are included in figure B15. On May 26, 2005, the weir, staff plate, and reference mark were observed to have been destroyed as a result of restoration work at the refuge.

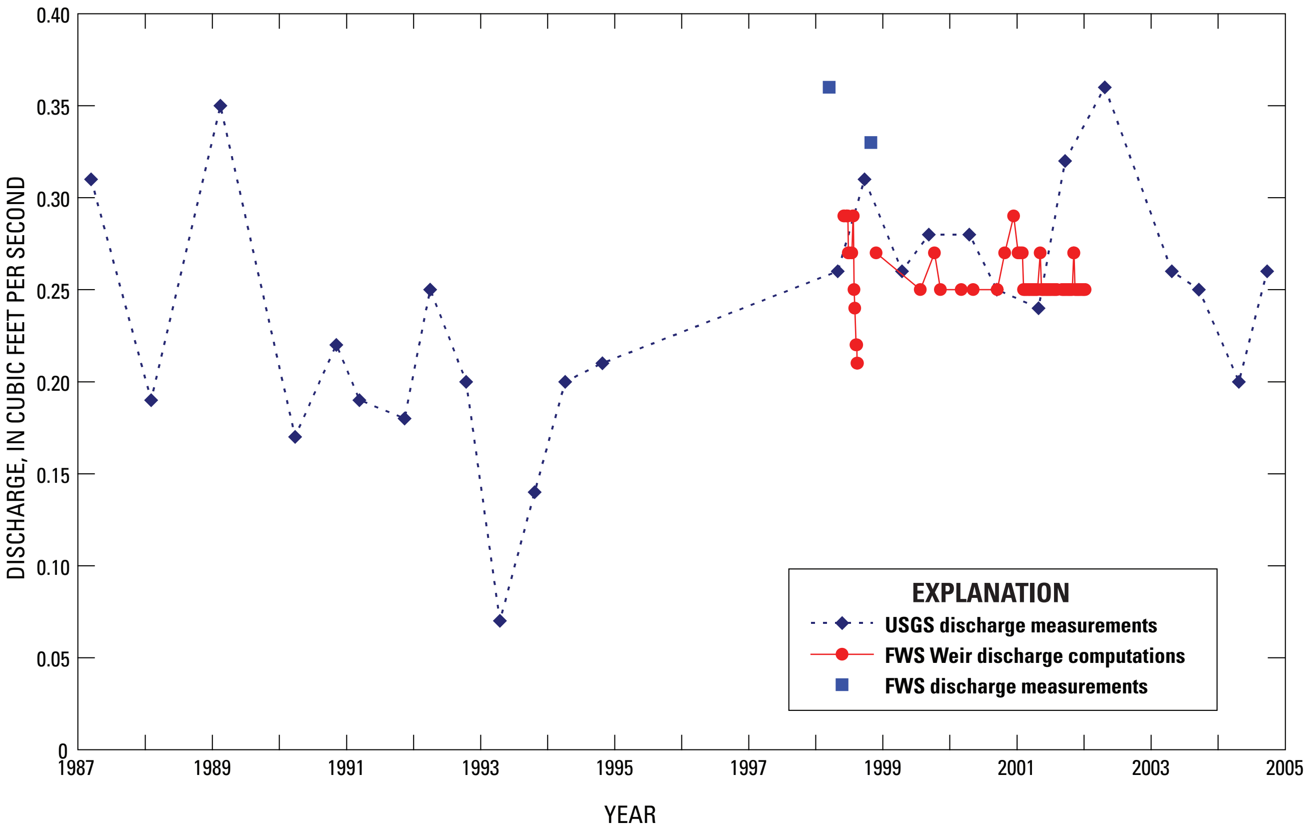

Figure B14. Periodic discharge measurements for partial-record stream-gaging station 364238114424201 Muddy River Springs (M-16) near Moapa, Nevada. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) database, accessed 2005, at http: //waterdata.usgs.gov, and U.S. Fish and Wildlife Service (FWS).

Table B7. Periodic discharge measurements for partial-record stream-gaging station 364238114424201 Muddy River Springs 16 (M-16) near Moapa, Nevada, 1987–2004.

Table B7 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B8. Periodic discharge measurements and weir discharge computations for partial-record stream-gaging station 364238114424201 Muddy River Springs 16 (M-16) near Moapa, Nevada, 1998–2002.

[Data from U.S. Fish and Wildlife Service]

Table B8 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

RM-1
(1,758.08 ft)

Figure B15. Location of U.S. Fish and Wildlife Service weir and staff plate, and reference mark (RM-1) at partial-record stream-gaging station 364238114424201 Muddy River Springs 16 (M-16) near Moapa, Nevada. Photographed June 10, 2004 by D. Beck. Elevation of RM-1 in feet above NAVD 88.

364238114424301 Muddy River Springs 20 (M-20) near Moapa, Nevada

The partial-record gaging station at Muddy River Springs 20 (M-20) was established by the U.S. Geological Survey (USGS) on October 25, 1994, and is about 50 ft upstream of the confluence of Plummer East with the Plummer Main tributary (fig. B9). Flow at Muddy River Springs 20 originates upstream of several springs that had been used to fill a large swimming pool previously operated by the former Desert Oasis Warm Springs Resort. The area is now part of the Moapa Valley National Wildlife Refuge. The U.S. Fish and Wildlife Service (FWS) has removed many of the resort's recreational facilities and currently is restoring the springs. Periodic discharge measurements have been made by the USGS since 1994. Discharge measurements for the period of record are plotted in figure B16 and listed in table B9.

Photograph of the staff plate established for the Muddy River Springs 20 monitoring station on June 10, 2004, is included in figure B17. On May 26, 2005, the large swimming pool upstream of the gage was observed to have been removed as part of the restoration program at the refuge.

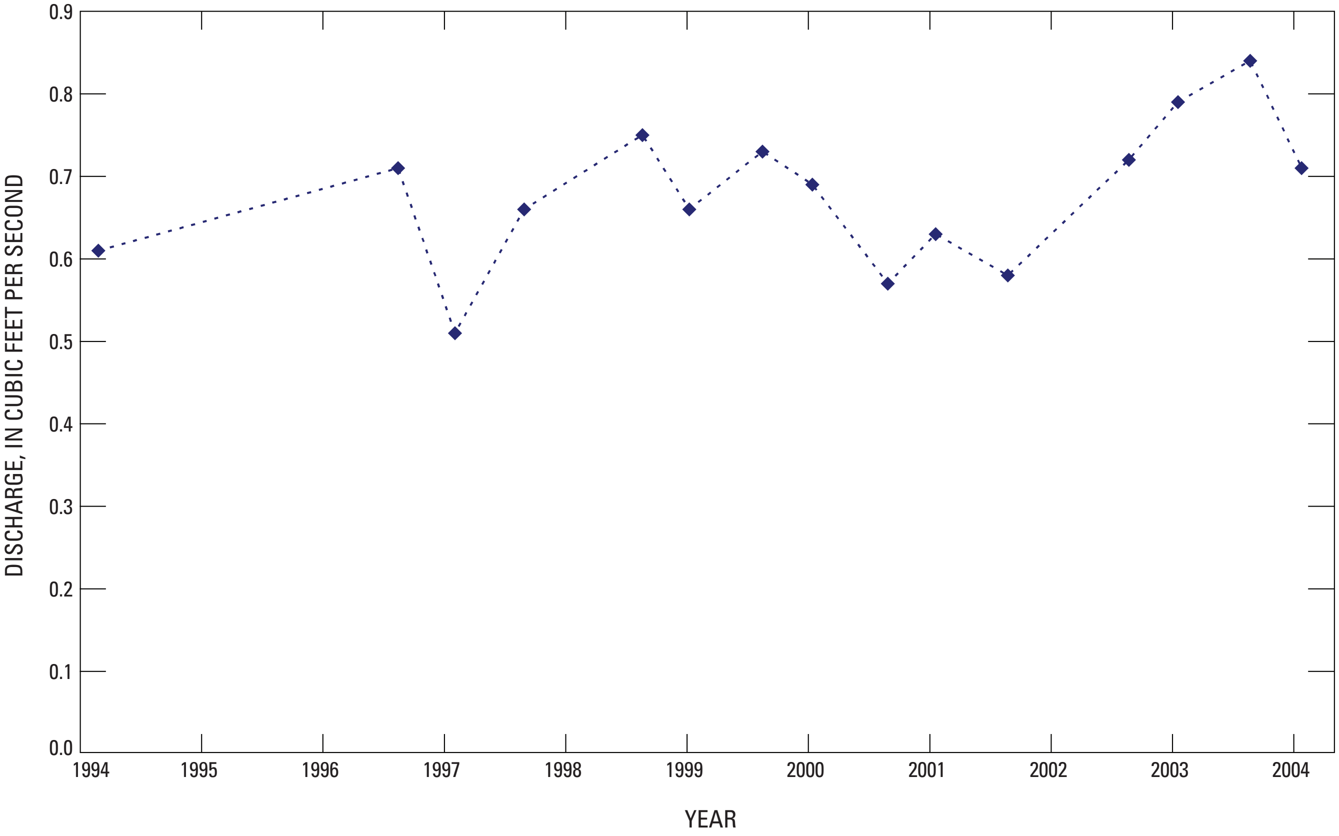

Figure B16. Periodic discharge measurements for partial-record stream-gaging station 364238114424301 Muddy River Springs 20 (M-20) near Moapa, Nevada, 1994–2004. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov

Table B9. Periodic discharge measurement for partial-record stream-gaging station 364238114424301 Muddy River Springs 20 (M-20) near Moapa, Nevada, 1994–2004.

[Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov]

Table B9 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Swimming pool upstream of M-20

Figure B17. Location of the staff plate at partial-record stream-gaging station 364238114424301 Muddy River Springs 20 (M-20) near Moapa, Nevada, and view of the spring-fed swimming pool upstream of the gage. Photographed June 10, 2004 by D. Beck.

Miscellaneous Water-Quality Sites in the Plummer Springs Group near Moapa, Nevada

Converse Consultants, on contract with Nevada Power Company, have been measuring water temperature and specific conductance at selected spring sites in the Warm Springs area since 1997. Eight springs were measured within the Plummer Springs Group on the Moapa Valley National Wildlife Refuge and were designated, by Converse Consultants (2004) as sites S1a, S1b, S34, S42, S43, S44, S44a, and S56. Sites S44 and S44a were tributary to Plummer West; sites S1a, S1b, S42, and S43 were tributary to Plummer Central; and sites S34 and S56 were tributary to Plummer East (fig. B9). Quarterly measurements have been made by Converse Consultants since April 1997. Water-temperature and specific-conductance measurements for the period of record are plotted in figures B18 through B25 and listed in tables B10 through B17.

By December 2004, restoration work on the springs within the refuge had destroyed all the sampling sites listed above. As a result, Converse Consultants are now measuring water temperature and specific conductance at the U.S. Geological Survey partial-record stations at Muddy River Springs 15, 16, and 20 (fig. B9).

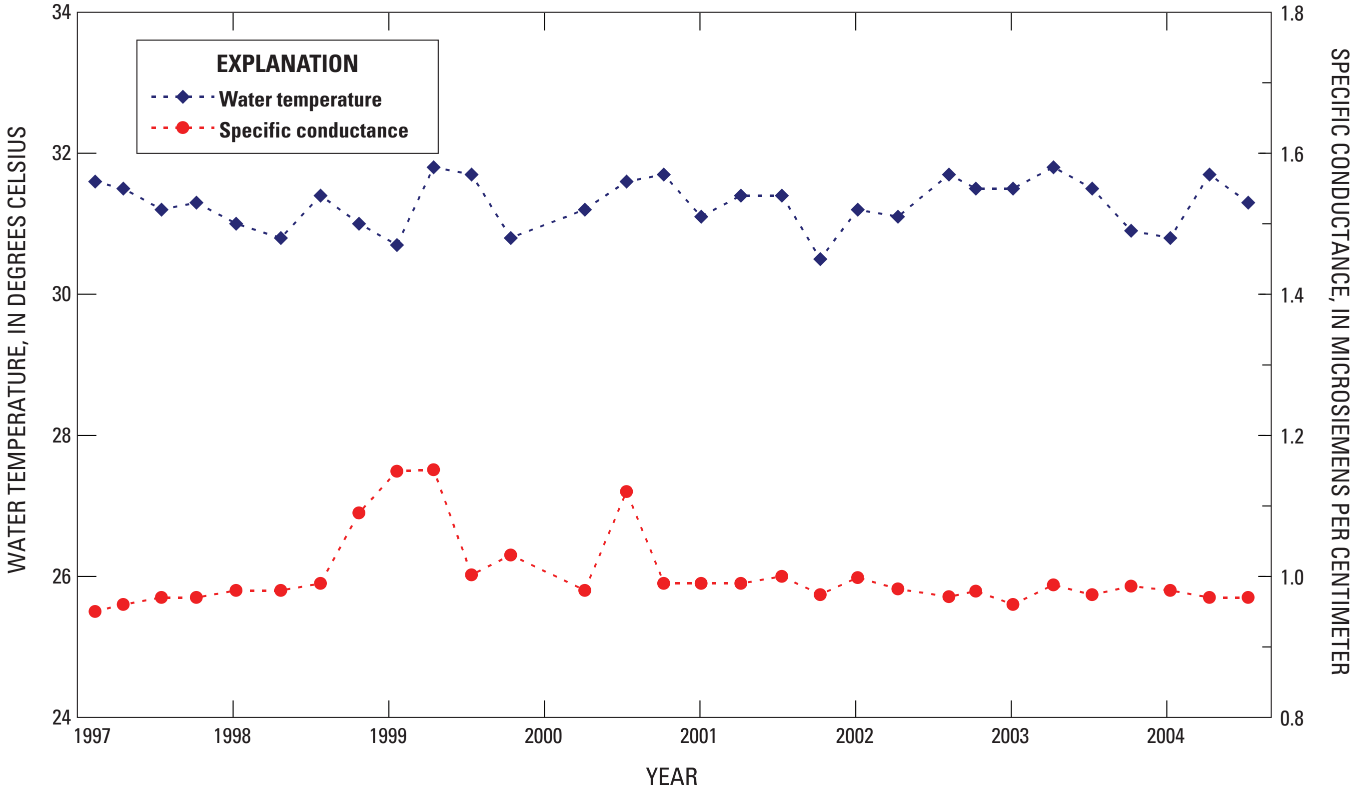

Figure B18. Water-temperature and specific-conductance measurements by Converse Consultants at site S1a in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

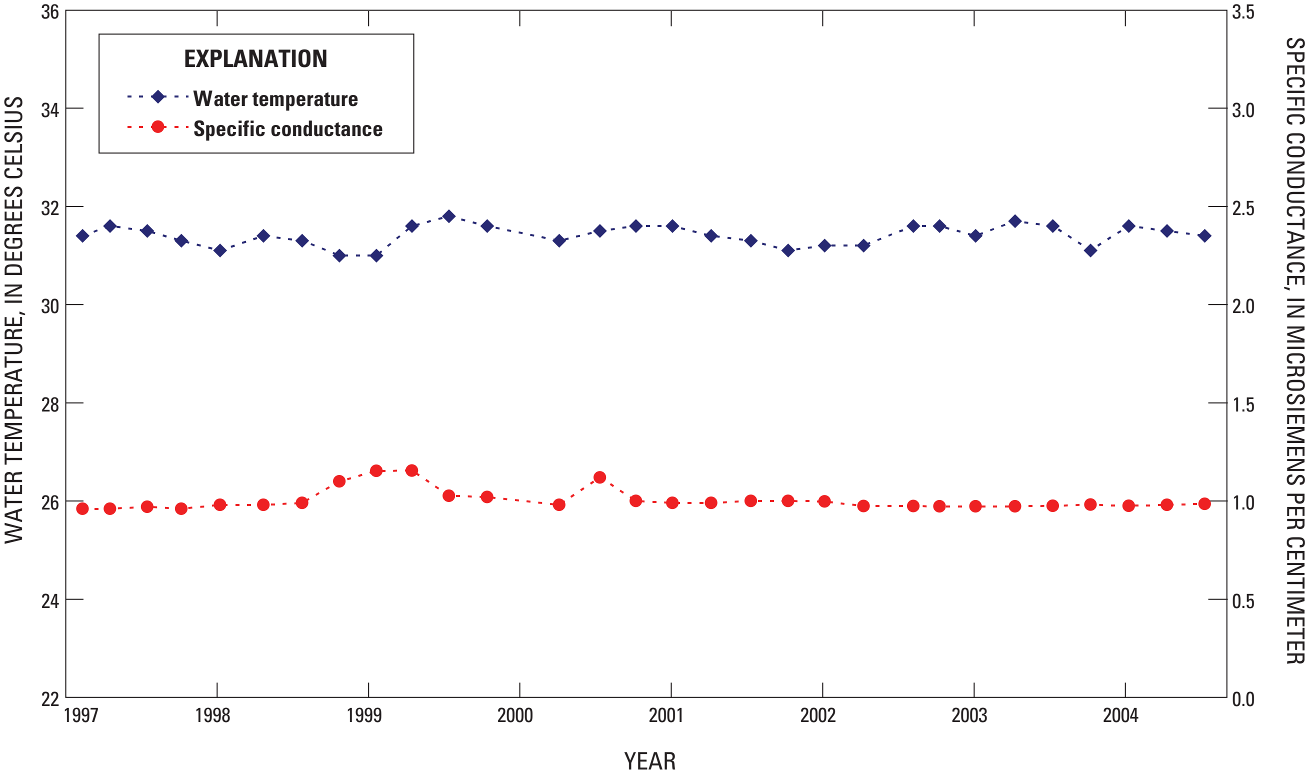

Figure B19. Water-temperature and specific-conductance measurements by Converse Consultants at site S1b in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

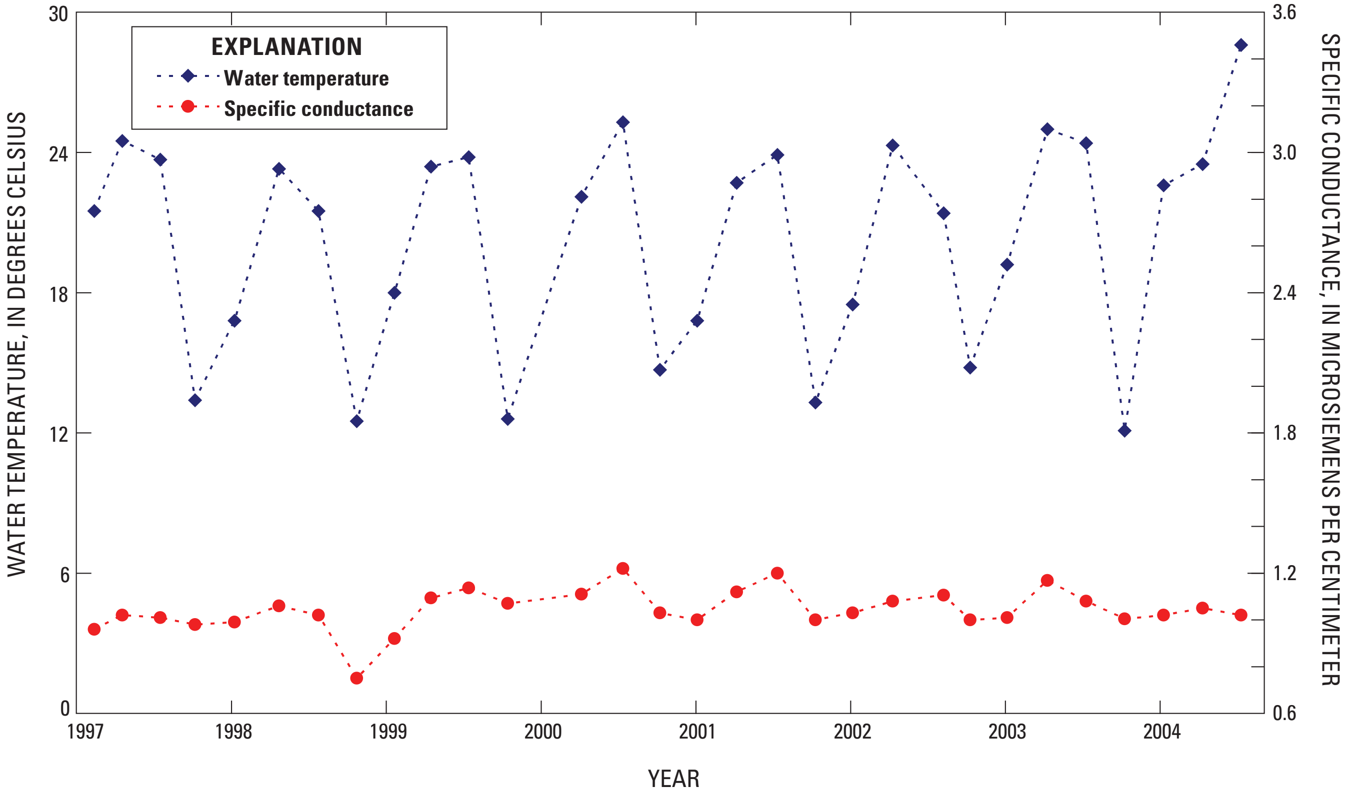

Figure B20. Water-temperature and specific-conductance measurements by Converse Consultants at site S34 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

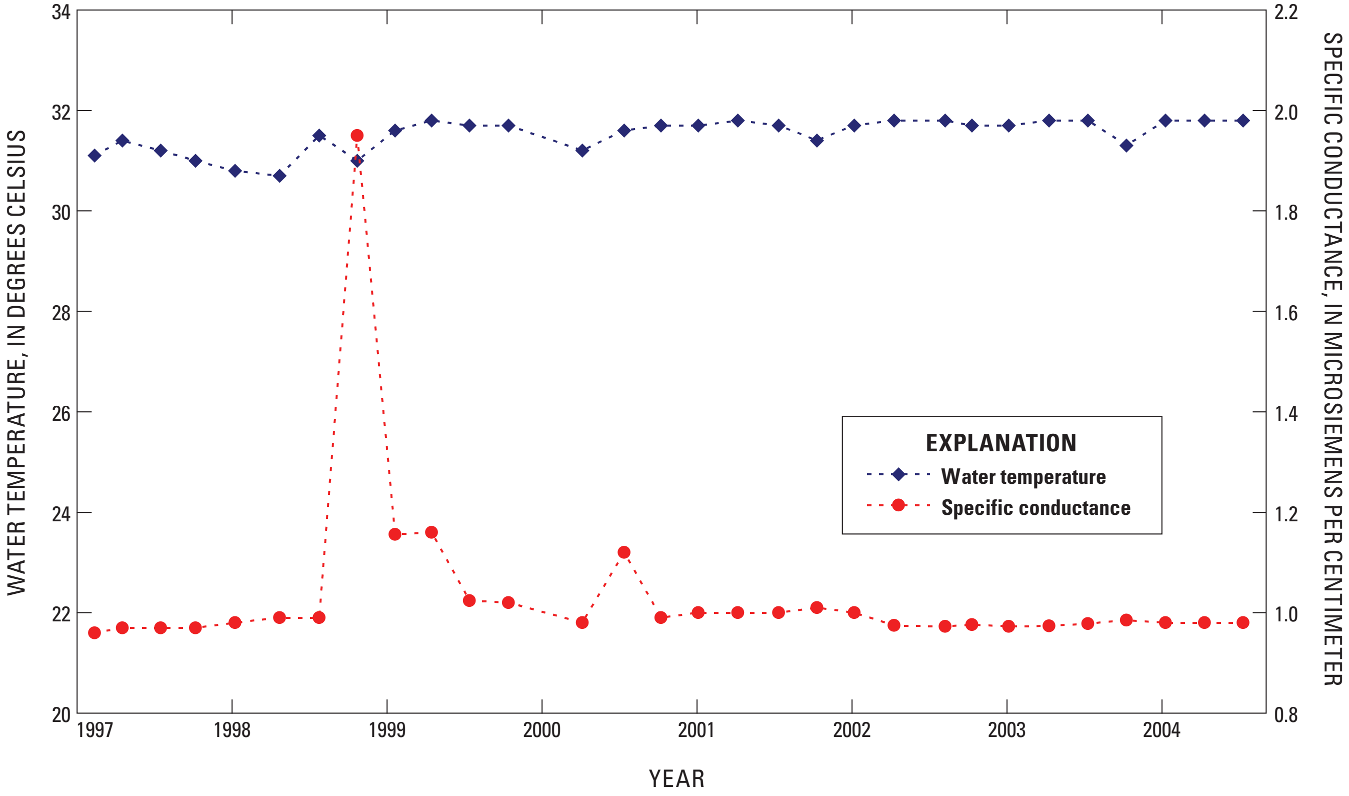

Figure B21. Water-temperature and specific-conductance measurements by Converse Consultants at site S42 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

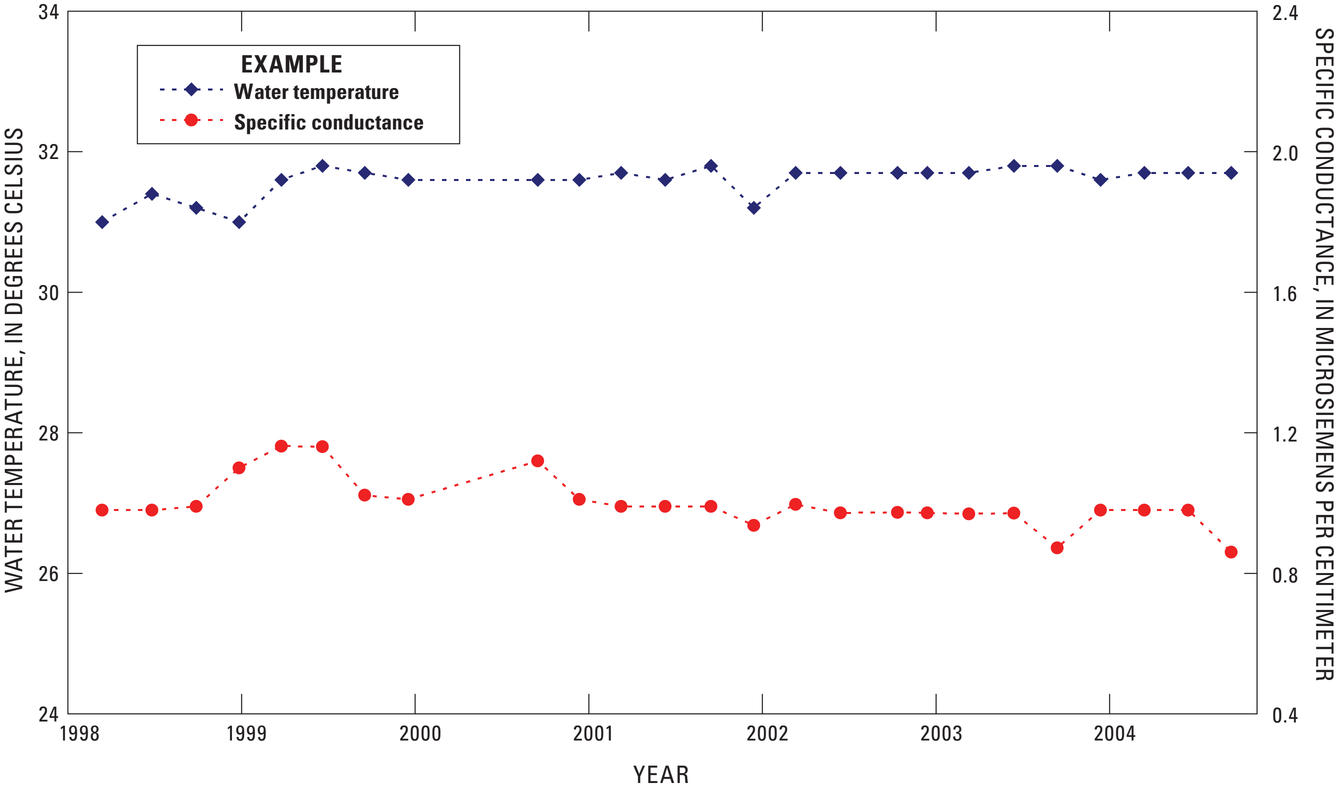

Figure B22. Water-temperature and specific-conductance measurements by Converse Consultants at site S43 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

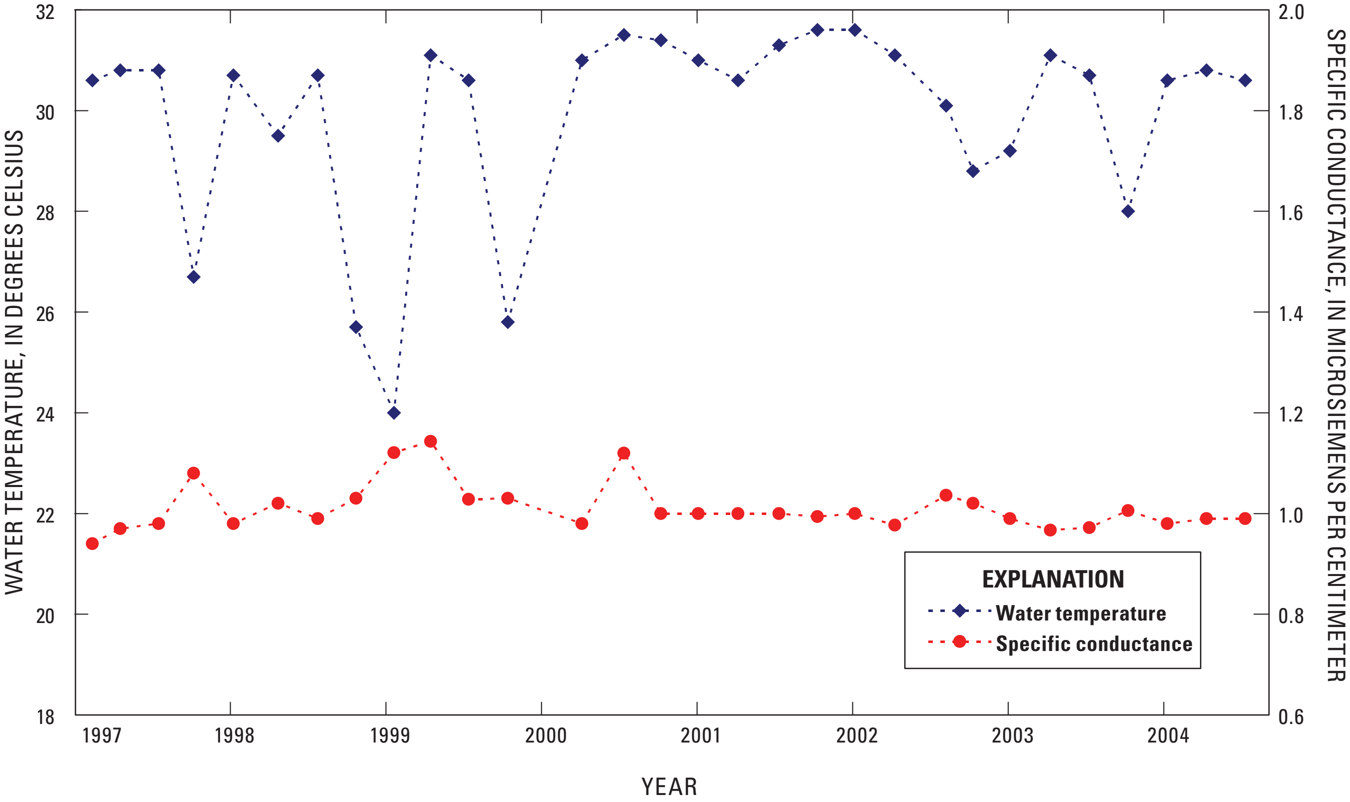

Figure B23. Water-temperature and specific-conductance measurements by Converse Consultants at site S44 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

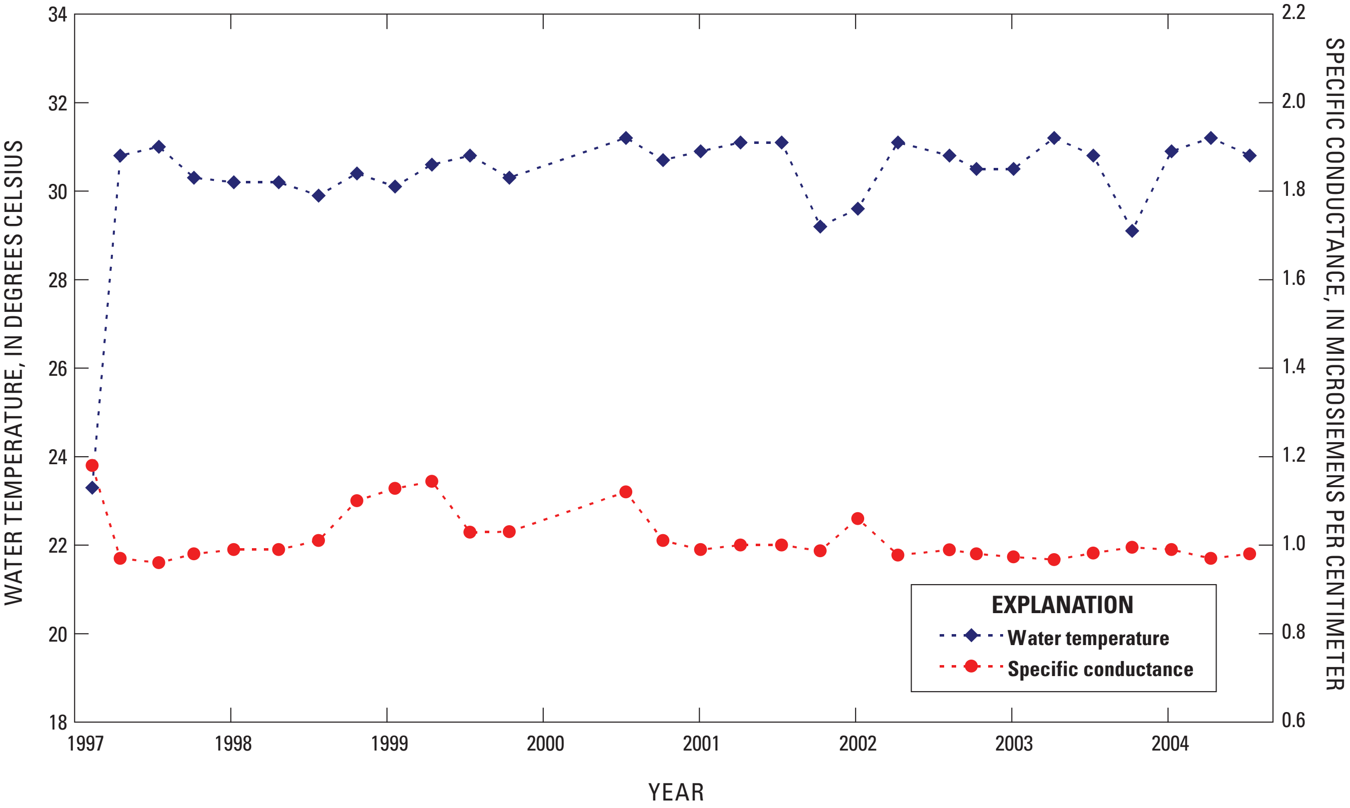

Figure B24. Water-temperature and specific-conductance measurements by Converse Consultants at site S44a in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

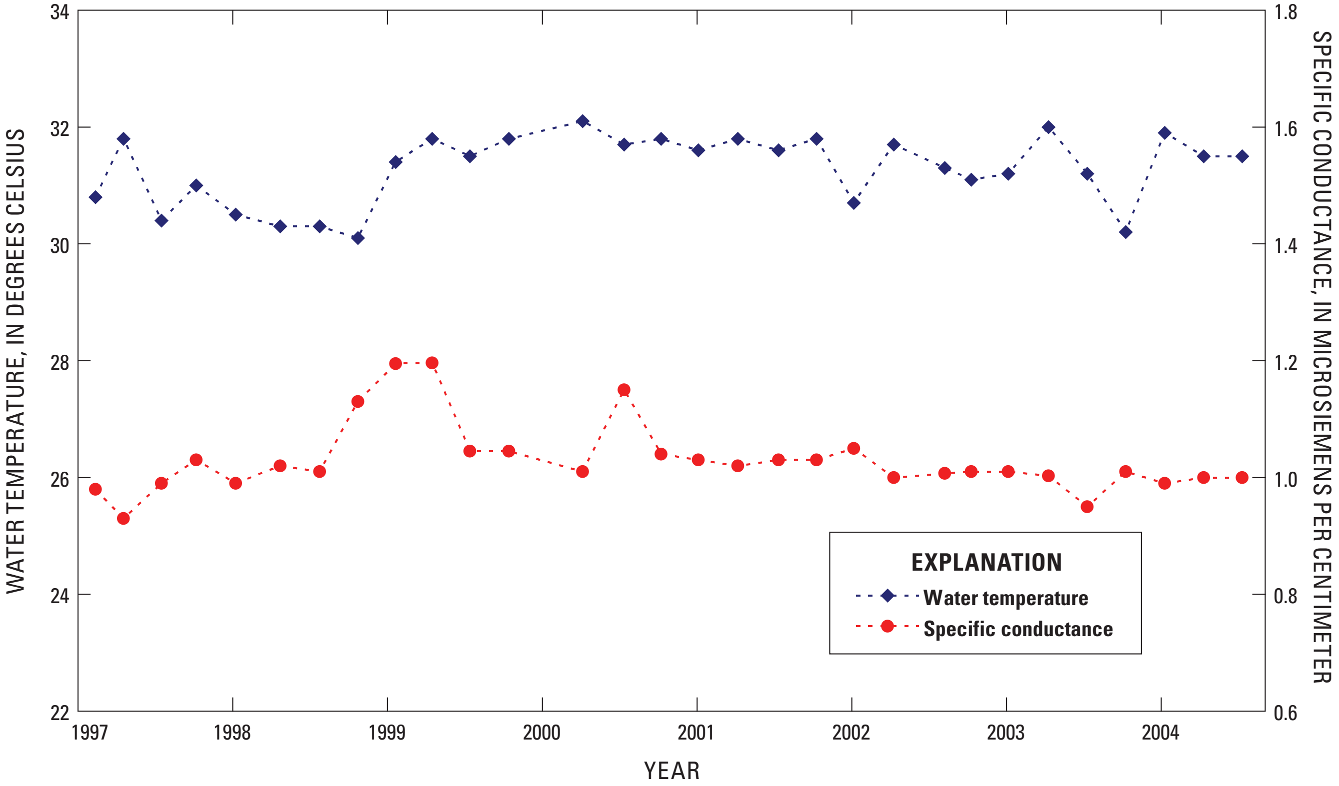

Figure B25. Water-temperature and specific-conductance measurements by Converse Consultants at site S56 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B10. Water-temperature and specific-conductance measurements by Converse Consultants at site S1a in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B10 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B11. Water-temperature and specific-conductance measurements by Converse Consultants at site S1b in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B11 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B12. Water-temperature and specific-conductance measurements by Converse Consultants at site S34 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B12 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B13. Water-temperature and specific-conductance measurements by Converse Consultants at site S42 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B13 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B14. Water-temperature and specific-conductance measurements by Converse Consultants at site S43 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B14 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B15. Water-temperature and specific-conductance measurements by Converse Consultants at site S44 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B15 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B16. Water-temperature and specific-conductance measurements by Converse Consultants at site S44a in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B16 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B17. Water-temperature and specific-conductance measurements by Converse Consultants at site S56 in the Plummer Springs Group near Moapa, Nevada, 1997–2004.

Table B17 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

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Pederson Springs Group

The following sites are included within this section:

09415908 Pederson East Spring near Moapa, Nevada (2002–04)
09415910 Pederson Spring near Moapa, Nevada (1987–2004)
364235114425201 Muddy River Springs 11 (M-11) near Moapa, Nevada (1987–2004)
364237114425401 Muddy River Springs 12 (M-12) near Moapa, Nevada (1987–2004)
364236114425401 Muddy River Springs 13 (M-13) near Moapa, Nevada (1986–2004)
364235114425301 Muddy River Springs 19 (M-19) near Moapa, Nevada (1998–2004)
09415920 Warm Springs West near Moapa, Nevada (1967–2005)

09415908 Pederson East Spring near Moapa, Nevada

A continuous-record stream-gaging station was established by the U.S. Geological Survey (USGS) on Pederson East Spring on May 9, 2002. The hydraulic control is a 90-degree v-notch weir that was installed by the U.S. Fish and Wildlife Service in collaboration with the Southern Nevada Water Authority and the U.S. Bureau of Reclamation. Pederson East Spring is about 100 ft north of the Moapa Valley National Wildlife Refuge service road (fig. B26) and is part of a cluster of springs that drain to the northeast. Flow from Pederson East Spring joins with discharge from Pederson Spring about 200 ft downstream from the gage.

Daily mean discharges for the period of record are plotted on figure B27 and listed in table B18. Photographs of the gage and weir, and selected reference marks established for this gage on June 9, 2004, are shown in figure B28.

Water samples were collected at this site on January 12, and May 18, 2004, by the Desert Research Institute (DRI) and analyzed for major ions and stable hydrogen and oxygen isotopes. The results of the analyses are shown in table B19.

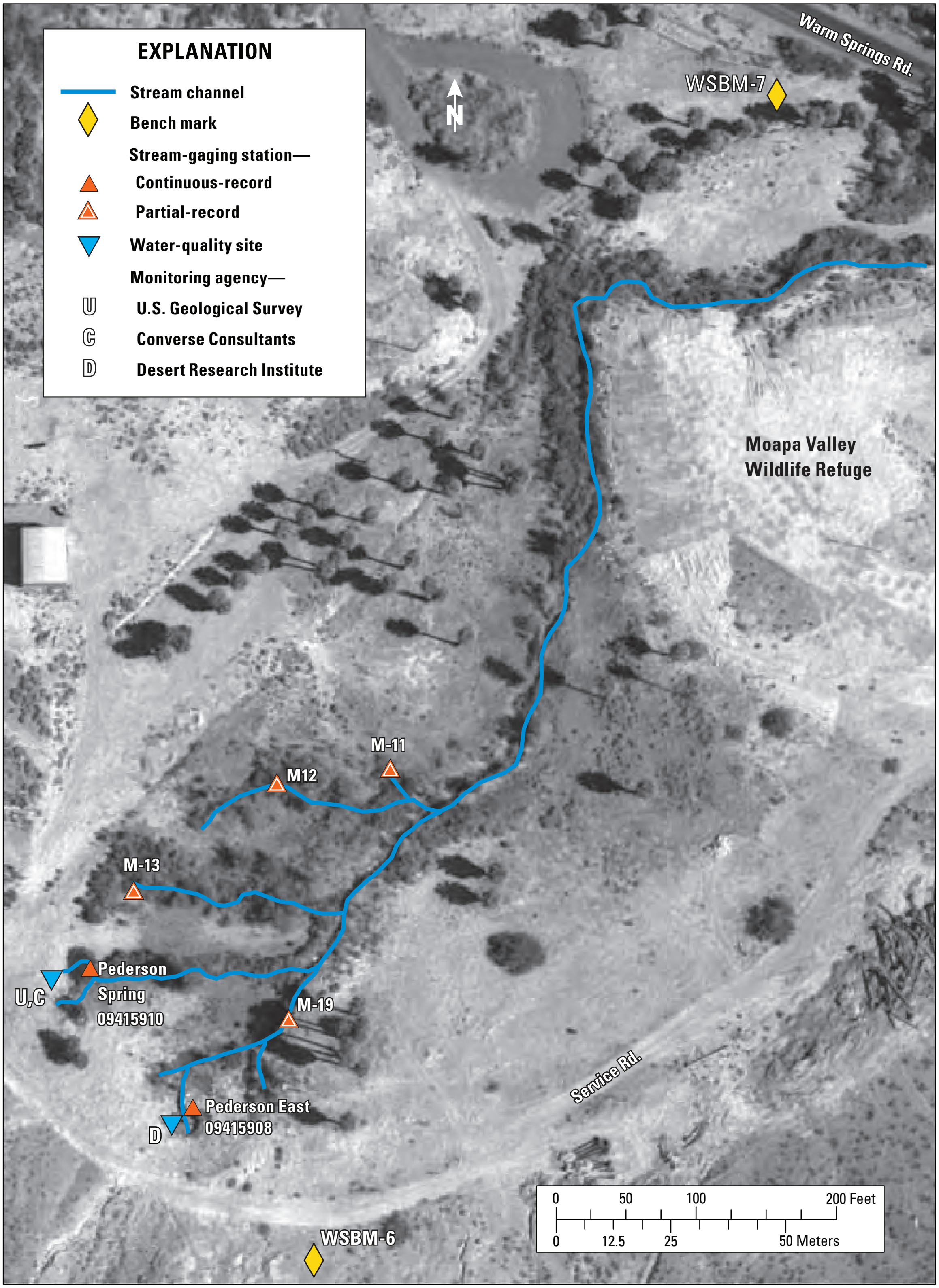

Figure B26. Location of Pederson Springs Group monitoring sites and bench marks WSBM-6 and WSBM-7 in the Warm Springs area near Moapa, Nevada.

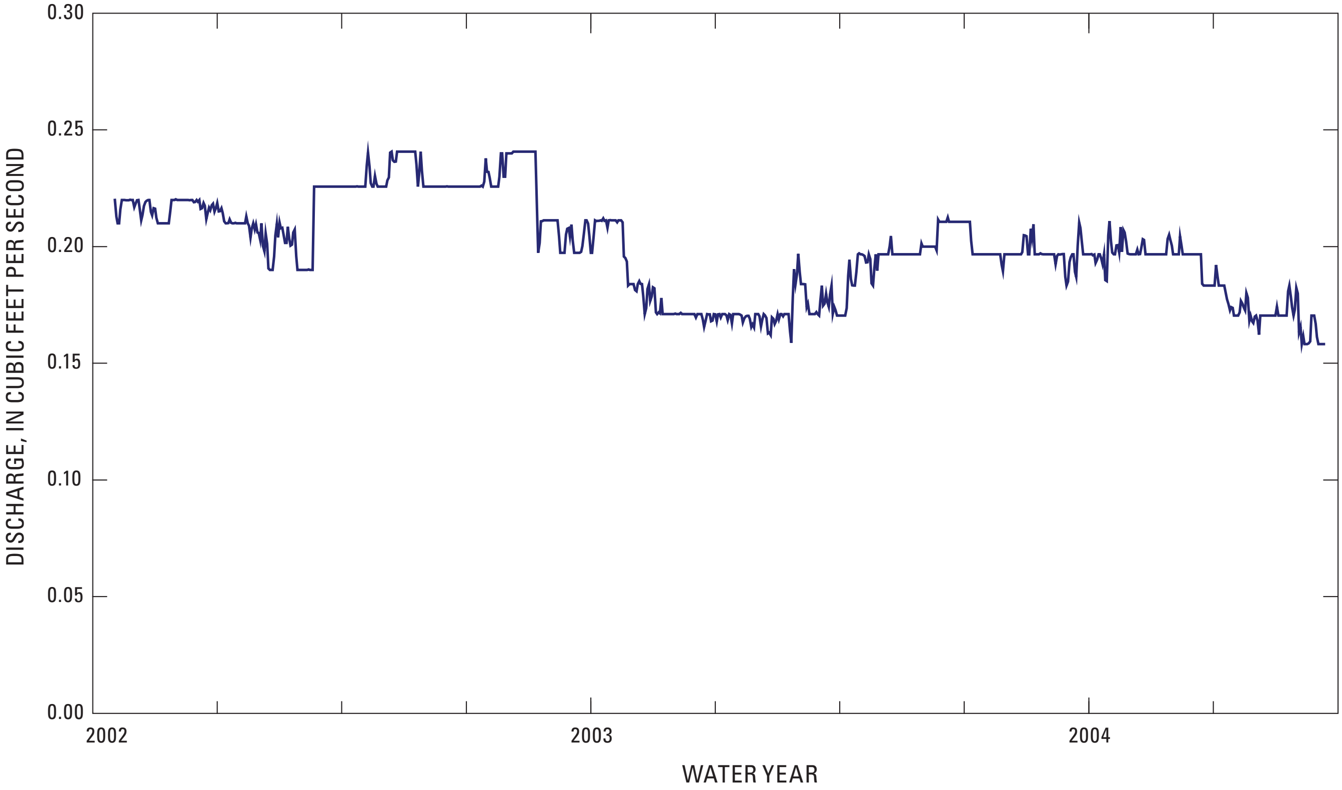

Figure B27. Daily mean discharges for continuous-record stream-gaging station 09415908 Pederson East Spring near Moapa, Nevada, water years 2002–04.

Table B18. Daily mean discharges for continuous-record stream-gaging station 09415908 Pederson East Spring near Moapa, Nevada, water years 2002–04.

Table B18 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B28. Location of staff plate and selected reference marks (RM) for station 09415908 Pederson East Spring in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet above NAVD 88.

Table B19. Water-quality data collected by Desert Research Institute at continous-record stream-gaging station 09415908 Pederson East Spring near Moapa, Nevada, January 12 and May 18, 2004.

Table B19 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

09415910 Pederson Spring near Moapa, Nevada

A continuous-record stream-gaging station with 45 degree v-notch aluminum weir was established by the U.S. Geological Survey (USGS) on Pederson Spring on October 1, 1986. Pederson Spring is about 50 ft northeast of the Moapa Valley National Wildlife Refuge service road (fig. B26) and is part of a cluster of springs that drains to the northeast. Flow from Pederson Spring joins with discharge from Pederson East Spring about 250 ft downstream from the gage. Reclamation of the spring and an adjacent area by the U.S. Fish and Wildlife Service began in 2002; a new weir, with 45 degree v-notch, was installed on April 27, 2004 (fig. B29). The new weir was installed because water was leaking around the old weir and the gage was not measuring the flows accurately.

Daily mean discharges for the period of record are plotted on figure B30 and listed in table B20. Photographs of the gage and weir and of selected reference marks established for this gage on June 9, 2004, are shown in figure B31.

Water-quality data are available for this site from Converse Consultants and the USGS. Beginning April 22, 1997, Converse Consultants began quarterly water temperature and specific conductance measurements. Data collected from 1997 through December 2004 are plotted on figure B32 and listed in table B21.

Water samples were collected by the USGS on July 30, 2003, as part of the National Water-Quality Assessment Program. An extensive suite of analyses were made, and the results are listed in table B22.

A. **View of first weir being installed in 1986.**

B. **View of new weir installed in 2004.**

Figure B29. Looking downstream at continuous-record stream-gaging station 09415910 Pederson Spring near Moapa, Nevada.

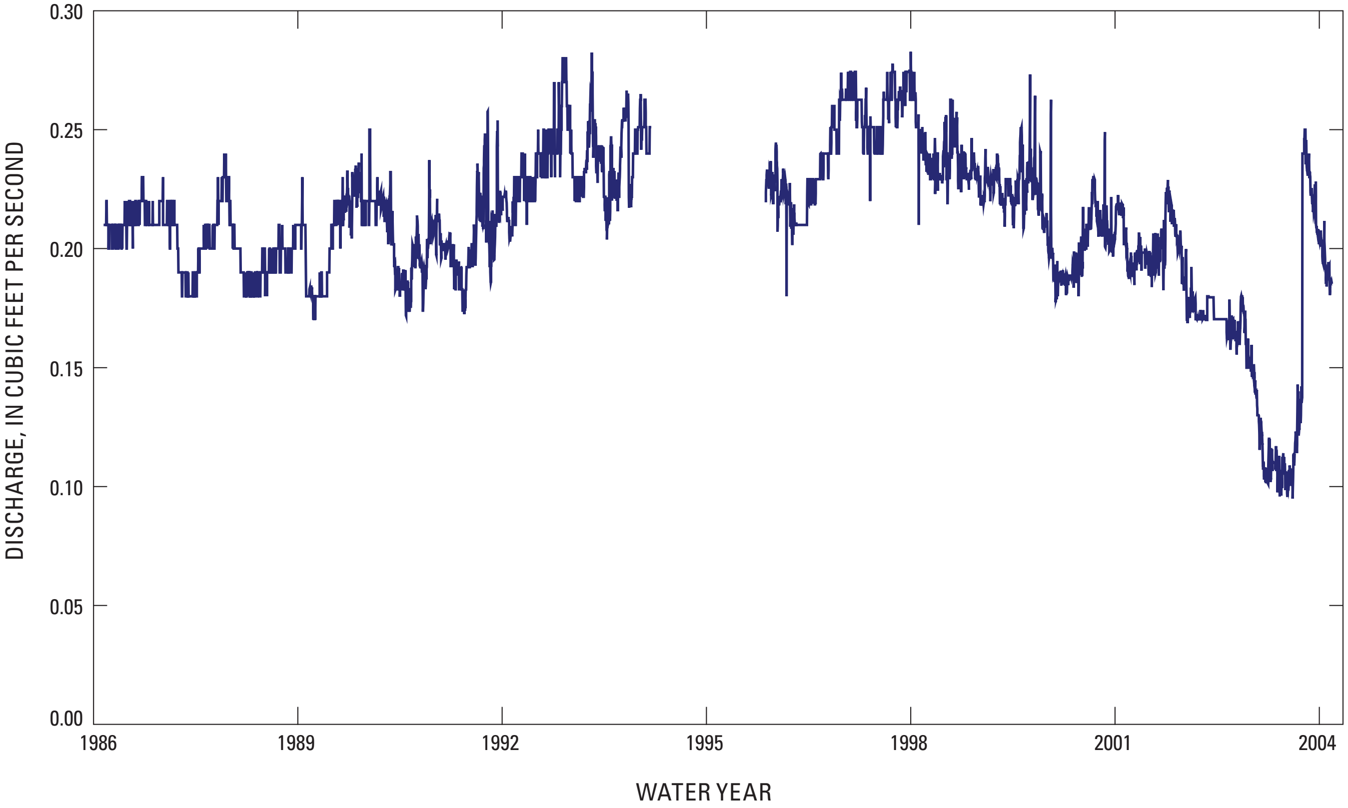

Figure B30. Daily mean discharges for continuous-record stream-gaging station 09415910 Pederson Spring near Moapa, Nevada, water years 1987–2004.

Table B20. Daily mean discharges for continuous-record stream-gaging station 09415910 Pederson Spring near Moapa, Nevada, water years 1987–2004.

Table B20 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

RM-6
(1,810.95 ft)

RM-5 (foreground)
(1,814.04 ft)
RM-4 (background)
(1,809.32 ft)

View of weir
from
downstream

Figure B31. Location of selected reference marks (RM) at continuous-record stream-gaging station 09415910 Pederson Spring in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet above NAVD 88.

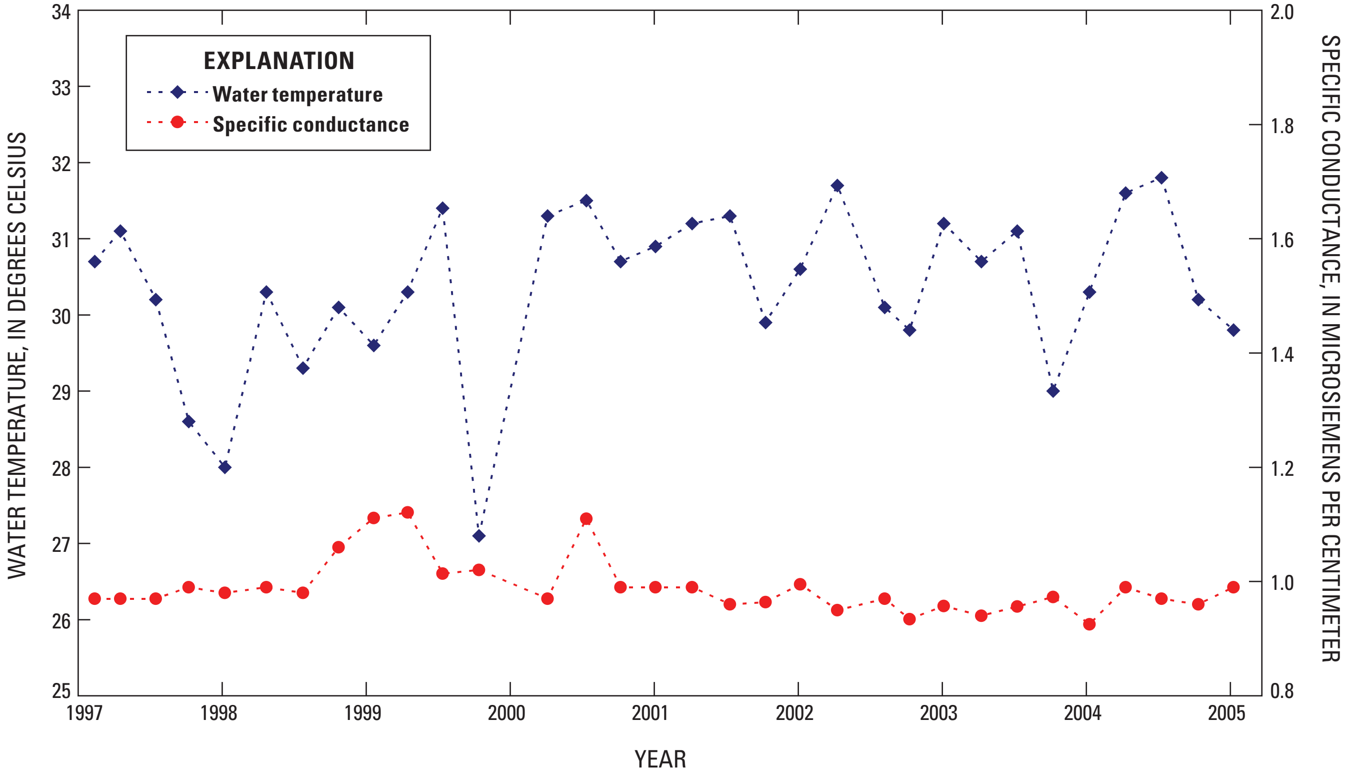

Figure B32. Water-temperature and specific-conductance measurements by Converse Consultants for station 09415910 Pederson Spring near Moapa, Nevada, 1997–2005.

Table B21. Water-temperature and specific-conductance measurements by Converse Consultants at station 09415910 Pederson Spring near Moapa, Nevada, 1997–2005.

Table B21 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B22. Water-quality data collected for continuous-record stream-gaging station 09415910 Pederson Spring near Moapa, Nevada, July 30, 2003.

Table B22 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

364235114425201 Muddy River Springs 11 (M-11) near Moapa, Nevada

The partial-record stream-gaging station at Muddy River Springs 11 (M-11) was established by the U.S. Geological Survey (USGS) on March 12, 1987, and is about 50 ft upstream of the main channel that drains the combined flow of Pederson and Pederson East spring tributaries (fig. B26). Discharge at Muddy River Springs 11 originates about 20 ft upstream and is part of a cluster of springs known as the Pederson Spring Group that drains to the northeast.

Periodic discharge measurements have been made by the USGS since March 1987. Discharge measurements for the period of record are plotted in figure B33 and listed in table B23. Photographs of the staff plate and a selected reference mark established for the Muddy River Springs 11 monitoring site on June 9, 2004, are included in figure B34.

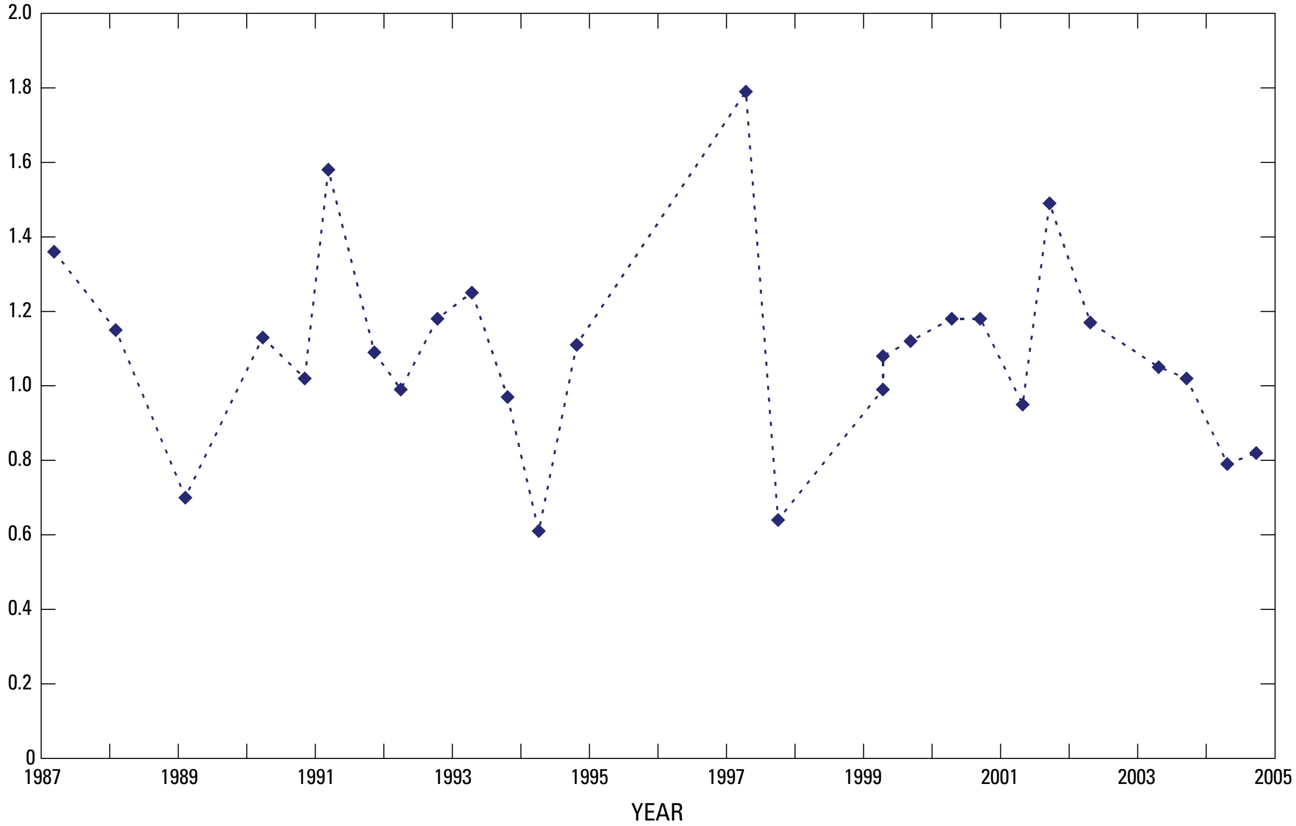

Figure B33. Periodic discharge measurements for partial-record stream-gaging station 364235114425201 Muddy River Springs 11 (M-11) near Moapa, Nevada, 1987–2004.

Table B23. Periodic discharge measurements for partial-record stream-gaging station 364235114425201 Muddy River Sprngs 11 (M-11) near Moapa, Nevada, 1987–2004.

Table B23 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B34. Location of staff plate and reference mark (RM-1) for partial-record stream-gaging station Muddy River Springs 11 (M-11) in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet NAVD 88.

364237114425401 Muddy River Springs 12 (M-12) near Moapa, Nevada

The partial-record stream-gaging station at Muddy River Springs 12 was established by the U.S. Geological Survey (USGS) on March 12, 1987, and is about 150 ft upstream of the confluence with the main channel that drains the combined flows from Pederson and Pederson East Spring tributaries (fig. B26). Flow at Muddy River Springs 12 originates approximately 10 ft upstream and is part of a cluster of springs known as the Pederson Spring Group that drains to the northeast.

Periodic discharge measurements have been made by the USGS since March 1987. Discharge measurements for the period of record are plotted in figure B35 and listed in table B24. Photographs of the staff plate and a selected reference mark established for the Muddy River Springs 12 monitoring site on June 9, 2004, are included in figure B36.

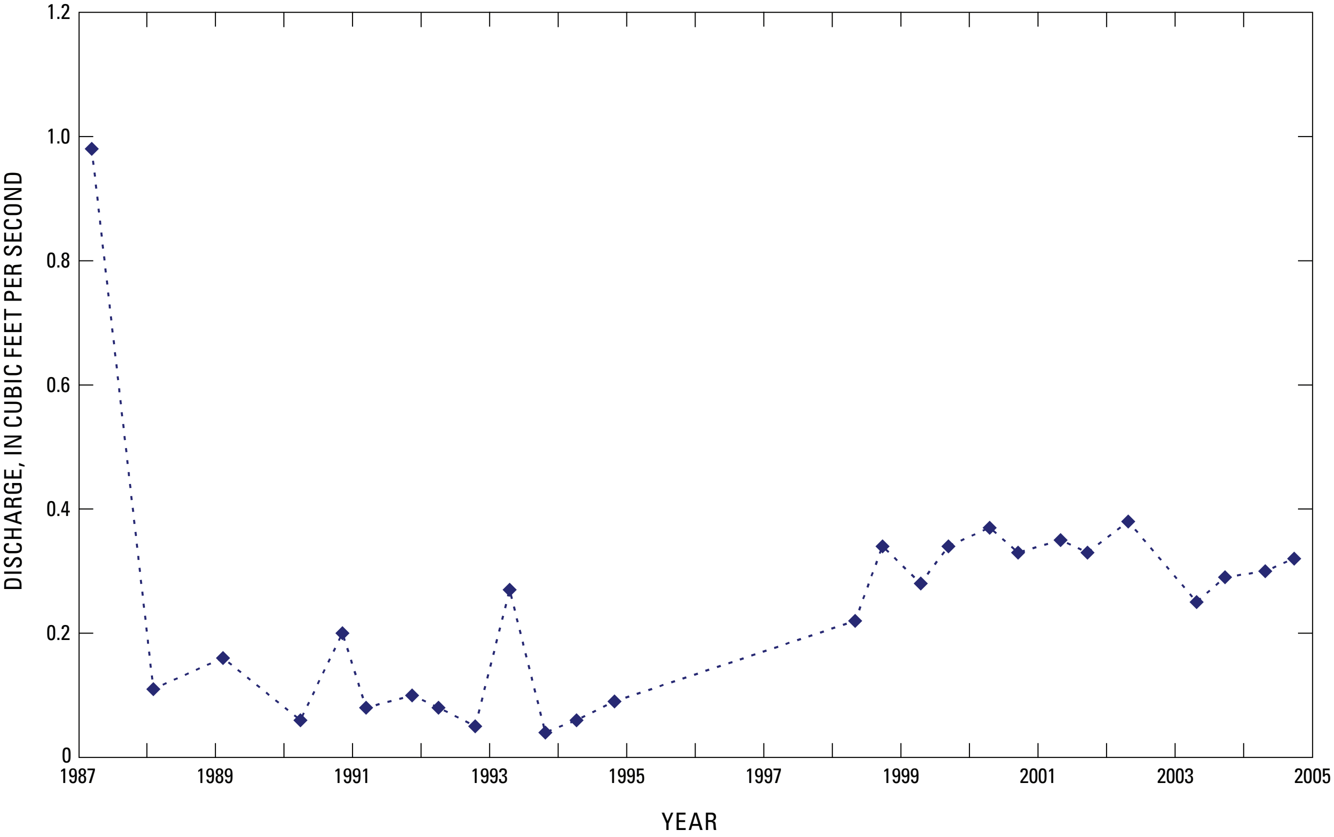

Figure B35. Periodic discharge measurements for partial-record stream-gaging station 364237114425401 Muddy River Springs 12 (M-12) near Moapa, Nevada, 1987–2004.

Table B24. Periodic discharge measurements for partial-record stream-gaging station 364237114425401 Muddy River Springs 12 (M-12) near Moapa, Nevada, 1987–2004.

Table B24 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B36. Location of staff plate and reference mark (RM-2) for partial-record stream-gaging station Muddy River Springs 12 (M-12) in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet above NAVD 88.

364236114425401 Muddy River Springs 13 (M-13) near Moapa, Nevada

The partial-record stream-gaging station at Muddy River Springs 13 was established by the U.S. Geological Survey (USGS) on January 28, 1986, and is about 150 ft upstream of the confluence with the main channel that drains the combined flows from Pederson and Pederson East Spring tributaries (fig. B26). Flow at Muddy River Springs 13 originates approximately 25 ft upstream and is part of a cluster of springs known as the Pederson Spring Group that drains to the northeast.

Periodic discharge measurements have been made by the USGS since January 1986. Discharge measurements for the period of record are plotted in figure B37 and listed in table B25. Photographs of the staff plate and a selected reference mark established for the Muddy River Springs 13 monitoring site on June 9, 2004, are included in figure B38.

Water samples were collected at this site on January 12 and May 18, 2004, by Desert Research Institute (DRI) and analyzed for major ions, physical and chemical parameters (dissolved oxygen, pH, and water temperature), and stable hydrogen and oxygen isotopes. The results of the analyses are shown in table B26.

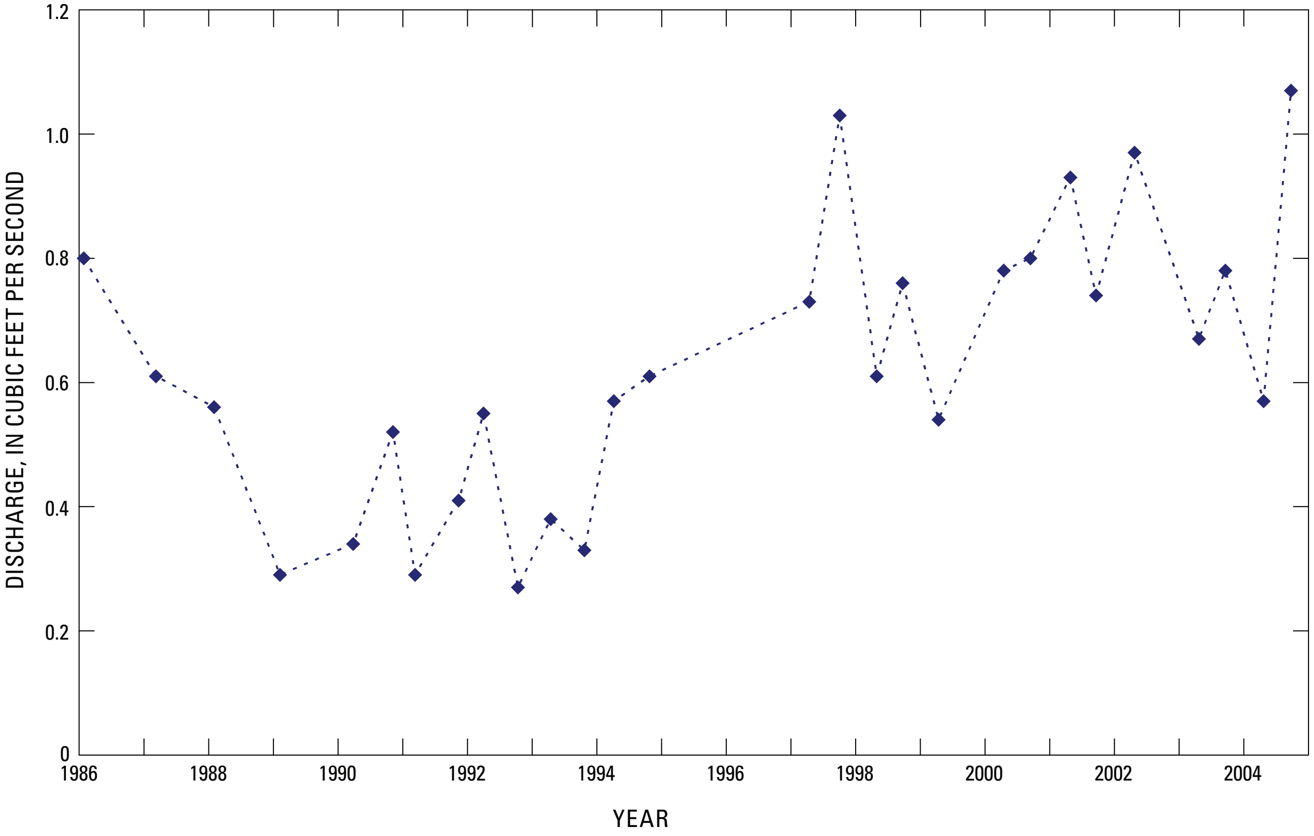

Figure B37. Periodic discharge measurements for stream-gaging station 364236114425401 Muddy River Springs 13 (M-13) near Moapa, Nevada, 1986–2004.

Table B25. Periodic discharge measurements for partial-record stream-gaging station 36426114425401 Muddy River Springs 13 (M-13) near Moapa, Nevada, 1986–2004.

Table B25 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B38. Location of staff plate and reference mark (RM-1) for partial-record stream-gaging station Muddy River Springs 13 (M-13) in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet above NAVD 88.

Table B26. Water-quality data collected by Desert Research Institute at station 364236114425401 Muddy River Springs 13 (M-13) near Moapa, Nevada, January 12 and May 18, 2004.

Table B26 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

364235114425301 Muddy River Springs 19 (M-19) near Moapa, Nevada

The partial-record stream-gaging station at Muddy River Springs 19 (M-19) was established by the U.S. Geological Survey (USGS) on April 28, 1990, and is about 100 ft downstream from the Pederson East Spring gage (fig. B26). Flow at Muddy River Springs 19 originates from water discharging at the Pederson East Spring pool and from three other spring pools downstream of the gage. Flow at M-19 drains to the northeast and joins with flow from Pederson Spring approximately 50 ft downstream.

Periodic discharge measurements have been made by the USGS since April 1998. Discharge measurements for the period of record are plotted in figure B39 and listed in table B27. Photographs of the staff plate and a selected reference mark established for the Muddy River Springs 19 monitoring site on June 9, 2004, are included in figure B40.

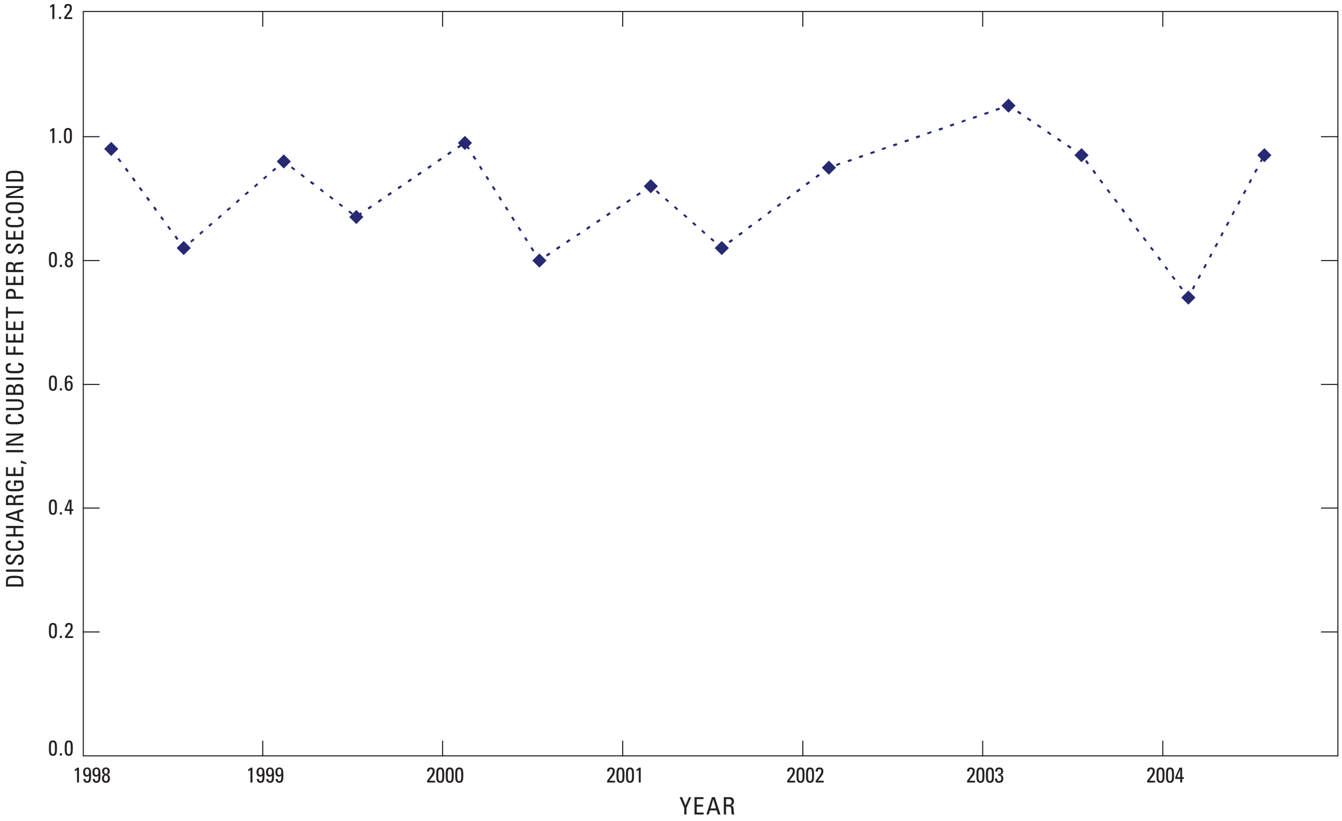

Figure B39. Periodic discharge measurements for partial-record stream-gaging station 3642235114425301 Muddy River Springs 19 (M-19) near Moapa, Nevada, 1998–2004.

Table B27. Periodic discharge measurements for partial-record stream-gaging station 364235114425301 Muddy River Springs 19 (M-19) near Moapa, Nevada, 1998–2004.

Table B27 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

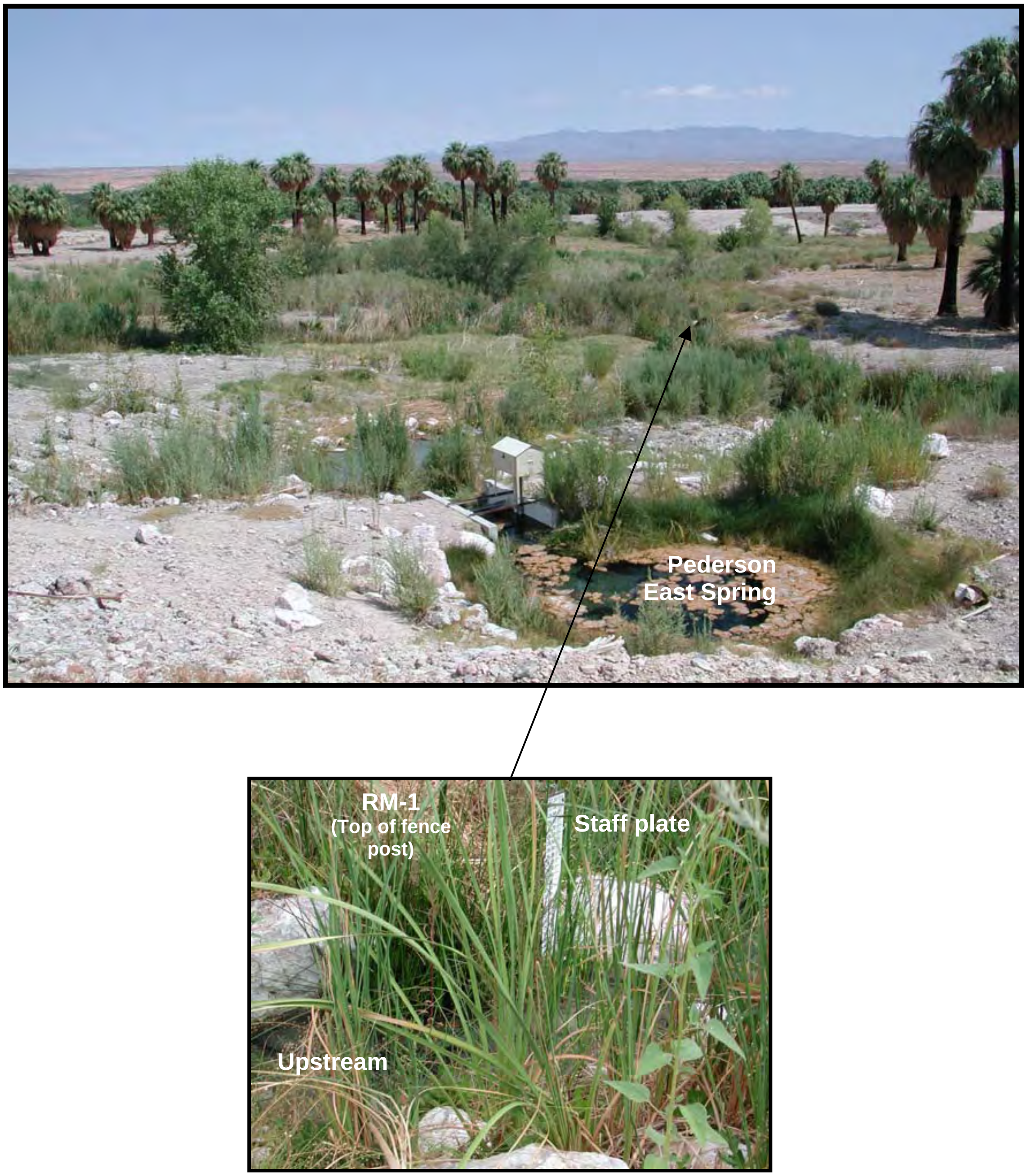

Figure B40. Location of staff plate and reference mark (RM-1) for partial-record stream-gaging station Muddy River Springs 19 (M-19) in the Moapa Valley National Wildlife Refuge near Moapa, Nevada. Photographed June 9, 2004 by D. Beck. Elevation in feet above NAVD 88.

09415920 Warm Springs West near Moapa, Nevada

A 1.5-foot (ft) Parshall flume was installed at the Warm Springs West stream-gaging station on September 20, 1967, by the Nevada Division of Water Resources (NDWR). Initially called the Pederson flume by NDWR, the exact location is unknown, but the flume is believed to have been installed in the vicinity of the current gage, just upstream of Warm Springs Road (fig. B41). At this site, the flume would have monitored the total flow discharging from all springs associated with the Pederson Spring Groups (fig. B26). Downstream from the flume, flow discharges under Warm Springs Road and then turns sharply to the east after exiting the culvert. About 0.1 mi below the culvert, flow merges with discharge draining the Plummer (Iverson) Spring Group.

Data provided by NDWR show that water levels at the Pederson flume generally were measured monthly from October 1967 to July 1981. A large gap in the record is evident from August 1971 to March 1974. Additional data provided by NDWR showed that a 1-ft Parshall flume, called the U.S. Fish and Wildlife Flume, was installed on May 6, 1981. The exact location of this flume also is unknown, but it is believed that it was near the location of the current gage. Water levels were concurrently measured at the Pederson and the Fish and Wildlife flumes during May, June, and July 1981. Water levels for the Fish and Wildlife Flume were measured daily from June 29, 1981, to September 27, 1981, and measured somewhat monthly from October 1981 to June 1986. Measurements were not available for July 1986 to July 1993 when a new 1-ft Parshall flume was installed. Monthly measurements resumed and continued though February 2005.

As only water-level measurements were provided by NDWR, discharge rates were computed using standard equations for the 1.5-ft and 1-ft Parshall flumes (Leupold and Stevens, 1987). Plots of the computed discharges from October 1967 to February 2005 are shown in figure B42. Listings of the water-level measurements and computed discharges are included in table B28 for October 1967 to July 1981; table B29 for May 1981 to June 1986; and table B30 for July 1993 to February 2005. Computed discharges from March 1974, after the large gap in record, until July 1981 are significantly lower than all other computed discharges. Although not noted in the records received from NDWR, the drop in discharge probably was the result of flow bypassing the flume.

A continuous-stage recorder was installed by the U.S. Geological Survey (USGS) on August 22, 1985, and maintained through September 30, 1994. The gage was reactivated in June 1996 and is routinely maintained as part of the current monitoring network. Daily mean discharges computed for the period of record have been included on the plot in figure B42 and listed in table B31. Photographs of the current flume and bench mark, and a selected reference mark established for this gage on June 3, 2004, are shown in figure B43.

Quarterly measurements of water temperature and specific conductance made at this gage from April 1997 to March 2005 were provided from Converse Consultants. These data are plotted on figure B44 and listed in table B32.

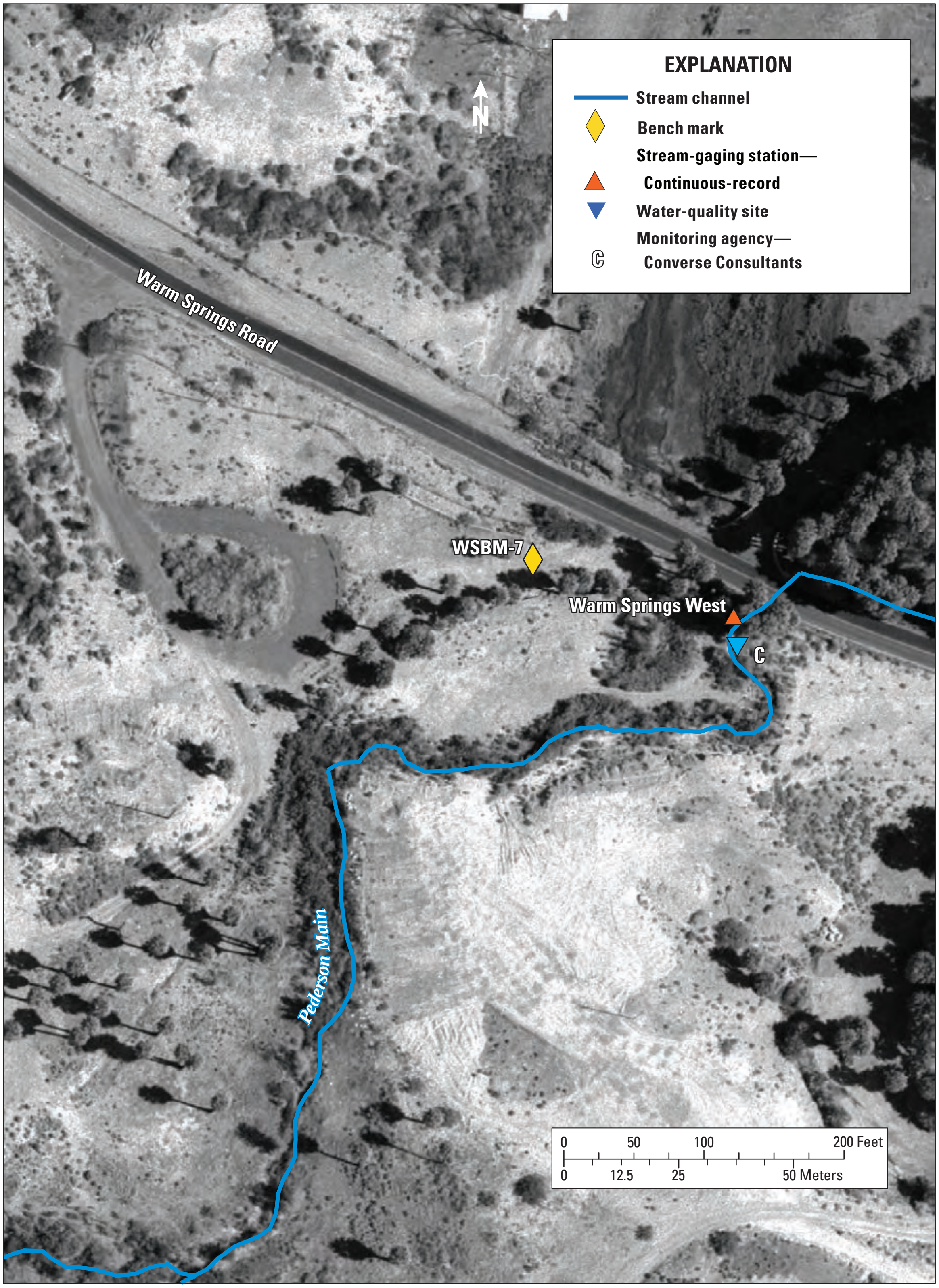

Figure B41. Location of continuous-record stream-gaging station 09415920 Warm Springs West and bench mark WSBM-7 in the Warm Springs area near Moapa, Nevada.

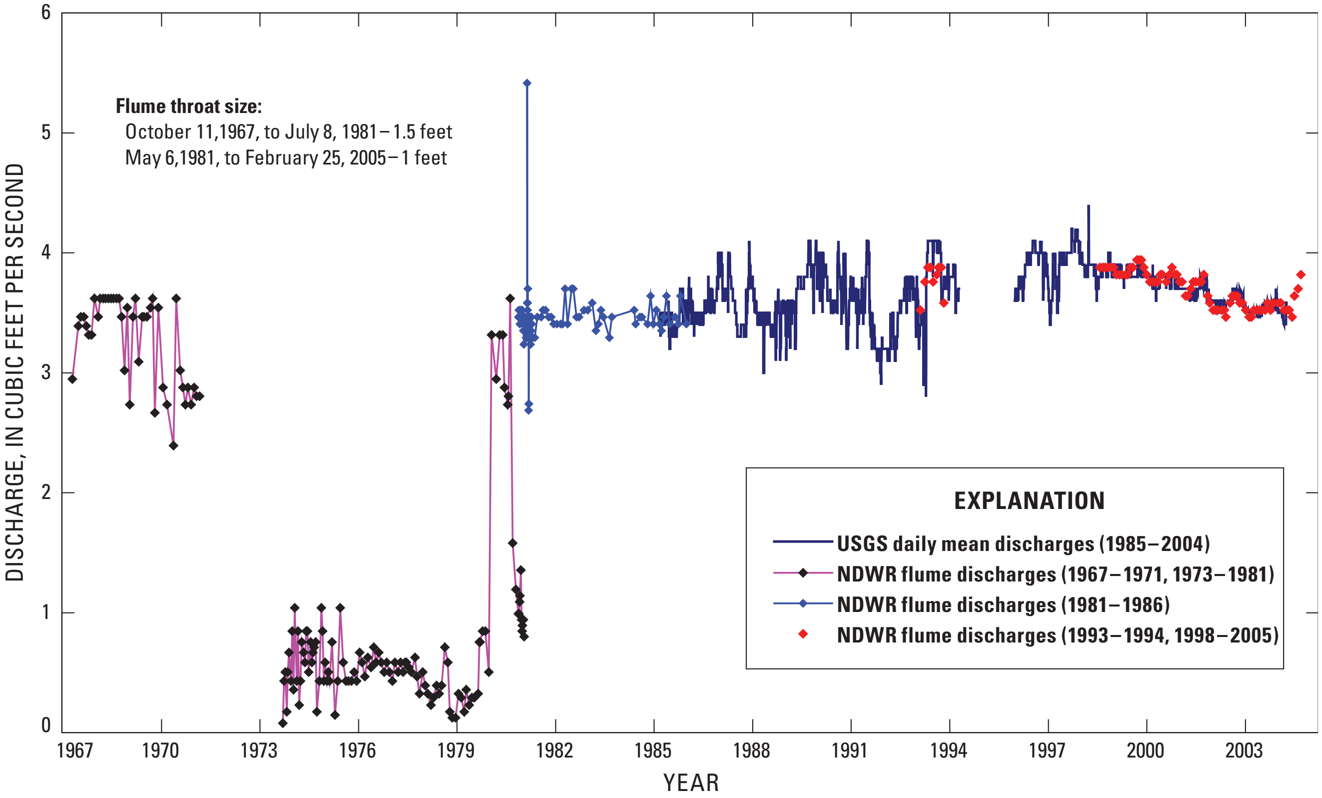

Figure B42. Instantaneous and daily mean discharges for continuous-record stream-gaging station 09415920 Warm Springs West near Moapa, Nevada, 1967–2005. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov. NDWR, Nevada Division of Water Resources.

Table B28. Water levels and computed instantaneous discharges for Pederson Flume near Moapa, Nevada, 1967–81.

[Data from Nevada Division of Water Resources.]

Table B28 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B29. Water levels and computed instantaneous discharges for U.S. Fish and Wildlife Service flume near Moapa, Nevada, 1981–86.

[Data from Nevada Division of Water Resources.]

Table B29 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B30. Water levels and computed instantaneous discharges for U.S. Fish and Wildlife Service flume near Moapa, Nevada, 1993–2005.

[Water levels provided by Nevada Division of Water Resources.]

Table B30 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B31. Daily mean discharges for continuous-record stream-gaging station 09415920 Warm Springs West near Moapa, Nevada, water years 1985–2004.

[Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov]

Table B31 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

WSBM-7
(1,776.93 ft)

RM-1
(1,772.94 ft)

Figure B43. Location of bench mark WSBM-7 and reference mark RM-1 for continuous-record stream-gaging station 09415920 Warm Springs West near Moapa, Nevada. The top picture shows the stream-gaging station photographed in 2001. Elevation of bench and reference marks in feet above NAVD 88.

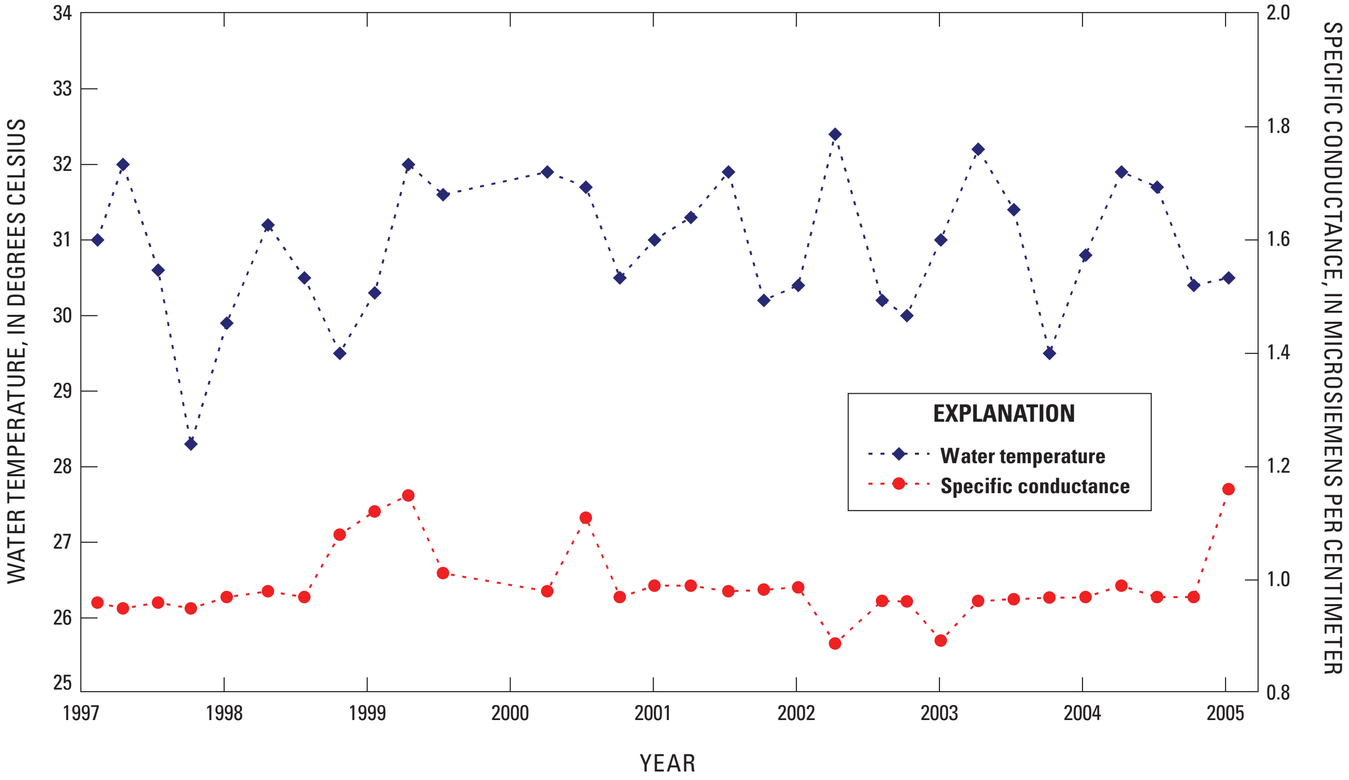

Figure B44. Water temperature and specific conductance measurements for continuous-record stream-gaging station 09415920 Warm. Springs West near Moapa, Nevada, 1997–2005. Data provided by Converse Consultants.

Table B32. Water-temperature and specific-conductance measurements by Converse Consultants at continuous-record streamgaging station 09415920 Warm Springs West near Moapa, Nevada, 1997–2005.

Table B32 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Muddy Springs

The following site is included within this section:

09415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada (1967–2005)

09415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada

A 1-foot (ft) Parshall flume was installed on Muddy (Big) Springs on August 25, 1967, by the Nevada Division of Water Resources (NDWR). The flume was located approximately 0.1 mi downstream from the former Francis Taylor mansion (fig. B45) located on the L.D.S. Recreation Area. Although there are several springs in the area, most flow emanates from a large spring-fed pond on the northwest side of the mansion. Discharge from the spring-fed pond is directed around both sides of the mansion and converges just north of the large swimming pool. From there, flow generally drains to the south and joins with Muddy River about 0.5 mi downstream. Springflow is frequently diverted to fill the large swimming pool.

Data provided by NDWR show that water levels in the 1-ft flume were measured monthly from August 1967 to August 1971. Measurements were not available between September 1971 and February 1974 at which time a larger (3-ft) Parshall flume was installed. Monthly measurements resumed and continued until November 1987, although during July and August 1981, daily readings were recorded. Between December 1987 to July 1993 only six measurements were made. On July 16, 1993, a new 3-ft Parshall flume was installed and monthly measurements resumed. Because only water-level measurements were provided by NDWR, discharge rates were computed using standard equations for the 1-ft and 3-ft Parshall flumes (Leupold and Stevens, 1987). Discharges for October 1967 to February 2005 are shown in figure B46. A complete listing of the water-level measurements and computed discharges is included in table B33.

A continuous-stage recorder was installed on the flume by the U.S. Geological Survey on August 22, 1985, and maintained until September 30, 1994. The gage was reactivated in June 1996 and is routinely maintained as part of the current monitoring network. Daily mean discharges computed for the period of record are also plotted on figure B46 and listed in table B34. Photographs of the current flume, bench mark, and selected reference marks established for this gage on June 3, 2004, are shown in figure B47.

Water samples were collected at this site on May 18, 2004, by Desert Research Institute (DRI) and analyzed for major ions, water temperature, and stable hydrogen and oxygen isotopes. The results of the analyses are shown in table B35.

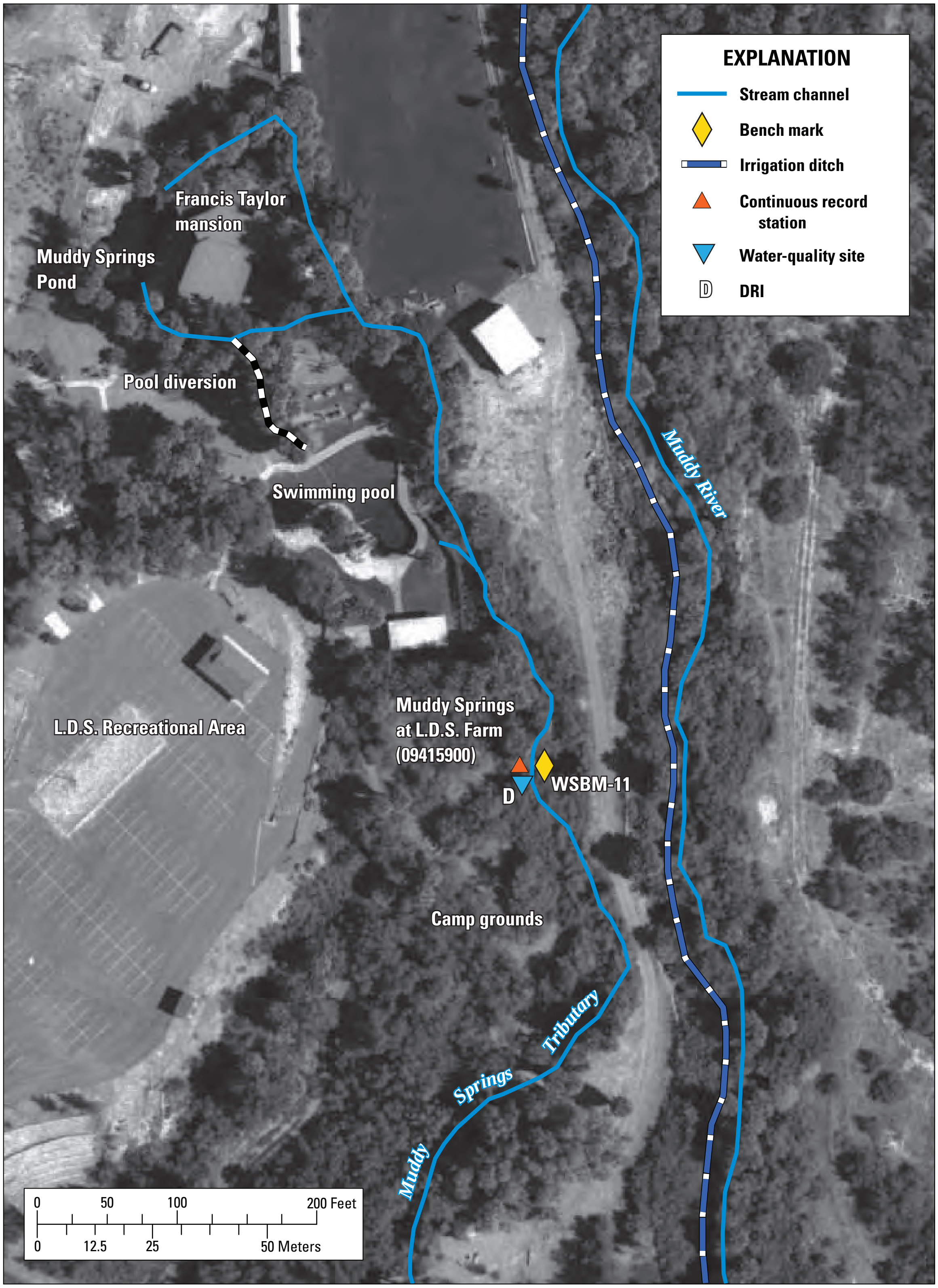

Figure B45. Location of Muddy Springs at Latter Day Saints (L.D.S.) Farm continuous-record stream-gaging station, L.D.S. Recreational Area, Desert Research Institute monitoring site, and bench mark WSBM-11 in the Warm Springs area near Moapa, Nevada.

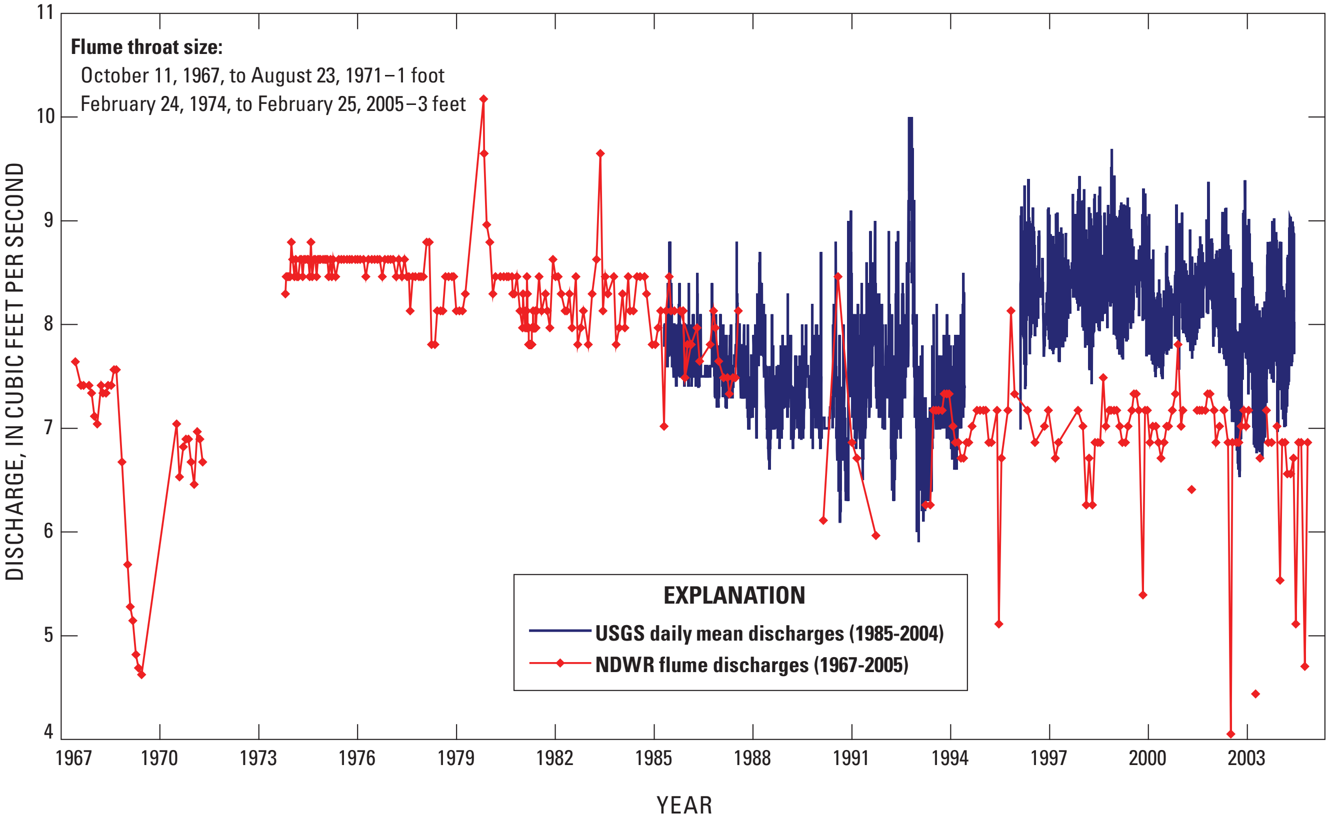

Figure B46. Instantaneous and daily mean discharge for continuous-record stream-gaging station 09415900 Muddy Springs at Latter Day Saints (L.D.S.) Farm near Moapa, Nevada, 1967–2005. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov. NWDR, Nevada Division of Water Resources.

Table B33. Water levels and computed instantaneous discharges for continuous-record stream-gaging 097415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada, 1967–2005.

Table B33 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B34. Daily mean discharges for continuous-record stream-gaging station 09415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada, water years 1985–2004.

Table B34 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B47. Location of bench mark WSBM-11 and reference marks RM-3 and RM-5 at stream-gaging station 09415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada. Photographed June 3, 2004 by D. Beck. Elevation of bench and reference marks in feet above NAVD 88.

Table B35. Water-quality data collected by Desert Research Institute for continuous-record stream-gaging at station 09415900 Muddy Springs at L.D.S. Farm near Moapa, Nevada, May 18, 2004.

Table B35 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Apcar (Pipeline Jones) Springs

The following sites are included within this section:

Garden Ditch Flume (1978–92)
North Tributary Water-Quality Site (1997–2005)
South Tributary Water-Quality Site (1997–2005)
Apcar Pumphouse Water-Quality Site (1997–2004)

Apcar (Pipeline Jones) Springs near Moapa, Nevada

Apcar Springs is about 0.1 mi west of Warm Springs Road in the south-central part of the Warm Springs area (fig. 2). Currently, two channels, the North Tributary and South Tributary, discharge water from the Apcar Spring area. The North Tributary drains to the northeast through a culvert under Warm Springs Road (fig. B48). Downstream of Warm Springs Road, flow continues in a dirt channel to the north for about 0.1 mi and then turns to the northeast. About 0.2 mi farther, the channel turns to the southeast and continues until it is just south of the confluence of Muddy Springs tributary and Muddy River (fig. 2). Most of the ditch between Warm Springs Road and the confluence is thickly overgrown. Near the confluence, flow from the ditch is directed into an old concrete irrigation trough that distributes water to the southeast fields, ultimately terminating into Refuge Stream about 0.4 mi downstream (fig. 2). The South Tributary generally drains to the east, eventually becoming Apcar Stream, which terminates into Refuge Stream about 0.55 mi downstream from the Warm Springs Road crossing (fig. 2). In 1960, a pump house (fig. B48) was constructed at the springs by the then Moapa Valley Water Company to supply water for residential and commercial areas within the southern towns of Moapa Valley.

A 9-inch (in.) Parshall flume was installed on Garden Ditch on January 4, 1978, by the Nevada Division of Water Resources (NDWR). This flume is reported to have been located on the North Tributary just upstream of the culvert at Warm Springs Road (fig. B48) (Testolin and others, 1993). The flume is no longer there; however, remnant pieces of concrete litter the area. Data provided by NDWR show that water-level measurements for the 9-in flume generally were made monthly from January 1978 until June 1981 and daily from July through September 1981. Monthly measurements resumed in October 1981 and ended in November 1987. No measurements were made from December 1987 until June 1990. From June 1990 to June 1992, only six measurements were made. No measurements are available after June 26, 1992. Because only water-level measurements were provided by NDWR, discharge rates were computed using a standard equation for the 9-in Parshall flume (Leupold and Stevens, 1987). Computed discharges from January 1978 to June 1992 are shown in figure B49. Water-level measurements and computed discharges are given in table B36.

In April 1997, Converse Consultants, on contract with Nevada Power Company, began quarterly field measurements of water temperature and specific conductance on the North and South Tributaries (fig. B48). Measurements for the North and South Tributary sites through March 2005 were provided by Converse Consultants and are plotted in figures B50 and B51 and listed in tables B37 and B38, respectively.

In December 1997, the Moapa Valley Water District (MVWD) began collecting water samples from a spigot at the Apcar Springs old pump house (fig. B48). Water samples generally are collected annually by MVWD and analyzed by Southwest Analytical, Inc., for major ions, trace metals, and selected chemical parameters (pH, specific conductance, total dissolved solids, and alkalinity). Although a new pump house was constructed during the summer of 2004 (fig. B48), all water-quality data provided by MVWD were from the original pump house (Susan Rose, Moapa Valley Water District, oral commun., 2005). The results of the analyses of the samples collected from December 1997 to August 2004 are given in table B39.

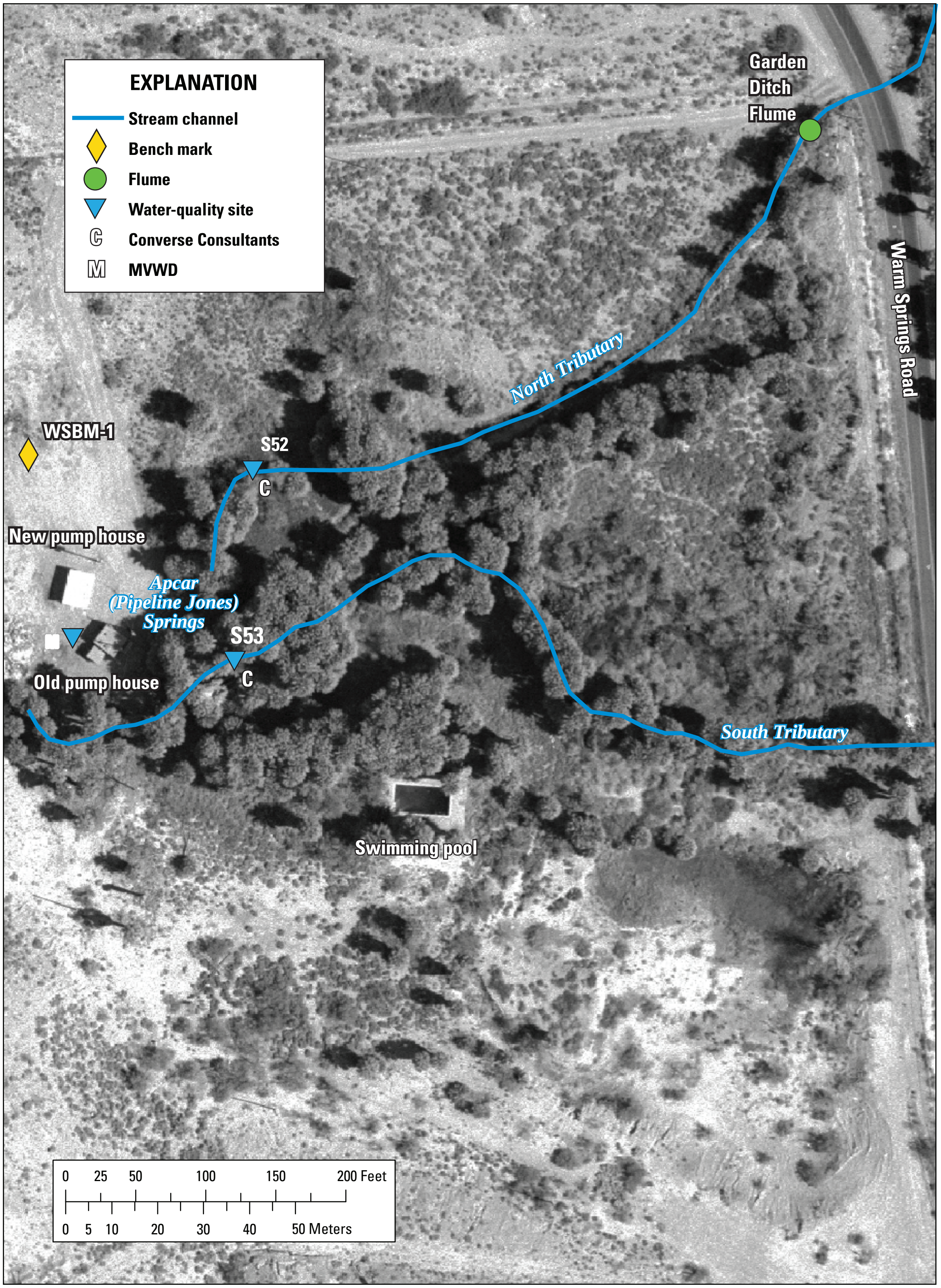

Figure B48. Location of Apcar (Pipeline Jones) Springs, pump houses, monitoring sites, and bench mark WSBM-1 in the Warm Springs area near Moapa, Nevada.

Garden Ditch Flume at Apcar (Pipeline Jones) Springs near Moapa, Nevada

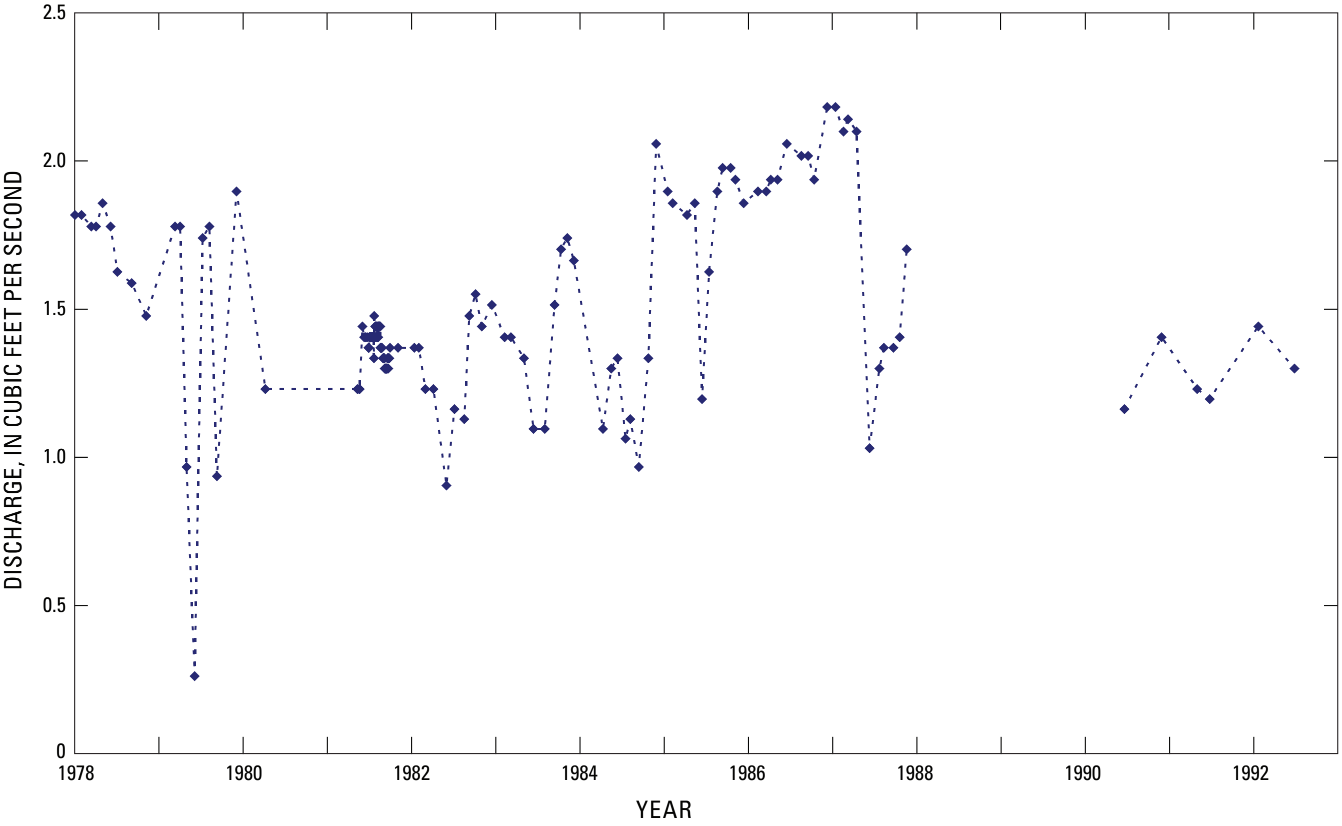

Figure B49. Instantaneous discharges computed from water-level measurements provided by Nevada Division of Water Resources for Garden Ditch Flume on North Tributary at Apcar (Pipeline Jones) Springs near Moapa, Nevada, 1978–92. Data provided by Nevada Division of Water Resources.

Table B36. Instantaneous discharges computed from water-level measurements for Garden Ditch Flume on North Tributary at Apcar (Pipelne Jones) Springs near Moapa, nevada, 1978–92.

[Data provided by Nevada Division of Water Resources.]

Table B36 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Water-Quality Sites at Apcar (Pipeline Jones) Springs near Moapa, Nevada

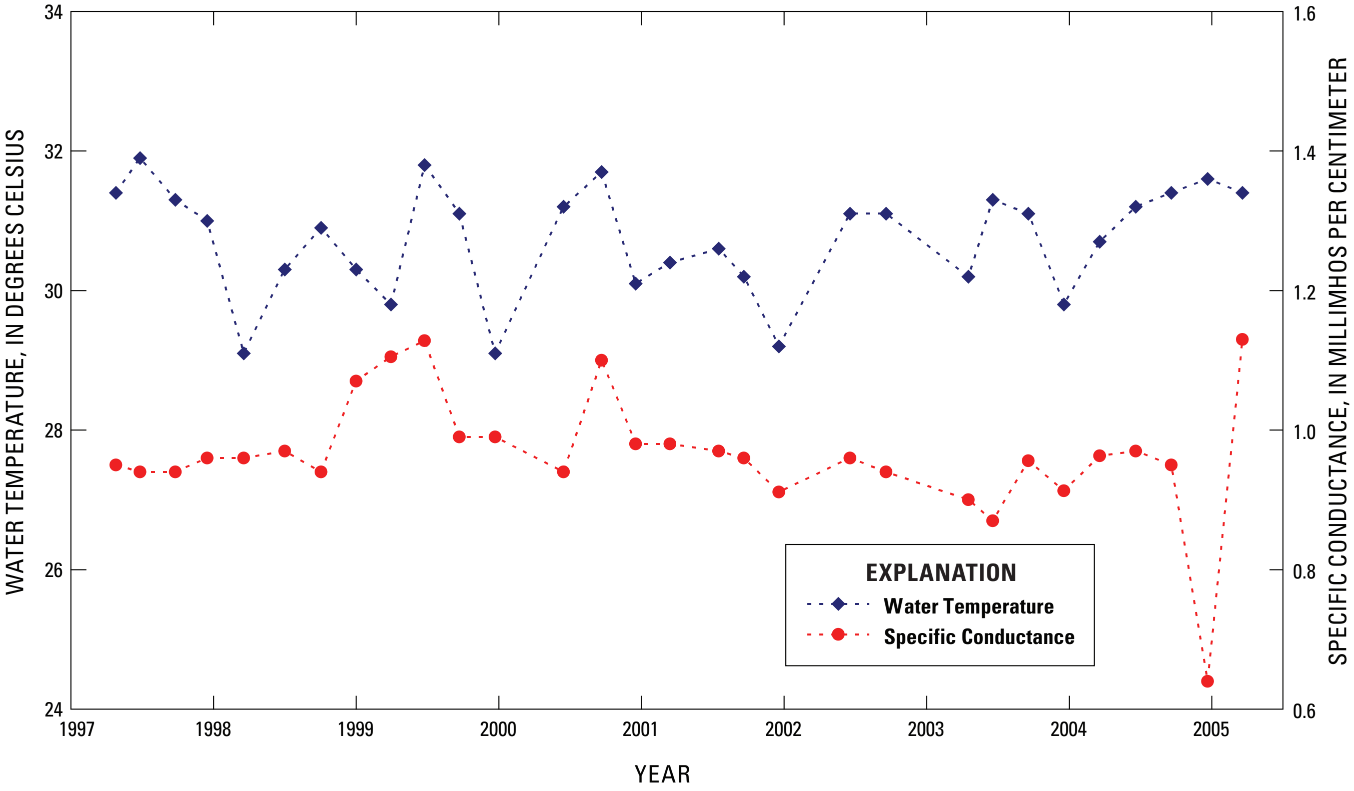

Figure B50. Water-temperature and specific-conductance measurements provided by Converse Consultants for site S52 on North Tributary at Apcar (Pipeline Jones) Springs near Moapa, Nevada, 1997–32005.

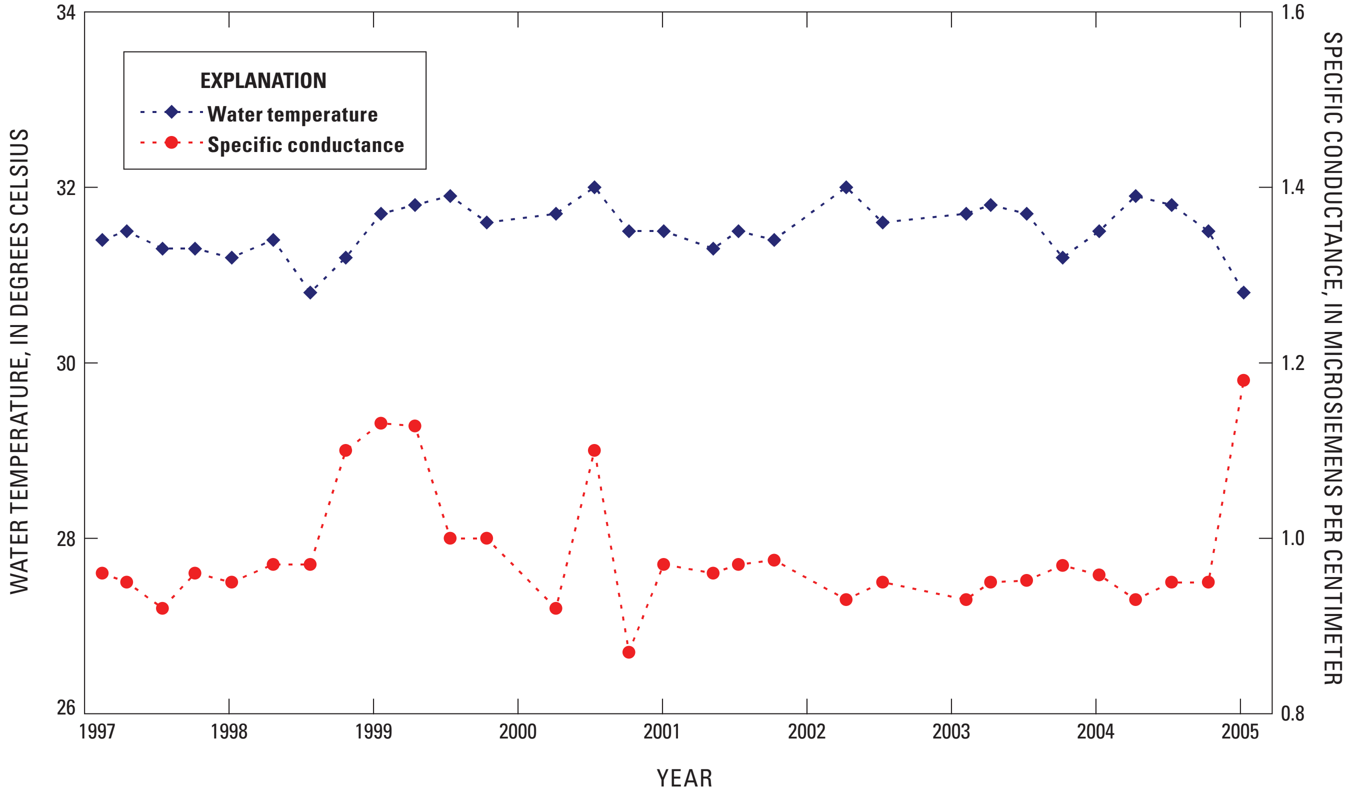

Figure B51. Water-temperature and specific-conductance measurements provided by Converse Consultants for site S53 on South Tributary at Apcar (Pipeline Jones) Springs near Moapa, Nevada, 1997–2005..

Table B37. Water-temperature and specific-conductance measurements provided by Converse Consultants for site S52 on North Tributary at Apcar (Pipeline Jones) Springs near Moapa, Nevada, 1997–2005.

Table B37 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B38. Water-temperature and specific-conductance measurements provided by Converse Consultants for site S53 on South Tributary at Apcar (Pipeline Jones) Springs near Moapa, Nevada, 1997–2005.

Table B38 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B39. Water-quality data for pump house at Apcar (Pipeline Jones) Springs, near Moapa, Nevada, 1997–2004.

Table B39 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Baldwin Springs

The following sites are included within this section:

Baldwin Cuts Flume (1967–85)
09415875 Baldwin Springs Flume near Moapa, Nevada (1967–2005)
Baldwin Springs Flume Water-Quality Site (1997–2005)
Baldwin Springs Pump House Water-Quality Sites (1997–2004)

Baldwin Springs near Moapa, Nevada

Baldwin Springs is about 0.2 mi north of Warm Springs Road and about 0.5 mi west of the L.D.S. Recreation Area (fig. 2). Discharge from the springs generally trends to the northeast, and contributes most of the flow of the South Fork Muddy River (fig. B52). In 1974, a pump house was constructed in the spring area by the Moapa Valley Water District (MVWD) to supply additional water to southern areas of the valley. Water not diverted at the springs is discharged directly into the channel about 20 ft north of the pump house (fig. B52).

A 9-inch (in.) Parshall flume, called Baldwin Cuts Flume, was installed at Baldwin Springs on October 11, 1967, by the Nevada Division of Water Resources (NDWR). The exact location of the flume is unknown, but it is believed to have been installed just downstream from the pump house. Data provided by NDWR show that water-level measurements for the 9-in. flume generally were made monthly October 1967 to August 1971, February 1974 to June 1981, and October 1981 to August 1985. During July, August, and September 1981, daily measurements were recorded. Because only water-level measurements were provided by NDWR, discharge rates were computed using a standard equation for the 9-in. Parshall flume (Leupold and Stevens, 1987). Computed discharges for October 1967 to August 1985 are shown in figure B53. A complete listing of the water-level measurements and computed discharges is given in table B40.

About the same time that the Baldwin Cuts flume was installed, a 1-foot (ft) Parshall flume, the Baldwin Springs Flume, was installed by NDWR on the South Fork Muddy River about 0.25 mi downstream from the pump house and about 75 ft north of Kimball Road (fig. B54). Data provided by NDWR show that monthly readings generally were made from October 1967 to August 1971. Similar to Baldwin Cuts flume, no measurements were made from September 1971 to January 1974. On February 22, 1974, a larger 2-ft Parshall flume was installed and monthly measurements were made until July 1984. On July 15, 1993, a new 2-ft Parshall flume was installed and monthly measurements were made through February 2005. Because only water-level measurements were provided by NDWR, discharge rates for this site were computed using standard equations for the 1-ft and 2-ft Parshall flumes (Leupold and Stevens, 1987). Computed discharges from October 1967 to February 2005 are given in figure B53, which also includes the measurements computed for the Baldwin Cuts Flume. A complete listing of the water-level measurements and computed discharges is given in table B41.

In April 1997, Converse Consultants, on contract with Nevada Power Company, began making quarterly field measurements of water temperature and specific conductance at the Baldwin Springs Flume. Measurements were compiled through March 2005 and are plotted in figure B55 and listed in table B42.

On June 2, 2004, the U.S. Geological Survey established bench mark WSBM-12 (table 2) and several reference marks (table 3) at Baldwin Springs Flume to determine water-surface elevations. Photographs of the flume, bench mark, and selected reference marks are included in figure B56.

In December 1997, the Moapa Valley Water District (MVWD) began collecting water samples from a spigot at the Baldwin Springs pump house (fig. B52). Water samples generally were collected annually by MVWD and analyzed by Southwest Analytical, Inc. for major ions, trace metals, and selected chemical and physical parameters (pH, specific conductance, total dissolved solids, and alkalinity). The results of the analyses of samples collected from December 1997 to August 2004 were provided by the MVWD are given in table B43.

On January 12 and May 18, 2004, water samples were collected at the pump house by Desert Research Institute and analyzed for major ions, selected chemical and physical parameters (pH, specific conductance, and dissolved solids), and stable hydrogen and oxygen isotopes. The results of the analyses are shown in table B44.

Baldwin Cuts Flume near Moapa, Nevada

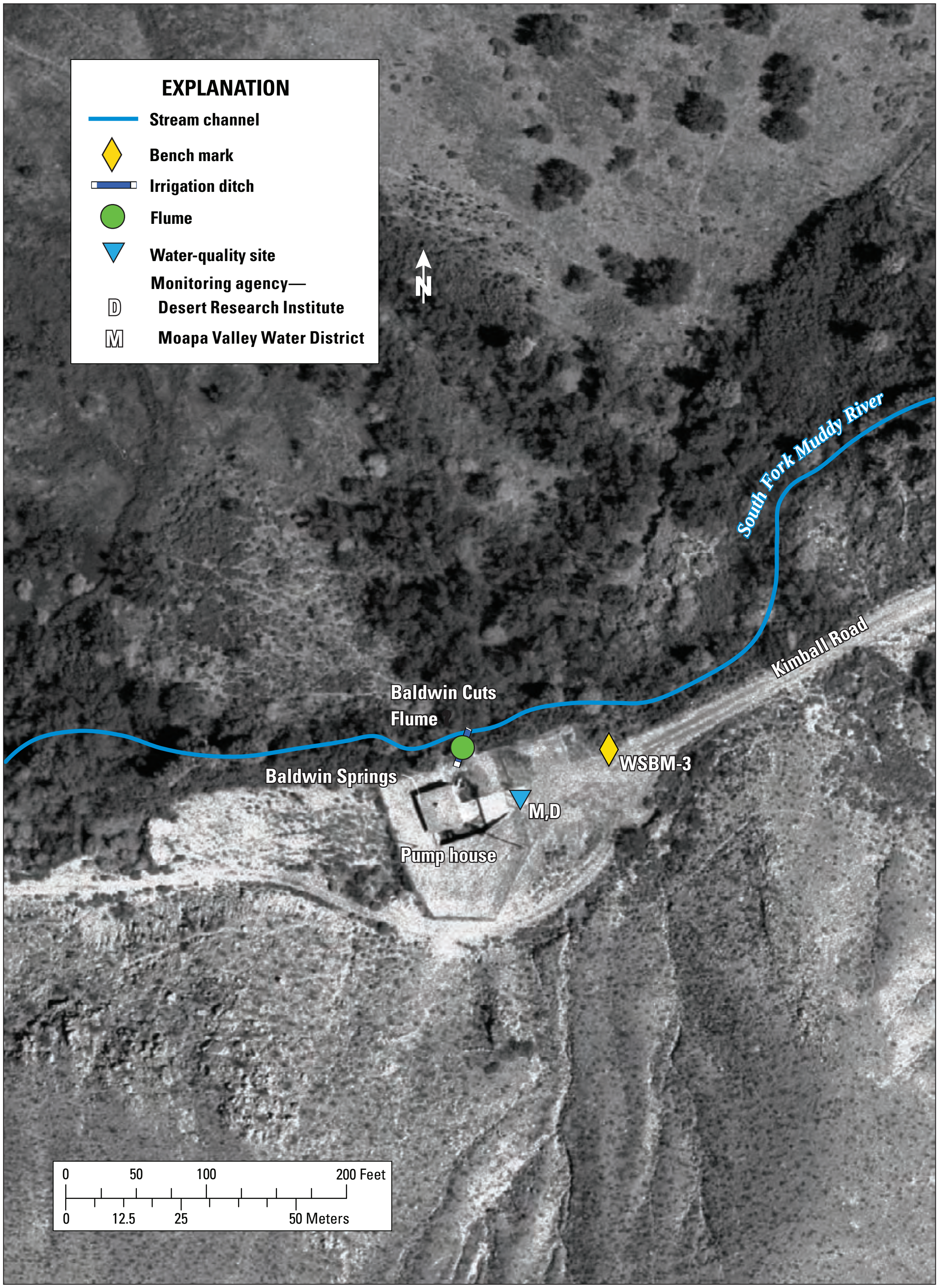

Figure B52. Location of Baldwin Springs, pump house, monitoring sites, and bench mark WSBM-3 in the Warm Springs area near Moapa, Nevada.

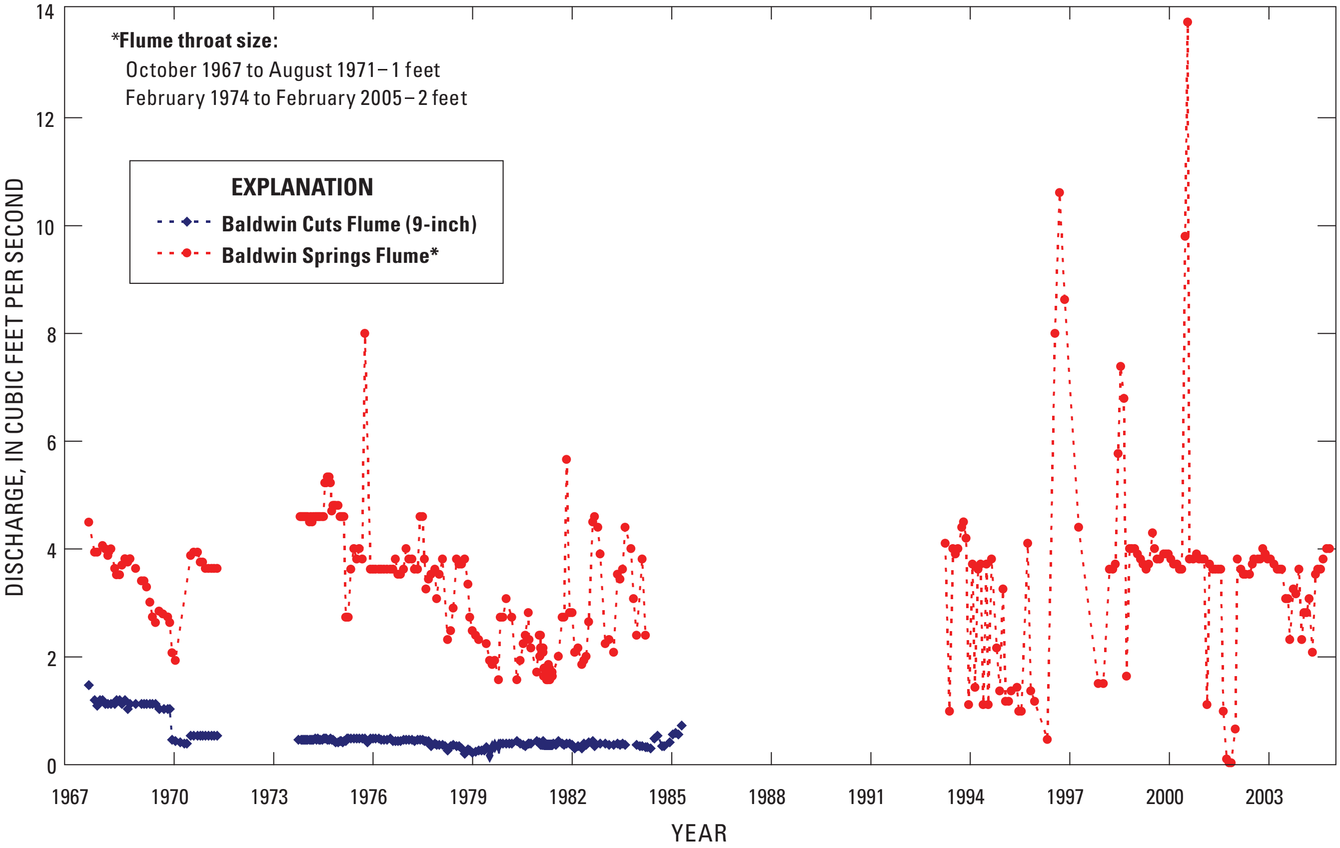

Figure B53. Instantaneous discharges computed from water-level measurements provided by Nevada Division of Water Resources for Baldwin Cuts and Baldwin Springs Flumes near Moapa, Nevada, 1967–2005.

Table B40. Instantaneous discharges computed from water-level measurements for Baldwin Cuts Flume near Moapa, Nevada, 1967–85.

Table B40 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

09415875 Baldwin Springs Flume near Moapa, Nevada

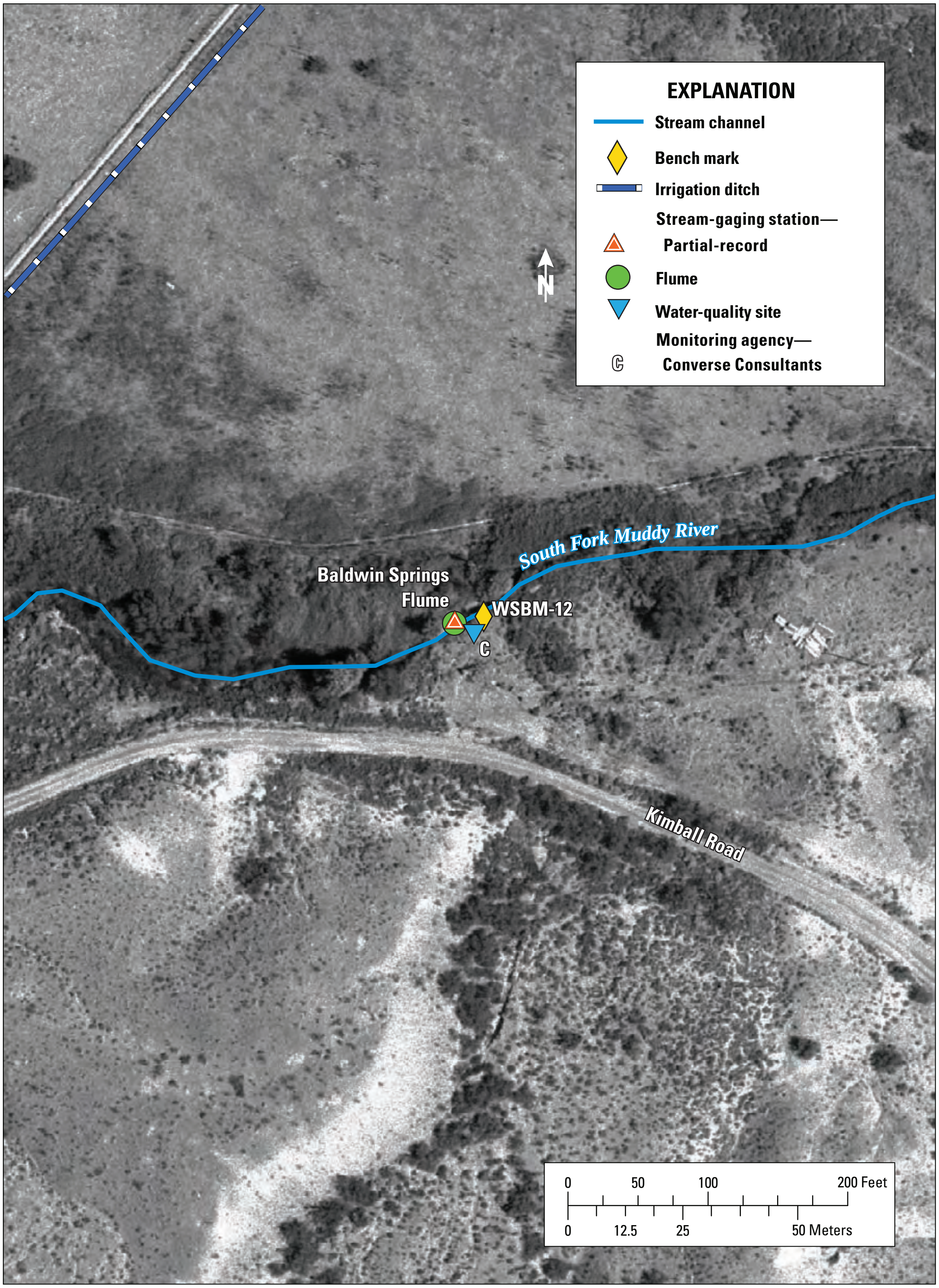

Figure B54. Location of Baldwin Springs Flume and bench mark WSBM-12 in the Warm Springs area near Moapa, Nevada.

Table B41. Water levels and computed instantaneous discharges for partial-record stream-gaging station 09415875 Baldwin Springs Flume near Moapa, Nevada, 1967–2005.

Table B41 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

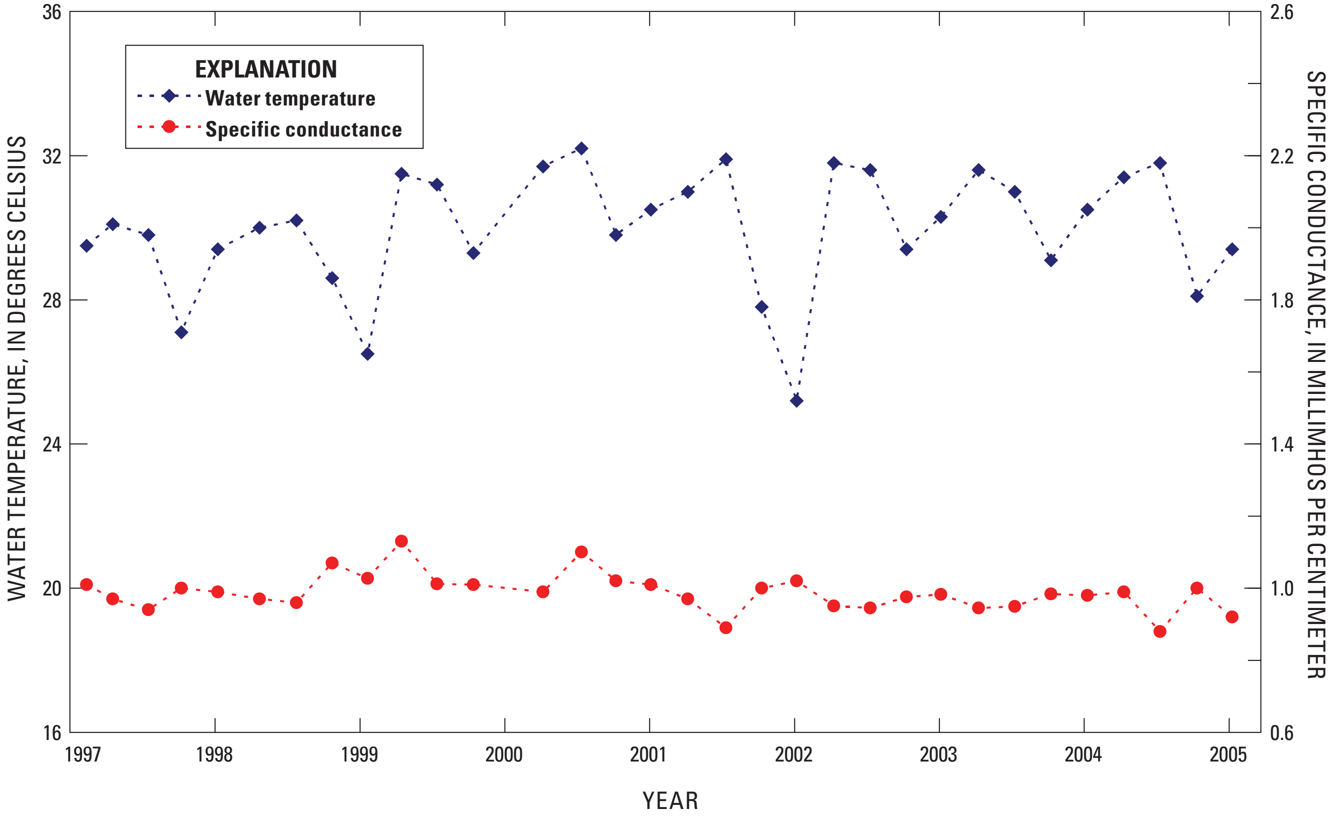

Figure B55. Water-temperature and specific-conductance measurements provided by Converse Consultants for Baldwin Springs Flume near Moapa, Nevada, 1997–2005.

Table B42. Water-temperature and specific-conductance measurements provided by Converse Consultants for Baldwin Springs Flume near Moapa, Nevada, 1997–2005.

Table B42 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

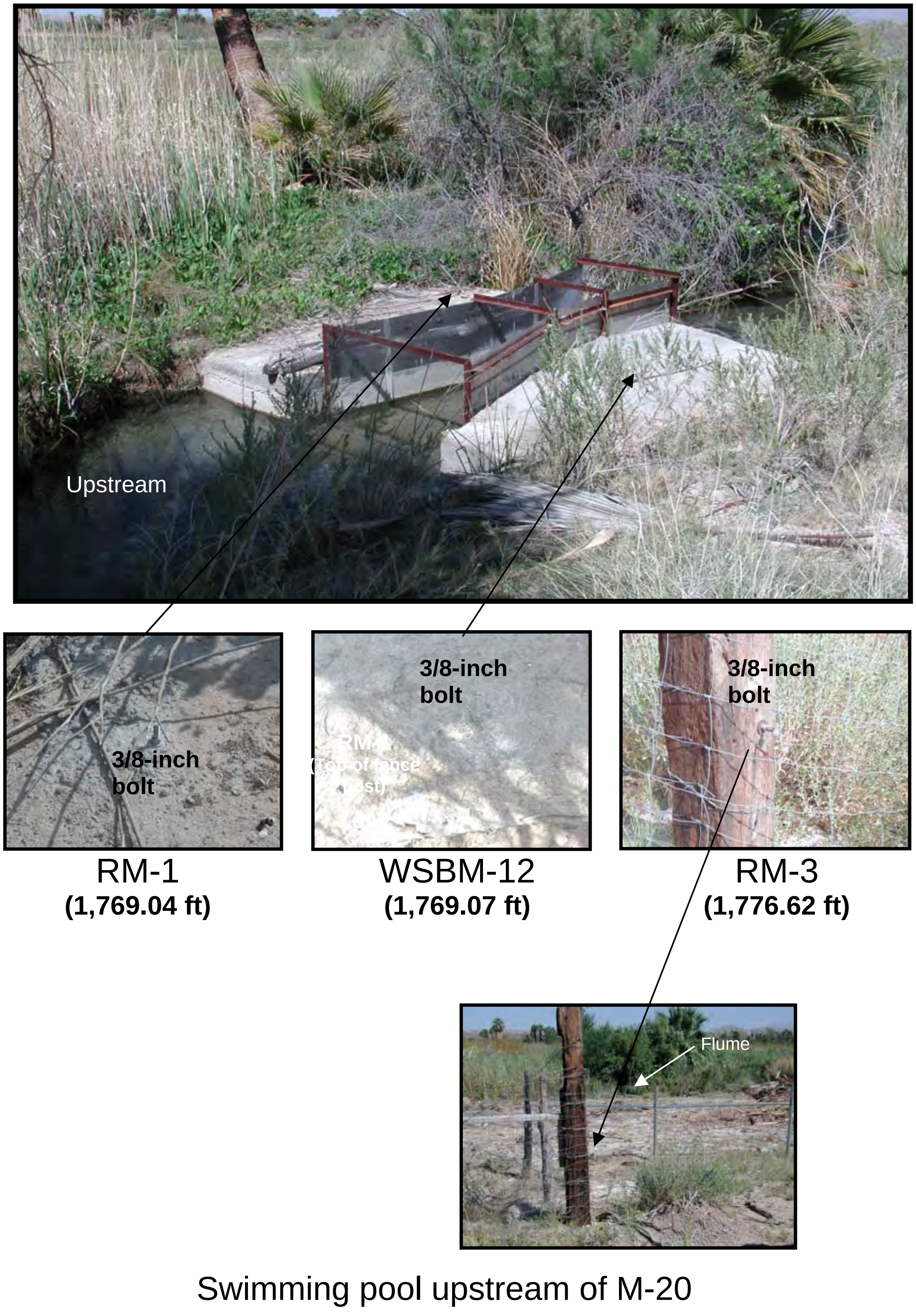

Figure B56. Location of bench mark WSBM-12 and reference marks RM-1 and RM-3 for Baldwin Springs Flume in the Warm Springs area near Moapa, Nevada. Photographed June 2, 2004 by D. Beck. Elevation of bench and reference marks in feet above NAVD 88.

Water-Quality Sites at Baldwin Spring Pump House near Moapa, Nevada

Table B43. Water-quality data provided by the Moapa Valley Water District for pump house at Baldwin Springs near Moapa, Nevada, 1997–2004.

Table B43 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B44. Water-quality data provided by the Desert Research Institute for pump house at Baldwin Springs near Moapa, Nevada, January 12 and May 18, 2004.

Table B44 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

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Cardy Lamb Springs

The following sites are included within this section:

Baldwin House Spring #1 (South) Flume (1967–80)
Baldwin House Spring #2 (North) Flume (1967–80)
364327114430801 Muddy River Springs 10 (1986–2004)
Water-Quality Site (S-15) at Cardy Lamb Pond (1997–2005)

Cardy Lamb Springs near Moapa, Nevada

Cardy Lamb Springs is about 0.1 mi east of Warm Springs Road and about 0.8 mi west-northwest of the L.D.S. Recreation Area (fig. 2). Discharge from this area generally trends to the southeast, but past agricultural and recreational developments in the area have modified or filled any pre-existing natural drainage channels. An intricate network of concrete irrigation ditches installed during the 1950s and 1960s distributed most of the flow from the springs onto agricultural fields to the east (fig. 2). Sometime during 1980, a swimming pond and a bathhouse were constructed in the area in an attempt to develop a recreational facility (fig. B57). The pond was constructed over one of the spring discharge areas and a drainage pipe was installed at the northeast wall to allow the pond to drain into the irrigation drainage network (fig. B57). Although the recreational area never materialized, the pond is still used today by the current owners to irrigate fields to the east for livestock grazing.

On October 11, 1967, two 6-inch Parshall flumes (Baldwin House Spring #1- South and Baldwin House Spring #2-North) were installed by the Nevada Division of Water Resources (NDWR) as part of a program to monitor spring discharges within the Warm Springs area. The exact location of the two flumes is unknown, but they are believed to have been located between the pond and the irrigation ditch to the east (fig. B57). Data provided by NDWR show that water-level measurements for flumes #1 and #2 generally were made monthly from October 1967 to May 1980 and October 1967 to April 1980, respectively, except during September 1971 to January 1974. Since the last measurement at both sites coincides with the installation date of the pond, the flumes are believed to have been removed at that time. Because only water-level measurements were provided by NDWR, discharge rates were computed using a standard equation for the 6-inch Parshall flumes (Leupold and Stevens, 1987). Plots of the computed discharges for both flumes from October 1967 to May 1980 are shown in figure B58. Complete listings of the water-level measurements and computed discharges for Spring #1 and Spring #2 are given in tables B45 and B46, respectively.

The partial-record station at Muddy River Springs 10 (M-10) was established by the U.S. Geological Survey (USGS) on January 28, 1986 and is located about 250 ft east of the swimming pond (fig. B57). The measurement site is inside an old concrete irrigation ditch about 2 ft downstream from a small concrete culvert. Most of the flow at Muddy River Springs 10 originates from flow within the swimming pond that discharges through the drainage pipe. Water exiting the drainage pipe flows into a small pond approximately 10 ft upstream of the concrete culvert and merges with flows from small springs to the southwest. Periodic discharge measurements have been made by the USGS since January 1986. Discharge measurements for the period of record are plotted in figure B59 and listed in table B47. Photographs of the bench mark, reference points, and selected reference marks established for the Muddy River Springs 10 monitoring site on June 3, 2004, are shown in figure B60.

In April 1997, Converse Consultants, on contract with Nevada Power Company, began quarterly field measurements of water temperature and specific conductance at site S15 (fig. B57) at the south end of the swimming pond. Measurements were compiled through March 2005 and are plotted in figure B61 and listed in table B48.

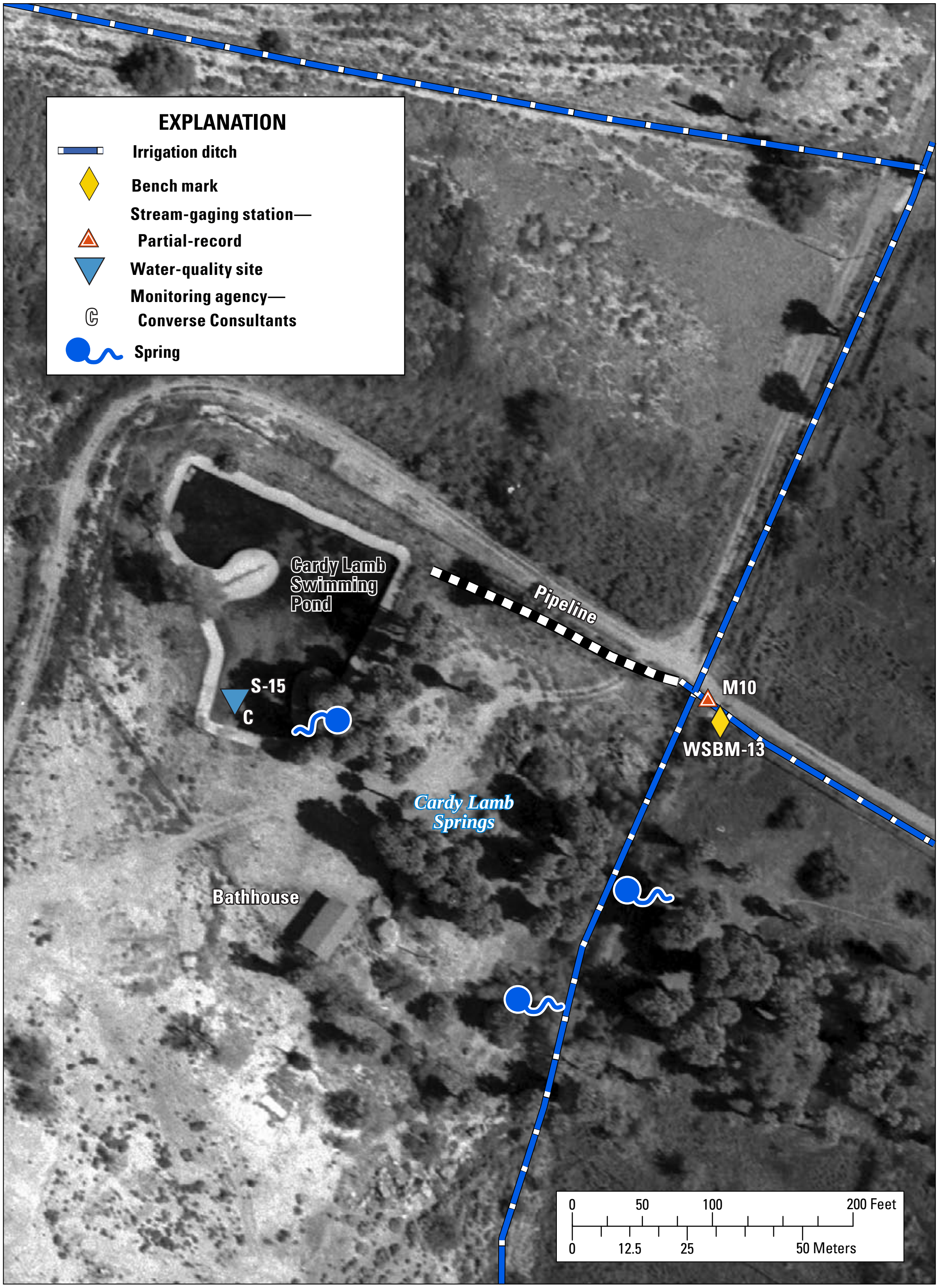


Figure B57. Location of Cardy Lamb Springs swimming pond, bench mark WSBM-13, and monitoring sites in the Warm Springs area near Moapa, Nevada.

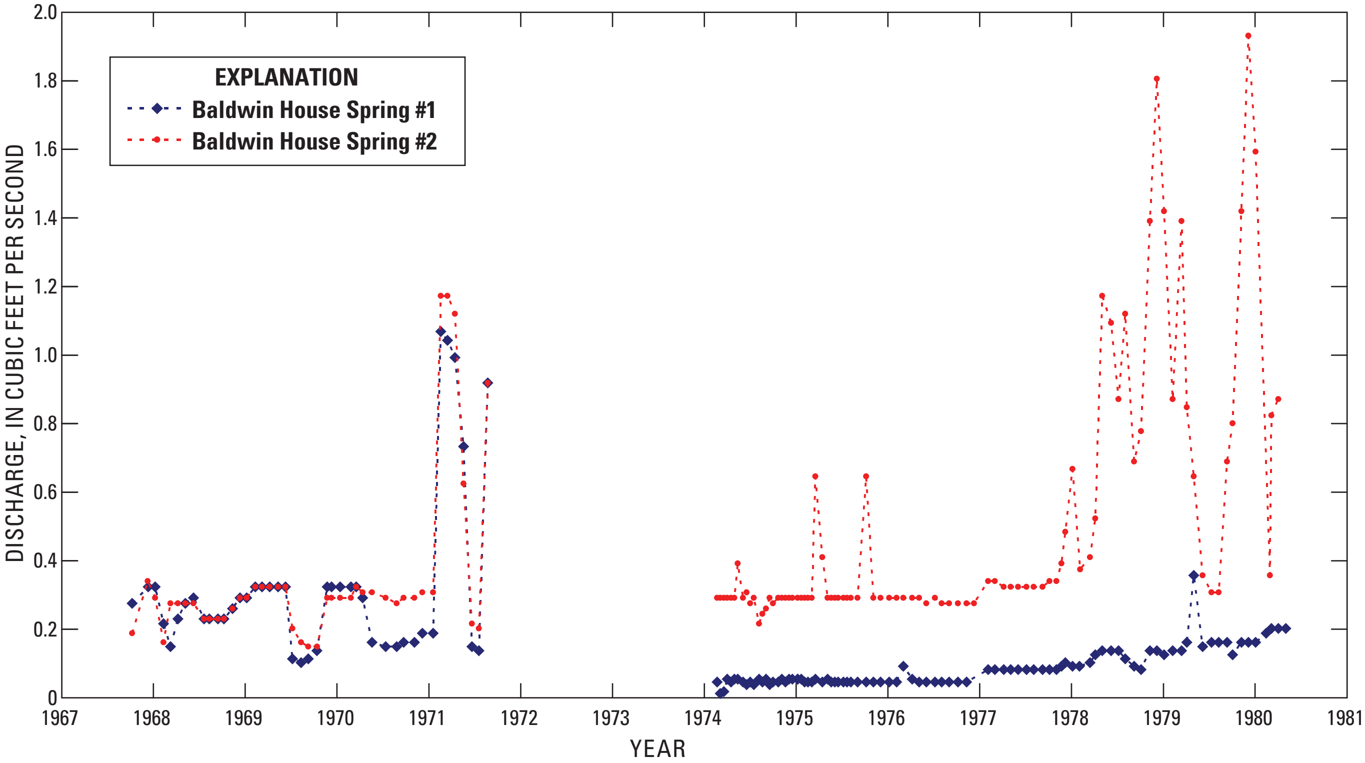


Figure B58. Instantaneous discharges for Baldwin House Springs #1 and #2 flumes at Cardy Lamb Springs near Moapa, Nevada, 1967–80. Data provided by Nevada Division of Water Resources.

Baldwin House Spring #1 (South) Flume near Moapa, Nevada

Table B45. Water levels and computed instantaneous discharges for Baldwin House Spring #1 (South) Flume at Cardy Lamb Springs near Moapa, Nevada, 1967–80.

Table B45 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Baldwin House Spring #2 (North) Flume near Moapa, Nevada

Table B46. Water levels and computed instantaneous discharges for Baldwin House Spring #2 (Nouth) Flume at Cardy Lamb Springs near Moapa, Nevada, 1967–80.

Table B46 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

364327114430801 Muddy River Springs 10 (M-10) near Moapa, Nevada

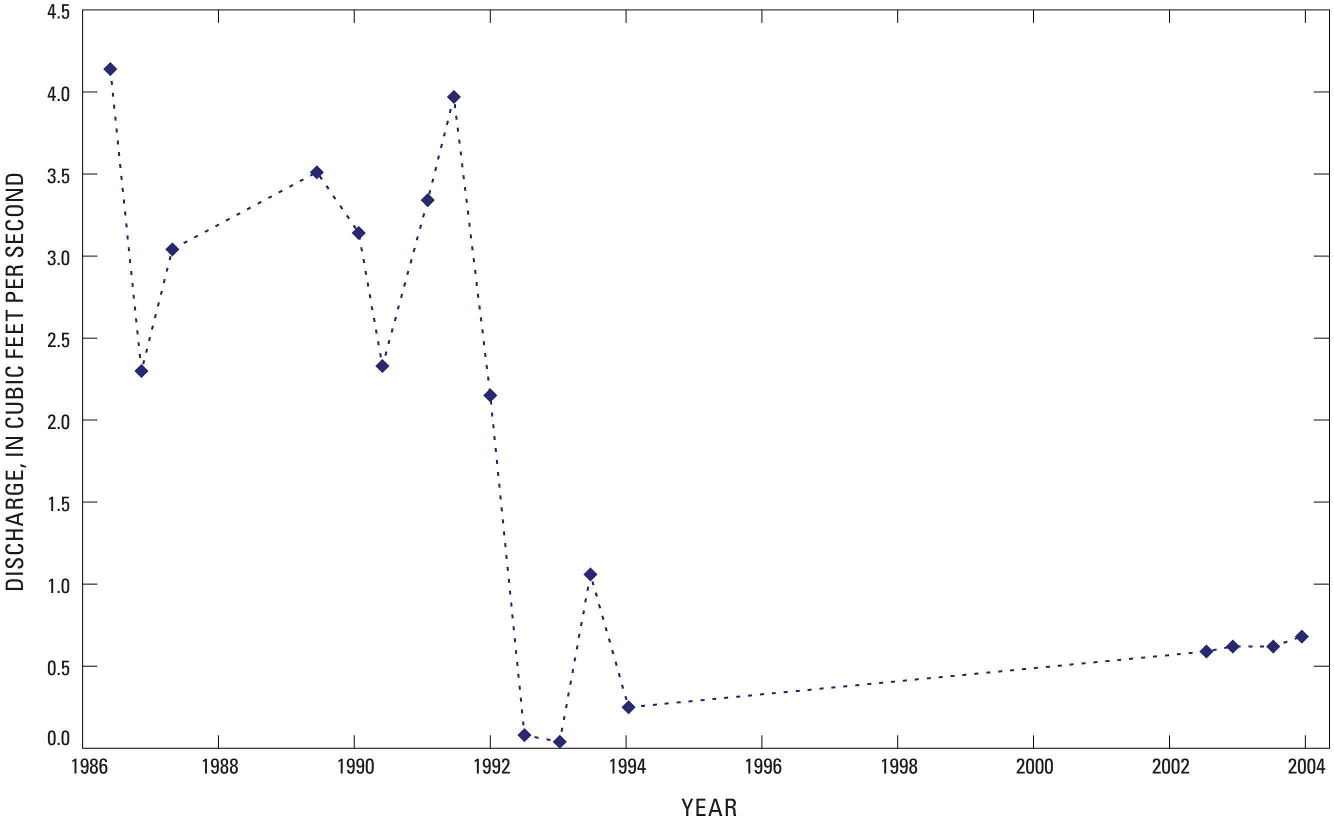


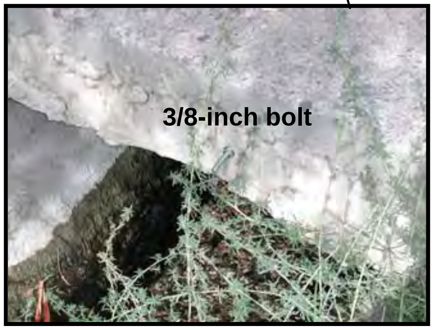
Figure B59. Periodic discharge measurements for partial-record stream-gaging station 364327114430801 Muddy River Springs 10 (M-10) at Cardy Lamb Springs near Moapa, Nevada, 1986–2004.

Table B47. Periodic discharge measurements for partial-record stream-gaging station 364327114430801 Muddy River Springs 10 (M-10) at Cardy Lamb Springs near Moapa, Nevada, 1986–2004.

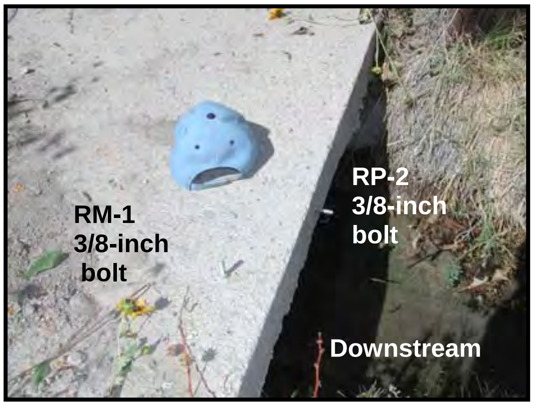
Table B47 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Site M-10

WSBM-13
(1,799.25 ft)



RP-1 **(1,798.38 ft)**
(Tape down point to measure water level)



RP-2 **(1,799.12 ft)** and RM-1
(1,799.46 ft) on North Ditch

RM-2
(1,800.51 ft)

Cardy Lamb Swimming Pond
upstream of M-10 channel

Figure B60. Location of bench mark WSBM-13, reference points RP-1 and RP-2, and reference marks RM-1 and RM-2 for partial-record station Muddy River Springs 10 (M-10) in the Warm Springs area near Moapa, Nevada. Photographed June 3, 2004 by D. Beck. Elevation of bench and reference marks in feet above NAVD 88.

Water-Quality Site at Cardy Lamb Pond near Moapa, Nevada

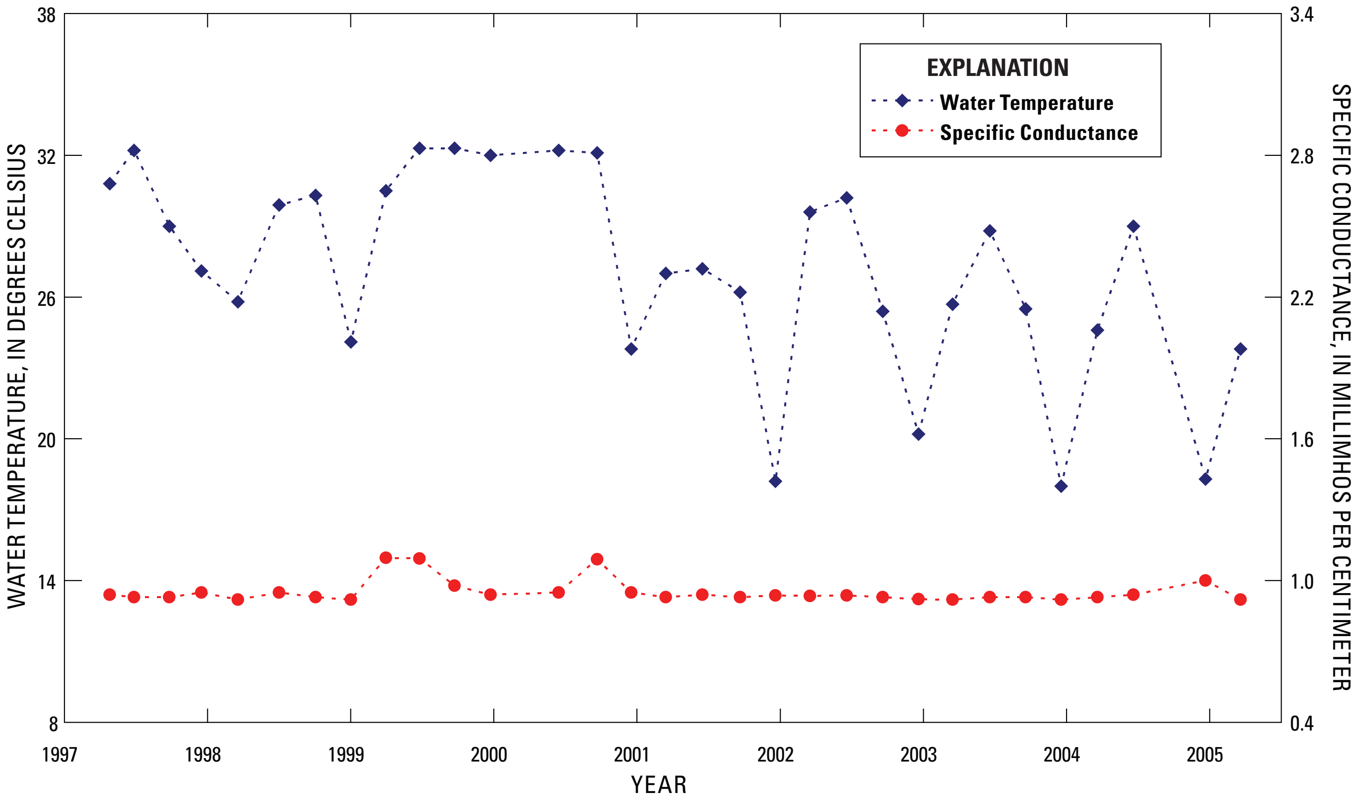


Figure B61. Water-temperature and specific-conductance measurements for site S15 at Cardy Lamb Springs near Moapa, Nevada, 1997–2005. Measurements provided by Converse Consultants.

Table B48. Water-temperature and specific-conductance measurements provided by Converse Consultants for site S15 at Cardy Lamb Springs near Moapa, Nevada, 1997–2005.

Table B48 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

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Miscellaneous Sites

The following sites are included within this section:

09415940 Apcar Stream at Pipeline Jones Flume near Moapa, Nevada (1967–2005)
09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada (1967–2005)
Unnamed Springs at L.D.S. East well near Moapa, Nevada (2004)
Miscellaneous Water-Quality Sites (1997–2005)

09415940 Apcar Stream at Pipeline Jones Flume near Moapa, Nevada

A 9-inch (in.) Parshall flume was installed on Apcar Stream on August 22, 1967, by the Nevada Division of Water Resources (NDWR). This flume is believed to have been located at or near the current flume site, which is about 670 ft north of Warm Springs Road (fig. B62) and about 0.6 mi downstream of Apcar Springs (fig. 2). Although flow at the flume originates from Apcar Springs, additional water enters the stream channel from other springs and seeps downstream of the Warm Springs Road crossing. Below the flume, flow generally drains to the east and is tributary to Refuge Stream about 0.4 mi downstream.

Data provided by NDWR show that water-level measurements for the 9-in flume were made monthly from August 1967 until May 1969. Monthly measurements resumed on February 22, 1974, when a new, 2-ft Parshall flume was installed. Measurements ended on February 7, 1985, and didn’t resume until July 1993 when a new 3-ft Parshall flume was installed. Because only water-level measurements were provided by NDWR, discharge rates were computed using standard equations for the 9-in., 2-ft, and 3-ft Parshall flumes (Leupold and Stevens, 1987). A plot of the computed discharges from October 1967 to February 2005 is shown in figure B63. A complete listing of the water-level measurements and computed discharges is given in table B49.

Two discharge measurements were made at this site on February 7, 2001, as part of a multi-agency synoptic seepage run in the Warm Springs area. The discharges for the two measurements were averaged and the resulting value was plotted on figure B63. Discharge values and related information for the two measurements made during the seepage run are included in Appendix E.

On July 20, 2004, the U.S. Geological Survey installed a staff plate on the flume and established one bench mark and two reference marks at the site as part of this study. Photographs of the flume, bench mark, and reference marks are shown in figure B64. During the installation of the staff plate, backwater conditions were observed at the flume caused by a large palm tree that had fallen across the channel about 40 ft downstream. Until the blockage is removed, computed discharges from water-level measurements will show erroneous higher rates of flow.

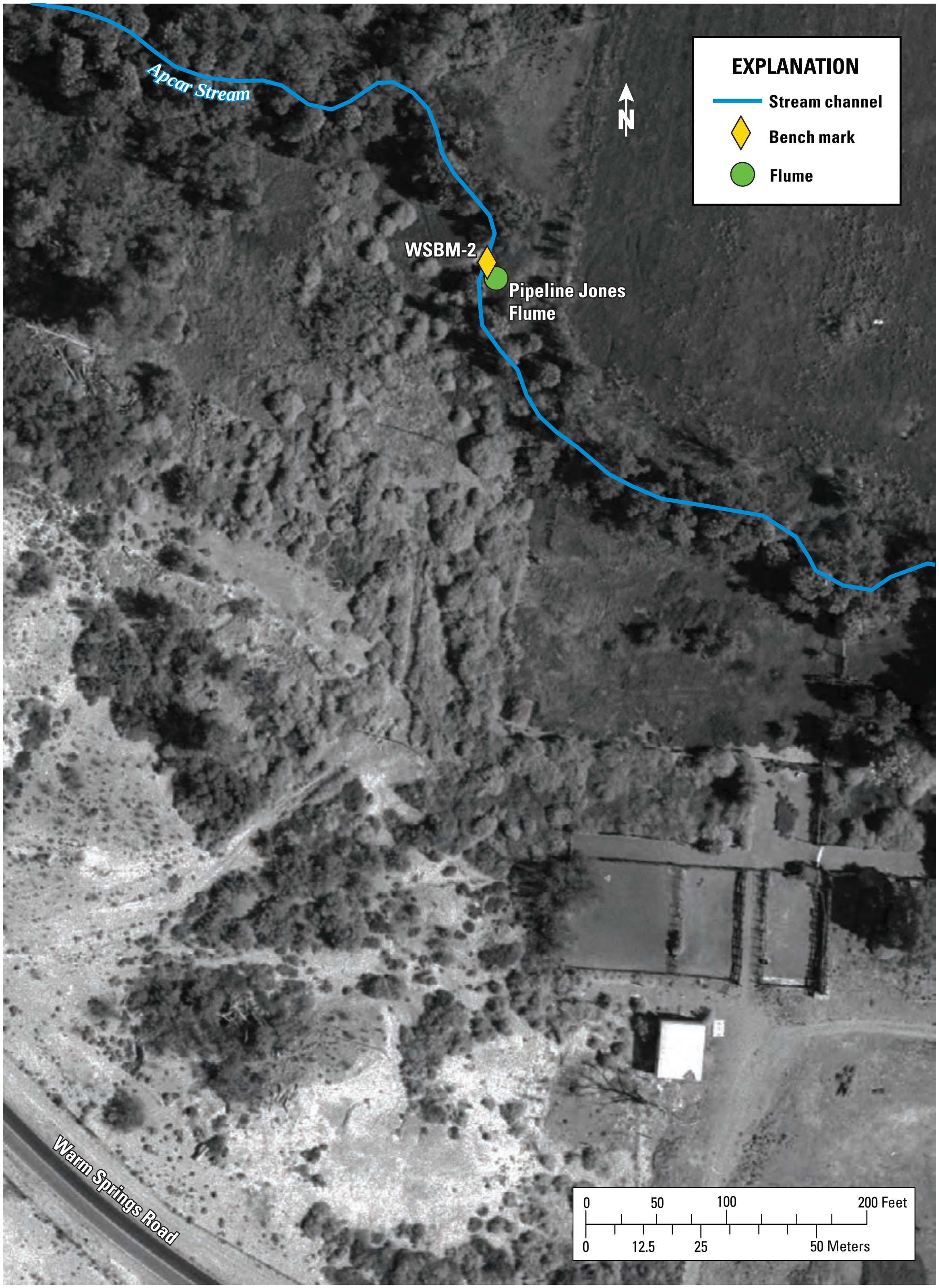

Figure B62. Location of Pipeline Jones Flume and bench Mark WSBM-2 in the Warm Springs area near Moapa, Nevada.

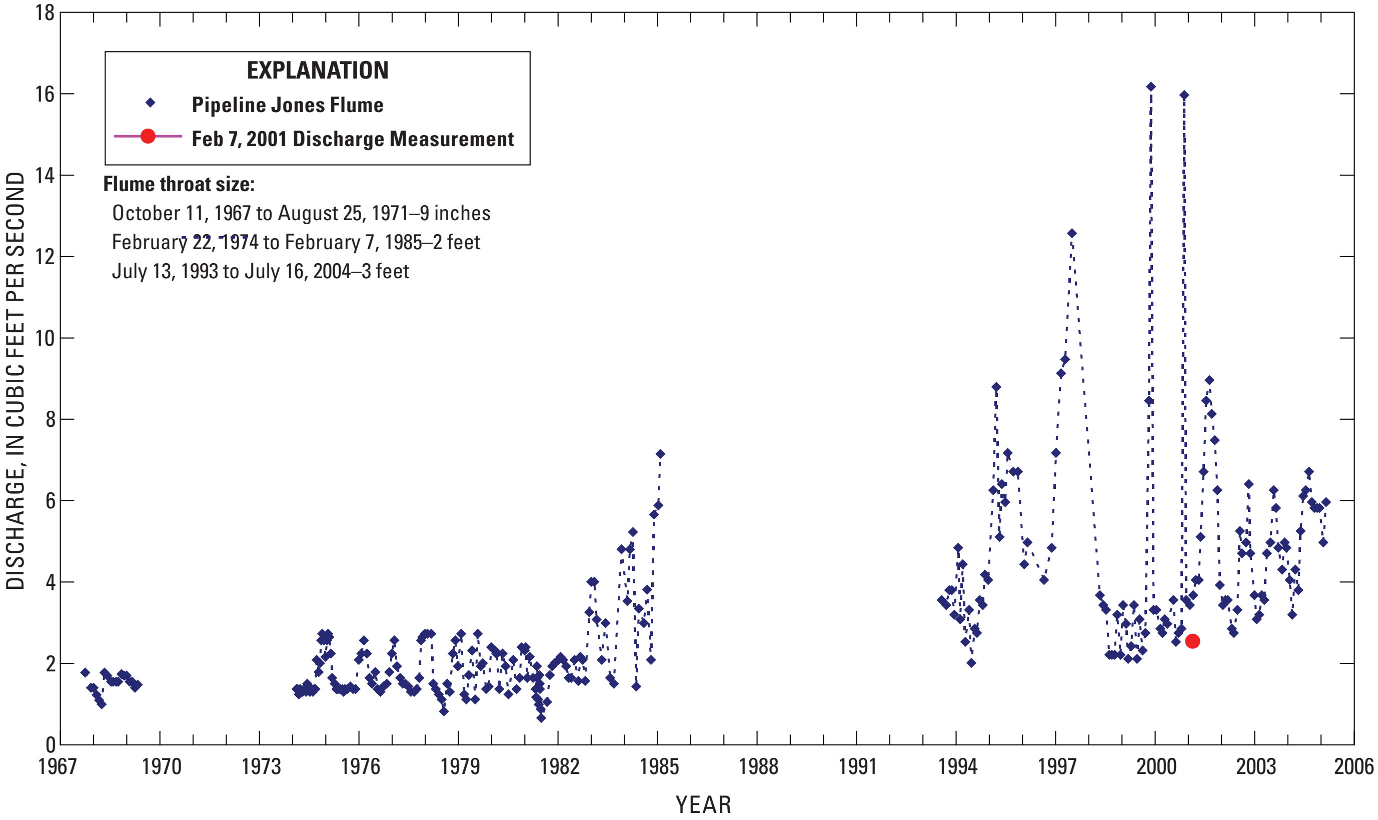

Figure B63. Instantaneous discharges compiled for 1967–2005, and discharge measurement made on February 7, 2001, for partial-record stream-gaging station 09415940 Apcar Stream at Pipeline Jones Flume near Moapa, Nevada.

Table B49. Water levels and computed instantaneous discharges for partial-record stream-gaging station 09415940 Apcar Stream at Pipeline Jones Flume near Moapa, Nevada, 1967–2005.

[Data from Nevada Division of Water Resources.]

Table B49 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

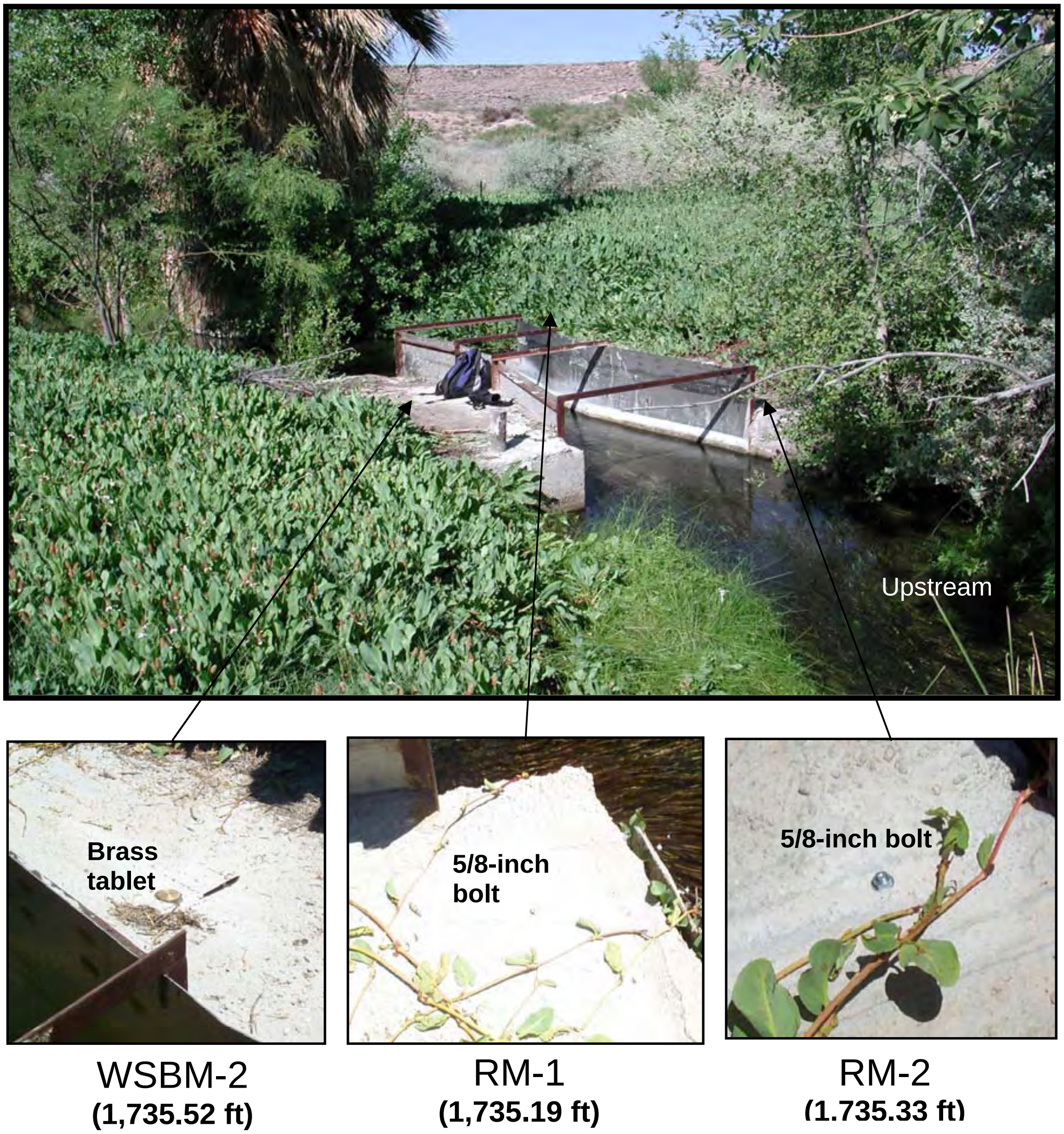

Figure B64. Location of bench mark WSBM-2 and reference marks RM-1 and RM-2 at partial-record stream–gaging station 09415940 Apcar Stream at Pipeline Jones Fume near Moapa, Nevada. Photographed July 20, 2004 by D. Beck. Elevation of bench and reference marks in feet above NAVD 88.

09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada

A 1-foot (ft) Parshall flume was installed on Refuge Stream on October 11, 1967, by the Nevada Division of Water Resources (NDWR). The flume was located approximately 0.8 mi southeast of the L.D.S. Recreational Area and about 250 ft north of Warm Springs Road (fig. B65). Flow at this flume is the combined discharges from the Plummer and Pederson Spring groups. Below the flume, flow generally drains to the northeast and is tributary to the Muddy River about 0.3 mi downstream. Flow from Apcar Stream enters Refuge Stream from the west about 800 ft downstream from the flume.

Data provided by NDWR show that water-level measurements for the 1-ft Parshall flume generally were made monthly from October 1967 until August 1971. Monthly measurements resumed on February 24, 1974, when a new, 3-ft Parshall flume was installed. Measurements ended on November 19, 1987, and didn’t resume until July 1993 when a new 3-ft Parshall flume was installed. The site is still visited monthly by NDWR. Because only water-level measurements were provided by NDWR, discharge rates were computed using standard equations for the 1-ft and 3-ft Parshall flumes (Leupold and Stevens, 1987). A plot of the computed discharges from October 1967 to February 2005 is shown in figure B66. A complete listing of the water-level measurements and computed discharges are given in table B50.

A continuous-stage recorder was installed at the flume by the U.S. Geological Survey on October 1, 2001, and maintained through September 30, 2004. From the time that the gage was installed, submerged flow conditions have been in effect owing to the growth of a large palm tree and other plants in the channel downstream from the flume. Discharge measurements are routinely made at the site and used to define the stage-discharge relation for the flume. Daily mean discharges computed for the period of record have been included for comparison on the plot in figure B66 and listed in table B51. Photographs of the current flume, bench mark, and a selected reference mark established for this gage on June 3, 2004, are shown in figure B67.

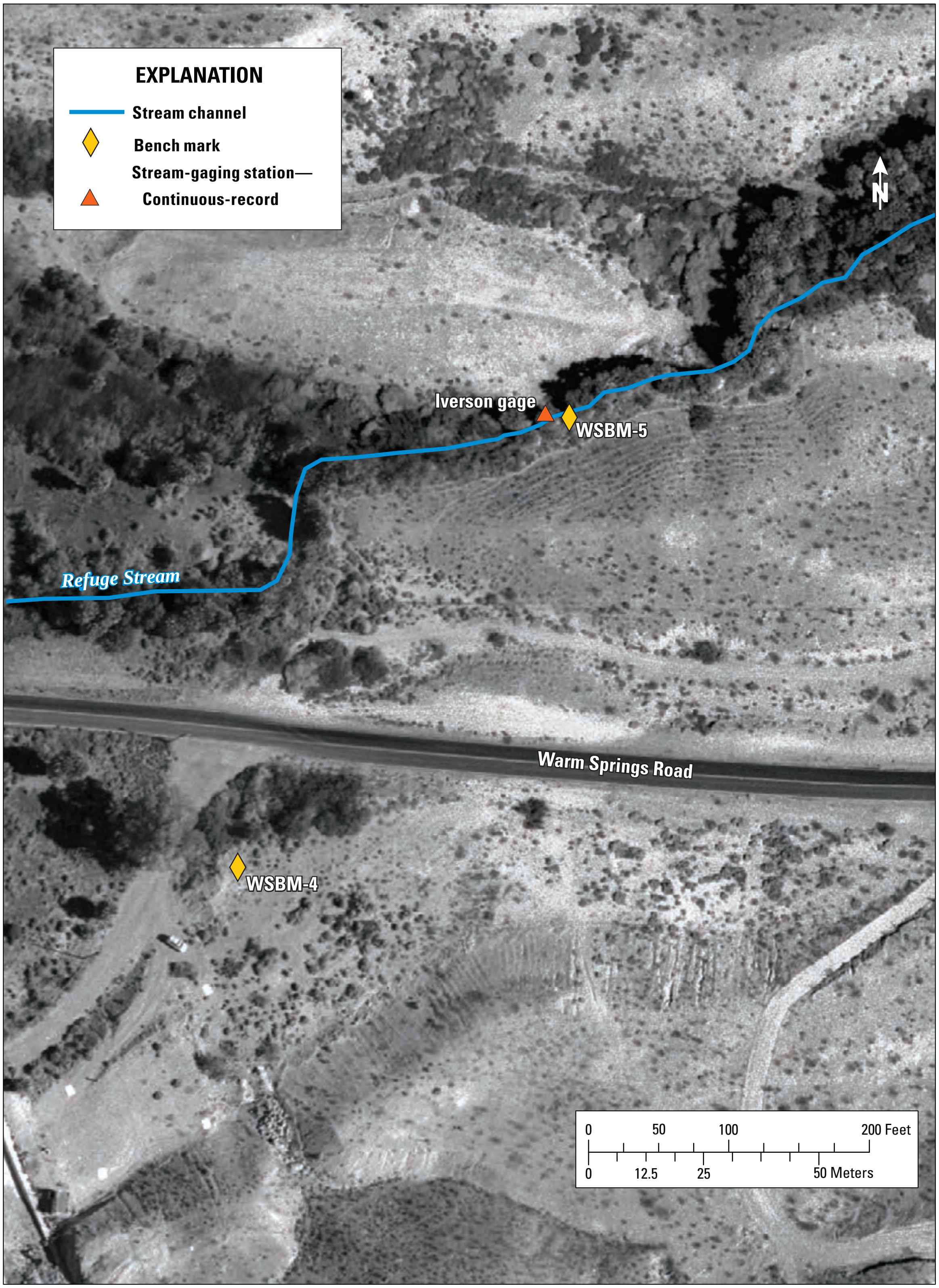

Figure B65. Location of continuous-record stream-gaging station 09415927 and bench marks, WSBM-4 and WSBM-5, Warm Springs Confluence at Iverson Flume near Moapa, Nevada.

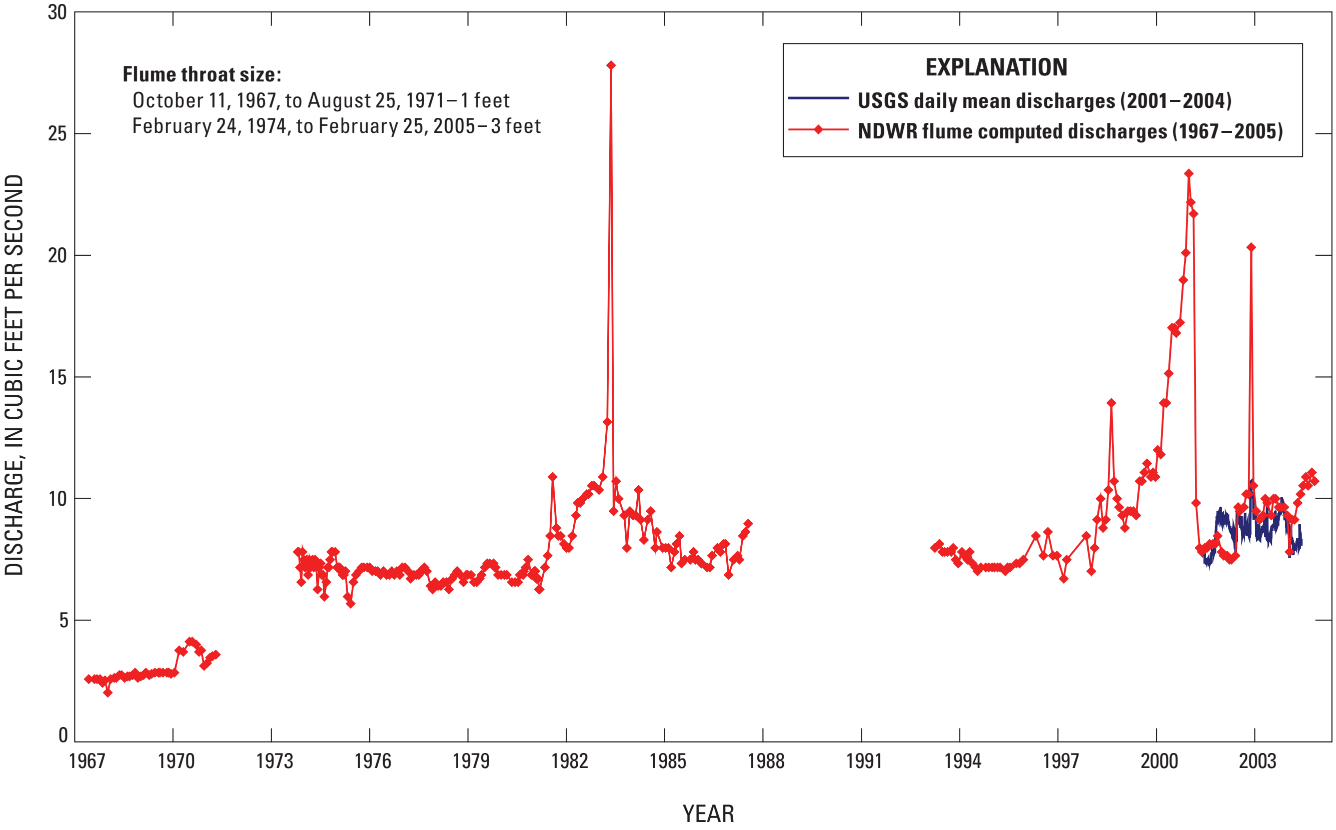

Figure B66. Instantaneous and daily mean discharges for continuous-record stream-gaging station 09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada, 1967–2005. Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov. Water level measurements used to compute discharges were provided by Nevada Division of Water Resources (NDWR).

Table B50. Water levels and computed instantaneous discharges for continuous-record stream-gaging station 09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada, 1967–2005.

[Water-level measurements provided by Nevada Division of Water Resources.]

Table B50 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B51. Daily mean discharges for continuous-record stream-gaging station 09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada, water years 2002–04.

[Data from U.S. Geological Survey (USGS) National Water Information System (NWIS) data base, accessed 2005 at http://waterdata.usgs.gov]

Table B51 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Figure B67. Location of bench mark WSBM-5 and reference mark RM-3 at continuous-record stream-gaging station 09415927 Warm Springs Confluence at Iverson Flume near Moapa, Nevada. Photographed June 3, 2004 by D. Beck. Elevation of bench and reference marks in feet above NAVD 88.

Unnamed Springs at L.D.S. East Well near Moapa, Nevada

An unnamed group of springs is located just to the south and east of L.D.S. Well East adjacent to State Highway 168 in the north-central part of the Warm Springs area (figs. 2 and B68). Discharge from the springs may have been perennial in the past; however, discharge is currently intermittent, occurring mainly during the winter when pumpage from the well and evapotranspiration rates are at their lowest. Flow from the area generally is to the southeast, but a network of irrigation ditches distributes flow to the east and south. During field reconnaissance of the Warm Springs area in February 2004, discharge from the springs was observed flowing into the Muddy River at two locations. The first site was about 100 ft upstream of the confluence with Refuge Stream. The second site was about 0.3 mi downstream from the confluence with Refuge Stream.

On August 17, 2004, surface-water elevations at all U.S. Geological Survey monitoring sites within the Warm Springs area were measured. At this time, the unnamed springs were not discharging; therefore, the elevation of a small spring pool about 100 ft to the east of L.D.S. Well East was measured using optical theodolite surveying techniques (Kennedy, 1988). Elevation for the water-surface measurement was determined using a bench mark (WSBM-10) established at the well by the Las Vegas Valley Water District (table 2). The surface-water elevation of the pond on August 17, 2004, is given in table 4. Photographs showing the location of the bench mark and measurement site are included in figure B69.

In April 1997, Converse Consultants, on contract with Nevada Power Company, initiated quarterly field measurements of water temperature and specific conductance at the unnamed spring area (fig. B68). Measurements were compiled through March 2005 and are plotted in figure B70 and listed in table B52.

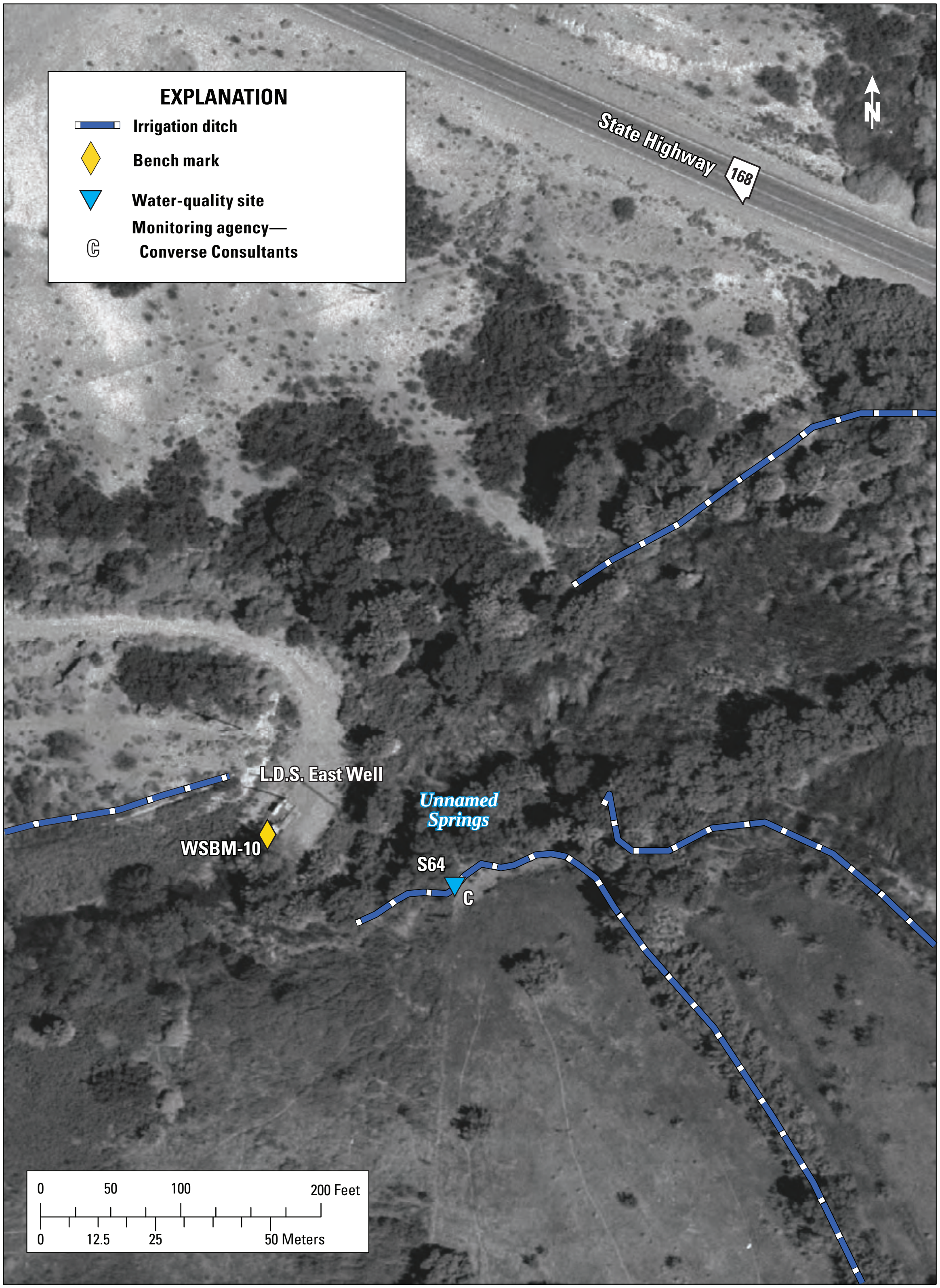

Figure B68. Location of unnamed springs near L.D.S. East well and bench mark WSBM-10 in the Warm Springs area near Moapa, Nevada.

Figure B69. Location of bench mark WSBM-10 at L.D.S. East well and spring-fed pool surveyed on August 17, 2004, at unnamed springs near Moapa, Nevada. Elevation of bench mark in feet above NAVD 88.

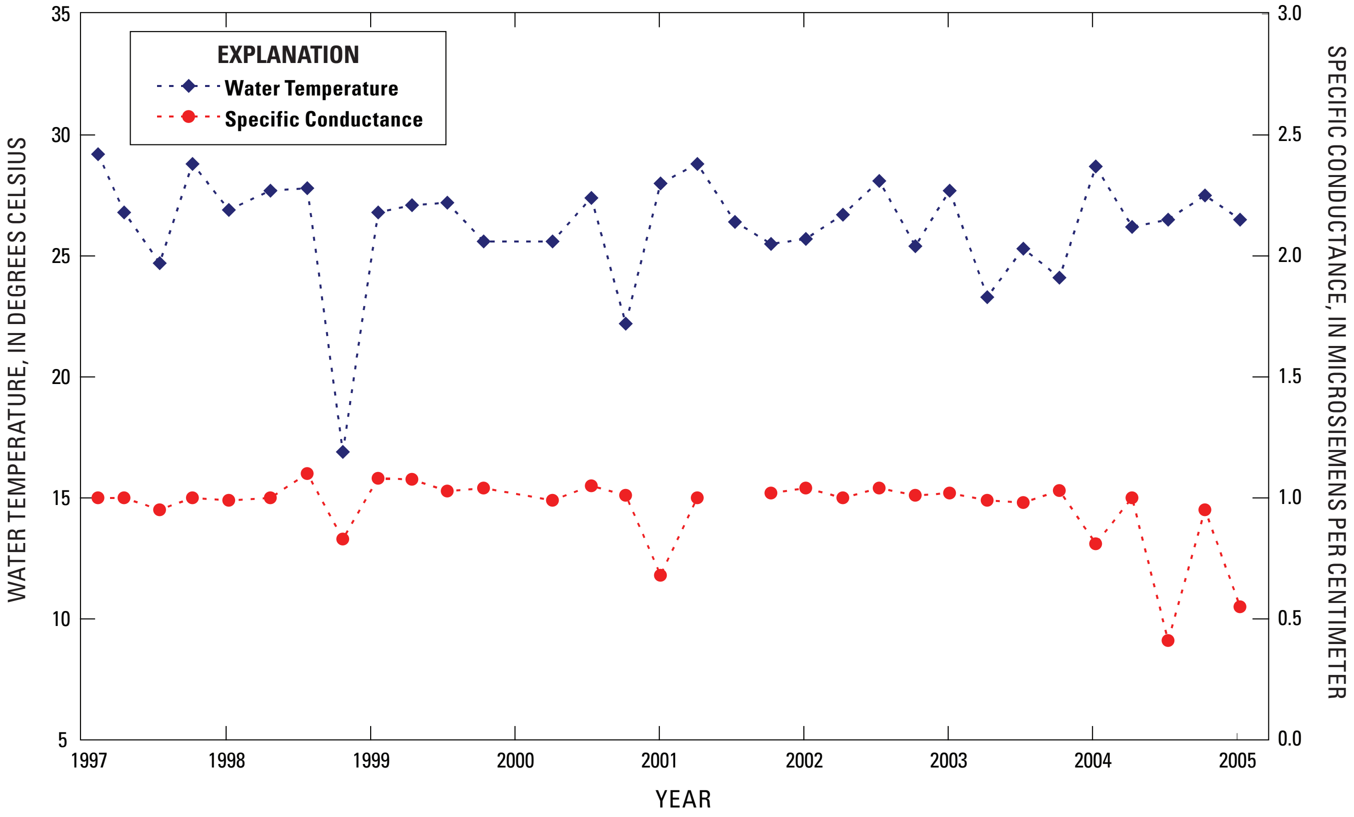

Figure B70. Water-temperature and specific-conductance measurements for spring pond at unnamed springs at L.D.S. East well near Moapa, Nevada, 1997–2005. Measurements provided by Converse Consultants.

Table B52. Water-temperature and specific-conductance measurements by Converse Consultants for spring pond at unnamed springs at L.D.S. East well near Moapa, Nevada, 1997–2005.

Table B52 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Miscellaneous Water-Quality Sites in the Warm Springs area near Moapa, Nevada

In April 1997, Converse Consultants, on contract with Nevada Power Company, began quarterly field measurements of water temperature and specific conductance at selected springs within the Warm Springs area. Most of the measurement sites are located at springs that are included as part of the major spring groups, such as Plummer, Pederson, Apcar, Muddy, and Cardy Lamb, and are discussed elsewhere in this report. Other measurement sites that are not part of the major spring groups include S6, S7a, and S65. The locations of these sites are shown in figure B71.

Water temperature and specific conductance data for the period of record for sites S6, S7a, and S65 are plotted in figures B72, B73, and B74 and listed in tables B53, B54, and B55, respectively.

Figure B71. Location of Converse Consultants water-quality sites S6, S7a, and S65 in the Warm Springs area near Moapa, Nevada.

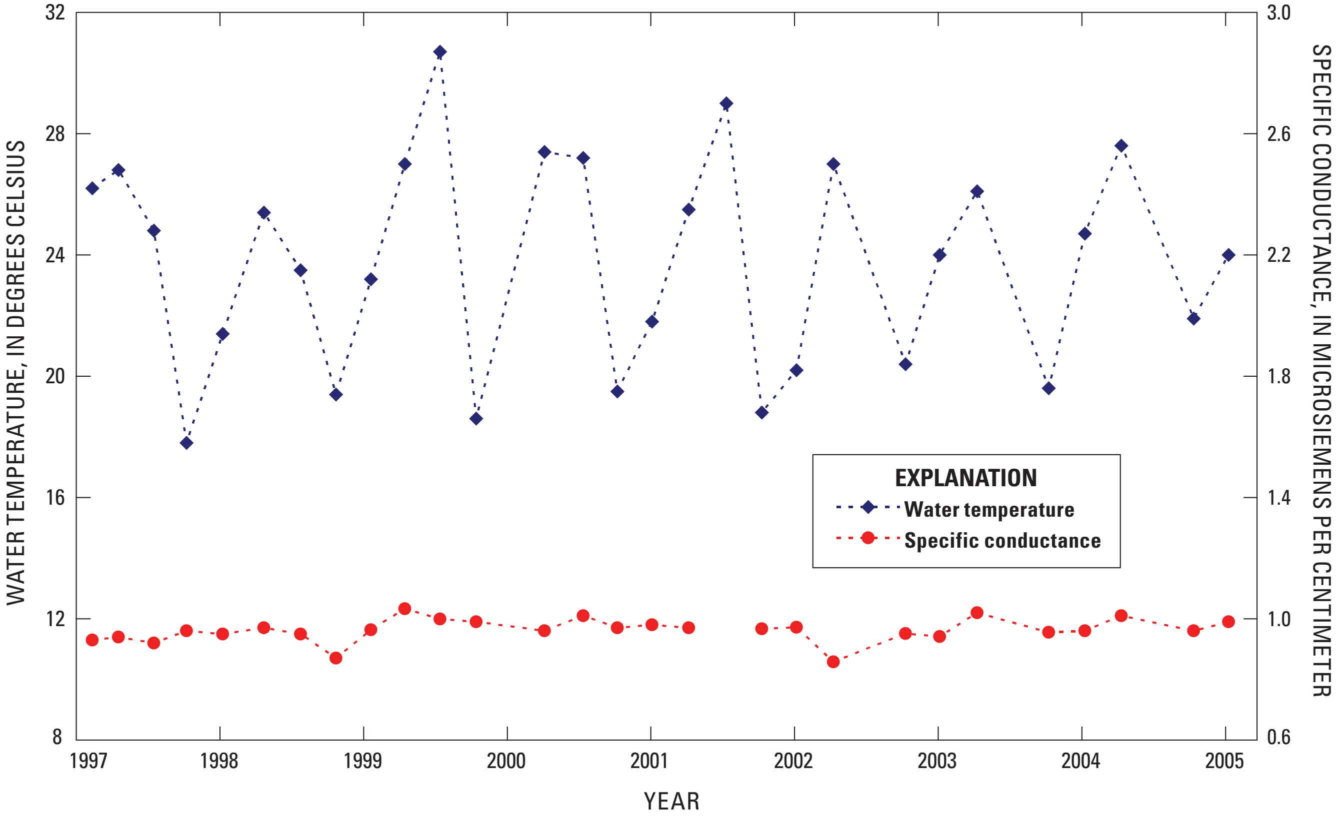

Figure B72. Water-temperature and specific-conductance measurements for site S6 in the Warm Springs area near Moapa, Nevada, 1997–2005. Measurements provided by Converse Consultants.

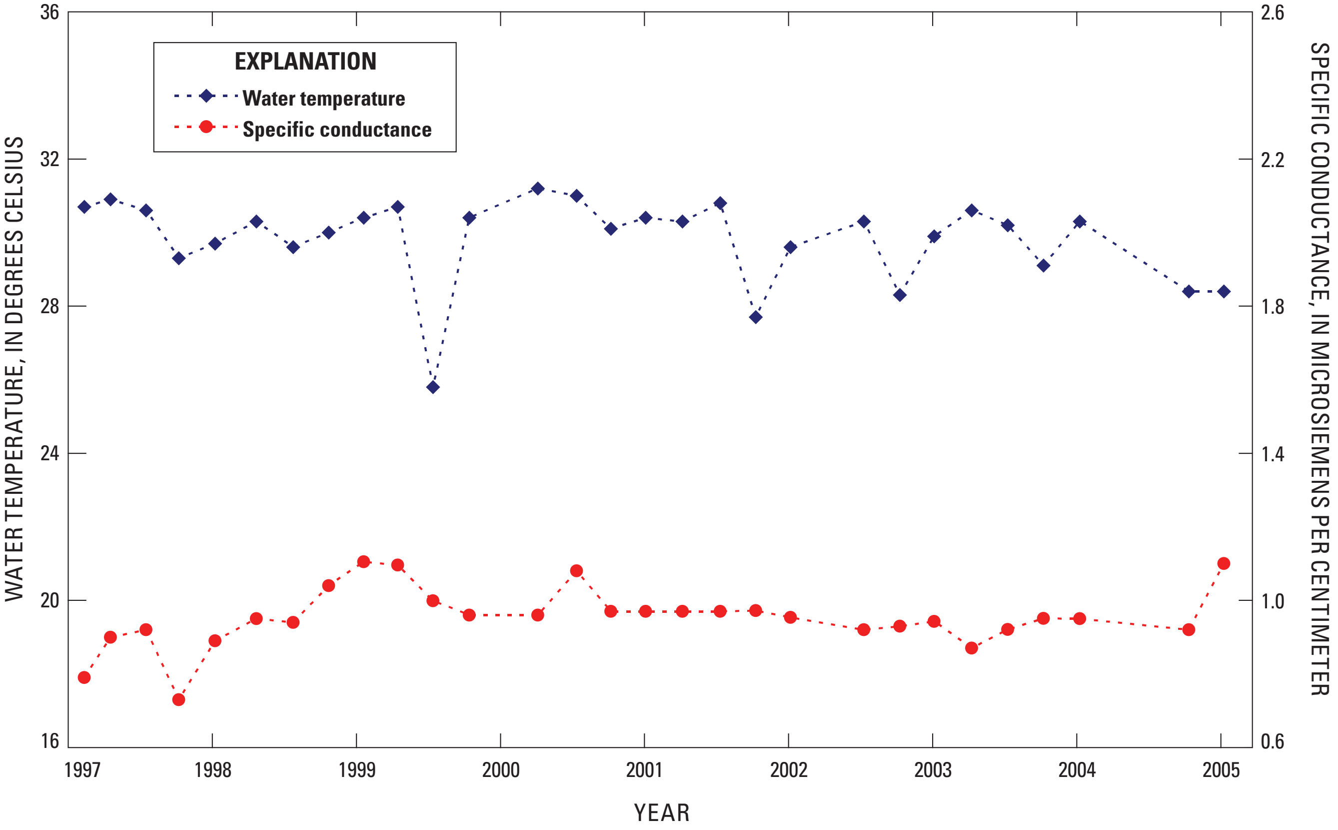

Figure B73. Water-temperature and specific-conductance measurements for site S7a in the Warm Springs area near Moapa, Nevada, 1997–2005. Measurements provided by Converse Consultants.

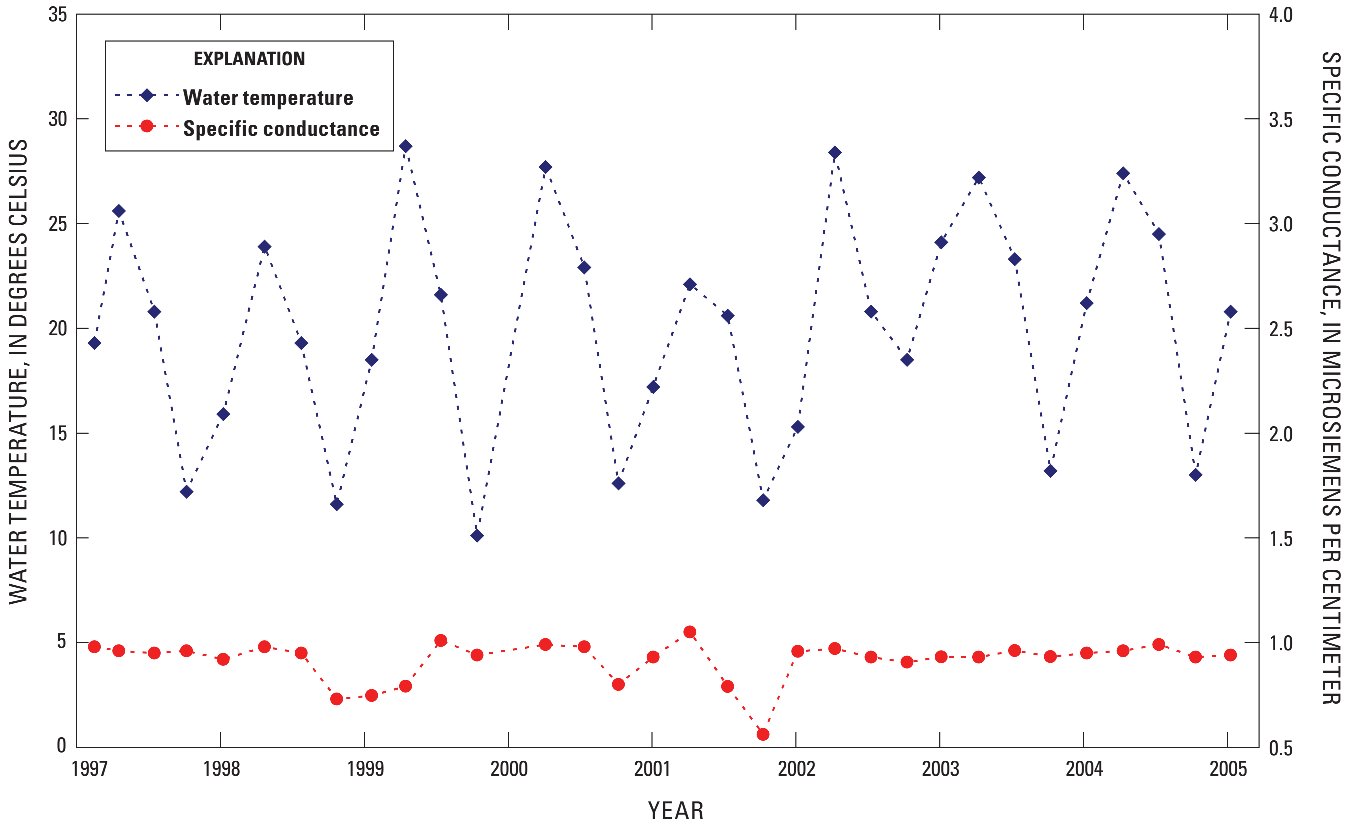

Figure B74. Water-temperature and specific-conductance measurements for site S65 in the Warm Springs area near Moapa, Nevada, 1997–2005. Measurements provided by Converse Consultants.

Table B53. Water-temperature and specific-conductance measurements by Converse Consultants at site S6 in the Warm Springs area near Moapa, Nevada, 1997–2005.

Table B53 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B54. Water-temperature and specific-conductance measurements by Converse Consultants at site S7a in the Warm Springs area near Moapa, Nevada, 1997–2005.

Table B54 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table B55. Water-temperature and specific-conductance measurements by Converse Consultants at site S65 in the Warm Springs area near Moapa, Nevada, 1997–2005.

Table B55 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

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Appendix C. National Geodetic Survey OPUS Solution Reports for Bench Marks Established in the Warm Springs Area near Moapa, Nevada

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WSBM-1 Jones Spring Box

```
 FILE: PJONES0370.04o 000181204    WSBM-1 JONES SPRING BOX

                           NGS OPUS SOLUTION REPORT
                           ========================

      USER: ray.overgaard@lvvwd.com                   DATE: June 18, 2004
RINEX FILE: pjon037r.04o                              TIME: 17:03:39 UTC


  SOFTWARE: page5 0310.28 master.pl                  START: 2004/02/06 17:26:00
 EPHEMERIS: igs12565.eph [precise]                    STOP: 2004/02/06 20:54:00
  NAV FILE: brdc0370.04n OBS                          USED: 6407 / 6719 :
95%
  ANT NAME: TRM39105.00                       # FIXED AMB: 34 / 34 :
100%
ARP HEIGHT: 2.0                               OVERALL RMS: 0.012(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2004.1006)

         X: -2140784.624(m)       0.013(m)        -2140785.306(m)   0.013(m)
         Y: -4650263.659(m)       0.018(m)        -4650262.351(m)   0.018(m)
         Z:  3792408.497(m)       0.013(m)         3792408.467(m)   0.013(m)

       LAT: 36 42 54.57120        0.022(m)       36 42 54.58793      0.022(m)
     E LON: 245 16 50.36615       0.006(m)      245 16 50.31915      0.006(m)
     W LON: 114 43 9.63385        0.006(m)       114 43 9.68085      0.006(m)
    EL HGT:      514.513(m)       0.009(m)              513.772(m)   0.009(m)
 ORTHO HGT:      541.260(m)       0.026(m)   [Geoid03 NAVD88]

PLANE COORDINATES    North(Y)        East(X)    Convergence (deg) Point Scale
  UTM(Zone 11): 4065699.133(m)  703693.822(m)      1.36393077      1.00011119
SPC(2701 NV E): 8218368.507(m)  277184.288(m)      0.51655125      0.99997337

US NATIONAL GRID DESIGNATOR: 11SQA0369465699(NAD 83)


                              BASE STATIONS USED
PID       DESIGNATION                    LATITUDE   LONGITUDE    DISTANCE(m)
AI8811 RAIL RAILROAD VALLEY CORS ARP    N381649.535  W1153953.379   192820.1
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP   N360934.026  W1151128.797    74796.5
AI8817 ECHO ECHO CANYON S.P. CORS ARP   N375455.904  W1141551.242   139221.2

                     NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                       N364330.247  W1144238.752     1342.7


This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
```

WSBM-1 Jones Spring Box

```
 FILE: 63371260.04o 000186248       WSBM-1 JONES SPRING BOX

                             NGS OPUS SOLUTION REPORT
                             ========================

      USER: wstout@stantec.com                      DATE: July 06, 2004
RINEX FILE: 6337126s.04o                            TIME: 13:24:32 UTC


  SOFTWARE: page5  0310.28 master13.pl             START: 2004/05/05  18:39:00
 EPHEMERIS: igs12693.eph [precise]                  STOP: 2004/05/05  21:49:00
  NAV FILE: brdc1260.04n                        OBS USED:  7338 /  7789   :  94%
  ANT NAME: TRM22020.00+GP                    # FIXED AMB:    46 /    47   :  98%
ARP HEIGHT: 1.513                             OVERALL RMS: 0.015(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3438)

         X:     -2140784.616(m)   0.008(m)         -2140785.303(m)   0.008(m)
         Y:     -4650263.643(m)   0.020(m)         -4650262.335(m)   0.020(m)
         Z:      3792408.487(m)   0.016(m)          3792408.455(m)   0.016(m)

       LAT:   36 42 54.57129      0.025(m)        36 42 54.58793      0.025(m)
     E LON:  245 16 50.36617      0.007(m)       245 16 50.31899      0.007(m)
     W LON:  114 43  9.63383      0.007(m)       114 43  9.68101      0.007(m)
    EL HGT:           514.493(m)  0.010(m)                513.752(m)  0.010(m)
 ORTHO HGT:           541.240(m)  0.027(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065699.136(m)   703693.822(m)     1.36393077      1.00011119
SPC(2701 NV E):  8218368.510(m)   277184.288(m)     0.51655125      0.99997337

US NATIONAL GRID DESIGNATOR: 11SQA0369465699(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74796.5
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139221.2
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  179188.7

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1342.7

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
```

WSBM-2 Pipeline Jones Flume

```
FILE: PLJF2022.04O 000197690        WSBM-2 PIPELINE JONES FLUME

                              NGS OPUS SOLUTION REPORT
                              ========================

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RINEX FILE: pljf202q.04o                             TIME: 23:23:16 UTC


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 EPHEMERIS: igs12802.eph [precise]                  STOP: 2004/07/20  19:22:00
  NAV FILE: brdc2020.04n                        OBS USED:  4913 /  5407   :
91%
  ANT NAME: ASH701975.01B                    # FIXED AMB:    44 /    52   :
85%
ARP HEIGHT: 1.618994284                      OVERALL RMS: 0.023(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.5512)

         X:     -2140422.324(m)   0.032(m)          -2140423.016(m)   0.032(m)
         Y:     -4650504.929(m)   0.093(m)          -4650503.621(m)   0.093(m)
         Z:      3792297.200(m)   0.061(m)           3792297.167(m)   0.061(m)

       LAT:   36 42 50.36476      0.014(m)        36 42 50.38133      0.015(m)
     E LON:  245 17  7.69085      0.014(m)       245 17  7.64348      0.015(m)
     W LON:  114 42 52.30915      0.014(m)       114 42 52.35652      0.015(m)
    EL HGT:           502.227(m)   0.114(m)                501.487(m)   0.114(m)
 ORTHO HGT:           528.987(m)   0.117(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065579.735(m)   704126.795(m)     1.36677342      1.00011337
SPC(2701 NV E):  8218242.737(m)   277615.388(m)     0.51941452      0.99997419

US NATIONAL GRID DESIGNATOR: 11SQA0412765580(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74935.1
DG4673 NVCS CARLTON SQUARE CORS ARP        N361311.196 W1151019.335   68482.8
DG4263 NVLK A M SMITH WTF CORS ARP         N360410.758 W1144847.501   72049.9

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1278.2

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-3 Baldwin Spring

```
FILE: BALDW0370.04o 000179255    WSBM-3 BALDWIN SPRING

                            NGS OPUS SOLUTION REPORT
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      USER: sean.corkill@lvvwd.com                DATE: June 14, 2004
RINEX FILE: bald037r.04o                          TIME: 16:47:25 UTC

  SOFTWARE: page5 0310.28 master11.pl            START: 2004/02/06 17:48:00
 EPHEMERIS: igs12565.eph [precise]                STOP: 2004/02/06 22:21:00
  NAV FILE: brdc0370.04n OBS                      USED: 8527 / 8987 :
95%
  ANT NAME: TRM39105.00                    # FIXED AMB: 38 / 38 :
100%
ARP HEIGHT: 2.0                            OVERALL RMS: 0.011(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)         ITRF00 (EPOCH:2004.1007)

         X: -2140993.956(m)       0.011(m)         -2140994.639(m) 0.012(m)
         Y: -4649779.403(m)       0.014(m)         -4649778.096(m) 0.014(m)
         Z:  3792880.888(m)       0.016(m)          3792880.858(m) 0.016(m)

       LAT:  36 43 13.68727       0.022(m)          36 43 13.70397 0.022(m)
     E LON: 245 16 34.54462       0.005(m)         245 16 34.49760 0.006(m)
     W LON: 114 43 25.45538       0.005(m)         114 43 25.50240 0.006(m)
    EL HGT:       514.520(m)      0.005(m)              513.779(m) 0.005(m)
 ORTHO HGT:       541.243(m)      0.025(m)    [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)      East(X)    Convergence (deg) Point Scale
  UTM(Zone 11):  4066278.958(m) 703287.239(m)    1.36146974       1.00010915
SPC(2701 NV E):  8218954.202(m) 276786.380(m)    0.51398731       0.99997262

US NATIONAL GRID DESIGNATOR: 11SQA0328766279(NAD 83)


                               BASE STATIONS USED
PID        DESIGNATION                  LATITUDE   LONGITUDE    DISTANCE(m)
AI8811 RAIL RAILROAD VALLEY CORS ARP   N381649.535  W1153953.379    192119.4
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP  N360934.026  W1151128.797     75061.4
AI8817 ECHO ECHO CANYON S.P. CORS ARP  N375455.904  W1141551.242    138770.8

                      NEAREST NGS PUBLISHED CONTROL POINT
GR0790       M 301                     N364354.     W1144332.         1257.1


This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-3 Baldwin Spring

```
 FILE: 98511260.04o 000186245       WSBM-3 BALDWIN SPRING

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: wstout@stantec.com                      DATE: July 06, 2004
RINEX FILE: 9851126s.04o                            TIME: 13:20:22 UTC


  SOFTWARE: page5  0310.28 master10.pl             START: 2004/05/05  18:08:00
 EPHEMERIS: igs12693.eph [precise]                  STOP: 2004/05/05  21:37:00
  NAV FILE: brdc1260.04n                        OBS USED:  8091 /  8608   :  94%
  ANT NAME: TRM22020.00+GP                   # FIXED AMB:    60 /    61   :  98%
ARP HEIGHT: 1.532                            OVERALL RMS: 0.013(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3438)

         X:     -2140993.957(m)   0.012(m)          -2140994.645(m)   0.012(m)
         Y:     -4649779.394(m)   0.036(m)          -4649778.087(m)   0.036(m)
         Z:      3792880.876(m)   0.020(m)           3792880.844(m)   0.020(m)


       LAT:   36 43 13.68711      0.024(m)        36 43 13.70372      0.024(m)
     E LON:  245 16 34.54444      0.005(m)       245 16 34.49723      0.005(m)
     W LON:  114 43 25.45556      0.005(m)       114 43 25.50277      0.005(m)
    EL HGT:          514.506(m)   0.038(m)               513.766(m)   0.038(m)
 ORTHO HGT:          541.229(m)   0.045(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4066278.953(m)   703287.235(m)     1.36146971      1.00010915
SPC(2701 NV E):  8218954.197(m)   276786.375(m)     0.51398727      0.99997262

US NATIONAL GRID DESIGNATOR: 11SQA0328766279(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                          LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   75061.4
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  138770.8
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  179877.2

                 NEAREST NGS PUBLISHED CONTROL POINT
GR0790      M 301                          N364354.    W1144332.       1257.1

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
```

WSBM-4 Warm Springs Road near Iverson Flume

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 FILE: 63371280.04o 000186246      WSBM-4 WARM SPRINGS ROAD NEAR IVERSON FLUME

                             NGS OPUS SOLUTION REPORT
                             ========================

      USER: wstout@stantec.com                       DATE: July 06, 2004
RINEX FILE: 6337128p.04o                             TIME: 13:22:43 UTC


  SOFTWARE: page5  0310.28 master10.pl              START: 2004/05/07  15:10:00
 EPHEMERIS: igs12695.eph [precise]                   STOP: 2004/05/07  19:09:00
  NAV FILE: brdc1280.04n                         OBS USED:  8626 /  9082   :  95%
  ANT NAME: TRM22020.00+GP                     # FIXED AMB:    41 /    45   :  91%
ARP HEIGHT: 1.509                              OVERALL RMS: 0.018(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2004.3490)

         X:     -2140193.907(m)   0.006(m)          -2140194.595(m)   0.006(m)
         Y:     -4650873.598(m)   0.027(m)          -4650872.290(m)   0.026(m)
         Z:      3791988.550(m)   0.030(m)           3791988.518(m)   0.029(m)


       LAT:   36 42 37.69617      0.026(m)        36 42 37.71281      0.025(m)
     E LON:  245 17 22.26060      0.007(m)       245 17 22.21339      0.006(m)
     W LON:  114 42 37.73940      0.007(m)       114 42 37.78661      0.006(m)
    EL HGT:          509.641(m)   0.027(m)               508.900(m)   0.027(m)
 ORTHO HGT:          536.419(m)   0.037(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065197.918(m)   704497.654(m)     1.36908269      1.00011524
SPC(2701 NV E):  8217855.531(m)   277980.509(m)     0.52179138      0.99997489

US NATIONAL GRID DESIGNATOR: 11SQA0449865198(NAD 83)



                             BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74823.8
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139494.8
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  178428.4

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1625.2

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-5 Iverson Flume

```
FILE: IVRF1340.02o 000181214   WSBM-5 Iverson Flume

                            NGS OPUS SOLUTION REPORT
                            ========================

      USER: timothy.wolf\@lvvwd.com                 DATE: June 20, 2002
RINEX FILE: ivrf1340.02o                            TIME: 00:45:56 UTC
      Iverson Flume

  SOFTWARE: page5  0203.19                         START: 2002/05/14  18:19:00
 EPHEMERIS: igs11662.eph [precise]                  STOP: 2002/05/14  21:32:00
  NAV FILE: brdc1340.02n                       OBS USED:  6548 /  8503   :  77%
  ANT NAME: TRM33429.00-GP                  # FIXED AMB:    56 /    88   :  64%
ARP HEIGHT: 2.064                            OVERALL RMS: 0.031(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2002.3667)

         X:     -2140100.670(m)   0.040(m)          -2140101.316(m)   0.039(m)
         Y:     -4650849.449(m)   0.039(m)          -4650848.146(m)   0.039(m)
         Z:      3792063.111(m)   0.035(m)           3792063.095(m)   0.035(m)

       LAT:   36 42 40.81624      0.043(m)        36 42 40.83353      0.044(m)
     E LON:  245 17 25.26635      0.045(m)       245 17 25.22076      0.056(m)
     W LON:  114 42 34.73365      0.045(m)       114 42 34.77924      0.056(m)
    EL HGT:           505.380(m)   0.020(m)               504.638(m)   0.020(m)
 ORTHO HGT:           532.232(m)   0.032(m) [Geoid99 NAVD88]

       UTM:          Zone  11
  NORTHING:      4065295.862(m)
   EASTING:       704569.942(m)

       SPC:      Zone  2701(NV)
  NORTHING:      8217952.382(m)
   EASTING:       278054.227(m)

                              BASE STATIONS USED
PID       DESIGNATION                     LATITUDE LONGITUDE   DISTANCE(m)
AJ1826 lvwd LAS VEGAS VALLEY CORS ARP      N360934 W1151128       74945
AI8817 echo ECHO CANYON S.P. CORS ARP      N375455 W1141551      139381
AM7015 king KINGMAN CORS ARP               N351150 W1140229      178493

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330 W1144235        1521

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-6 Pederson Spring

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 FILE: 98511270.04o 000186254       WSBM-6 PEDERSON SPRING

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: wstout@stantec.com                    DATE: July 06, 2004
RINEX FILE: 9851127r.04o                          TIME: 13:28:22 UTC


  SOFTWARE: page5  0310.28 master16.pl           START: 2004/05/06  17:05:00
 EPHEMERIS: igs12694.eph [precise]                STOP: 2004/05/06  19:18:00
  NAV FILE: brdc1270.04n                      OBS USED:  5013 /  5505   :  91%
  ANT NAME: TRM22020.00+GP                  # FIXED AMB:    38 /    39   :  97%
ARP HEIGHT: 1.352                           OVERALL RMS: 0.014(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3463)

         X:     -2140635.851(m)   0.021(m)          -2140636.539(m)   0.021(m)
         Y:     -4650789.717(m)   0.050(m)          -4650788.409(m)   0.050(m)
         Z:      3791874.611(m)   0.033(m)           3791874.579(m)   0.033(m)

       LAT:   36 42 32.62813      0.023(m)        36 42 32.64476      0.022(m)
     E LON:  245 17  4.67332      0.006(m)       245 17  4.62611      0.006(m)
     W LON:  114 42 55.32668      0.006(m)       114 42 55.37389      0.006(m)
    EL HGT:          528.567(m)   0.057(m)               527.826(m)   0.057(m)
 ORTHO HGT:          555.339(m)   0.062(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065031.300(m)   704064.957(m)     1.36611433      1.00011306
SPC(2701 NV E):  8217695.352(m)   277545.456(m)     0.51885352      0.99997406

US NATIONAL GRID DESIGNATOR: 11SQA0406565031(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74444.4
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139768.1
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  178431.5

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1828.5

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-7 Warm Spring West

```
  FILE: 63371270.04o 000186256       WSBM-7 WARM SPRINGS WEST

                             NGS OPUS SOLUTION REPORT
                             ========================

      USER: wstout@stantec.com                    DATE: July 06, 2004
RINEX FILE: 6337127q.04o                          TIME: 13:30:09 UTC


  SOFTWARE: page5  0310.28 master12.pl           START: 2004/05/06  16:35:00
 EPHEMERIS: igs12694.eph [precise]                STOP: 2004/05/06  20:44:00
  NAV FILE: brdc1270.04n                      OBS USED:  9299 / 10186   :  91%
  ANT NAME: TRM22020.00+GP                  # FIXED AMB:    76 /    77   :  99%
ARP HEIGHT: 1.489                          OVERALL RMS: 0.018(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3464)

         X:     -2140471.493(m)   0.017(m)          -2140472.180(m)   0.017(m)
         Y:     -4650688.064(m)   0.041(m)          -4650686.756(m)   0.041(m)
         Z:      3792067.647(m)   0.025(m)           3792067.615(m)   0.025(m)

       LAT:   36 42 40.77093      0.024(m)        36 42 40.78757      0.024(m)
     E LON:  245 17  8.97619      0.006(m)       245 17  8.92901      0.006(m)
     W LON:  114 42 51.02381      0.006(m)       114 42 51.07099      0.006(m)
    EL HGT:           514.841(m)  0.041(m)                514.100(m)  0.041(m)
 ORTHO HGT:           541.609(m)  0.048(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065284.811(m)   704165.745(m)     1.36690186      1.00011356
SPC(2701 NV E):  8217947.310(m)   277649.968(m)     0.51959559      0.99997426

US NATIONAL GRID DESIGNATOR: 11SQA0416665285(NAD 83)



                             BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74711.2
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139497.0
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  178630.4

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1559.9

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-8 Plummer Springs

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 FILE: lowerspg.04o 000186250       WSBM-8 PLUMMER SPRINGS

                              NGS OPUS SOLUTION REPORT
                              ========================

      USER: wstout@stantec.com                      DATE: July 06, 2004
RINEX FILE: lowe127r.04o                            TIME: 13:26:19 UTC


  SOFTWARE: page5  0310.28 master11.pl             START: 2004/05/06  17:44:00
 EPHEMERIS: igs12694.eph [precise]                  STOP: 2004/05/06  21:10:00
  NAV FILE: brdc1270.04n                        OBS USED:  6437 /  8167   :  79%
  ANT NAME: TRM22020.00+GP                   # FIXED AMB:    59 /    62   :  95%
ARP HEIGHT: 1.497                            OVERALL RMS: 0.018(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3465)

         X:     -2140333.281(m)   0.025(m)          -2140333.969(m)   0.025(m)
         Y:     -4650782.745(m)   0.059(m)          -4650781.438(m)   0.059(m)
         Z:      3792016.409(m)   0.035(m)           3792016.377(m)   0.035(m)

       LAT:   36 42 38.89120      0.025(m)        36 42 38.90782      0.025(m)
     E LON:  245 17 15.62940      0.008(m)       245 17 15.58221      0.008(m)
     W LON:  114 42 44.37060      0.008(m)       114 42 44.41779      0.008(m)
    EL HGT:           506.840(m)   0.064(m)               506.099(m)   0.064(m)
 ORTHO HGT:           533.613(m)   0.068(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065230.818(m)   704332.224(m)     1.36799107      1.00011440
SPC(2701 NV E):  8217890.869(m)   277815.607(m)     0.52069416      0.99997458

US NATIONAL GRID DESIGNATOR: 11SQA0433265231(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   74758.8
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139505.8
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  178519.3

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1594.2

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-9 Moapa Gage

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 FILE: moapa.04o 000186252          WSBM-9 MOAPA GAGE

                              NGS OPUS SOLUTION REPORT
                              ========================

     USER: wstout@stantec.com                      DATE: July 06, 2004
RINEX FILE: moap128o.04o                            TIME: 13:28:36 UTC


  SOFTWARE: page5  0310.28 master13.pl             START: 2004/05/07  14:43:00
 EPHEMERIS: igs12695.eph [precise]                  STOP: 2004/05/07  19:16:00
  NAV FILE: brdc1280.04n                        OBS USED:  9839 / 10565   :  93%
  ANT NAME: TRM22020.00+GP                   # FIXED AMB:    55 /    60   :  92%
ARP HEIGHT: 1.482                            OVERALL RMS: 0.018(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2004.3489)

         X:     -2138947.267(m)   0.011(m)          -2138947.955(m)   0.011(m)
         Y:     -4651393.485(m)   0.031(m)          -4651392.178(m)   0.030(m)
         Z:      3792031.313(m)   0.014(m)           3792031.281(m)   0.014(m)

       LAT:   36 42 39.75208      0.020(m)        36 42 39.76870      0.020(m)
     E LON:  245 18 16.64346      0.005(m)       245 18 16.59627      0.005(m)
     W LON:  114 41 43.35654      0.005(m)       114 41 43.40373      0.005(m)
    EL HGT:          496.181(m)   0.030(m)               495.441(m)   0.030(m)
 ORTHO HGT:          522.985(m)   0.039(m) [Geoid03 NAVD88]

PLANE COORDINATES     North(Y)         East(X)   Convergence (deg) Point Scale
  UTM(Zone 11):  4065293.640(m)   705845.624(m)     1.37814070      1.00012205
SPC(2701 NV E):  8217931.299(m)   279329.556(m)     0.53083001      0.99997751

US NATIONAL GRID DESIGNATOR: 11SQA0584665294(NAD 83)



                              BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
AJ1826 LVWD LAS VEGAS VALLEY CORS ARP      N360934.026 W1151128.797   75663.6
AI8817 ECHO ECHO CANYON S.P. CORS ARP      N375455.904 W1141551.242  139059.9
AM7015 KING KINGMAN CORS ARP               N351150.480 W1140229.275  178031.7

                 NEAREST NGS PUBLISHED CONTROL POINT
GR0789      K 301                          N364305.    W1144136.        801.7

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-10 L.D.S. East Well

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FILE: LDSE1360.020 000181207   WSBM-10 L.D.S. EAST WELL


                            NGS OPUS SOLUTION REPORT
                            ========================

      USER: timothy.wolf\@lvvwd.com                 DATE: June 20, 2002
RINEX FILE: ldse1360.02o                            TIME: 00:49:18 UTC
      LDS East

  SOFTWARE: page5  0203.19                         START: 2002/05/16  16:39:00
 EPHEMERIS: igs11664.eph [precise]                  STOP: 2002/05/16  18:48:00
  NAV FILE: brdc1360.02n                       OBS USED:  4462 /  4699   :  95%
  ANT NAME: TRM39105.00                     # FIXED AMB:    29 /    31   :  94%
ARP HEIGHT: 2.045                            OVERALL RMS: 0.020(m)


 REF FRAME: NAD83(CORS96)(EPOCH:2002.0000)            ITRF00 (EPOCH:2002.3719)

         X:     -2139830.827(m)   0.012(m)          -2139831.473(m)   0.011(m)
         Y:     -4650119.731(m)   0.041(m)          -4650118.428(m)   0.041(m)
         Z:      3793106.491(m)   0.028(m)           3793106.474(m)   0.028(m)

       LAT:   36 43 22.98995      0.028(m)        36 43 23.00722      0.028(m)
     E LON:  245 17 22.85263      0.007(m)       245 17 22.80702      0.009(m)
     W LON:  114 42 37.14737      0.007(m)       114 42 37.19298      0.009(m)
    EL HGT:           507.381(m)   0.045(m)               506.639(m)   0.045(m)
 ORTHO HGT:           534.195(m)   0.051(m) [Geoid99 NAVD88]

       UTM:          Zone  11
  NORTHING:      4066594.241(m)
   EASTING:       704478.975(m)

       SPC:      Zone  2701(NV)
  NORTHING:      8219251.782(m)
   EASTING:       277982.483(m)

                              BASE STATIONS USED
PID       DESIGNATION                     LATITUDE LONGITUDE   DISTANCE(m)
AJ1826 lvwd LAS VEGAS VALLEY CORS ARP      N360934 W1151128       75976
AI8817 echo ECHO CANYON S.P. CORS ARP      N375455 W1141551      138151
AM7015 king KINGMAN CORS ARP               N351150 W1140229      179736

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330 W1144238         218

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-11 L.D.S. Gage

```
FILE: LDSG1340.020 000181206    WSBM-11 L.D.S. GAGE


                            NGS OPUS SOLUTION REPORT
                            ========================

      USER: timothy.wolf\@lvvwd.com               DATE: June 20, 2002
RINEX FILE: ldsg1340.02o                          TIME: 00:44:33 UTC
      LDS Gage

  SOFTWARE: page5  0203.19                       START: 2002/05/14  17:58:00
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   EASTING:       704018.131(m)

       SPC:      Zone  2701(NV)
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   EASTING:       277518.107(m)

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AI8817 echo ECHO CANYON S.P. CORS ARP      N375455 W1141551      138510
AM7015 king KINGMAN CORS ARP               N351150 W1140229      179674

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330 W1144238         635

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-11 L.D.S. Gage

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                                NGS OPUS SOLUTION REPORT
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US NATIONAL GRID DESIGNATOR: 11SQA0401866348(NAD 83)



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DG4263 NVLK A M SMITH WTF CORS ARP         N360410.758 W1144847.501   72803.4

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752     627.6

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-12 Baldwin Flume

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                              NGS OPUS SOLUTION REPORT
                              ========================

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99%
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     W LON:  114 43 17.43571      0.008(m)       114 43 17.48299      0.008(m)
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 ORTHO HGT:          539.212(m)   0.026(m) [Geoid03 NAVD88]

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DG4263 NVLK A M SMITH WTF CORS ARP         N360410.758 W1144847.501   72768.0

                 NEAREST NGS PUBLISHED CONTROL POINT
GR1414      L 301                          N364330.247 W1144238.752    1052.2

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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WSBM-13 M-10

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                                   NGS OPUS SOLUTION REPORT
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     W LON:  114 43 38.58223      0.005(m)       114 43 38.62950      0.005(m)
    EL HGT:          521.710(m)   0.017(m)               520.970(m)   0.016(m)
 ORTHO HGT:          548.411(m)   0.030(m) [Geoid03 NAVD88]

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US NATIONAL GRID DESIGNATOR: 11SQA0294866856(NAD 83)



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DG4263 NVLK A M SMITH WTF CORS ARP         N360410.758 W1144847.501   73213.6

                 NEAREST NGS PUBLISHED CONTROL POINT
GR0790      M 301                          N364354.    W1144332.        680.0

This position was computed without any knowledge by the National Geodetic
Survey regarding the equipment or field operating procedures used.
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Appendix D. Discharge and Water-Quality Data Collected by the U.S. Geological Survey During September 10–12, 1963, in the Warm Springs Area Near Moapa, Nevada

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WSBM-1 Jones Spring Box

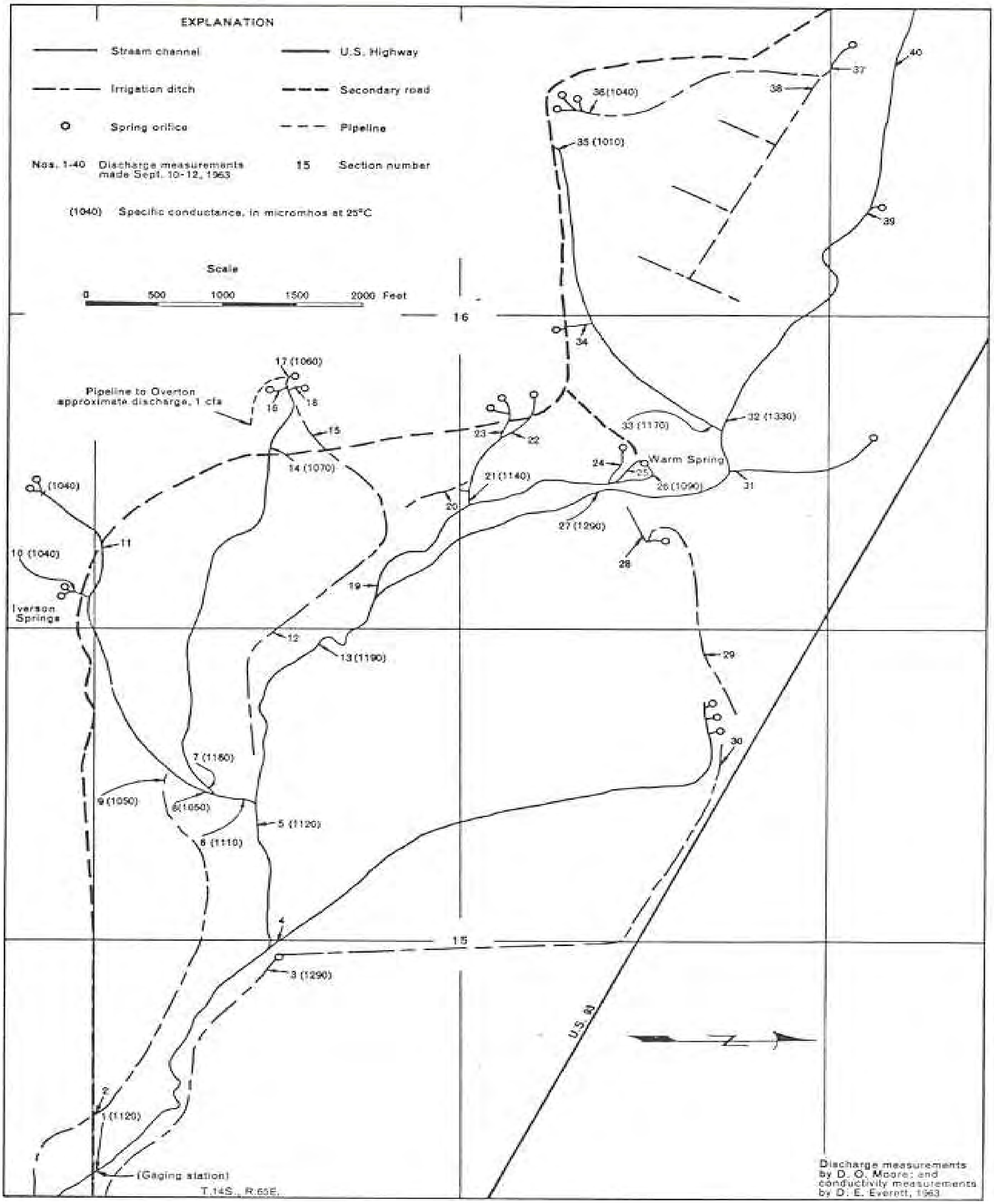

Figure D1. Sketch map showing location of discharge measurement sites in the Warm Springs area, September 12, 1963. (From Eakin, 1964.)

Table D1. Index of discharge and specific-conductance measurements in the Warm Springs area, September 10–12, 1963.

TableD1 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Appendix E. Discharge and Water-Quality Data Collected by the U.S. Geological Survey, U.S. Fish and Wildlife Service, Nevada Division of Water Resources, and Southern Nevada Water Authority on February 6–7, 2001, in the Warm Springs Area Near Moapa, Nevada

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Table E1. Index of discharge and water-quality measurement sites in the Warm Springs area, near Moapa, Nevada.

TableE1 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table E2. Discharge measurements made on February 7, 2001, in the Warm Springs area near Moapa, Nevada.

TableE2 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

Table E3. Water-quality data collected on February 6–7, 2001, in the Warm Springs area near Moapa, Nevada.

TableE3 data are available in an Excel data base for download at URL: http://pubs.water.usgs.gov/ofr2006-1311.

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Carson City, Nevada 89701
http://nv.water.usgs.gov

Beck and others

Water-Surface Elevations, Discharge, and Water-Quality Data for Selected Sites in the Warm Springs Area near Moapa, Nevada

OFR 2006-1311

U.S. Department of the Interior
U.S. Geological Survey

Hydraulic-Property Estimates for Use With a Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California

Water-Resources Investigations Report 01-4210

Prepared in cooperation with the
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U.S. DEPARTMENT OF ENERGY
National Nuclear Security Administration
Nevada Operations Office, under
Interagency Agreement DE-AI08-96NV11967

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Hydraulic-Property Estimates for Use With a Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California

By Wayne R. Belcher, Peggy E. Elliott, *and* Arthur L. Geldon

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Carson City, Nevada
2001

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PLATE

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic meter per day (m^3/d)	35.31	cubic foot per day
centimeter (cm)	0.394	inch
kilometer (km)	0.62137	mile
square kilometer (km^2)	0.3861	square mile
kilopascal (kPa)	0.14503	pound per square inch
liter (L)	0.26417	gallon
liter per second (L/s)	15.85	gallon per minute
meter (m)	3.2808	foot
meter per day (m/d)	3.2808	foot per day
meter squared per day (m^2/d)	10.76	foot squared per day
meter squared per day (m^2/d)	0.055916	gallon per minute per foot
meter squared per day (m^2/d)	80.52	gallon per day per foot
square meter (m^2)	10.76	square foot

Temperature: Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation: °F = (1.8 x °C) + 32.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Acronyms:

ACU	Alluvial confining unit
ANCOVA	Analysis of covariance
BRU	Belted Range unit
CFVU	Crater Flat volcanic unit
CHVU	Calico Hills volcanic unit
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DVRFS	Death Valley regional ground-water flow system
HGU	Hydrogeologic unit
HRMP	Hydrologic resources management program
ICU	Intrusive confining unit
LCA	Lower carbonate aquifer
LCCU	Lower clastic confining unit
LFU	Lava flow unit
NTS	Nevada Test Site
NWIS	National Water Information System
OAA	Older alluvial aquifer
OVU	Older volcanics unit
PVA	Paintbrush volcanic aquifer
SCU	Sedimentary confining unit
SWNVF	Southwest Nevada volcanic field
TMVA	Thirsty Canyon/Timber Mountain volcanic aquifer
TV	Tertiary volcanics
UCA	Upper carbonate aquifer
UCCU	Upper clastic confining unit
UGTA	Underground Testing Area
USGS	U.S. Geological Survey
VSU	Volcaniclastics and sediments unit
WVU	Wahmonie volcanic unit
YAA	Younger alluvial aquifer
YMP	Yucca Mountain Project
YVU	Younger volcanic unit
XCU	Crystalline confining unit

Hydraulic-Property Estimates for Use With a Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California

By Wayne R. Belcher, Peggy E. Elliott, *and* Arthur L. Geldon

ABSTRACT

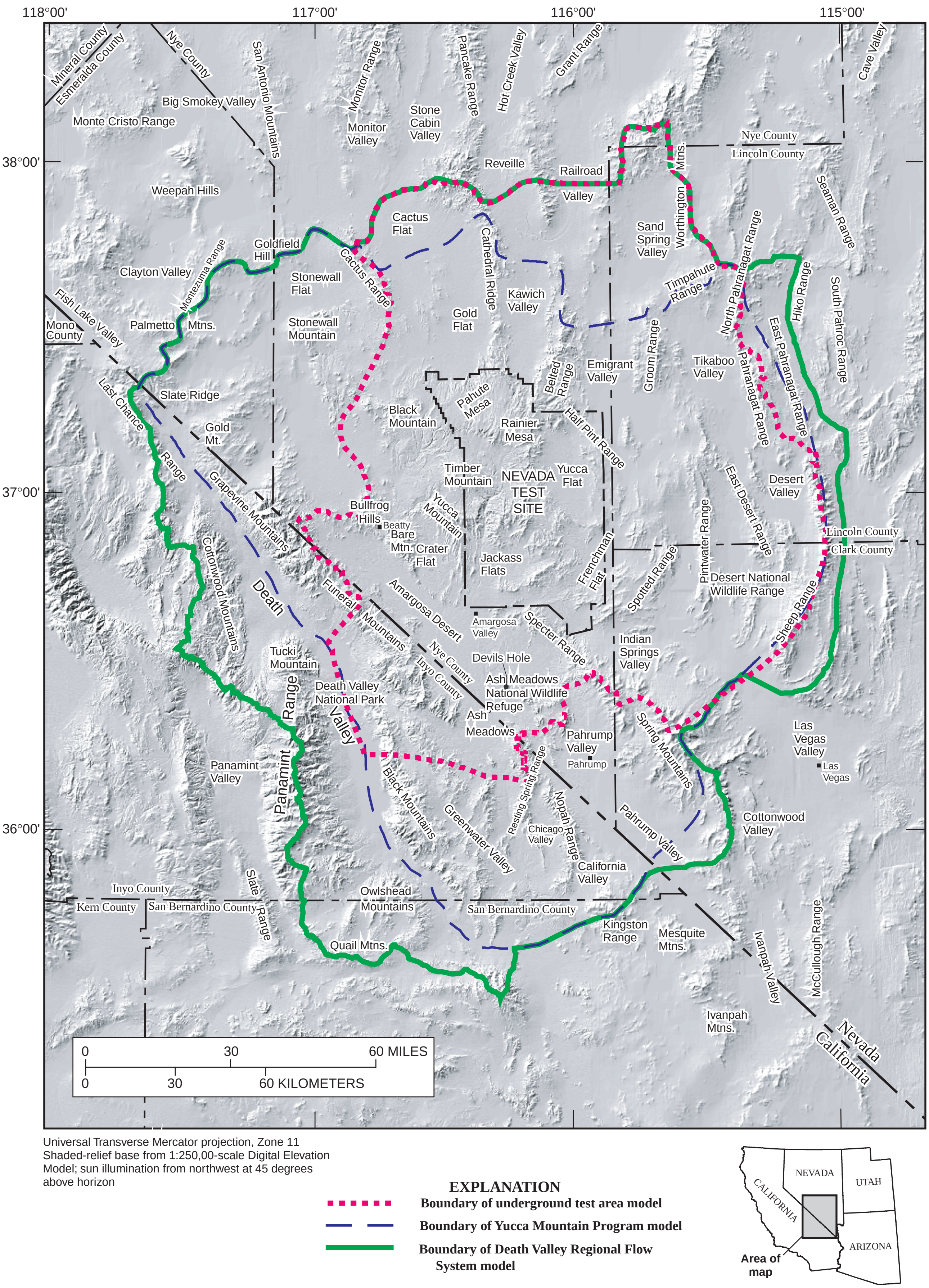
The Death Valley regional ground-water flow system encompasses an area of about 43,500 square kilometers in southeastern California and southern Nevada, between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west. The study area is underlain by Quaternary to Tertiary basin-fill sediments and mafic-lava flows; Tertiary volcanic, volcaniclastic, and sedimentary rocks; Tertiary to Jurassic granitic rocks; Triassic to Middle Proterozoic carbonate and clastic sedimentary rocks; and Early Proterozoic igneous and metamorphic rocks. The rock assemblage in the Death Valley region is extensively faulted as a result of several episodes of tectonic activity.

This study is comprised of published and unpublished estimates of transmissivity, hydraulic conductivity, storage coefficient, and anisotropy ratios for hydrogeologic units within the Death Valley region study area. Hydrogeologic units previously proposed for the Death Valley regional transient ground-water flow model, were recognized for the purpose of studying the distribution of hydraulic properties. Analyses of regression and covariance were used to assess if a relation existed between hydraulic conductivity and depth for most hydrogeologic units. Those analyses showed a weak, quantitatively indeterminate, relation between hydraulic conductivity and depth.

INTRODUCTION

The U.S. Department of Energy (DOE) and the U.S. Department of Defense (DOD) conducted various types of underground nuclear tests at the Nevada Test Site (NTS) in southern Nevada (fig. 1) between 1951 and 1992. Those tests produced radionuclides that contaminated ground water beneath portions of the NTS. In 1972, DOE established a long-term monitoring program to detect the presence of any radioactivity that may have been related to nuclear testing activities. Currently, DOE is evaluating contaminated areas as part of the Environmental Restoration program. The U.S. Geological Survey (USGS), in cooperation with the DOE, is evaluating the geologic and hydrologic characteristics of an area near Yucca Mountain, adjacent to the NTS, which is being considered for construction of an underground high-level nuclear waste repository. As part of these programs, the USGS is evaluating the regional ground-water flow system in the Death Valley region.

USGS evaluations include a detailed characterization of the ground-water flow system including development of a regional three-dimensional (3-D) conceptual and numerical ground-water flow model to help: (1) characterize regional 3-D ground-water flow paths, (2) define boundaries of the subregional and local flow systems, (3) define locations of regional ground-water discharges, (4) estimate magnitudes and rates of regional subsurface flux, (5) evaluate existing and potential anthropogenic effects on ground-water flow, (6) characterize potential impacts of the regional carbonate aquifer on subregional and local flow components, (7) determine potential effects of regional



Universal Transverse Mercator projection, Zone 11
Shaded-relief base from 1:250,00-scale Digital Elevation
Model; sun illumination from northwest at 45 degrees
above horizon

EXPLANATION

- ▪▪▪▪▪ **Boundary of underground test area model**
- — — **Boundary of Yucca Mountain Program model**
- ━━ **Boundary of Death Valley Regional Flow System model**

Figure 1. Geographic features and boundaries of the Death Valley regional ground-water flow system.

geologic structure on the flow system, (8) establish regional hydrologic boundaries of ground-water resources that may be unsafe for domestic or municipal use, and (9) prioritize ongoing local investigations.

Steady-state and time-dependent (transient) numerical ground-water flow models are being developed by the USGS to integrate and expand upon the existing ground-water models (Frank D'Agnese, U.S. Geological Survey, written commun., 2001). The USGS has compiled, analyzed, and synthesized hydraulic-property estimates for rocks and sediments within the Death Valley region for the basis of assigning hydraulic-property values to the various hydrogeologic units within the study area.

Location and Topography

The Death Valley regional ground-water flow system (DVRFS) is located within the Great Basin section of the Basin and Range physiographic province in southeastern California and southern Nevada between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west (fig. 1). The topography typically consists of northerly and northwesterly trending mountain ranges separated by broad sediment-filled basins. The Spring Mountains, the highest topographic feature in the area, rise to about 3,600 m above mean sea level. Other prominent topographic features within the region include the Sheep Range, Pahute Mesa, the Funeral Mountains, and the Panamint Range. The inter-mountain basins generally decrease in altitude from north to south. The lowest altitude in the study area (86 m below sea level) is in Death Valley National Park. Other areas of national importance within the study area include the Nevada Test Site (NTS), Yucca Mountain, the Ash Meadows National Wildlife Refuge, the Desert National Wildlife Refuge, and several military installations. Pahrump, Nevada, is the largest of several towns in the study area.

The DVRFS model area encompasses about 45,000 km^2. The area of the current study is significantly larger than the DVRFS model area to permit an adequate characterization of areas that contain sites important for defining hydraulic characteristics of hydrogeologic units (HGUs; fig. 2).

Purpose and Scope

The purpose of this report is to compile and statistically summarize published and unpublished hydraulic-property estimates (such as transmissivity, hydraulic conductivity, storativity, and specific storage) and to provide a statistical range of quality-assured hydraulic-property estimates for use in ongoing DVRFS simulation activities. The estimates are presented by proposed HGUs for use in a transient numerical ground-water flow model of the Death Valley region. Descriptive statistics of the estimates provide ranges and trends of the parameters for use in the model.

Previous Work

Ground-water flow in the Death Valley region was discussed and simulated independently by D'Agnese and others (1997) and IT Corporation (1996a). The two steady-state numerical models resulting from these investigations, the Yucca Mountain Project–Hydrologic Resources Management Program (YMP–HRMP) flow model (D'Agnese and others, 1997) and the Underground Test Area (UGTA) Phase I flow model (IT Corporation, 1996a), respectively, have overlapping domains (fig. 1). Both models were based on digital 3-D geologic framework models and both used 3-D finite-difference codes to simulate ground-water flow. The two models differ in the numerical codes used, the number of model layers, and the distribution of hydraulic properties within discrete layers.

Hydraulic-property estimates were compiled for use in the YMP–HRMP and UGTA ground-water flow models. Estimated values for the YMP–HRMP flow model (D'Agnese and others, 1997), however, were not developed from a hydraulic-properties database compiled as part of the simulation effort. Instead, model-layer properties were estimated from a plot of statistically distributed hydraulic properties for rock types in the Basin and Range province (Bedinger and others, 1989) as part of a study of the geology and hydrology of the province. Data compiled for their report consisted of published field and laboratory tests within the Basin and Range province, as well as general studies from rocks with similar characteristics from outside the province. Individual aquifer tests used to develop the statistical plot presented in Bedinger and others (1989) were not discussed, and no hydraulic data were evaluated.

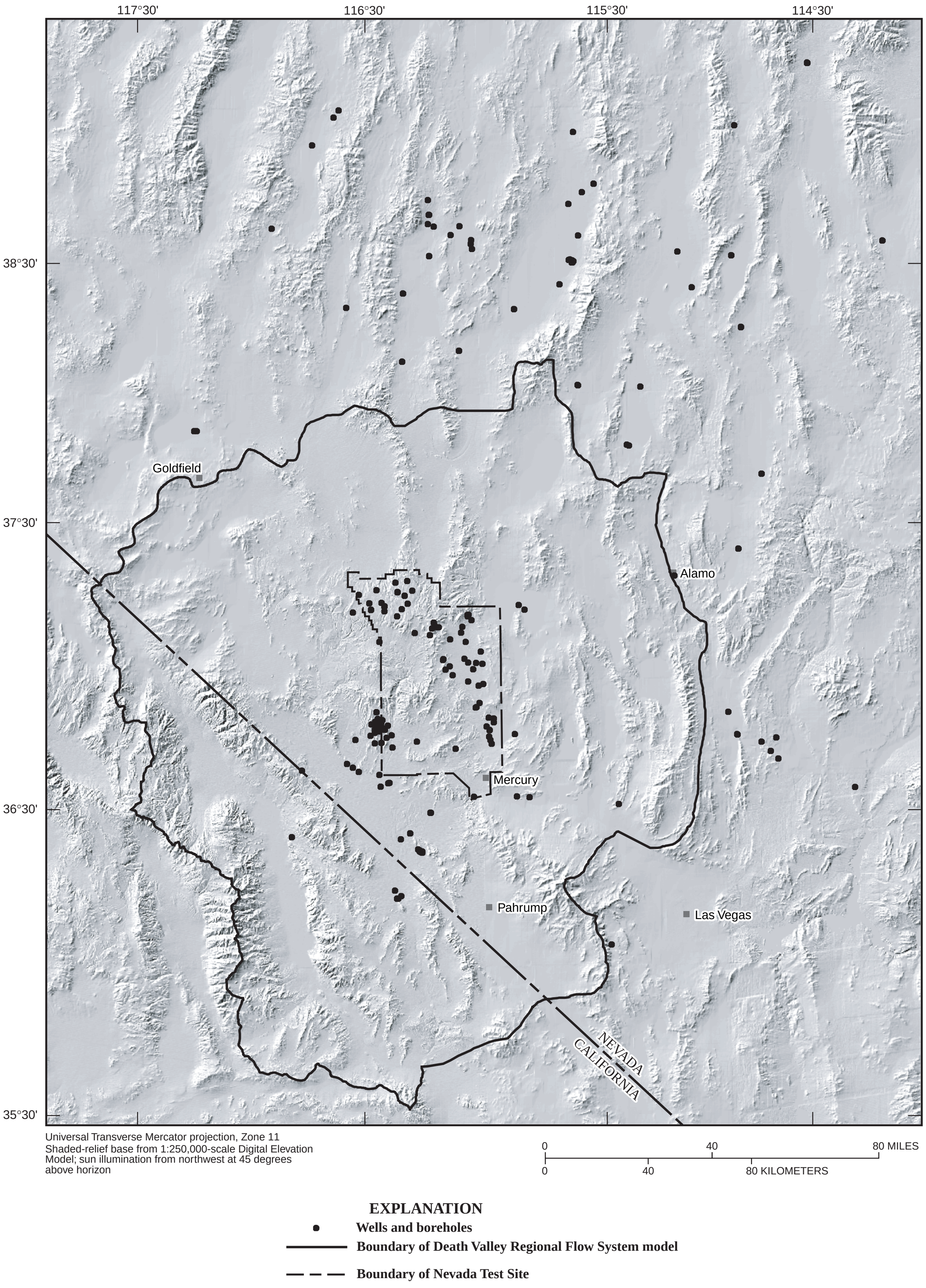


Figure 2. Locations of wells and boreholes used to determine estimates of hydraulic property.

IT Corporation (1996b) compiled a database that contains 731 analyses of transmissivity and hydraulic conductivity for the UGTA Phase I ground-water flow model. UGTA evaluated hydraulic properties from the literature (including re-interpretation of published data) and from UGTA-specific tests. Because the flow model was time independent, no values of storativity or specific yield were compiled. Databases from those simulation efforts have been expanded upon in this study.

Acknowledgments

We thank Dr. Keith Halford and Mr. David Prudic (both with the U.S. Geological Survey, Carson City, Nev.), Dr. Richard Waddell (GeoTrans, Denver, Colo.), and Mr. William Fryer (IT Corporation, Las Vegas, Nev.) for their thorough and critical reviews of the initial manuscript. Their efforts have greatly enhanced the quality of this work. We also acknowledge the efforts of Mr. Robert Bangerter (U.S. Department of Energy, Environmental Restoration Program, Nevada Operations) for providing the funding to complete this work.

HYDROGEOLOGIC SETTING

The Death Valley region has an active geologic history, including intermittent marine and non-marine sedimentation, large-scale compressive deformation, plutonism, volcanism, and extensional tectonics (Stewart, 1980; Mifflin, 1988). Much of the study area has undergone deformation, and some parts have experienced nearly continuous tectonic activity since the late Proterozoic (Grose and Smith, 1989). The structural features and faulting in the region are a result of the complex interaction of the North American and Pacific lithospheric plates (Smith and Sbar, 1974; Atwater and Stock, 1998). Combinations of normal, reverse, and strike-slip faulting and folding episodes (Carr, 1988) have resulted in a complex distribution of rocks. Consequently, diverse rock types, ages, and deformational structures are often juxtaposed and subsurface conditions are variable and complex. Knowledge of the geology beneath the alluvial basins is indirect in most of the region.

The rocks of the Death Valley region are comprised of Proterozoic and Cambrian siliciclastics and metamorphics; Paleozoic siliciclastic and carbonates; Mesozoic siliciclastics and intrusives; Pliocene fluvial, paludal, and playa sedimentary deposits; Tertiary volcanics and alluvium; and Tertiary alluvium and colluvium; and Quaternary eolian deposits (Waddell, 1982). Plate 1 presents a generalized stratigraphy of the Death Valley region.

Regional Ground-Water Hydrology

Hydraulic connection between basins within the DVRFS occurs through unconsolidated sediments present atop low interbasinal topographic divides and by deep interbasinal flow beneath valley floors and adjacent mountains through fractured Paleozoic carbonate rocks (Winograd and Thordarson, 1975; Prudic and others, 1995).

Faults can disrupt stratigraphic continuity, thereby diverting water in regional circulation to subregional and local outlets. Within the Death Valley region, faults and related fractures exert the greatest influence on ground-water flowing through bedrock aquifers (Faunt, 1997).

Ground-water flow is controlled also by lithologic variability along flow paths. In basin-fill sediments, changing depositional environments over short distances may result in substantial facies changes that can affect transmissivity and hydraulic conductivity, particularly where silt and clay become intermixed or interbedded with sand and gravel (Plume, 1996). In volcanic rocks, a characteristic change from lava flows to welded tuffs and, ultimately, non-welded and bedded tuffs with increasing distance from eruptive centers can cause hydraulic properties of the stratigraphic unit to exhibit great spatial variability (Laczniak and others, 1996).

Lateral facies changes within Paleozoic rocks might affect permeability. For example, a westward facies change in Mississippian rocks from predominantly limestone and dolomite to predominantly argillite and quartzite produce a barrier to regional ground-water flow in the vicinity of the NTS (Winograd and Thordarson, 1975). Cambrian and Proterozoic clastic, igneous, and metamorphic rocks force water upward into overlying aquifers and create flow-system boundaries throughout the Death Valley region (Winograd and Thordarson, 1975).

Factors other than lithology and structure in the Death Valley region that influence permeability and ground-water flow include increasing cementation of basin-fill sediments with age and decreasing fracture volume in bedrock aquifers (Winograd and Thordarson, 1975), alteration and welding in tuffs (Laczniak and others, 1996), and the effects of hydrochemical changes in response to thermal gradients (Moore and others, 1984).

Hydrogeologic Units

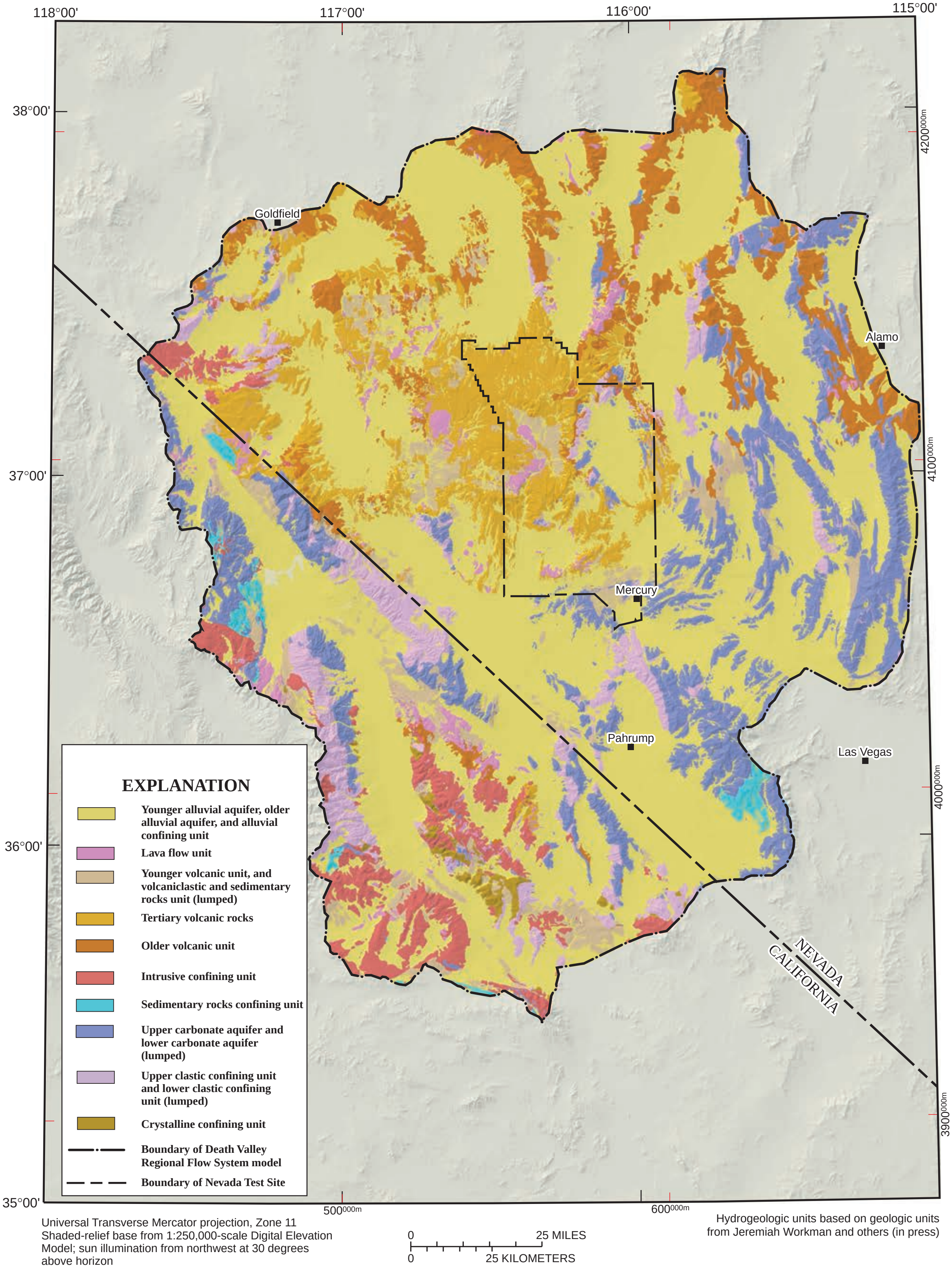
Physical characteristics were used by Winograd and Thordarson (1975) to group geologic formations of hydrologic significance in the vicinity of the NTS into HGUs. The seven HGUs defined by Winograd and Thordarson (1975), from oldest to youngest are: the lower clastic aquitard (currently termed the lower confining unit); the lower carbonate-rock aquifer; the upper clastic aquitard (currently termed the upper confining unit); the upper carbonate-rock aquifer; the tuff aquifers (currently termed volcanic-rock aquifers); volcanic aquitards (currently termed the volcanic confining units); and the valley-fill aquifer (currently termed alluvial aquifer). The lower confining unit forms the basement and generally is present beneath the other units except in caldera complexes. The lower carbonate-rock aquifer is the most extensive and transmissive in the region, but does not control ground-water flow within the caldera complexes. The upper confining unit is present in the north-central section of the NTS and restricts flow between overlying and underlying units; this unit also is associated with many of the steep hydraulic gradients in and around the NTS. The upper carbonate aquifer exists where it is physically separated from the lower carbonate aquifer by the upper clastic confining unit. The volcanic-rock aquifers and the volcanic confining units form a stacked series of alternating aquifers and confining units in and around the Southwest Nevada Volcanic Field (SWNVF). The volcanic-rock aquifers are moderately transmissive and are saturated in the western section of the NTS. The alluvial aquifer, though discontinuous, forms an important regional aquifer.

The major HGUs originally defined by Winograd and Thordarson (1975) form the basis of HGUs used in previous modeling studies (D'Agnese and others, 1997; IT Corporation, 1996a), in the ongoing DVRFS transient modeling study (Claudia Faunt, U.S. Geological Survey, written commun., 2001), and in this report. Although all the major geological features were retained, many of the smaller geologic units were grouped into larger entities by generalizing lithologic and hydrologic properties of the formations (fig. 3). Furthermore, the categorization of aquifers and confining units as distinct strata fails to account for structurally and lithologically controlled variations in hydraulic properties within geologic units and vertical ground-water flow between geologic units with different lithologies. On a regional scale, those factors exert strong influences on ground-water flow. While these terms are a useful designation, readers are cautioned about inferring hydraulic properties for a particular HGU, generally obtained from local-scale tests, to the hydraulic connectivity regional scale.

The DVRFS transient modeling study has further subdivided the unconsolidated sediments and consolidated rocks into 19 HGUs (table 1). For the purposes of this study, several of the DVRFS transient model HGUs were combined into a single HGU, such that a total of 11 HGUs are used (table 1). Each of the 11 HGUs has a quasi-uniform geological, structural, and hydrological characteristic and is laterally extensive.

DATA ANALYSIS AND SYNTHESIS

In this study, all aquifer-test results compiled from published reports were verified by re-analyzing the aquifer-test data using analytical solutions appropriate to the hydrogeologic setting in which those tests were conducted. If the published results agreed to within a factor of 2, the published results were accepted. If the difference between the published data and the independent calculations exceeded a factor of 2, and no independent justification was found for using the published data, the calculated values were reported. Because of the uncertainty associated with converting specific capacity data to transmissivity values, specific capacity data were not used. Because of the low volume of geologic material samples, results from the permeameter tests were not used in the analyses discussed in this report (with the exception of the clastic confining units). Following the elimination of suspect data and the addition of newly analyzed data, statistical methods were used to evaluate the distribution of hydraulic properties in the 11 DVRFS derived HGUs. Except for wells located on the Colorado Plateau in Utah, figure 2 shows the locations of the wells and boreholes used to collect data for the estimation of



Universal Transverse Mercator projection, Zone 11
Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

Hydrogeologic units based on geologic units from Jeremiah Workman and others (in press)

Figure 3. Surface distribution of hydrogeologic units in the Death Valley region.

Table 1. Geologic units and hydrogeologic units in the Death Valley regional ground-water flow system (DVRFS)

Hydrogeologic unit (this report)	Representative geologic units	Proposed transient DVRFS hydrogeologic unit [1]
Younger and older alluvial aquifers (YAA and OAA)	Quaternary stream-channel alluvium Quaternary eolian deposits Quaternary-Tertiary fan alluvium Quaternary-Tertiary landslide deposits	Younger alluvial aquifer (YAA) Older alluvial aquifer (OAA)
Alluvial confining unit (ACU)	Quaternary-Tertiary lacustrine and playa sediments; Quaternary-Tertiary spring-carbonate deposits	Alluvial confining unit (ACU)
Lava flow unit (LFU)	Basalt of Crater Flat-Amargosa Valley area Basalt of Jackass Flats Post-Thirsty Canyon basalt flows Funeral Formation Basalt of Lunar Crater area	Lava flow unit (LFU)
Younger volcanic unit and volcaniclastic and sedimentary rocks unit (YVU and VSU)	Furnace Creek Formation Artist Drive Formation Muddy Creek Formation Horse Spring Formation Pavits Spring Formation Panuga Formation Amargosa Valley Formation Titus Canyon Formation Sheep Pass Formation	Younger volcanic unit (YVU) Volcaniclastic and sedimentary rocks unit (VSU)
Tertiary volcanic rocks	Volcanics of Fortymile Canyon Volcanics of Stonewall Mountain Thirsty Canyon Group Timber Mountain Group Paintbrush Group Crater Flat Group Belted Range Group Calico Hils Formation Wahmonie Formation	Thirsty Canyon/Timber Mountain volcanic aquifer (TMVA) Paintbrush volcanic aquifer (PVA) Calico Hills volcanic unit (CHVU) Wahmonie volcanic unit (WVU) Belted Range/Crater Flat unit (BRCFU)
Older volcanic unit (OVU)	Kane Wash Tuff Tub Spring Tuff Hiko Tuff Shingle Pass Tuff Monotony Tuff Volcanics of Quartz Mountain Volcanic of Oak Spring Butte Volcanics of Kawich Valley Tunnel Formation Leach Canyon Formation Pahranagat Formation Tuff of Williams Ridge and Morey Peak	Older volcanic unit (OVU)
Intrusive confining unit (ICU)	Tertiary intrusive rocks Cretaceous intrusive rocks Jurassic intrusive rocks	Intrusive confining unit (ICU)

Table 1. Geologic units and hydrogeologic units in the Death Valley regional ground-water flow system (DVRFS)— Continued

Hydrogeologic unit (this report)	Representative geologic units	Proposed transient DVRFS hydrogeologic unit [1]
Sedimentary rocks confining unit (SCU)	Chinle Formation Moenkopi Formation Kaibab Limestone Toroweap Formation Permian redbeds	Sedimentary rocks confining unit (SCU)
Upper and lower carbonate aquifer (UCA and LCA)	Monte Cristo Group Pogonip Group Joana Limestone Guilmette Formation Nopah Formation Bonanza King Formation Carrara Formation Ely Springs Dolomite Bird Spring Formation Simonson Dolomite Sevy Dolomite Laketown Dolomite Ely Springs Dolomite	Upper carbonate aquifer (UCA) Lower carbonate aquifer (LCA)
Upper and lower clastic confining units (UCCU and LCCU)	Eleana Formation Chainman Shale Johnnie Formation Pilot Shale Wood Canyon Formation Zabriskie Quartzite Stirling Quartzite Pahrump Group	Upper clastic confining unit (UCCU) Lower clastic confining unit (LCCU)
Crystalline confining unit (XCU)	Middle Proterozoic igneous and metamorphic rocks	Crystalline confining unit (XCU)

[1] Claudia Faunt, U.S. Geological Survey, written commun., 2001.

hydraulic properties presented in this report. The Colorado Plateau wells are not contained in the USGS National Water Information System (NWIS) database and do not have exact locations associated with them. These wells were included in the analysis of hydraulic properties because they are completed in the sedimentary confining unit (table 1), of which data are sparse in the DVRFS.

The following hydraulic parameters are the primary focus of this study because of their use in ongoing numerical flow-modeling studies. The parameters were defined by Lohman (1979, p. 6 and 8):

Hydraulic conductivity (unit length per unit time): The coefficient that describes the ability of a geologic medium to "… transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow." Hydraulic conductivity can be calculated by dividing the transmissivity by the aquifer thickness (Lohman, 1979).

Transmissivity (square unit length per unit time): "… The rate at which water of the prevailing kinematic viscosity is transmitted [horizontally] through a unit width of the aquifer under a unit hydraulic gradient."

Specific yield (unitless): "The ratio of (1) the volume of water which after being saturated, it [rock or soil] will yield by gravity to (2) its [rock or soil] own volume." Specific yield is virtually the same as the storativity for unconfined aquifers.

Storage Coefficient or Storativity (unitless): "The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head."

Methods Used to Analyze Aquifer Tests

Aquifer tests in unconsolidated sediments throughout the Death Valley region were analyzed by conventional methods developed for porous media (Dawson and Istok, 1991; Driscoll, 1986; Lohman, 1979). Because the consolidated sedimentary and igneous rocks of the region tend to be heavily fractured and the aquifer volume generally is large enough to permit an equivalent porous-media response to pumping, porous-media analysis methods were deemed adequate. This assumption is examined in more detail in the section "Fractured Media and Equivalent Porous Media." Once a match has been determined, a point is selected and the corresponding coordinate values for head, time, dimensionless head, and dimensionless time are selected.

Several different methods were used to analyze the data which were acquired from tests of constant-rate pumping, slug (injection and bailing), swabbing, and drill stem. Common analytical methods are briefly described below, while details can be found in the cited references. Uncommon analytical methods used in this study are cited with the aquifer-test results (app. A).

Constant-rate pumping and injection tests were analyzed by curve-fitting methods. Theoretical solutions to aquifer-test problems are represented as dimensionless curves. Data in the form of water levels or recovery are plotted as a function of elapsed time on log-log scales. These data curves are then matched to the dimensionless curves. These match-point values are then substituted into analytical equations to estimate hydraulic-property values. The Theis (1935) solution was used for aquifer tests in non-leaky confined aquifers. Residual drawdown in pumping tests and residual water-level rise in injection tests were analyzed to determine transmissivity, storativity, and, if the representative thickness of the aquifer is known, hydraulic conductivity. For this method, water-level change was plotted as a function of the log of the ratio of elapsed time since pumping or injection started to the elapsed time since pumping or injection ceased (Theis, 1935). The Theis method, as do those methods discussed below for confined aquifers, assumes that observation wells completely penetrate homogeneous, isotropic, confined aquifer of infinite extent. Curve-fitting techniques for estimating transmissivity and storativity for leaky, confined aquifers without storage in the confining unit were developed by Hantush and Jacob (1955) and Cooper (1963). Curve-fitting methods for estimating the transmissivity and storativity for leaky, confined aquifers with storage in the confining unit were developed by Hantush (1961) and Bourdet (1985). For unconfined aquifers with anisotropy but using the other assumptions previously mentioned for confined aquifer methods, Boulton (1963), Stallman (1965), and Neuman (1975) developed curve-fitting techniques to estimate transmissivity, anisotropy, and storativity. It should be noted that the Neuman (1975) method may not be appropriate for use with fractured rock. Fractured rock has a "dual-porosity" response that comes from the immediate de-watering of fractures (being the most permeable), followed by the delayed response of de-watering from the matrix. The Neuman (1975) method assumes that this delayed response is due to aquifer depressurization and dewatering. In fractured rock, the delayed response is believed to be from the exchange of water between fractures and matrix rock. Neuman analyses reported in the database are primarily from non-fractured media (e.g., alluvium). Where the Neuman (1975) method was applied to fractured volcanic rocks, the database (app. A) contains the previously published values. Because of the above-mentioned conditions, vertical anisotropy estimates for fractured rock using the Neuman method are suspect.

In fractured hydrogeologic media, fluid can be contributed to the system either from fractures or the matrix. This "dual-porosity" concept involves the exchange of water between the fractures and the matrix. Several specialized methods involving this concept have been developed, some of which were used in the published hydraulic-property estimates compiled for this report. The two methods whose results are reported in the database are by Moench (1984) and Streltsova-Adams (1978). Both methods use derived type curves for dual-porosity solutions to aquifer-test problems to match time-drawdown data from pumping and observation wells.

Straight-line fitting methods involve fitting a straight line through drawdown or residual drawdown data as a function of the log time or distance from the test well, and then substituting the slope of this line into analytical equations to estimate hydraulic-property values. Under the same assumptions applicable for the Theis (1935) solution, the slope of a straight-line fit to drawdown or recovery data plotted as a function of log time the values of transmissivity and storativity can be determined (Cooper and Jacob, 1946).

In bailing tests, water is bailed repeatedly for an extended period, but some recovery of water level in well occurs as the bailer is brought to the surface, emptied, and then returned to the test interval. The average withdrawal rate, which is the total volume of water removed divided by the time that the well was bailed, does not account for drainage back to the well between bailing runs or variations in the rate of bailing. In most bailing tests, residual drawdown from bailing can be analyzed using the recovery method of Theis (1935).

In swabbing tests, a mechanical device is lowered into the well to displace water. After repeated runs, the average withdrawal rate is calculated in the same way that the average bailing rate is calculated. Residual drawdown is then analyzed using the recovery method of Theis (1935).

In slug tests, a known volume of water either is instantaneously removed from or is injected into a well, and the time history of water-level recovery to the static water level is monitored. Cooper and others (1967) developed a method for analyzing slug tests, which was later modified by Bredehoeft and Papadopulos (1980). In the solution of Cooper and others (1967), ratios of the water-level drawdown or rise to the static water level (H/H_0) are plotted as a function of log time since the test was initiated. Similar to the other curve-fitting techniques previously described, the data curve is then matched to a dimensionless type curve to obtain values of hydraulic properties.

Drill-stem tests are the standard way in which hydraulic properties of potential oil and gas reservoirs are evaluated by the petroleum industry (Bredehoeft, 1965). This test measures the pressure drop as the formation fluid (such as oil) moves from an isolated section of the borehole into a drill stem lowered into the borehole. In the method of Horner (1951), fluid-pressure recovery during the second shut-in period is plotted as a function of the ratio of the time elapsed during the shut-in period and preceding flow period to the time elapsed during the shut-in period.

Statistical Analyses

Descriptive statistics, including the geometric and arithmetic means, range, and the 95-percent confidence interval (±1.96 standard deviations from the geometric mean) of the hydraulic conductivity, storage parameters, and anisotropy ratios are reported for each of the HGUs. These parameters will be used to aid in the calibration of the DVRFS transient ground-water flow model. Because hydraulic conductivity tends to be log normally distributed (Neuman, 1982), the geometric mean of the estimates is reported. The arithmetic mean also is reported. Storage parameters tend to be normally distributed (Neuman, 1982) and because of this, the arithmetic mean of the estimates is reported. Values of hydraulic conductivity derived from pumping well data, when an observation well was available, were not used in the statistical calculations to avoid bias from re-sampling the same aquifer test. For similar reasons, slug tests from intervals that overlapped each other, although present in the database (app. A), were not used in the statistical calculations.

Fractured Media and Equivalent Porous Media

Most of the analytical methods used in this work assume that an aquifer is a porous medium. However, the influence of fractures is fundamental to the flow of water in volcanic and carbonate rocks. In order to apply these aquifer-test methods to fractured rocks it is necessary to assume that the rocks are sufficiently homogeneously fractured and interconnected such that the rock being tested can be considered “an equivalent porous medium.” The spacing of fractures, as well as their interconnectivity, can affect the results of an aquifer test. In areas where fractures are tightly spaced and interconnected, transmissivities generally are higher than in areas where the fractures are widely spaced and not interconnected. In a study on transmissivity in crystalline rock, slug tests using either porous or fractured media methods, provided estimates of transmissivity within an order of magnitude of each other (Shapiro and Hsieh, 1998). In the cases examined here, the equivalent-porous-medium assumption cannot be ruled out because plots of drawdown or recovery of water levels in wells conform to type curves derived for porous media.

Effects of Test Scale on Determination of Hydraulic Properties

Hydraulic-conductivity and transmissivity estimates are functions of test scale (Dagan, 1986; Neuman, 1990). As media test volume increases, more aquifer heterogeneity is encountered and influences the test results. For example, the potential exists to involve a larger network of fractures in the aquifer response to the imposed stress. In laboratory permeameter tests of core samples for determining rock matrix properties, unfractured core is needed for successful results. Because only matrix rock properties are determined from permeameter tests, the estimates generally are not useful for regional-scale ground-water flow models of fractured-rock aquifer systems. Thus, results for permeameter tests of core samples are not utilized in the descriptive statistical calculations of the hydraulic parameters (with the exception of the clastic confining units). Similarly, slug tests only examine a relatively small amount of aquifer material adjacent to the borehole. Because of this, hydraulic-property estimates from slug tests might not be representative of an entire unit. Single-well aquifer tests (including the pumping or injection well in multiple-well tests) optimally determine hydraulic properties in the near-borehole environment, but the accuracy of these tests can be decreased by inefficient borehole construction, convergence of flow lines and related head losses as water flows into or out of sections of perforated casing, and head loss as water moves between the test-interval depth and the pump-intake depth. As such, for the same set of wells transmissivity estimates derived from single-well tests tend to be less than those of multiple-well tests. Similarly, estimates of storage coefficients from single-hole tests are less reliable than those from multiple-well tests. Multiple-well aquifer tests tend to be more reliable because they manifest the influence of field-scale features, such as faults and fractures, as well as the water-transmitting properties of the rock matrix.

The hydraulic-property estimates presented in this report are based on the results of mostly field-scale tests involving wells. These tests include only a small amount of the volume of aquifer material within an HGU and thus are testing only a very small part of the HGU. The hydraulic-property estimates presented herein are intended to serve only as the basis for constraining flow estimates obtained from the simulation process. The scaling-up of these values for use in calibrating a regional ground-water flow model is problematic and is not explicitly addressed in this report.

General Limitations

General guidelines were used for selecting hydraulic-property data for compilation. These include: (1) the use of published aquifer-test results from wells in the DVRFS area. Selected unpublished data and aquifer-test results were evaluated and analyzed to fill spatial or hydrogeologic data gaps. (2) analyses of aquifer tests using methods appropriate to regional numerical ground-water flow models and (3) analyses for each HGU should be sufficient to provide adequate spatial coverage and statistically describe variance resulting from differences in lithology, fracturing, and faulting. Based on Freund (1992), about 30 samples are a sufficient number to statistically describe parameters. Because wells and boreholes often are installed for purposes other than obtaining hydraulic-property data (such as water supply or monitoring), the above quidelines were not satisfied completely. Selected unpublished DVRFS area aquifer-test results and published data are from hydrologically similar areas.

Analytical methods used to determine the hydraulic-property estimates presented in this report rely on assumptions about the type and configuration of the aquifer. These assumptions are necessary to simplify the flow system so that mathematical equations representing ground-water flow can be solved analytically but result in some uncertainty in the computed hydraulic properties.

Most analytical methods assume that flow to a pumping well is derived from an aquifer of infinite extent. This assumption may not be accurate for many aquifer tests presented in this report because of faults in the study area that may act as either recharge or barrier boundaries.

The most commonly applied analytical methods for pumping tests in the study area, those of Theis (1935) and Cooper and Jacob (1946), assume radial flow to the pumping well under an axisymmetric hydraulic gradient. However, because of media heterogeneities, hydraulic gradients may vary directionally. Differing results in hydraulic-property values obtained from multiple-well aquifer tests involving multiple observation wells may arise as a result of non-radial flow occurring in a part of the flow system monitored by one or more, but not all observation wells. Disregarding a non-uniform hydraulic gradient seemingly would result in inaccurate computations of hydraulic properties, if the solutions of Theis (1935) or Cooper and Jacob (1946) are used. Only a single estimate of transmissivity and storage properties should be reported for these particular tests. To obtain these single results, the average of the property estimates could be used. Because the purpose of this report is to compile and report on estimates of hydraulic properties for use with a numerical flow model, all estimates are considered to be independent with respect to the descriptive statistics (central tendency and spread). Estimates from a pumping well are excluded when one or more observation wells were available due to inaccuracies inherent in the pumping well estimates. Several estimates from the same well (in the case of packer tests) or the same test (in the case of multiple observation wells) can give a range of values reflecting varying material properties of the unit. It is reasoned that because the statistics describe the central tendency and the spread of these parameters for a particular unit, use of most the estimates is appropriate (except where tested intervals straddle each other). One limitation to this approach is that the statistics may be biased toward the estimates obtained from multiple-well tests.

Single-well pumping or slug tests can provide estimates of storativity. These estimates, however, may vary up to an order of magnitude of the actual value (Cooper and others, 1967, p. 267). The slug-test solution of Cooper and others used in these analyses is very insensitive to storativity. Storativity values calculated from slug tests were not used in the statistical summaries of the hydraulic-property estimates and are not reported in the database.

Spatial bias could be significant for the hydraulic-property estimates compiled in this report. Wells and boreholes were drilled to meet the original goals of their respective studies, not to collect data to determine statistically representative regional-scale hydraulic properties. Most information was collected from wells clustered around Yucca Mountain and the NTS. Data were collected for studies of these areas and the number of wells decreases away from these areas. Many wells also were installed in relatively shallow formations because of the difficulties and cost associated with drilling deep wells.

Limitations Regarding Hydraulic Conductivity Estimates

To obtain hydraulic-conductivity estimates for use in the calibration of the DVRFS model, transmissivity estimates were divided by the thickness or length of the open interval of the tested or monitored well or borehole. The aquifer thickness was not used as this generally was unknown. Because most wells are open to the productive intervals, in a heterogeneous aquifer, coupled with usage of the open-interval thickness, hydraulic-conductivity estimates may be biased toward the larger values. Thus, the statistical means and variances presented here may be only representative of the hydraulic properties of the more productive zones within an HGU.

Other limitations of the hydraulic-property estimates involve the variability inherent in the hydrogeologic media. Lithologic factors, such as facies changes in sedimentary rock, welding in volcanic rocks, and degree of fracturing can cause hydraulic properties to vary greatly over relatively short distances. Variability also can be caused by sampling biases. For example, differences in the overlap between lithologic or sedimentologic bedding and the tested interval can cause estimates of hydraulic conductivity to vary. Sampling variability also can arise in fractured rocks as a result of a borehole failing to penetrate rock fractures especially for vertical boreholes penetrating rocks with steeply dipping (subvertical) fractures. Because of the inherent nature of variability, longer-term aquifer tests typically will produce more representative hydraulic-property estimates (hydraulic conductivity and storativity) than shorter-term aquifer tests or tests with shorter screened intervals (such as packer tests). Because of this, a smaller statistical constraint on the parameter estimates during calibration of the DVRFS model where this condition applies.

HYDRAULIC PROPERTIES

The hydraulic-property estimates from aquifer-test results are statistically summarized for each of the HGUs in the hydrogeologic framework of the DVRFS. Horizontal hydraulic conductivity values are presented for all tests; specific yield and storativity values are presented for each HGU, if available. A summary of the hydraulic conductivity estimates of HGUs and subunits for HGUs are presented in table 2. A compilation of hydraulic-property estimates is provided in appendix A.

Younger Alluvial Aquifer and Older Alluvial Aquifer

Most basin-fill sediments are included in the younger alluvial aquifer (YAA) and the older alluvial Aquifer (OAA; fig. 3). The YAA and OAA consist of Holocene to Pliocene sand, gravelly sand, sandy gravel, and gravel, with cobbles, boulders, silty to clayey intervals, and thin interbeds of clay and silt, that

Table 2. Hydraulic conductivity distribution in Death Valley regional ground-water flow system hydrogeologic units

[Abbreviations: —, no data; m/d, meters per day; ACU, alluvial confining unit; BRU, Belted Range unit; CFVU, Crater Flat volcanic unit; ICU, intrusive confining unit; K, hydraulic conductivity in meters per day; LCA, lower carbonate aquifer; LCCU, lower clastic confining unit; LFU, lava flow unit; OAA, older alluvial aquifer; OVU, older volcanic unit; PVA, Paintbrush volcanic aquifer; SCU, sedimentary rocks confining unit; TMVA, Thirsty Canyon/Timber Mountain volcanic aquifer; TV, Tertiary volcanic rocks; UCA, upper carbonate aquifer; UCCU, upper clastic confining unit; VSU, volcaniclastic and sedimentary rocks unit; XCU, crystalline confining unit; YAA, younger alluvial aquifer; YVU, younger volcanic unit]

Hydrogeologic unit or subunit	Geometric mean K (m/d)	Arithmetic mean K (m/d)	Minimum K (m/d)	Maximum K (m/d)	95-percent confidence interval of geometric mean (m/d)	Number of analyses
YAA and OAA	2	11	0.001	130	0.6 – 4	43
ACU	3	11	.003	34	.6 – 10	13
LFU	—	—	.002	4	—	2
YVU and VSU	.06	1.5	.00004	6	.01 – .4	15
TV	.1	4	.000001	180	.08 – .2	159
Rhyolitic to rhyodacitic lava flows	.1	.6	.000007	4	.04 – .4	25
Ash-flow tuff	.1	5	.000002	180	.06 – .2	109
Non-welded to partially welded	.06	7	.003	180	.03 – .2	43
Partially to moderately welded	.04	1	.000002	19	.03 – .1	35
Moderately to densely welded	2	13	.02	55	.18 – 15	7
Unaltered	.4	8	.00002	180	.2 – .9	71
Zeolitized and argillized	.04	1	.000002	25	.02 – .08	63
Tuff breccia and ash-flow tuff	.3	4	.0008	15	.03 – 3	11
Bedded ash-fall and reworked tuff and ash-flow tuff	.1	2	.00009	15	.03 – .7	14
TMVA	.01	2	.0002	20	.001 – .01	11
PVA	.02	4	.000007	22	.001 – .09	9
CHVU	.2	.6	.008	2	.08 – .5	14
BRU	.3	1	.01	4	.06 – 2	6
CFVU	.2	6	.000002	180	.09 – .3	91
OVU	.004	.07	.000001	1	.001 – .01	46
ICU	.01	.3	.0006	1	.001 – .01	7
SCU	.002	.02	.0002	.3	.0007 – .005	16
UCA and LCA	.6	90	.00001	820	.2 – 2	51
Faulted and karstic	3	120	.01	820	3 – 4	18
Unfaulted	.1	2	.0001	14	.02 – .5	19
UCCU and LCCU	.00003	.2	.00000003	5	.000003 – .0003	30
UCCU (shales)	.01	.07	.0003	.4	.002 – .06	9
LCCU (quartzites)	.0000006	5	.00000003	5	.00000007 – .000005	19
XCU	—	—	.00000002	[1]<.4	—	—

[1] Based on the 14.5 percent upper confidence level of Bedinger and others (1989) weathered metamorphic rocks hydraulic conductivities, and the lower 14.5 percent estimate for deep unweathered metamorphic rocks. Confidence levels are based on the 50th percentile estimate of their sample.

were deposited mostly in alluvial fans, floodplains, and stream channels. Eolian silt and sand, landslide deposits, debris flows, talus, colluvium, basalt flows, and tuff layers are present locally (that is, are discontinuous and not considered regional, areal-extensive units). Sediments generally are uncemented at and near the water table, but become more indurated with increasing depth. This combined HGU tends to be an aquifer where present, but finer grained sediments and intercalated volcanics locally can impede ground-water movement.

Forty-three analyses of hydraulic properties were compiled for the combined YAA and OAA, 25 from single-well aquifer tests and 18 from multiple-well aquifer tests. Tested intervals of the boreholes ranged from 6 to 161 m. Aquifer-test pumping rates ranged from 0.5 to 84 L/s with a minimum pumping time of 91 minutes. Aquifer-test analyses for pumping wells were omitted from the statistical summary, when an observation well was available to avoid biasing.

The horizontal hydraulic-conductivity values ranged from 0.001 to 130 m/d with geometric and arithmetic means of 2 m/d and 11 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.6 to 4 m/d.

Specific-yield estimates from late-time data (water levels measured near the end of the aquifer test), estimated in 14 analyses using Neuman (1975). These estimates ranged from 0.0004 to 0.2 with an arithmetic mean of 0.03 with the low value excluded (the low minimum value of 0.0004 suggests that the Neuman (1975) method was not applicable because of possible aquifer heterogeneity or dual-porosity conditions).

Alluvial Confining Unit

The alluvial confining unit (ACU) consists of Holocene to Pliocene playa, lake, marsh, and spring-deposited clay, marl, limestone, silt, sand, gravel; evaporite deposits, and thin tuff layers. The ACU tends to be a regional confining unit, but limestone and sand layers can be productive local aquifers, although the limestone component is probably limited in areal extent. The ACU is restricted to the topographically lowest areas of structural basins in the Death Valley region (fig. 3). Sediments that comprise the ACU may interfinger with those of the YAA and OAA, can be absent with depth, or may be present elsewhere beneath deposits of sand and gravel. The YAA and OAA and the ACU are shown as a single unit in figure 3.

Fifteen analyses of hydraulic properties were compiled for the ACU, 7 from single-well aquifer tests and 8 from multiple-well aquifer tests from 12 wells in the Amargosa Desert and Cave Valley. Test-interval thicknesses ranged from 0.3 to 235 m. Aquifer-test pumping rates ranged from 14 to 114 L/s with a minimum pumping time of 160 minutes. To avoid biasing, aquifer-test analyses for pumping wells were omitted from the statistical summary when an observation well was available.

Horizontal hydraulic-conductivity values ranged from 0.003 to 34 m/d with geometric and arithmetic means of 3 m/d and 11 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.6 to 10 m/d. The high value of 34 m/d was for a well in the Amargosa Desert and may reflect the hydraulic properties of spring-carbonate deposits, rather than clayey playa deposits.

Estimates of the horizontal hydraulic conductivity (app. A) for the ACU unit are equal or slightly greater than those of the YAA and OAA units. This result appears to be counter intuitive since confining units are expected to have hydraulic conductivities significantly lower than those of aquifers. However, the wells used for the ACU aquifer tests may be completed in more permeable alluvial deposits rather than playa deposits of lower permeability. Thomas and others (1989) indicate that playa deposits within the Smith Creek Valley in Lander County, Nev., possess vertical hydraulic-conductivity values of about 0.03 m/d, which suggests that the hydraulic conductivity of playa deposits is much less than that estimated for this unit using estimates from within the DVRFS.

Storativity values from seven analyses ranged from 0.00009 to 0.04 with an arithmetic mean of 0.01 (app. A). The specific yield from one analysis was estimated to be 0.01 (app. A). The apparent overlap of storativity and specific-yield values for this HGU may indicate that ground water in the ACU is variably confined, semi-confined, or unconfined.

Lava Flow Unit

The lava flow unit (LFU) consists of Holocene to Miocene basaltic and rhyolitic lava flows (typically with interbedded tuffs) interbedded with, and underlying, basin-fill sediments as well as localized cinder cones in topographic basins (fig. 3). Individual lava flows are not laterally extensive. Cinder cones typically are above the water table. Figure 3 includes some rhyolitic to rhyodacitic lava flows assigned to underlying volcanic HGUs and omits older basalt and andesite lava flows that do not have surface exposure.

Only two hydraulic-property analyses were conducted in the LFU at two separate locations. One analysis was from a single-well pumping test and the other from a slug-injection test. Test-interval thicknesses for the boreholes ranged from 61 to 80 m. For the pumping test the well was pumped at a rate of 8.4 L/s for 220 minutes. The horizontal hydraulic-conductivity value from this test was 4 m/d. The horizontal hydraulic-conductivity estimate from the slug test was 0.002 m/d. Because of the small number of hydraulic-property estimates available for this unit, estimates for the lava-flow component of the Tertiary volcanics HGU may be useful for numerical simulation of the LFU (see "Tertiary Volcanic Rocks”).

Younger Volcanic Unit and Volcaniclastic and Sedimentary Rocks Unit

The younger volcanic unit (YVU) and the volcaniclastic and sedimentary rocks unit (VSU) consists of Pliocene to Eocene variably cemented conglomerate, gravelly sandstone, sandstone, siltstone, shale, calcareous shale, limestone, and intercalated tuff layers. The YVU and the VSU consist of erosional and faulted remnants of sedimentary rocks deposited in diverse terrestrial settings within syntectonic basins (fig. 3). Coarser-grained rocks, if not permeated by calcite or other cementing minerals, can be very productive aquifers. Finer-grained rocks typically impede groundwater flow over large areas. With decreasing cementation, lithologies comprising this HGU grade into those in the YAA, the OAA, and the ACU. The YVU and the VSU are considered as separate units in the DVRFS hydrogeologic framework but are combined in this report (table 1).

Fifteen analyses of hydraulic properties were compiled for the YVU and VSU, all of which represent single-well aquifer tests. Test-interval thicknesses ranged from 8 to 70 m. Aquifer-test pumping rates ranged from 0.2 to 41 L/s with a minimum pumping time of 180 minutes.

Horizontal hydraulic-conductivity values for the YVU and the VSU ranged from 0.00004 to 6 m/d with geometric and arithmetic means of 0.06 m/d and 1.5 m/d, respectively. The 95-percent confidence interval about the geometric mean of the horizontal hydraulic-conductivity values ranged from 0.01 to 0.4 m/d. Storativity was estimated from one aquifer test to be 0.006 (app. A).

Tertiary Volcanic Rocks

The Tertiary volcanic rocks unit (TV) consists of Pliocene to Miocene non-welded to densely welded ash-flow tuff, depositional and fault-related tuff breccia, ash-fall tuff, reworked tuff, volcaniclastic rocks, and rhyolite, comendite, and trachyte lava flows. This HGU represents a combination of several proposed hydrogeologic units for the transient DVRFS flow model and includes the Thirsty Canyon/Timber Mountain volcanic aquifer (TMVA), the Paintbrush volcanic aquifer (PVA), the Calico Hills volcanic unit (CHVU), the Wahmonie volcanic unit (WVU), the Belted Range unit (BRU), and the Crater Flat volcanic unit (CFVU). The volcanic rocks that comprise this HGU tend to have both fracture and matrix permeability. Fracturing, which is most intense near faults, can enhance permeability (Faunt, 1997). Alteration of rock-forming minerals to zeolite, clay, carbonate, silica, and other minerals, which is most intense toward eruptive centers, can reduce permeability (Laczniak and others, 1996). Therefore, hydraulic properties within this HGU are extremely variable laterally and with depth. Moreover, certain combinations of lithology and structure can result in very transmissive intervals or as major impediments to ground-water flow over large areas. The Tertiary volcanics unit is widely distributed in the west-central part of the Death Valley region (fig. 3). The distribution of this HGU is controlled largely by the extent of nested calderas from which middle Miocene and younger volcanic rocks of the SWNVF erupted. The Tertiary volcanics intertongue with the YAA, the OAA, the ACU, the YVU, and the VSU.

One-hundred fifty-nine analyses of hydraulic properties were compiled for the Tertiary volcanics, 116 from single-well aquifer tests and 43 from multiple-well aquifer tests. Test-interval thicknesses for boreholes screened in the Tertiary volcanics ranged from 7 m to almost 1,600 m. Aquifer-test pumping rates ranged from 0.1 to 44 L/s with a minimum pumping time of 89 minutes. To avoid biasing, aquifer-test analyses for pumping wells were omitted from the statistical summary when an observation well was available and slug-injection tests conducted over a number of smaller intervals within a larger interval also were omitted.

Horizontal hydraulic-conductivity values ranged from 0.000001 to 180 m/d with geometric and arithmetic means of 0.1 m/d and 4 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.08 to 0.2 m/d.

The hydraulic-conductivity estimates also were assigned to the corresponding lithostratigraphic formation or group (corresponding to the DVRFS units) and statistically summarized. Tests in wells with open intervals contained in more than one of these proposed HGUs were not used in the statistical summaries. No data were obtained for the WVU. Table 2 presents the geometric mean for the various lithostratigraphically based hydrogeologic units within the Tertiary volcanics.

Four categories of rock were recognized as a basis for evaluating lithology as an influence on hydraulic conductivity: (1) non-welded to densely welded ash-flow tuff (85 analyses); (2) rhyolite, rhyodacite, and trachyte lava flows with or without a tuff component (25 analyses); (3) tuff breccia with or without a tuff component (15 analyses); and (4) bedded tuff with or without an ash-flow tuff component (15 analyses). The presence of tuff intercalated with other rock types was unavoidable because of limitations in available data. However, the presence of tuff interbeds in intervals consisting mostly of lava flows is considered inconsequential hydraulically. Despite some ambiguity in the data (mainly from variability in the rock property descriptions for the test intervals), it appears that ash-flow tuffs, bedded tuffs, and lava flows are about equally permeable and that all of these lithologies are less permeable than tuff breccias (table 2). Ubiquitous zeolitic and argillic alteration of bedded tuff probably controls the hydraulic properties of test intervals containing bedded tuff and ash-flow tuff (Laczniak and others, 1996, p. 26).

To assess the effect of the degree of welding of ash-flow tuff on hydraulic conductivity, the results of 85 analyses of hydraulic conductivity were categorized by rock type (table 2). Three categories were selected: (1) non-welded to partially welded tuff (43 analyses); (2) partially to moderately welded tuff (35 analyses); and (3) moderately to densely welded tuff (7 analyses). Overlapping rock types, such as non-welded to densely welded tuff, were omitted from the analysis. The hydraulic conductivity of ash-flow tuff generally increases as the degree of welding increases (table 2). This welding increases the propensity of the ash-flow tuffs to fracture, which enhances permeability (Laczniak and others, 1996, p. 25).

On the basis of qualitative descriptions in borehole lithologic logs, ash-flow tuff, bedded tuff, and tuff breccia (omitting lava flows) were combined into two rock categories, unaltered tuff (71 analyses) and altered (zeolitized or argillized) tuff (63 analyses). Clay minerals from the alteration tend to reduce permeability (Laczniak and others, 1996, p. 26). Test intervals of partly altered tuff were omitted from the analysis. Results of the analyses of 134 samples suggest that the mean horizontal hydraulic conductivity of unaltered tuff is greater than altered tuff by about an order of magnitude (table 2).

Storativity in 45 analyses of aquifer tests from the Tertiary volcanics ranged from 0.00004 to 0.004 with an arithmetic mean of 0.001 (app. A). Specific yield from 10 analyses for the Tertiary volcanics ranged from 0.001 to 0.2 with an arithmetic mean of 0.03 (app. A).

Older Volcanic Unit

The older volcanic unit (OVU) consists mostly of Miocene to Oligocene ash-flow tuff, ash-fall tuff, reworked tuff, tuff breccia, volcaniclastic rocks, rhyolite, comendite, rhyodacite, and dacite lava flows, and shale, sandstone, and conglomerate of sedimentary origin. The volcanic rocks that comprise the OVU tend to have both fracture and matrix permeability. Ash-flow tuffs tend to be non-welded, but can be partly to densely welded. Alteration of ash-flow, ash-fall, and reworked tuffs to zeolite, clay, carbonate, silica, and other minerals is common. The OVU tends to be a regional confining unit and has widespread outcrop exposure in the northern part of the Death Valley region (fig. 3). Older tuffs and lava flows of the OVU also underlie the YVU and the VSU where they are present throughout the NTS. These older tuffs and lava flows can pinch out and intertongue with Tertiary sedimentary rocks in areas such as the southern end of Yucca Mountain (R.W. Spengler, U.S. Geological Survey, written commun., 2001) and between the Bullfrog Hills and Grapevine Mountains (Snow and Lux, 1999).

Forty-six analyses of hydraulic properties were compiled for the OVU, all of which were single-well tests. Test-interval thicknesses ranged from 6 to 1,054 m. Aquifer-test pumping rates ranged from 0.2 to 22 L/s with a minimum pumping time of 620 minutes. Available analyses are spatially well distributed from Railroad Valley to Monitor Valley, immediately north of the Death Valley region model area (figs. 1 and 2), but are spatially restricted from Yucca Flat and Pahute Mesa to Yucca Mountain.

Formations comprising the OVU were among the first volcanic rocks penetrated in shafts and boreholes completed at the NTS to conduct underground nuclear tests (Winograd and Thordarson, 1975). Because these rocks produced little water, Winograd and Thordarson (1975) designated them “the tuff aquitard.” Where these rocks produced water, production was erratic and attributed to interconnection of fractures in the aquitard with overlying or underlying aquifers (Winograd and Thordarson, 1975, p. 52). Only eight constant-rate pumping and injection tests were available. Aquifer-test results for OVU probably underestimate its transmissive properties because the estimates come from tests which only sample a relatively small amount of the aquifer.

Horizontal hydraulic-conductivity estimates for OVU ranged from 0.000001 to 1 m/d with geometric and arithmetic means of 0.004 m/d and 0.07 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.001 to 0.01 m/d. No storativity or specific yield estimates were available.

Intrusive Confining Unit

The rocks of the intrusive confining unit (ICU) consist of Jurassic to Oligocene granodiorite, quartz monzonite, granite, and tonalite. The ICU granitic rocks generally are limited in exposure within the DVRFS (fig. 3). Although these intrusive rocks can produce small quantities of water from fractures and weathered zones where present, they generally impede ground-water flow. In most of the DVRFS, Tertiary and Jurassic granitic rocks occur as small stocks, such as the Climax Stock in Yucca Flat and the Gold Meadows Stock on Rainier Mesa (Houser and others, 1961). On both sides of Death Valley, intrusive bodies are larger, more irregular in shape, and more common than elsewhere in the Death Valley region (Grose and Smith, 1989).

Few aquifer tests have been conducted in this unit in or near the DVRFS. Seven analyses were completed using slug tests, swabbing tests, and a constant-rate injection test in wells at the Climax and Belmont Stocks. Test-interval thicknesses ranged from 8 to 416 m. The injection rate for the constant-rate injection was 4 L/s for 97 minutes.

Horizontal hydraulic-conductivity values estimated for the ICU ranged from 0.0006 to 1 m/d with geometric and arithmetic means of 0.01 m/d and 0.3 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.001 to 0.01 m/d. No storativity estimates were obtained.

Sedimentary Rocks Confining Unit

The sedimentary rocks confining unit (SCU) consists of Permian to Jurassic interbedded conglomerate, gravelly sandstone, sandstone, siltstone, shale, calcareous shale, limestone, and gypsum. Hydraulic properties are extremely variable. The Shinarump Conglomerate and the Kaibab Limestone are regional aquifers. Other sandstone and limestone intervals transmit water locally. Intervals predominantly composed of shale, such as upper members of the Chinle Formation, are regional confining units. The SCU is exposed in the DVRFS in the upper plate of the Keystone Thrust Fault at the southern end of the Spring Mountains (fig. 1) and also is exposed just east of the DVRFS in the lower plate of the Keystone Thrust Fault in Cottonwood Valley (figs. 1 and 3). A deep well drilled to explore for oil and gas (Virgin River USA 1-A) penetrated the Moenkopi Formation and Kaibab Limestone at Mormon Mesa, just east of the DVRFS (McKay and Kepper, 1988).

Sixteen analyses were used to define the hydraulic-property estimates for the SCU. A drill-stem test from the petroleum exploration well at Mormon Mesa adjacent to the DVRFS provided the only data for this HGU. Fifteen analyses of drill-stem tests of Permian sedimentary rocks in the Colorado Plateau region of southwest Utah have been included in this report to provide additional hydraulic property estimates. The Permian sedimentary rocks of the Colorado Plateau are thought to be hydrologically similar to Mesozoic and Permian sedimentary rocks in the DVRFS because they include some of the same stratigraphic formations and have similar lithologies. Test-interval thicknesses ranged from 4 to 35 m. Aquifer-test pumping rates ranged from 0.1 to 215 L/s with a minimum pumping time of 430 minutes.

Horizontal hydraulic-conductivity values ranged from 0.0002 to 0.3 m/d with geometric and arithmetic means of 0.002 m/d and 0.02 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.0007 to 0.005 m/d. No estimates of storativities were obtained for the SCU.

Upper Carbonate Aquifer and Lower Carbonate Aquifer

The upper carbonate aquifer (UCA) and the lower carbonate aquifer (LCA) interfinger with the upper and lower clastic confining units. The UCA and LCA are Cambrian to Permian carbonate rocks consisting of cherty, siliceous, silty, shaly, and fine-grained limestone and cherty, silty, sandy, and fine-grained dolomite with subordinate chert, shale, siltstone, sandstone, and quartzite. Although clastic intervals confine flow, limestones and dolomites contained in these strata are aquifers that are present in the eastern two-thirds of the Great Basin (Harrill and Prudic, 1998). The LCA is separated physically from the UCA by the Eleana Formation and Chainman Shale (upper clastic confining unit). The Paleozoic carbonate rocks of the UCA and LCA are widely distributed in the eastern and southern parts of the DVRFS (fig. 3). These rocks are missing from the northwestern part of the study area because of thick accumulations of volcanic rocks and a facies change in Mississippian rocks from predominantly limestone and dolomite to predominantly argillite and quartzite.

Thirty-eight analyses of hydraulic properties were compiled for the upper and lower carbonate aquifers, 33 from single-well aquifer tests and 5 from multiple-well aquifer tests. Test-interval thicknesses ranged from 8 to 508 m. Aquifer-test pumping rates ranged from 0.9 to 7 L/s with a minimum pumping time of 180 minutes. To avoid biasing, aquifer-test analyses available for pumping wells were omitted from the statistical summaries when data or analyses for an observation well were available.

Horizontal hydraulic-conductivity values ranged from 0.00001 to 820 m/d with geometric and arithmetic means of 0.6 m/d and 90 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.2 to 2 m/d. Storativity values from 10 analyses of the pumping tests ranged from 0.0008 to 0.006 with an arithmetic mean of 0.003 (app. A).

The analyses were subdivided and statistically summarized to evaluate differences in hydraulic conductivity for rocks with extensive faulting with or without karst development, and rocks without extensive structural disturbance. The geometric mean of the horizontal hydraulic-conductivity values for extensively faulted and karstic limestone and dolomite was 3 m/d, whereas the geometric mean of hydraulic-conductivity values of unfaulted to simply faulted limestone and dolomite was 0.1 m/d. The difference between the geometric means of these two groups suggests that extensive faulting and karst development significantly increase hydraulic conductivity of the UCA and the LCA.

Upper Clastic Confining Unit and Lower Clastic Confining Unit

The upper clastic confining unit (UCCU) and the lower clastic confining unit (LCCU) consists of Late Proterozoic to Permian argillite, shale, siltstone, quartzite, sandstone, and conglomerate with subordinate chert, limestone, dolomite, and diabase. The UCCU and LCCU are regional confining units although the limestone, dolomite, and clastic rocks contained in them locally transmit water. Clastic rocks comprising the UCCU and the LCCU are widely exposed in mountainous areas bordering Yucca Flat, Pahrump Valley, and Death Valley (fig. 1). Upper Cambrian to Mississippian formations in this HGU intertongue with the LCA. The UCCU and the LCCU are considered as separate units in the DVRFS hydrogeologic framework but are combined in this report.

Twelve single-well analyses of hydraulic properties were compiled for the UCCU and the LCCU. Seventeen results of permeameter tests also were available. These permeameter tests were used to obtain estimates of matrix permeabilities of these confining units. Available analyses were from wells in and near the central and northeastern sections of the DVRFS. Test-interval thicknesses ranged from 15 to 1,285 m.

Horizontal hydraulic-conductivity values for the UCCU and the LCCU ranged from 0.00000003 to 5 m/d with geometric and arithmetic means of 0.00003 m/d and 0.2 m/d, respectively. The 95-percent confidence interval about the geometric mean for these values ranged from 0.000003 to 0.0003 m/d. The maximum hydraulic-conductivity value was obtained from an aquifer test in the Funeral Mountains (fig. 1) where the quartzites of the LCCU in this area possibly are sufficiently fractured to allow water to flow from Amargosa Desert into Death Valley (D'Agnese and others, 1997).

Because of different deformation behaviors, the UCCU and LCCU were subdivided for further statistical analyses. The UCCU is composed primarily of shale and the LCCU is composed primarily of quartzites. Shales tend to deform plastically, sealing fractures, while quartzites tend to be more brittle when deformed (Faunt, 1997).

Nine analyses of aquifer tests were available for the shale lithologies of the UCCU (Chainman Shale and the Eleana Formation). The geometric and arithmetic means of the horizontal hydraulic-conductivity values were 0.01 m/d and 0.07 m/d, respectively, with a range from 0.0003 to 0.4 m/d. The 95-percent confidence interval about the geometric mean for these values ranged from 0.002 m/d to 0.06 m/d.

Nineteen analyses of aquifer tests (field and laboratory) were available for the quartzitic lithologies of the LCCU. The geometric and arithmetic means of the hydraulic-conductivity values were 0.0000006 m/d and 5 m/d, respectively, with a range from 0.00000003 to 5 m/d. The 95-percent confidence interval about the geometric mean for these values ranged from 0.00000007 to 0.000005 m/d. However, using only the three pumping tests available for the quartzitic formations, a higher geometric mean hydraulic conductivity of 0.05 m/d is obtained with a range from 0.0002 to 5 m/d.

Crystalline Confining Unit

The crystalline confining unit (XCU) consists of Middle Proterozoic crystalline metamorphic and igneous rocks and metamorphosed Late Proterozoic sedimentary rocks. These granites and metamorphic rocks crop out mainly along the southwestern margins of the study area, in the Panamint Range and Black Mountains bordering Death Valley, and in the Nopah Range, Kingston Range, and Mesquite Mountains between Death Valley and Pahrump Valley (fig. 1; Grose and Smith, 1989). In most other areas, the crystalline confining unit forms the basement rock, which is generally deeply buried.

Although these rocks can produce small quantities of water through fractures and weathered zones, they are relatively impermeable and considered the base confining unit (Prudic and others, 1995; Bedinger and others, 1989). Bedinger and others report that rocks of this type, subdivided into weathered, shallow depth (less than 300 m), and deep depth (greater than 300 m) are characterized by hydraulic conductivities represented by geometric means of 0.03, 0.0005, and 0.0000003 m/d, respectively. The 85-percent confidence interval for weathered metamorphic rocks is 0.002 to 0.4 m/d; for shallow depth metamorphics is 0.00001 to 0.02 m/d; and for deep metamorphics is 0.00000002 to 0.000006 m/d (Bedinger and others, 1989).

RELATION OF HYDRAULIC CONDUCTIVITY WITH DEPTH

Researchers have estimated the depth of the flow system underlying the NTS area and postulated a somewhat qualitative relation between hydraulic conductivity and depth in the region. Winograd and Thordarson (1975) indicate that fractures in the carbonate aquifers are “open” (more permeable) to about 1,300 m below land surface and are “tighter” (less permeable) below this depth. D’Agnese and others (1997) indicate qualitatively that between depths of 300 to 1,000 m the hydraulic conductivity of most rocks in the DVRFS decreases rapidly. At depths greater than 1,000 m, matrix permeability probably dominates, except when within regional fault zones. Below 5,000 m, confining pressures likely keep faults and fractures closed (D’Agnese and others, 1997). The IT Corporation (1996b, p. 29) has postulated a relation of exponentially decreasing hydraulic conductivity with depth in the alluvial aquifer (equivalent to the YAA, OAA, and ACU), in the volcanic aquifer (equivalent to part of the Tertiary volcanics unit), and in the lower carbonate aquifer. While decreasing trends are apparent (IT Corporation, 1996b, figs. 6-1, 6-2, and 6-3), a great deal of scatter in the data also is apparent.

The relation of hydraulic conductivity and depth were examined for the 10 hydrogeologic units that overlie the XCU. Linear regression analysis showed the greatest correlation to depth occurred with the $\log_{10}$ transform of all hydraulic-conductivity estimates. The coefficient of determination (r^2) for the depth and non-transformed estimates is 0.003, while for the $\log_{10}$ transformed estimates it is 0.296. In contrast, the coefficient of determination of $\log_{10}$ transformed depth and non-transformed hydraulic-conductivity estimates was 0.245. The best relation, based on regression simulation, is the non-transformed depth with the transformed hydraulic-conductivity estimates and this model was used for the analyses of covariance (ANCOVA; see Neter and others (1985) for an explanation of analysis of covariance).

A plot of the $\log_{10}$ transform of hydraulic conductivity and the mid-point depth of the tested interval for the 10 HGUs are shown in figure 4. Visual examination

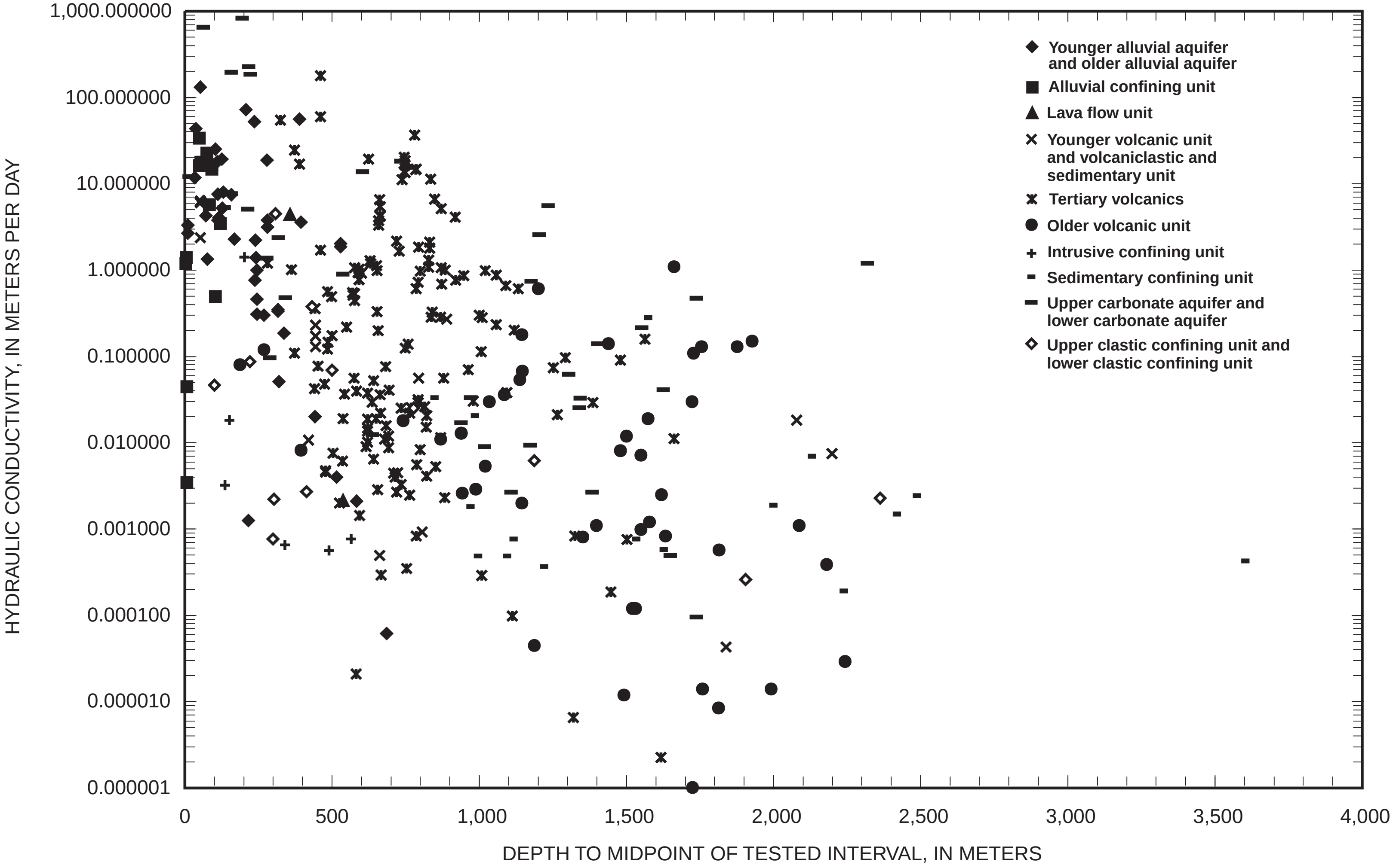


Figure 4. Relation between hydraulic conductivity and depth for hydrogeologic units in the Death Valley region.

Table 3. Analysis of variance for $\log_{10}$ hydraulic conductivity for estimates from aquifer tests as influenced by hydrogeologic unit and depth

[Abbreviation: HGU, hydrogeologic unit]

Source of variation	Degrees of freedom	Sum of squares	Mean square	F value [1]
Model (overall)	10	379.039	37.904	21.668
Error	339	593.295	1.750	
Total	349	972.334		
By model components				
Depth	1	288.286	288.286	164.722
HGU	9	90.753	10.084	5.762

[1] F value significant at probability level of 0.025.

of this plot shows an apparent relation between hydraulic conductivity and depth, but relatively high data scatter. ANCOVA initially were done on all hydraulic conductivity and depth data combined into a single data set to assess whether changes in hydraulic conductivity were related to HGU and depth. ANCOVA for the $\log_{10}$ transformed hydraulic conductivity estimates and depth for all HGUs indicate that depth and HGU are both significant factors at a probability level of 0.025 (table 3).

Since the HGU and depth were determined to be significant factors with the change of hydraulic-conductivity values, hydraulic-conductivity and depth data were categorized by an individual HGU and individually analyzed. Results from the ANCOVA for each individual HGU show a significant relation between depth and $\log_{10}$ transformed hydraulic conductivity at a probability level of 0.025 for five of the HGUs (YAA and OAA, YVU and VSU, Tertiary volcanics, OVU, and UCA and LCA. Although the ANCOVA of $\log_{10}$ transformed hydraulic-conductivity estimates indicate that depth may be a significant factor for the variation of hydraulic conductivity in five of the HGUs, the estimates can still vary considerably at a given depth. These large variations probably are caused by other factors (such as bedding, lithologic heterogeneities, or structural influences) that are not accounted for in these analyses. Additionally, some of the decrease in hydraulic conductivity with depth may be the result of using test-interval thickness for calculating hydraulic conductivity. That is, some of this decreasing trend in hydraulic conductivity possibly may be an artifact of the procedure used to calculate hydraulic conductivity from transmissivity.

SUMMARY AND CONCLUSIONS

The Death Valley region encompasses an area of about 43,500 km^2 in southeastern California and southern Nevada, between latitudes 35° and 38°15′ north and longitudes 115° and 117°45′ west. The study area is underlain by Quaternary to Tertiary basin fill sediments and mafic lava flows, Tertiary volcanic, volcaniclastic, and sedimentary rocks, Tertiary to Jurassic granitic rocks, Triassic to Middle Proterozoic carbonate and clastic sedimentary rocks, and Middle Proterozoic igneous and metamorphic rocks. As a result of several episodes of tectonic activity, rocks in the Death Valley region are faulted extensively. The hydraulic-properties database was compiled to support regional-scale ground-water flow modeling in the Death Valley region.

The DVRFS consists of interconnected hydrographic basins. Hydraulic connection between basins most commonly is maintained through unconsolidated sediments that were deposited across low topographic divides between the basins. Deep interbasin flow beneath valley floors and adjacent mountains and hills occurs primarily through fractured Paleozoic carbonate rocks.

Within the DVRFS, faults and related fractures are the largest influence on ground-water flow through bedrock aquifers. Faults disrupt stratigraphic continuity, which can divert water in regional circulation to subregional and local outlets. Less important than structure, but also an influence on ground-water flow is the lithology of rocks along flow paths.

Eleven HGUs were recognized in the DVRFS for the purpose of studying the distribution of hydraulic properties. Hydraulic properties were compiled and organized by these HGUs. Analyses also were performed to examine the relation between hydraulic conductivity and depth. Intuitively, hydraulic conductivity should decrease with depth as confining pressures seal fractures and faults and compress sedimentary units. ANCOVA indicate that depth is a significant factor in the variation of hydraulic conductivity, but the estimates can still vary a great deal at a given depth.

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APPENDIX

APPENDIX A: Hydraulic Properties Database

A hydraulic-properties database was compiled to support current Death Valley ground-water flow system simulations. The database contains individual worksheets for 10 of the 11 HGUs in the study area. No data were collected, and hence, no worksheet was required, for the Crystalline confining unit (XCU). Data reported in the body of the report for the XCU are from Bedinger and others (1989).

Entries for each HGU are organized by the well from which data were obtained (the observation well, if different from the pumping or injection well). Each entry in the database contains the following information:

1. Observation well name — A name commonly applied to the well from which hydraulic-property data were obtained.

2. USGS site identification (ID) number — A unique 15-digit number given to all inventoried wells in the USGS National Water Information System (NWIS) database. The site ID number consists of latitude, in degrees, minutes, and seconds, followed by longitude, in degrees, minutes, and seconds, followed by a sequence number. This field was left blank for wells that did not have a site ID number. Because data for wells in Permian sedimentary rocks from the Colorado Plateau that are in the database were obtained from a report in which these wells are identified by their land-net coordinates, a column containing land-net coordinates was added for these wells.

3. Universal Transverse Mercator (UTM) coordinates (meters). All well coordinates are in UTM zone 11, except those on the Colorado Plateau which are in UTM zone 12.

4. Land surface altitude at the well (meters). All altitudes are referenced to the National Geodetic Vertical Datum of 1929.

5. Well depth (meters).

6. Depths to the top and bottom of the test interval (meters).

7. Thickness (meters) — open interval of borehole.

8. Radius or interwell distance (meters) — for single-well aquifer tests, the borehole radius was listed if known; if the borehole radius was unknown, the casing radius was listed. For multiple-well aquifer tests, the reported, calculated, or scaled distance between the pumping or injection well and the observation well was listed.

9. Geologic units and lithologies present in the test interval — in test intervals spanning several geologic units, negligibly transmissive geologic units were omitted. For the Tertiary volcanics unit, columns describing alteration, degree of welding in ash-flow tuff, and the intensity of fracturing and faulting were added.

10. Pumped or injection well if different from the observation well (for HGUs with no multiple-well test data, this column was omitted).

11. Starting and ending test dates.

12. Length of the analyzed record, in minutes.

13. Type of aquifer test

14. Average discharge or injection rate (liters per second).

15. Analyzed data (typically drawdown, residual drawdown, recovery, specific capacity, or flux).

16. Hydraulic conductivity (meters per day) — Depending on available data, columns were added to list horizontal, vertical, fracture, and matrix hydraulic conductivity separately.

17. Vertical to horizontal anisotropy (for HGUs without data necessary to calculate this property, this column was omitted).

18. Transmissivity (meters squared per day).

19. Storativity (unitless).

20. Specific yield (unitless).

21. Analytical method, with analyses performed for this study identified.

22. Sources of hydraulic-property data, the aquifer-test analysis, and supporting data.

ground water

Issue Paper/

Ground Water Development—The Time to Full Capture Problem

by J. Bredehoeft[1] and T. Durbin[2]

Abstract

Ground water systems can be categorized with respect to quantity into two groups: (1) those that will ultimately reach a new equilibrium state where pumping can be continued indefinitely and (2) those in which the stress is so large that a new equilibrium is impossible; hence, the system has a finite life. Large ground water systems, where a new equilibrium can be reached and in which the pumping is a long distance from boundaries where capture can occur, take long times to reach a new equilibrium. Some systems are so large that the new equilibrium will take a millennium or more to reach a new steady-state condition. These large systems pose a challenge to the water manager, especially when the water manager is committed to attempting to reach a new equilibrium state in which water levels will stabilize and the system can be maintained indefinitely.

Introduction

This article is an issue paper, a philosophical paper that expresses our viewpoint. A discussion of our perspective will provide a road map for readers. We are concerned with the management of ground water development; we restrict ourselves to water quantity—water quality is always an issue, but it is not our concern here.

Undeveloped ground water systems are commonly found in a state of equilibrium, where, on average, equal amounts of water are recharged and discharged. Ground water systems tend to filter out higher frequency fluctuations in weather; the larger the system, the more filtering it tends to provide. The base flow of streams reflects the effects of the ground water system as a filter. In other words, the larger the ground water system, the more the equilibrium between inflow and outflow reflects long-term averaging of fluctuations in weather. Our analyses generally assume that climate is stationary; if the climate is changing, as recent evidence suggests, then the assumption of equilibrium should be questioned.

Ground water development perturbs the natural equilibrium. We are assuming that a principal objective in managing ground water development is to extend the life of the development as long as is feasible. It is possible for some ground water developments to reach a new equilibrium that includes pumping—we assume that this is desirable from a management perspective. In the new equilibrium state, pumping can be continued indefinitely. In reaching the new equilibrium, the natural state will be perturbed—there will be inevitable impacts on the natural system. Society may decide that the impacts imposed in reaching the new equilibrium are too detrimental, and they may in some way constrain the development. Our focus in this paper is the length of time that some ground water systems take to transition to a new equilibrium state that includes pumping.

Hydrogeologists predict the response time of ground water systems using models. Models provide good predictions in the near field at early times. For example, pumping test analyses give good predictions on how to size the infrastructure, well dimensions, pump size, and so forth. As predictions extend in both time and space, they become more uncertain. Much has been written about this uncertainty. We use model predictions from field situations to illustrate some of our ideas; we are aware of the many pitfalls in modeling and the resulting uncertainty associated

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with predictions (Konikow and Bredehoeft 1992; Bredehoeft 2003, 2005). Nowhere in these discussions of uncertainty did the authors argue that the predictions are not useful. Quite the contrary, we argued that predictions were worthwhile but should be used with a full awareness of the difficulties and resulting uncertainties.

We use Nevada as a prototype for our discussion. Nevada ground water law codifies some of the basic principles of ground water hydrology; for this reason, it is a nice example. Hence, we illustrate our ideas with two examples from Nevada. The most recent example is the proposal by the Southern Nevada Water Authority (SNWA) to develop a large ground water supply in eastern Nevada. The proposed SNWA development is ongoing and in the news. We present model predictions of the proposed SNWA development as an illustration of the major point of our paper. We also discuss how the water manager, in this instance the Nevada State Engineer, dealt with the model prediction that a long time would be required to reach a new equilibrium that includes the proposed pumping.

Nevada, with a few exceptions, treats each individual valley as a legally distinct ground water system. Some of the valleys are hydrologically self-contained; others are integrated by the underlying Carbonate Aquifer that underlies the region. SNWA is seeking water rights in a number of valleys. Each of these valleys requires a separate hearing and ruling by the State Engineer—granting or denying applications to pump ground water. So far there have been two hearings and ruling by the State Engineer who provided SNWA with rights to pump in Spring Valley and more recently in Cave, Dry Lake, and Delamar valleys.

The Water Budget

Meinzer (1931) elaborated on the idea of the water budget to estimate the "safe yield" of aquifers. Meinzer was not the first to express these ideas; he refers back to the earlier work of C.H. Lee from 1908 to 1911 in Owens Valley, California. According to Meinzer (1931), "Before any large ground-water developments are made, the average rate of discharge for any long period is obviously equal to the average rate of recharge." This was obvious to Meinzer and presumably his colleagues in the ground water community of the day—we have yet to find who first stated this idea. The principle establishes the reciprocal relationship between recharge and discharge in the undeveloped state and allows us to measure one as a surrogate of the other. Meinzer went on to urge the periodic inventory of the system in order to establish the elements of the budget through time.

A budget is a static accounting of the state of the system at a given time, often before the system is developed. Meinzer's idea was that the amount that could be developed depended upon the quantity of discharge from that system that could be salvaged. Nevada water law codified this idea in their definition of perennial yield:

> *Perennial yield* of a ground-water reservoir may be defined as the maximum amount of ground water that can be salvaged each year over the long term without depleting the ground water reservoir. Perennial yield is ultimately limited to the maximum amount of the natural discharge that can be salvaged for beneficial use . . . .

It follows that:

$$R_0 = D_0 \tag{1}$$

where R_0 is the undeveloped recharge and D_0 is the undeveloped discharge. We can introduce pumping into this expression:

$$R_0 - (D_0 - \Delta D_0) - P = \mathrm{d}V/\mathrm{d}t \tag{2}$$

where ΔD_0 is the change in the discharge created by the pumping (the salvage or capture), P is the rate of pumping, and $\mathrm{d}V/\mathrm{d}t$ is the rate of change of ground water in storage in the system.

Meinzer and others recognized that water must be removed from storage before a new equilibrium state could be reached. Again, Nevada water law codified this storage:

> *Transitional storage reserve* is the quantity of water in storage in a particular ground water reservoir that is extracted during the transition period between natural equilibrium and new equilibrium conditions under the perennial yield concept of ground water development. . . . the transitional storage reserve of such a reservoir means the amount of stored water which is available for withdrawal by pumping during the non-equilibrium period of development (i.e., the period of lowering of water levels).

At the new equilibrium state, the water budget is as follows:

$$\mathrm{d}V/\mathrm{d}t = 0 \quad \text{(by definition)} \tag{3}$$

$$P = \Delta D_0, \quad \text{where } \Delta D_0 \leq D_0 \tag{4}$$

and we constrain the pumping to be less than or equal to the discharge in order to allow a new equilibrium. If we allow for pumping to induce recharge, then at the new equilibrium:

$$P = \Delta R_0 + \Delta D_0 \tag{5}$$

where ΔR_0 is the change in undeveloped recharge produced by the pumping, ΔD_0 is the change in recharge produced by the pumping, and $\Delta R_0 + \Delta D_0$ is defined as the *capture*.

Capture

Theis (1940) introduced the principle of capture. Later, the USGS in Lohman (1972) published the following definition of capture:

> Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture.

Capture is an all-important concept in managing ground water; a ground water system can only be maintained indefinitely if the pumping is equaled by the capture—a combined *decrease* in the undeveloped discharge and *increase* in undeveloped recharge. If pumping continually exceeds capture, then water levels in the system can never stabilize, and the system will continue to be depleted. In other words, if pumping exceeds the potential capture in the system, a new equilibrium state that includes the pumping can never be reached. Again, let us remind the reader that our focus in this discussion is ground water systems that, when developed, can be maintained indefinitely.

The water budget applies to the system at a given time—a snapshot in time. The usual practice is to calculate a budget for the undeveloped state and then for the final state when the system reaches the new equilibrium. In discussing the budget, or inventory idea, Meinzer (1931) drew the analogy to a surface water reservoir. One can pump anywhere from a surface water body and have a similar impact; however, where one pumps in a ground water system becomes important, as we show subsequently. While the water budget describes the state of the system at a given time, it does not inform us about the time path the system will take to reach the new equilibrium state; the time path depends upon aquifer dynamics. It should be remembered that in 1931, when Meinzer wrote his paper, Theis' (1935) seminal paper that presented a general transient ground water flow equation had not yet been published.

In 1931, hydrogeologists did not have the ability to predict the time to reach a new equilibrium state. However, we argue that the expectation of Meinzer's work, and the work of others, was that once pumping was introduced, a new equilibrium would be reached in a reasonable period of time. However, it takes some ground water systems an inordinately long period to reach a new equilibrium. The time may be so long that the fact that a new equilibrium eventually is reached becomes meaningless. It is this problem we address subsequently.

Aquifer Dynamics

Theis (1935) introduced time into ground water theory. This allowed hydrogeologists to make temporal predictions. Historically, the profession went through several phases of prediction. In the 1940s, well hydraulics blossomed. Led by Theis and Jacob, ground water hydrologists solved the boundary value problem associated with various conceptual models of the aquifer and the associated confining layers. The predictive capability associated with the solutions allowed hydrogeologists to estimate relevant parameters of the ground water system—transmissivity, storage coefficient, leakance of a confining layer, and so forth. Armed with a theoretical conceptual model, one could predict response to pumping, which in turn allowed for well design, the sizing of pumps, and well spacing, among other facets of development.

Hydrologists of the day also sought to investigate ground water systems; however, they recognized the limitations imposed by the theoretical approach. Bob Bennett and Herb Skibitski, working at the USGS in the 1950s, developed the resistor/capacitor network, analog model of ground water systems. This allowed the creation of analog models of field systems in which realistic boundary conditions and internally variable parameter distributions could be simulated. The USGS created an analog model laboratory in Phoenix in approximately 1960, where models were constructed and predictions made for several tens of ground water systems. Walton and Prickett (1963) created a similar laboratory at the Illinois State Water Survey where they built analog models of Illinois ground water systems.

By the late 1960s, digital computers had advanced to the point that realistic ground water models could be constructed and analyzed using digital methods (Pinder and Bredehoeft 1968). The technology for solving the resulting massive matrix inversion problems had been pioneered by petroleum reservoir engineers and applied mathematicians working for petroleum companies. Reservoir engineers are involved with solving the same basic flow equation that we use for ground water, and the techniques were readily adapted to ground water problems. Digital computers have become increasingly more powerful; as the computer advanced, so did the ground water modeling technology. One can now create very realistic ground water models on a PC. Techniques are available to optimize the parameter distributions within the models (Hill and Tiedeman 2007). Advances in technology now make it feasible to make predictions of the behavior of complex ground water systems. Predictions, even in the best-calibrated model, have an associated uncertainty. Our predictive capability has grown steadily since Theis (1935) used the analogy between the flow of ground water and the flow of heat and Jacob (1940), starting from first principles, showed that the analogy was correct. Hydrogeologists now routinely predict ground water system behavior.

The Time to Reach a New Equilibrium

Given our ability to predict, it is of interest how long it takes for a ground water system to reach a new equilibrium, assuming that a new equilibrium state is possible. One can envision ground water systems in which the pumping greatly exceeds any potential capture. In such an instance, the system can never reach a new equilibrium, and water levels within the system will continue to decline until the system is depleted. We are concerned here with systems in which a new equilibrium state is feasible—that is, pumping can ultimately be balanced by capture.

Hypothetical Basin- and Range-Valley-Fill Aquifer

We first examine a hypothetical system that resembles some of the valleys in the Basin and Range (Figure 1). The two streams entering the basin on the left provide on

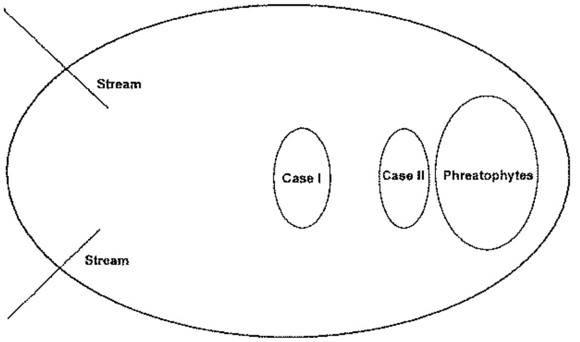

Figure 1. Plan view of a hypothetical valley-fill aquifer in the Basin and Range.

average 100 cubic feet per second (cfs) of recharge to the aquifer. The area of phreatophytes, to the right, discharges on average 100 cfs of ground water through evapotranspiration (ET) before ground water development. We consider two scenarios of ground water development located in the areas labeled case I and case II, respectively; each development pumps at a rate equal to the recharge—100 cfs.

We assume two-dimensional horizontal flow and the properties listed in Table 1. In our hypothetical system, we assume that ground water consumption by phreatophytes is diminished as pumping lowers the water table in the area containing phreatophytes. We deliberately created a ground water system in which capture of water that would otherwise be lost by ET can occur. As the water table drops between 1 and 5 feet, the consumption of ground water by ET is linearly reduced. The phreatophyte reduction function is applied to each cell in the model.

In order for this system to reach a new state of sustained yield, the phreatophyte consumption must be eliminated entirely. Using the model, we can examine the phreatophyte use as a function of time. Figure 2 is a plot of the phreatophyte use in our system vs. time since pumping was initiated. The location of the pumping makes a significant difference in the dynamic response of the system. In case II, where the pumping is close to the phreatophytes, the ET is reduced to 65 cfs in 10 years. In contrast, in case I, the ET is reduced to approximately 5 cfs in 10 years. Case I takes a long time to fully eliminate the ET; it is approximately 1000 years before the ET is totally eliminated. Even seasoned hydrologists are surprised at how long it can take an unconfined system to reach a new equilibrium state in which no more water is removed from storage.

We can also investigate the total amount of water removed from storage in our hypothetical valley-fill aquifer (Figure 3). It is important to notice that even though the two developments (case I and case II) are equal in size, the aquifer responds differently depending upon where the developments are sited. In case II, where the pumping is close to the phreatophytes, the amount of water removed from storage is approximately 50% less than that in case I. In case I, a large cone of depression must be created in order to impact the phreatophyte ET.

Table 1
Aquifer Properties for Hypothetical Basin Shown in Figure 1

Basin size	50 × 25 miles
Model cell dimensions	1 × 1 mile
Hydraulic conductivity	0.00025 ft/s
Saturated thickness	2000 feet
Transmissivity	0.5 ft^2/s (~43,000 ft^2/d)
Storage coefficient	0.1%–10%
Phreatophyte consumption	100 cfs
Wellfield pumping	100 cfs
Recharge	100 cfs

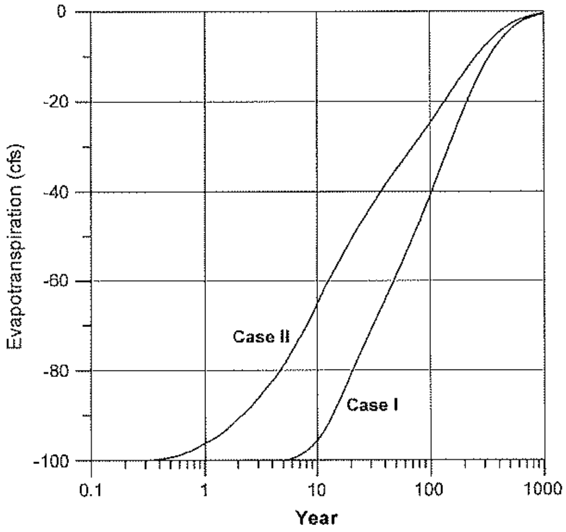

Figure 2. ET vs. time in our hypothetical valley-fill aquifer.

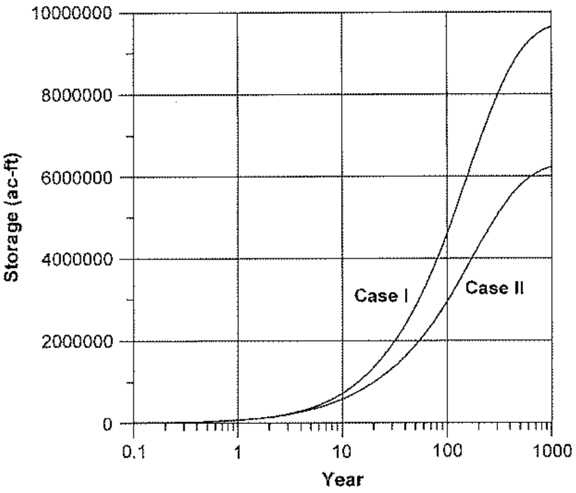

Figure 3. The volume of water removed from storage as a function of time in our hypothetical valley-fill aquifer with two developments—case I and case II (Figure 1).

This example of our rather simple Basin- and Range-valley-fill aquifer illustrates the importance of understanding the dynamics of aquifer systems. While this is a simple example, the principles illustrated apply to aquifers everywhere. In this case, it is the rate at which the phreatophyte consumption can be captured that determines how this system reaches sustainability; this is a dynamic process. Capture always involves the dynamics of the aquifer system. It makes a big difference in the response of the system where the wells are located. Thomas et al. (1989) describe the ground water hydrology of Smith Creek Valley, Nevada, where the USGS did a Regional Aquifer Systems Analysis (RASA) investigation; our simple example has many of the elements of Smith Creek Valley.

Paradise Valley

Alley and Leake (2003) explored the concept of "sustainability"; they used as their example a development in Paradise Valley in northern Nevada. The Humboldt River flows across the southern end of the valley. They used a model of ground water pumping near the southern end of the valley, not too far to the north of the Humboldt River, to examine the source of the ground water pumped vs. time (Figure 4). There are four sources of water that support the pumping: (1) water from storage; (2) capture of ET; (3) capture of surface water leaving the valley; and (4) induced recharge from the Humboldt River. Each of these sources varies with time.

The principal source of ground water in Paradise Valley during the early period is depletion of storage in the system. The storage declines to only 4% of the supply in year 300. The capture of water from ET grows from 20% in year 1 to approximately 75% of the total in year 300. The induced recharge from the Humboldt River grows from 0% in the early years to approximately 20% of the total in year 300. The capture of outflow from the valley grows to 3% in 300 years. The ground water system in Paradise Valley will take more than 300 years to reach a new equilibrium state. The time is about one-third as long as in case I in our hypothetical valley-fill aquifer explored earlier. Even after 300 years, 4% of the water pumped is still coming from storage.

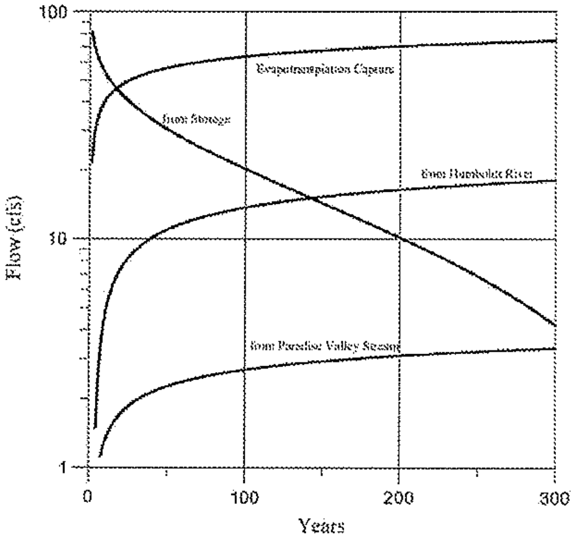

Figure 4. Computed sources of ground water to supply the pumping in Paradise Valley, Nevada (data from Alley and Leake 2003).

Both the induced recharge from the Humboldt River and the reduced outflow from the valley decrease the streamflow of the Humboldt River. This poses a potential future problem since the surface water in the Humboldt River, like most streams in the West, is overappropriated. Downstream surface water users will be hurt as this ground water development goes forward. An investigation of the undeveloped water budget for Paradise Valley would not have indicated induced recharge from the Humboldt River to be a significant source of water to the wells.

SNWA Development

The SNWA is proposing to pump 170,000 acre-feet/year of ground water just to the south of Ely, Nevada—approximately 200 miles north of Las Vegas. The water will be conveyed, via a pipeline, to Las Vegas. This will increase the water supply for Las Vegas by perhaps 40%; the fraction depends upon how much water is available in the future for Las Vegas from the Colorado River. The cost of the pipeline is currently estimated to be more than $3.5 billion.

The area under consideration for development is within the Carbonate Rock Province as defined by the USGS RASA investigation (Prudic et al. 1995), where there is a thick sequence of Paleozoic carbonate rocks. This sequence of rocks usually contains a Carbonate Aquifer that has the potential to integrate ground water flow between the valleys in the area (Eakin 1966). Analyzing ground water flow in this system entails investigating a much larger set of valleys than simply those that contain the pumping. The proposed SNWA pumping is situated mostly within the White River Regional Flow System (Figure 5).

There are several estimates of the recharge and/or discharge for portions of the ground water system pictured in Figure 5 (Eakin 1966; Las Vegas Valley Water District 2001; Welch and Bright 2007). A USGS RASA study of the system indicated that the pumping would reach a new steady state (Schaefer and Harrill 1995). The RASA, while calculating the impacts of a new equilibrium that included the pumping, did not estimate the time to reach the new state, other than to indicate that it was more than 200 years.

We realize that uncertainties associated with models and model predictions place confidence bounds around predicted values. However, we present single-valued graphs of predicted results to illustrate our points; we recognize that this oversimplifies the results. Figure 6 is a model prediction of the expected drawdown of the water table at the new equilibrium state that includes the

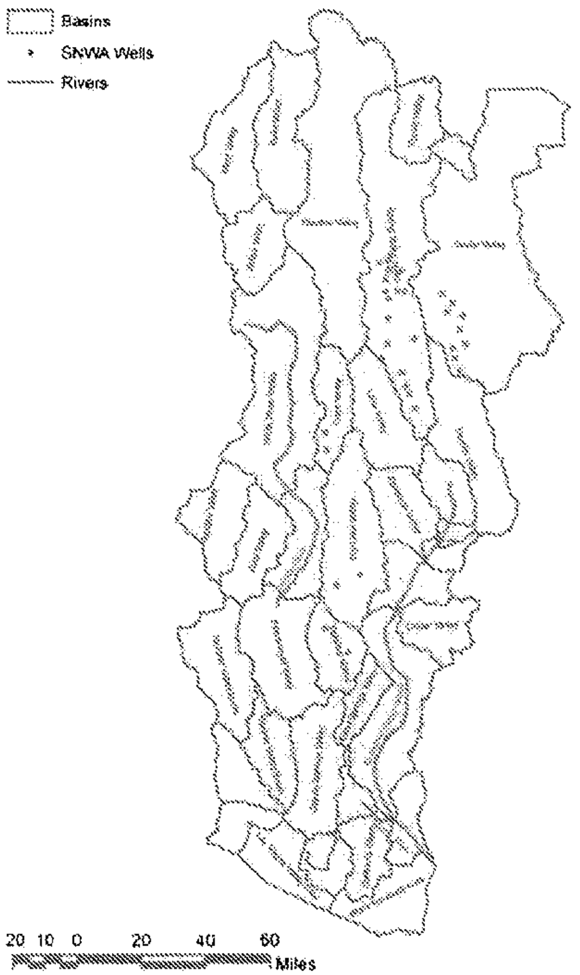

Figure 5. Map of the valleys in Nevada impacted by the proposed SNWA development. The proposed pumping wells are indicated.

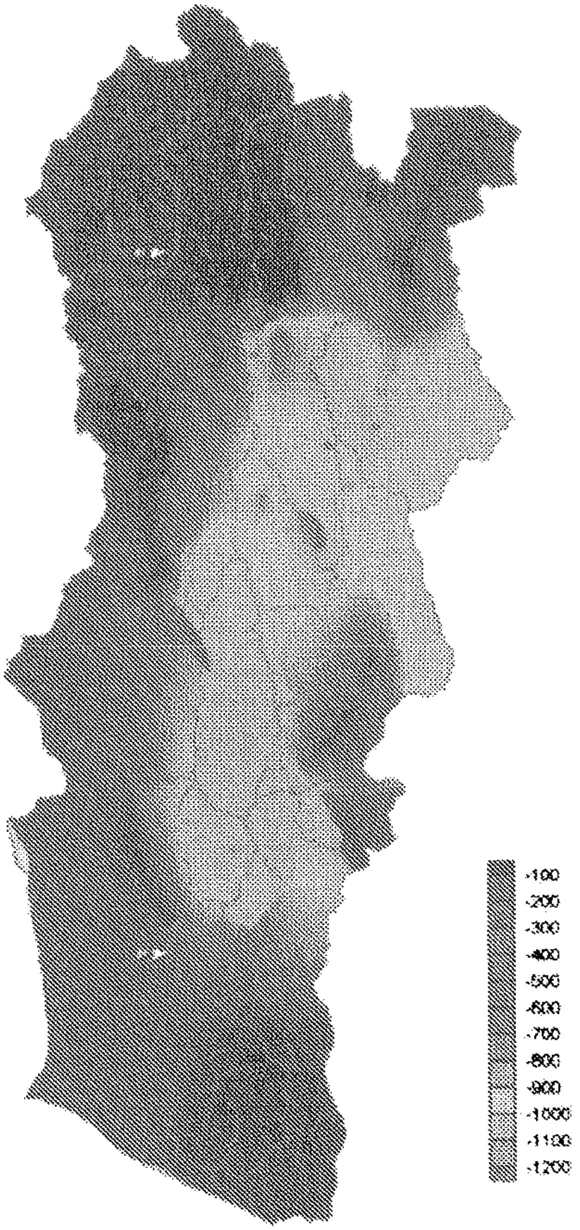

Figure 6. Computed expected drawdown in the water table at the new equilibrium state that includes the proposed SNWA pumping—predicted steady-state model.

proposed SNWA pumping. There is a very large area where the drawdown exceeds 700 feet. The deeper Carbonate Aquifer has similar drawdowns. Of particular interest is how long this system takes to reach the new equilibrium. Figure 7 is a plot of the change in storage in the system vs. time.

This figure is especially telling. The storage should level out and reach a stable level as the system reaches a new equilibrium (as in Figure 3), but this system is not close to reaching a new equilibrium state after 2000 years of projected pumping. A plot of the predicted ET vs. time (Figure 8) shows that the system has not reached a new equilibrium in 2000 years.

Combining Figures 7 and 8, we see that at 500 years, approximately 32% of the water pumped is coming from the depletion of storage and 65% from capture of ET. At 1000 years, 23% is coming from storage and 74% from capture of ET. At 2000 years, 14% is still coming from storage, while 82% is from capture of ET.

Nevada water law has only an implied reference to time; it only requires that the system reaches a new equilibrium state at some undetermined future time. The law was written before the tools were available to predict the future dynamics of ground water developments. The fact that the model predicts times more than 2000 years to reach a new equilibrium should change one's perspective on ground water management of this system.

Monitoring to Control Impacts

A strategy known as adaptive management relies on preventing impacts by monitoring the ground water

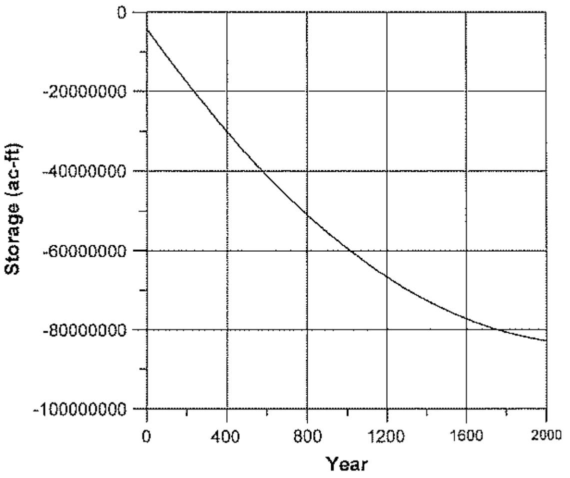

Figure 7. Predicted change in storage with proposed SNWA pumping.

system and changing the pumping stress when an undesirable impact is observed. The federal government entered into such agreements with SNWA before withdrawing their objections to the project. However, long-term monitoring also suffers from a prediction problem associated with the response time of the ground water system. We illustrate the monitoring problem with our hypothetical aquifer (Figure 1). We will examine a situation where we are attempting to maintain a spring at the lower end of our valley. Let us imagine that rather than having an area of phreatophytes discharging ground water, we have a single spring that discharges at 100 cfs before development. Our objective is to maintain the spring flow. We now start the case I ground water development that also pumps at 100 cfs.

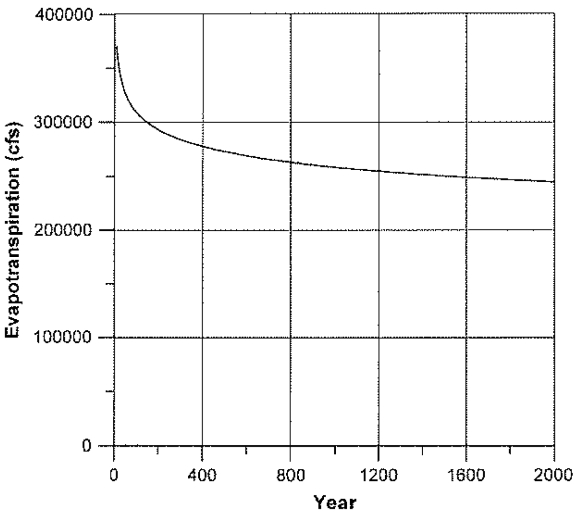

Figure 8. Computed plot of ET vs. time.

Let us further suppose we impose a monitoring and control strategy on the system. We monitor the spring with the intent that once the spring flow drops below 90 cfs (a 10% decline in flow), we will stop pumping ground water; in other words, our intent (as stated earlier) is to preserve the spring flow. We will use a 10% drop in flow as an observable signal that indicates that pumping is impacting the spring; smaller drops in flow could be ambiguous. (We are not arguing that this is a rational policy; rather we are illustrating a point.) Figure 9 shows the discharge of our spring vs. time; pumping stopped in area 1 in approximately 50 years when the spring discharge dropped to 90 cfs. The minimum spring flow occurs at approximately 75 years, 25 years after we stopped pumping. The reduction in flow is 13 cfs—larger than what it was when we stopped pumping. The maximum drawdown at the spring, created by the pumping, takes 25 years after pumping stops to work its way through the system.

We also see that the system does not recover readily to its predevelopment state even though the spring discharge equaled the recharge and was 100 cfs. Perhaps this is best understood if we look at the water removed from storage by the pumping and the rate at which it is replenished. During the period of pumping, the spring flow drops more or less linearly from 100 to 90 cfs. The amount of water removed from storage during this period averages approximately 95 cfs. The reduction in spring discharge averaged 5 cfs over the 50-year period—the capture of spring discharge averaged 5 cfs over the period. In other words, 95% of the ground water pumped during the 50 years of pumping came from storage. During the remaining 250 years since pumping stopped, the spring discharge averaged approximately 90 cfs. During that period, we are putting back in storage, on average, 10 cfs. This means that during the 250 years since the pumping ceased, we have restored just more than 50% of the water that was removed from the storage during the pumping period. You can easily see that this simple system will take approximately 500 years to return to its original state.

This hypothetical model illustrates the monitoring problem. If the monitoring point is some distance removed from the pumping, there will be (1) a time lag between the maximum impact and the stopping of pumping and (2) the maximum impact will be greater than what is observed when pumping is stopped (unless one has reached a new equilibrium state during the pumping period). The time for full recovery of the system will be long, even in the case where one has not reached the new equilibrium.

The real world is more complex. Those that advocate monitoring seldom envision totally stopping the pumping; rather, they imagine changes in the development that minimize damages. Stopping the pumping is a management action of last resort and we showed that it has problems. Less stringent management actions have a correspondingly lesser beneficial impact and even more problems.

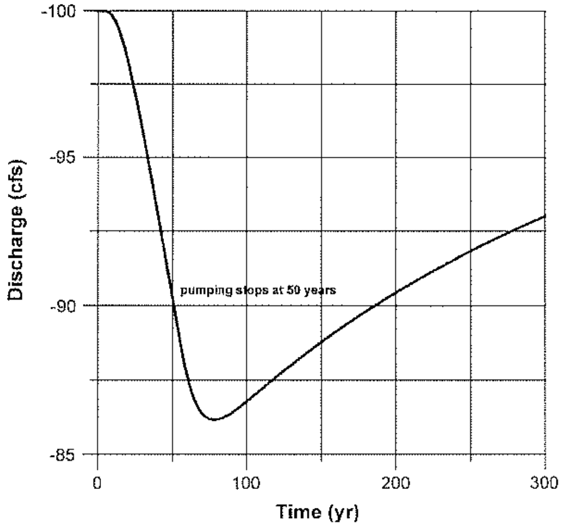

Figure 9. Predicted spring flow from a hypothetical aquifer (Figure 1 with phreatophytes in area 1 replaced by a spring). Pumping ceases after 50 years when the spring flow drops to 90 cfs.

Discussion

We do not think that the SNWA development in Nevada is all that unique nor do we think that this is typically only a western problem. Large aquifer systems exist throughout the country and the world. The response time problem is typical of large systems; there are other developments where the hydrologic boundaries where capture can take place are far from the pumping. Long times will be involved before the system can reach a new equilibrium—assuming that a new equilibrium is feasible. When the time to reach, or even approach, a new equilibrium exceeds a millennium or more, one has to ask—"Is the fact that the system will ultimately reach a new equilibrium meaningful?" It may be too distant in the future to have much meaning—too much can happen, civilizations change, the climate itself may change, and so forth. The bottom line is—it is important to predict the time trajectory of ground water systems, especially if one hopes to manage the system. Hydrogeologists have the tools to make these predictions.

The more vexing problem faces the water managers. For example, the SNWA development in Nevada can, given thousands of years, reach a new equilibrium. The question for the water manger, in this case the State Engineer, is how to deal with a system that takes so long to reach the new state—clearly, the law did not anticipate such long times.

Monitoring for control also has fundamental problems. The maximum impacts are larger than those observed at the time pumping stops, and they occur some time after the pumping stops. This is especially true if the monitoring is some distance away from the pumping. In addition, ground water systems will be very slow to recover to their predevelopment state once pumping is stopped.

In the case of SNWA's recent applications to pump in Cave, Dry Lake, and Delamar valleys, the Nevada State Engineer (2008) dealt with the problem as follows:

> The State Engineer finds that there is no dispute that the basins of the White River Flow System are hydrologically connected, but that does not mean that isolated ground-water resources should never be developed. The State Engineer finds he has considered the hydrologic connection and is fully aware that there will eventually be some impact to down-gradient springs where water discharges from the carbonate-rock aquifer system, but the time frame for significant effects to occur is in the hundreds of years.
>
> The State Engineer finds that a monitoring-well network and surface-water flow measurements will be part of a comprehensive monitoring and mitigation plan that will be required as a condition of approval and will provide an early warning for potential impacts to existing rights within the subject basins and the down-gradient basins of White River Flow System. The State Engineer finds that if unreasonable impacts to existing rights occur, curtailment in pumping will be ordered unless impacts can be reasonably and timely mitigated.

Conclusions

Some ground water systems in which a new equilibrium state that includes pumping can be achieved may take a long time to reach the new equilibrium. This is especially true where the discharge from the system that can potentially be captured by the pumping is a long distance away from the pumping center. Such a system may take more than a millennium, some more than two millennia, to reach the new equilibrium state.

This can pose a problem for the water manager, especially if the manager seeks to achieve a new equilibrium that will allow the pumping to persist for a prolonged period—essentially indefinitely.

One strategy, adopted by the State Engineer in Nevada, is to allow a large amount of pumping, more that can be sustained by a new equilibrium, while monitoring the system for adverse impacts. This strategy poses two problems: (1) a large ground water system creates a delayed response between the observation of an impact and its maximum effect and (2) there is a long time lag between changing the stress and observing an impact at a distant boundary.

If a water manager allows more pumping than the pumping can capture, then sooner or later the pumping must be curtailed or a new equilibrium can never be reached and the system will be depleted.

Acknowledgments

The authors wish to thank the editor and reviewers for their helpful suggestions.

Disclaimer

In fairness to the reader, we need to state that both authors of this paper acted as consultants on issues related to proposed ground water development in eastern Nevada. We consulted on opposing sides—Durbin for SNWA and Bredehoeft for the environmental coalition that opposes the development. Durbin's model of the proposed development for SNWA was documented, including its calibration, in a public document presented to the Nevada State Engineer at a hearing on SNWA's application for permits to pump ground water in Spring Valley, Nevada. Both authors presented the results of Durbin's model analysis in a public statement to the Nevada State Engineer at a hearing on SNWA's application to pump ground water in Cave, Dry Lake, and Delamar valleys, Nevada. The results are presented here as an example of model predictions; the predictions reflect all the caveats stated earlier.

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ground water

Guest Editorial/

It Is the Discharge

by John Bredehoeft

We all know the mantra *Keep It Simple*—the principle KISS. I have been thinking of another mantra for ground water—*It Is the Discharge*. Let me explain: In a recent conversation with one of my distinguished colleagues, he bemoaned our lack of understanding of ground water recharge. I keep thinking about that conversation. In a broad sense as hydrogeologists, we are hoping to understand how aquifer systems function, more particularly how much water is flowing through a particular system—the focus on recharge is simply one facet of the larger task. In studying the system, there are at least three aspects that we can focus on—(1) the recharge; (2) the aquifer itself as a transmission mechanism; and (3) the discharge from the aquifer.

One of the first principles of hydrogeology is that the recharge is balanced by the discharge before the system is perturbed. One tack commonly taken is to focus on the discharge and assume that recharge equals discharge. Of course, when we model a system in a virgin state, the mathematics demand conservation of mass, and the recharge, flow through the aquifer, and the discharge are balanced (or we do not have a solution to the problem). Often it is the capacity of the aquifer to transmit water that determines both the recharge and the discharge—the aquifer can accommodate only so much flow.

Generally, the recharge is the most difficult component of the ground water system to quantify, which brings me back to my colleague's comment—Shouldn't we be spending additional research effort to understand the recharge? My response is that it is more fruitful to examine the discharge. However, rarely do I hear hydrogeologists say that they are studying ground water discharge, especially in the academic community. Yet, the discharge is generally there to be observed—it occurs as springs, as base flow to streams, and as water for phreatophytes in the desert environment. There is a reason why hydrogeologists in Nevada still use the Maxey/Eakin method to estimate recharge, a method published in 1949—no one has come up with an improved procedure to estimate recharge even given 50+ years of further investigation. On the other hand, the methods of measuring phreatophyte discharge are greatly improved.

Furthermore, human activities that impact a ground water system ultimately impact the discharge. It is usually the ground water discharge that is captured during ground water development. The USGS (1972) in *Definitions of Selected Ground Water Terms* published the following definition of *capture*:

> Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture.

Many aquifers can be analyzed mathematically as if they are linear systems; this includes all confined aquifers and even water table aquifers where the change in head, caused by a given stress, does not change the saturated thickness greatly. In this case, neither the recharge nor the discharge is of concern; rather, the changes in these quantities, caused by the stress—the capture, are of interest. In the linear mathematical system, if one knows (1) the geometry of the aquifer system, (2) its hydrologic properties (permeability and storage), and (3) the boundary conditions, one can determine the impact of a given stress on the system. Often it is the discharge that we end up capturing.

Even if the recharge is not of pragmatic concern, it still may be of interest—we would like to fully understand the ground water system. Other factors such as how contaminants are transported through the system sometimes depend upon the recharge.

I have no doubt that studying recharge will be high on the list of research topics for the future. I am also confident that the recharge is better understood through the discharge where there is an integrated and observable hydrologic signal, and that discharge is of much more pragmatic concern than recharge. Harold Thomas, the distinguished professor of Water Resources at Harvard, was working on the problem by studying stream hydrographs; unfortunately, he died before he could publish his ideas. I tried unsuccessfully to point out the importance of the discharge in commenting on a proposed National Academy of Sciences/National Research Council research agenda—my remarks had no impact. Still, my argument is—*It Is the Discharge*.

Editor's Note: Opinions expressed in the editorial column are those of the author(s) and do not necessarily reflect those of the National Ground Water Association or the staff of the journal.

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Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity[1]

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ABSTRACT / The flow regime is regarded by many aquatic ecologists to be the key driver of river and floodplain wetland ecosystems. We have focused this literature review around four key principles to highlight the important mechanisms that link hydrology and aquatic biodiversity and to illustrate the consequent impacts of altered flow regimes: Firstly, flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition; Secondly, aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes; Thirdly, maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species; Finally, the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. The impacts of flow change are manifest across broad taxonomic groups including riverine plants, invertebrates, and fish. Despite growing recognition of these relationships, ecologists still struggle to predict and quantify biotic responses to altered flow regimes. One obvious difficulty is the ability to distinguish the direct effects of modified flow regimes from impacts associated with land-use change that often accompanies water resource development. Currently, evidence about how rivers function in relation to flow regime and the flows that aquatic organisms need exists largely as a series of untested hypotheses. To overcome these problems, aquatic science needs to move quickly into a manipulative or experimental phase, preferably with the aims of restoration and measuring ecosystem response.

The alteration of flow regimes is often claimed to be the most serious and continuing threat to ecological sustainability of rivers and their associated floodplain wetlands (Naiman and others 1995, Sparks 1995, Lundqvist 1998, Ward and others 1999). While the obvious and often irreversible impacts of large impoundments are now well recognized, there is also growing awareness of the pivotal role of the flow regime as a key driver of the ecology of rivers and their associated floodplain wetlands (Junk and others 1989, Poff and others 1997, Richter and others 1997, Puckridge and others 1998, Hart and Finelli 1999).

The primary goal of this review is to illustrate how altering flow regimes affects aquatic biodiversity in streams and rivers. To do so, we pose four guiding principles about the influence of flow regimes on aquatic biodiversity (Figure 1) and examine the consequences of changing flow regimes in light of each of these. The principles are:

Principle 1: Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition. We outline the influence of flow on stream habitats at the catchment scale (e.g., channel dimensions), reach scale (e.g., riffle-pool distribution), and patch scale (e.g., hydraulic conditions on individual stones) and discuss how habitat in turn influences the distribution and abundance of aquatic organisms. We then examine how modified flow regimes alter habitat at varying spatial scales and the influence of this on species distributions and abundance, as well as the composition and diversity of aquatic communities.

Principle 2: Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes. We discuss the degree to which flow pattern has a major influence on shaping life history patterns of aquatic species. We then consider how alteration of flow regimes can lead to recruitment failure and loss of biodiversity of native species.

Principle 3: Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species.

KEY WORDS: Ecological principles; Hydrology; Aquatic biodiversity; Flow regime; Life history; Longitudinal connectivity; Lateral connectivity; Introduced species

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[1] This is a contribution of the Scientific Committee on Water Research (SCOWAR) of the International Council for Science (ICSU).

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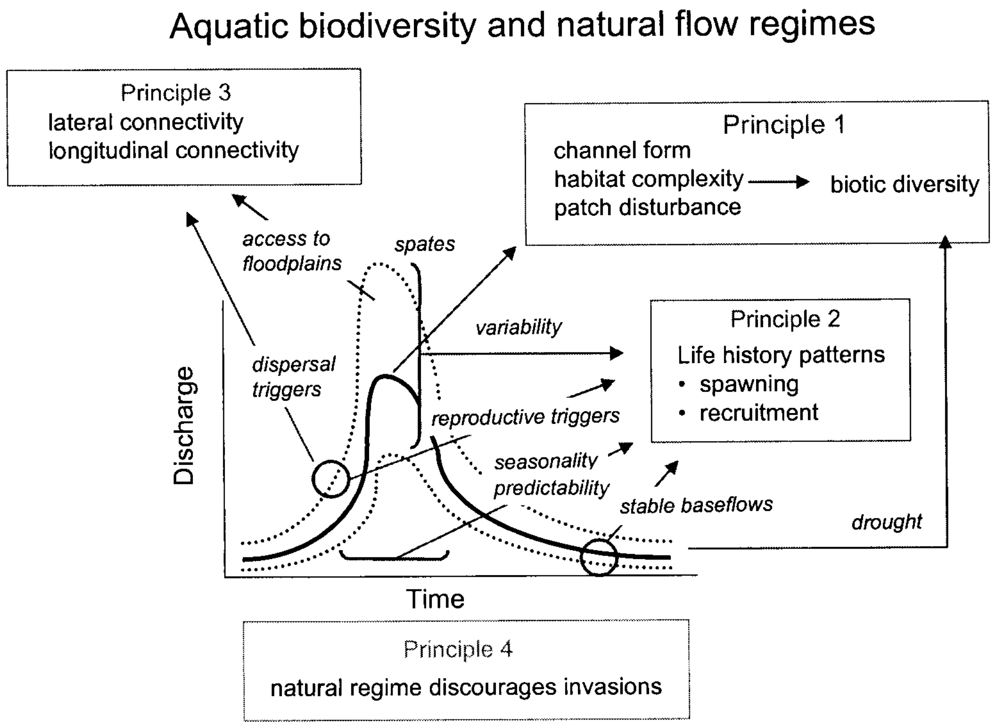

Figure 1. The natural flow regime of a river influences aquatic biodiversity via several interrelated mechanisms that operate over different spatial and temporal scales. The relationship between biodiversity and the physical nature of the aquatic habitat is likely to be driven primarily by large events that influence channel form and shape (principle 1). However, droughts and low-flow events are also likely to play a role by limiting overall habitat availability. Many features of the flow regime influence life history patterns, especially the seasonality and predictability of the overall pattern, but also the timing of particular flow events (principle 2). Some flow events trigger longitudinal dispersal of migratory aquatic organisms and other large events allow access to otherwise disconnected floodplain habitats (principle 3). The native biota have evolved in response to the overall flow regime. Catchment land-use change and associated water resource development inevitably lead to changes in one or more aspects of the flow regime resulting in declines in aquatic biodiversity via these mechanisms. Invasions by introduced or exotic species are more likely to succeed at the expense of native biota if the former are adapted to the modified flow regime (principle 4).

We discuss how the viability of populations of many species of fully aquatic organisms depends on their ability to freely move through the stream hierarchy, or between the river and floodplain wetlands. Loss of longitudinal and lateral connectivity through construction of barriers can lead to isolation of populations, failed recruitment and local extinction.

Principle 4: The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. Here, we briefly discuss the overall impact of modifying flow regimes on the establishment, spread, and persistence of exotic and introduced species. We also consider interbasin transfers of water as a major mechanism for the spread of exotic and introduced species, as well as disease.

Principle 1: Flow Is a Major Determinant of Physical Habitat in Streams, Which in Turn Is a Major Determinant of Biotic Composition

Flow Influences on Habitat

The movement of water across the landscape influences the ecology of rivers across a broad range of spatial and temporal scales (Vannote and others 1980, Junk and others 1989, Poff and Ward 1990, Poff and others 1997, Sparks 1995). The shape and size of river channels, the distribution of riffle and pool habitats, and the stability of the substrate are all largely determined by the interaction between the flow regime and local geology and landform (Frissel and others 1986, Cobb and others 1992, Newbury and Gaboury 1993). In turn this complex interaction between flows and phys-

Table 1. Summary of biotic responses to altered flow regimes in relation to flow induced changes in habitat (principle 1)[a]

Flow variables affected	Biotic responses	Sources
Increased stability of baseflow and reduction of flow variability	Excessive growths of aquatic macrophytes	Rørslett 1988, Røslett and others 1989, Walker and others 1994, French and Chambers 1996, Blanch and others 2000
	Proliferation of nuisance larval blackflies	De Moor 1986
	Reduction in fish populations	Converse and others 1998
	Increased standing crop and reduced diversity of macroinvertebrates	*Armitage 1977, Ward and Short 1978, Lillehammer and Saltveit 1979, Williams and Winget 1979*
Erratic (diurnal) patterns in flow below hydroelectric dams	Reduction in species richness of benthic macroinvertebrates	Munn and Brusven 1991, *Mullan and others 1976, Trotzky and Gregory 1974*
	Reduction in standing crop of benthic macroinvertebrates	Layzer and others 1989, *Mullan and others 1976, Trotzky and Gregory 1974, Radford and Hartland-Rowe 1971*
	Stranding of macroinvertebrates	*Kroger 1973*
	Stranding of fish	Bradford 1997, Bradford and others 1995
Conversion of lotic habitat to lentic	Decline of populations of riverine crayfish and snails	Walker and others 1992
	Elimination of salmonids and pelagic spawning fishes and dominance of generalist fish species	Copp 1990
	Loss of fishes adapted to turbid river habitats	Stanford and Ward 1986a
	Loss of fishes due to inundation of spawning grounds	*Hubbs and Pigg 1976*

[a] Additional examples (in italics) to those included in this review are from Petts (1984).

ical habitat is a major determinant of the distribution, abundance, and diversity of stream and river organisms (Schlosser 1982, Poff and Allan 1995, Ward and others 1999, Nilsson and Svedmark 2002). This is evident at even the smallest spatial scales, where subtle variations in flow and near-bed velocities can dictate the distribution and abundance of particular species of plants and animals (e.g., Wetmore and others 1990). Close associations with physical habitat can be found in many stream organisms ranging from algae and aquatic plants to invertebrates and fish.

Influence of Flow and Habitat on Aquatic Plants

The most commonly cited abiotic determinants of aquatic macrophyte assemblage structure are all flow-related factors (e.g., flow extremes, flow regime, hydraulics, substrate composition, and stability). Spatial and temporal variation in plant assemblage structure is influenced by flooding and scouring, desiccation, substrate stability and localized variations in water velocity, turbulence and shear stress (Chambers and others 1991, Biggs 1996, French and Chambers 1996). Aquatic macrophytes typically have patchy distributions as a result of spatial variations in disturbance frequency and intensity, colonization success and growth rates (Sand-Jensen and Madsen 1992, Rea and Ganf 1994).

Flow modifications to Scandinavian rivers (Rørslett and others 1989) and many rivers in the United States, Britain, France, southern Africa, India, Canada, and Australia are responsible for increases in macrophyte abundance (Table 1). For example, reduced summer floods and increased winter flows (i.e., a relatively stable flow throughout the year) cause excessive growths of submerged aquatic macrophytes in Norwegian rivers regulated by hydropower stations. Up to 55% of tailwater surface area and slow-flowing reaches further downstream in the River Otra were covered with prolific growths of the submerged phenotype of *Juncus bulbosus* L. (Rørslett 1988). In its pristine state, the flow regime of the Otra featured low winter flows and spring/summer floods, conditions that exposed plants to extreme stress caused by frost and ice scouring followed by the deleterious scouring effects of spring floods. The regulated regime ameliorates all of these conditions, allowing plants to accumulate massive biomass in regulated reaches.

Numerous species of aquatic plants from permanent backwaters and wetlands on the floodplain of the highly regulated lower Murray River in southeastern Australia have colonized the main channel, where the year-round baseflow in weir pools now provides ideal conditions (Walker and others 1994). Blanch and others (2000) suggest that reinstating a greater amplitude of weir pool water levels, more frequent shallow flooding, and longer periods of inundation would be beneficial for many plant species, promoting diversity by restoring a wider range of water regimes (Table 1).

Influence of Flow and Habitat on Aquatic Invertebrates

Physical disturbance from floods (and droughts) is thought to be a major determinant of the spatial and temporal dynamics of benthic communities in streams (e.g., Resh and others 1988). Rivers with unstable substrates tend to be characterized by low species diversity, and the biota present often have life history or behavioral characteristics of frequently disturbed environments (Sagar 1986, Cobb and Flannagan 1990, Cobb and others 1992).

Macroinvertebrates are vulnerable to rapid diurnal changes in flow, and regulated river reaches below hydroelectric dams, with erratic flow patterns, are typically characterized by species-poor macroinvertebrate communities (Munn and Brusven 1991) (Table 1). Sudden increases in flow can cause catastrophic downstream drift to the extent that as much as 14% of the standing crop of benthic biota can be eliminated each month in some hydropower operations due simply to drift resulting from increased shear stress (Layzer and others 1989). The impact of high flow water releases below hydropower dams can be very selective. Small insect nymphs and invertebrates, which cannot tolerate high velocities, are often underrepresented in downstream reaches (De Jalon and others 1994).

In some cases, flow regulation may favor the proliferation of specific taxa (e.g., orthoclad chironomids) (Munn and Brusven 1991) (Table 1). Since the construction of impoundments on the Lower Vaal River, South Africa, regulation of the once sporadic winter flow regime has allowed large populations of blackfly (Simuliidae) larvae to survive the winter and led to periodic plague outbreaks of adults in spring (De Moor 1986). It has been suggested that this pest species, which poses a health risk in the region, can be controlled to some extent by careful water level manipulations (De Moor 1986).

Influence of Flow and Habitat on Fish

Many fish species display a preference for particular types of habitat such as pools, riffles, or backwater areas (Matthews 1985, Angermeier 1987, Pusey and others 1993). The richness of the fauna often increases as habitat complexity increases, with depth, velocity, and cover being the most important variables governing this relationship (Gorman and Karr 1978, Schlosser 1982, Felley and Felley 1987, Pusey and others 1995). Fish assemblage structure (i.e., taxonomic composition and relative abundance pattern) is also strongly related to habitat structure (Meffe and Sheldon 1988, Pusey and others 1993, 1998, 2000).

Associations between fish and their habitat are influenced by flow variability at a range of spatial scales. Poff and Allan (1995) demonstrated regional differences in fish assemblage structure and functional organization in streams of differing flow variability in the northern midwestern United States. Hydrologically variable streams (i.e., those with a high coefficient of variation of daily flows, moderate frequency of spates) were characterized by species with generalized feeding strategies and preference for low water velocity, silt, and general substrata. In more stable streams, with high predictability of daily flows and stable baseflows, fish assemblages contained more silt-intolerant trophic specialists (Poff and Allan 1995).

Flow variability and habitat structure at smaller spatial scales within the drainage network can also influence fish assemblages. Pusey and others (1993) showed that stream discharge regime varied spatially in the Mary River, southeast Queensland, Australia, with some small tributaries prone to frequent periods of extended zero flows, whereas others have very constant base flows. Tributaries with extended periods of low flow were dominated by small, physiologically tolerant and generalist species (Pusey and others 1993).

Given the often-cited relationships between flow, habitat structure, and fish, it is not surprising that modifications to flow regimes affect fish diversity and the functional organization of fish communities in regulated rivers (Table 1). Impacts may involve any life history stage and have been observed at all spatial scales. For example, pulsed reservoir discharges associated with on-demand hydroelectric power generation limit the quality and quantity of habitat available (Reiser and others 1989, Valentin and others 1994, 1995). Stream fish can become stranded on gravel bars or trapped in off-channel habitats during rapid flow decreases. Susceptibility to stranding is a function of behavioral response to changing flows, and this varies with species, body size, water temperature, time of year and day, substrate characteristics, and the rate of flow reductions (Bradford 1997). For example, newly emerging salmon larvae, and juvenile salmonids hiding in the stream substrates during winter, are extremely susceptible to being stranded in the substrate during flow reductions (Bradford and others 1995, Bradford 1997). However, mature fish may be able to shift into temporarily suitable habitats to compensate for periodic reductions in the quality or availability of habitat (Kraft 1972, Bunt and others 1999).

The humpback chub (*Gila cypha*) historically ranged throughout the Colorado River system in the arid American southwest, living in swift canyon reaches now inundated or decimated by water development projects (Converse and others 1998). Operations of the Glen Canyon Dam directly affect the Colorado River through changes in flow, temperature, sediment transport and vegetation dynamics. Peak flows are considered important to the chub for habitat maintenance (via sediment transport) and perhaps as spawning cues, but base flows, which occur through the Grand Canyon for 7 to 10 months of the year, are also important. Elevated base flows now occur a greater proportion of the time in the regulated flow regime, and reduce habitat quality to the extent that subadult humpback chub are now much more numerous in the modified shoreline habitat provided by the exotic tamarisk (*Tamarix chinensis*) than in natural habitats (Converse and others 1998). In addition, the dam has altered the thermal regime such that the growth, reproduction and survival of native fishes have almost certainly been affected (e.g., Bulkley and others 1981).

Conversion of Lotic to Lentic Waterbodies

It is often argued that the loss of riverine habitat associated with impoundments is balanced by the creation of lake habitat. This is somewhat misleading, however, as natural lakes and wetlands often function in a very different way than river storages. In lakes and wetlands, much of the carbon and nutrient fluxes occur in the littoral margins (Bunn and Boon 1993, Wetzel 1990). Large impoundments are generally not operated at a constant water level, and productive littoral areas are rarely sustained. In addition, water levels are usually significantly elevated above natural stream levels, flooding part of the terrestrial–aquatic interface and creating a new littoral zone with steeper banks, less complex aquatic habitat, and different physicochemical conditions for aquatic plants and animals (Walker and others 1992).

The effects of weirs on river flow regimes and aquatic habitat can be complex and difficult to separate from the effects of exotic species, which often proliferate in the newly created lake habitat (see principle 4). In the Lower Murray River in southeastern Australia weirs have transformed the river into a chain of cascading pools, supplanting most of the riverine environment with pool habitats (Walker and others 1992). This has affected the distribution of the Murray crayfish (*Euastacus armatus*), now close to extinction, and several species of riverine and wetland snails have declined (Table 1).

Regulation of the lowland river Great Ouse, UK by weirs, embankments, navigation locks, and dredging has converted it into a series of relatively deep reservoirlike channels, separated by short, shallow lotic stretches. Impacts on fish include the absence of localized salmonids and pelagic spawning fishes (i.e., burbot), historically reported to be abundant; reduction in the range and abundance of rheophilic and limnophilic cyprinids; and the extreme dominance of generalist species (roach and minnows) throughout most of the system (Copp 1990).

The Colorado River is regulated by hundreds of reservoirs varying in area from <1 ha in high-altitude headwaters to >650 km^2 in lowland mainstem segments (Stanford and Ward 1986a). Conversion of one quarter of the river to lentic habitat has resulted in the loss of fishes adapted to turbid riverine habitats. In addition, numerous introductions of highly competitive exotic fishes (over 50 species), many thriving in impoundments and regulated river reaches, have contributed to the extirpation of native fishes in the Colorado River fauna (Stanford and Ward 1986b). Most of the native big-river fish face extinction (Stanford and Ward 1986b). In the headwaters of the upper basin, the range of the Colorado River cutthroat trout (*Salmo clarki pleuriticus*) is limited to a few isolated populations, and nearly all of the endemic desert stream fish are in severe decline.

Principle 2: Aquatic Species Have Evolved Life History Strategies Primarily in Direct Response to the Natural Flow Regimes

Influence of Flow Regime on Life History Patterns

The influence of river flows and wetland water regimes on recruitment and growth of aquatic plants is well established (Table 2). Changes in rates of water level fluctuation and disturbance frequency (floods and spates) and intensity (velocity and shear stress) can affect seedling survival, as well as plant growth rates (Blanch and others 1999, 2000, Froend and McComb 1994, Rea and Ganf 1994, Sand-Jensen and Madsen 1992). Rea and Ganf (1994) suggest that changes in

Table 2. Summary of life history responses to altered flow regimes (principle 2)[a]

Flow variables affected	Biotic responses	Sources
Rates of water level fluctuation	Aquatic macrophyte growth rates and seedling survival	Blanch and others 1999, 2000, Froend and McComb 1994, Rea and Ganf 1994
Timing of spates	Reduced survivorship of larval atyid shrimps following early summer spates	Hancock and Bunn 1997[b]
	Stable low flows required for spawning and recruitment of riverine fish	Milton and Arthington 1983[b], 1984, 1985, Humphries and Lake 2000
Reduced seasonality	Reduced synchrony of breeding in gammarid shrimps	Bunn 1988[b]
Timing of rising flows	Loss of cues for fish spawning and migration	Lowe-McConnell 1985, Nesler and others 1988, King and others 1998
Short-term fluctuations in flows	Adverse effect on species of stoneflies with long larval development times (autumn/winter)	*Henricson and Müller 1979*
Modified temperature regimes below dams	Delayed spawning in fish	Zhong and Power 1996
	Disrupted insect emergence patterns	*Lehmkuhl 1972, Gore 1977*, Ward and Stanford 1982
	Reduced benthic standing crop	*Lehmkuhl 1972*
	Elimination of temperature-specific species of fish	*Trautman and Gartman 1974*

[a] Additional examples (in italics) to those included in this review are from Petts (1984).

[b] Some examples are based on studies of responses to variation in natural flow regimes.

water regime have a profound effect on the establishment and survival of many aquatic plant species owing to their narrow range of tolerances and inability to regenerate under modified conditions. Conversely, the proliferation of species such as *Typha* in numerous artificial and altered aquatic habitats throughout southern Australia (Rea and Ganf 1994, Blanch and others 1999, 2000) is a function of several life history traits. These include high dispersal capabilities (production of large numbers of small seeds dispersed by wind over long distances), a high capacity to germinate while submerged (Finlayson and others 1983), high seedling density and, once established, rapid growth rates and vegetative reproduction (Froend and McComb 1994).

Although temperature regimes influence the life history patterns of many stream and river animals, the timing of particular flow or inundation events is also important (Sweeney 1984, Resh and others 1988) (Table 2). For example, temperature is a major factor influencing breeding in atyid shrimps (Atyidae) (e.g., de Silva 1988a,b). However, life history patterns are also strongly modified by the prevailing hydrology (see Hancock and Bunn 1997). Many Australian and New Zealand stream invertebrates have flexible life history patterns, which are thought to be a direct response to highly variable and unpredictable discharge regimes (Winterbourn and others 1981, Marchant and others 1984, Lake and others 1985). Evidence of greater synchrony of development is found only in regions with a more predictable flow regime (e.g., Bunn 1988). A spectacular example of the influence of flow on aquatic biota is the "boom or bust" dynamics of Australian arid-zone rivers and wetlands in response to unpredictable and episodic flood events (Walker and others 1995).

Flow plays a profound role in the lives of fish with critical life events linked to flow regime (e.g., phenology of reproduction, spawning behavior, larval survival, growth patterns and recruitment) (Welcomme 1985, Junk and others 1989, Copp 1989, 1990, Sparks 1995, Humphries and others 1999). Many of these life events are synchronized with temperature and day length, such that changes in flow regime that are not in natural harmony with these seasonal cycles may have a negative impact on aquatic biota.

Many species in streams with highly variable flow regimes have evolved life history strategies that ensure strong recruitment despite the disturbances wrought by spates (Table 2). Humphries and Lake (2000) proposed the "low flow recruitment hypothesis" to explain patterns of spawning in southeastern Australian fishes in response to seasonal pattern of river flow. Milton and Arthington (1983, 1984, 1985) suggested that small subtropical stream fishes recruit successfully by spawning in the months of low and relatively stable stream flows when their spawning habitats are least likely to be

Table 3. Summary of biotic responses to loss of longitudinal or lateral connectivity (principle 3)[a]

Flow variables affected	Biotic responses	Sources
Water abstraction	Reduction in migrating shrimp larvae	Pringle and Scatena 1999
Presence of in-stream barriers	Increased predation on juvenile migrating shrimp	Pringle and Scatena 1999
	Loss of migratory fish species	*Hubbs and Pigg 1976, Welcomme 1979*, Harris 1984a,b, Dauble and Geist 2000, Kareiva and others 2000, Reyes-Gavilan and others 1996, Joy and Death 2001
Reduced frequency, duration and area of inundation of floodplain wetlands	Reduced spawning areas and/or recruitment success of lowland river fish	*Jubb 1972, Whitley and Campbell 1974, Lake 1975, Welcomme 1979*, Geddes and Puckridge 1989, Cadwallader and Lawrence 1990
	Decline in waterbird species richness and abundance	Kingsford and Thomas 1995
	Decline in wetland vegetation	Kingsford 2000

[a] Additional examples (in italics) to those included in this review are from Petts (1984).

scoured out or stranded. Similar seasonal patterns of reproductive activity are emerging in many subtropical and tropical fish species (Arthington and Pullar 1990, Pusey and others 2001) and have also been recorded in freshwater turtles (Cann 1998) and the platypus, *Ornithorhynchus anatinus* (Grant 1984).

In contrast to low flow spawning, other aquatic species are cued to increases in flow or the timing of large floods (Lowe-McConnell 1985, Welcomme 1985). In southeastern Alaska, coho salmon (*Oncorhynchus kisutch*) enter many rivers for reproduction at the onset of autumn rains in September and October, whereas in Washington and Oregon rivers entry is delayed until the rains start in November (Naiman and others 2002). The timing of rising flows may also serve as a cue or trigger to the spawning of certain fish species. Examples are the Colorado River squawfish (*Ptychocheilus lucius*) in the Yampa River (Nesler and others 1988), and the Clanwilliam yellowfish (*Barbus capensis*) in South Africa (King and others 1998). In large floodplain rivers, many aquatic species ranging from benthic microorganisms, phytoplankton, zooplankton, and fish are cued to rising flood levels, emerging from resting stages or spawning in response to the cue of rising water levels and inundation.

Influence of Modified Temperature Regimes on Life History Patterns

In many regulated river systems modified flow regimes are accompanied by major shifts in the thermal regime, especially where dams have hypolimnetic water releases (Crisp and others 1983, Travnichek and others 1993) leading to the release of cold oxygen-deficient water downstream. Since aquatic insects and fish use the combined cue of day length and the summation of day-degrees to synchronize emergence as adults, the release of cooler water downstream of impoundments can influence the spawning behavior of fish and life history processes of invertebrates (Penaz and Jurajda 1995) (Table 2). In the long-term, hypolimnetic releases can cause selective disappearance of susceptible species from downstream reaches. Modified thermal patterns and day-length cues have been shown not only to disrupt insect emergence patterns but also to reduce population success (Ward and Stanford 1982). Coldwater releases have been found to delay spawning by up to 30 days in some fish species (Zhong and Power 1996).

Principle 3: Maintenance of Natural Patterns of Longitudinal and Lateral Connectivity Is Essential to the Viability of Populations of Many Riverine Species

Longitudinal Connectivity

The viability of populations of many species of fully aquatic organisms depends on their ability to move freely through the stream network. Large migratory macroinvertebrates such as shrimps and crabs are an important component of the biota of tropical and subtropical streams because of their direct influence on ecosystem level processes, such as primary production, organic matter processing, sedimentation, and the composition of benthic algal and invertebrate communities (Pringle and others 1993, Pringle and Blake 1994, Pringle 1996). Water abstraction and the construction of dams can have a major impact on the migration of large shrimp (Pringle and Scatena 1999) (Table 3). For example, damming of the lower reaches of one of the main drainages of the Caribbean National Forest in Puerto Rico has had a major impact on shrimp recruitment. More than 50% of migrating larvae were drawn into water intakes for municipal supplies and juvenile shrimps returning upstream faced severe predation below the dam (Pringle and Scatena 1999). Cessation of water abstraction during evening periods of peak nocturnal larval drift, upkeep of a functional fish ladder, and maintenance of a minimum flow could significantly reduce impacts of the dam and its operations.

Diadromous fishes, which migrate long distances within the main channels and larger tributaries of rivers, are particularly sensitive to barriers to longitudinal passage because obstruction of their migratory pathways may interfere with the completion of their life cycles (Table 3). The disappearance or decline of the major migratory fish species often follows river impoundment and the blocking of passage in the system (Bonetto and others 1989, Cadwallader 1986, Harris 1984a,b; Joy and Death 2001, Welcomme 1985, 1992). For example, an extensive network of hydroelectric dams, constructed between 1939 and 1975, has blocked access to or inundated most riverine habitat suitable for spawning by fall chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River Basin (Dauble and Geist 2000). More that 75% of the original 2500 km of mainstem spawning and rearing habitats has been eliminated. Although dam passage requirements have dramatically mitigated direct mortality, Snake River spring/summer populations are expected to decline toward extinction unless there are modest reductions in first-year mortality or estuarine mortality (Kareiva and others 2000). Migratory species such as shad, lamprey, and eels have disappeared from the Rhone River in France and the Guadalquivir River in Spain (Reyes-Gavilan and others 1996). In New Zealand, Joy and Death (2001) found that fish species richness in Taranaki Ring Plain streams was significantly reduced above dams due to their influence on movements of diadromous species.

In-stream barriers have contributed to the decline of populations of migratory fish species in southern Australia, such as Australian bass, Macquarie perch, and golden perch (Lake and Marchant 1990, Barmuta and others 1992). Barriers have affected 30%–50% of the potential habitat for migratory fish in 22 coastal drainages in southeastern Australia (Harris 1984a). Less than 10% of these barriers had fishways and, of these, only six of the 29 provided suitable conditions for fish migration at the time surveyed (Harris 1984b). River impoundment and the blocking of fish passage are often followed by the disappearance or decline of the major migratory species in river reaches upstream of barriers; this has been observed for Australian bass in east coast river systems (Harris 1984a,b).

It is important to note that the impact of barriers on mobile organisms is not confined to very large structures. Even small in-stream barriers, such as v-notch gauging weirs, can impede the movement of fish [e.g., western minnows (*Galaxias occidentalis*) in southwestern Australian forest streams (Pusey and others 1989)].

Lateral Connectivity

Hydrological connectivity between the river channel, floodplain, and groundwater structures the spatiotemporal heterogeneity of floodplain habitats (Ward and Stanford 1995), leading to characteristic high biodiversity (Ward and others 1999). The lateral expansion of floodplain habitats during flooding creates important spawning, nursery and foraging areas for many fish species and a variety of other vertebrates (Lowe-McConnell 1985, Welcomme 1985, Cadwallader 1986, Junk and others 1989, Ward and others 1999). The extent and duration of river flooding during the wet season can determine whether and for how long fish can gain access to nursery habitats and food (Bayley 1991, Heiler and others 1995), and whether fish will remain trapped in isolated floodplain waterbodies or are released back into the river system (Lowe-McConnell 1985). Mortality of fish trapped in dry season refuges may be very high due to deteriorating physicochemical conditions, reductions in food availability, and lack of refuge from predators (Kushlan 1976, Lowe-McConnell 1985, Woodland and Ward 1990). In turn, the duration and frequency of connection during periods of high flow (Halyk and Balon 1983, Hillman 1986), periodic isolation of floodplain waterbodies, and the proximity of such habitats to the main river channel are important in determining the composition of fish assemblages (Kushlan 1976, Hickley and Baley 1986, Lloyd and Walker 1986).

Flow regulation by dams, often compounded by other structural modifications such as channelization and levee banks, normally results in reduced connectivity and altered successional trajectories in floodplain rivers (Ward and Stanford 1995). Dams typically dampen flood peaks, reducing the frequency, extent, and often the duration of floodplain inundation. Smaller channel-forming flows modify patterns of channel migration, lowering habitat diversification on the floodplain. These changes ultimately reduce the biological diversity and ecological integrity of floodplain rivers (Ward and Stanford 1995) (Table 3).

Prior to river regulation, many species of fish in Australian rivers were thought to have used inundated floodplain wetlands of lowland rivers for breeding and juvenile habitat (Geddes and Puckridge 1989). River regulation to prevent flooding has seriously affected

Table 4. Summary of biotic responses to altered flow regimes in relation to invasion and success of exotic and introduced species (principle 4)[a]

Flow variables affected	Biotic responses	Sources
Loss of wet-dry cycles and increased stability of water levels	Reduced growth and survival of native aquatic macrophytes and increased invasion of exotics	Kingsford 2000, Mitchell and Gopal 1991
Reduced flow variability and increased seasonal stability	Favor populations of exotic fish species (carp, mosquitofish)	*Edwards 1978*, Faragher and Harris 1994, Walker and others 1995, Gehrke and others 1999
Conversion of lotic to lentic habitat	Proliferation of exotic fish species	Arthington and Bluhdorn 1994, Davies and Day 1998
Interbasin transfers of water	Transfer of schistosomiasis; translocation of fish species	Pitchford and Visser 1975, Skelton 1986, Cambray and others 1986

[a] Additional examples (in italics) to those included in this review are from Petts (1984).

such recruitment (Cadwallader and Lawrence 1990), and there is an obvious trend of reduced native species abundance with increasingly regulated catchments (e.g., Gehrke and others 1995). On the Macquarie River in eastern Australia, the Macquarie Marshes, a hemispheric wetland reserve for water birds have been reduced to 40%–50% of their original size by flow diversions and weirs (Kingsford and Thomas 1995). Low flows have eroded river channels, further reducing flows onto the floodplain, and a water diversion channel and levee banks have alienated parts of the floodplain from the river and retained floodwater on other parts for periods of more than 12 months. The area with river red gums halved between 1934 and 1981, as did the area of reed beds between 1963 and 1972 (Brander 1987). Over several hundreds of hectares of coolibahs (*Eucalyptus coolibah*) flooded behind levee banks have died since the 1970s. Abundance and species richness of water birds in the northern part of the Macquarie Marshes has declined over an 11-year period (Kingsford and Thomas 1995).

Principle 4: The Invasion and Success of Exotic and Introduced Species in Rivers Is Facilitated by the Alteration of Flow Regimes

For the purposes of this review, the term exotic (i.e., nonnative) species is defined as those that are not indigenous to a country. The term introduced is used more generally to refer to any species intentionally or accidentally released into an environment outside its natural range (Welcomme 1988). Exotic species are favored by many changes to flow regime, and the first three principles help to explain why some exotic plants and animals are so successful under modified flow conditions.

Influence of Altered Flow Regimes on Invasions

The loss of wet–dry cycles in floodplain wetlands often has major ecological impacts that favor exotic species. In Australia stable water levels may reduce the growth and survival of native aquatic macrophytes and encourage the invasion of *Typha* spp. and introduced water hyacinth (*Eichhornia crassipes*) (Kingsford 2000).

Although fish species have been introduced into a wide variety of environments, the greatest success has been achieved in waters which have been dammed, diverted, and otherwise modified, creating permanent standing water (reservoirs) and more constant flow regimes than previously existed (e.g., Moyle 1986, Arthington and others 1990) (Table 4). Long-term success (integration) of an invading fish species is much more likely in an aquatic system permanently altered by human activity than in a lightly disturbed system (Moyle and Light 1996a). The most successful invaders will be those adapted to the modified flow regime (Moyle and Light 1996b).

Moyle and Light (1996a,b) argue that failure of exotic fish species to establish populations in Californian (USA) streams is best attributed to their inability to adapt to abiotic conditions (rather than as a result of the biotic resistance of the recipient community). Invasions of nonnative fishes into Deer Creek, an unmodified tributary of the Sacramento River, have failed, prevented primarily by the natural flow regime (Baltz and Moyle 1993).

Regulation of flows in some Australian rivers is thought to favor exotic fish species such as carp (*Cyprinus carpio*) and mosquitofish (*Gambusia affinis*) (Pusey and others 1989, Faragher and Harris 1994, Walker and others 1995, Gehrke and others 1999). These species appear to benefit from seasonally stable, low flows and may displace native species adapted to more variable flows and heterogeneous habitat conditions. Common carp, tench (*Tinca tinca*), and European perch (*Perca fluviatilis*) have remained relatively insignificant in some Australian rivers for decades, whereas they have been favored by the increased stability of river flows in the Murray-Darling system (Cadwallader 1986). Gehrke and others (1999) have shown that regulated rivers in the Murray-Darling system have a lower diversity than relatively undisturbed rivers further inland, with the reduction in diversity largely due to greatly increased numbers of carp in regulated reaches.

Influence of Conversion of Lotic to Lentic Habitat on Biological Invasions

Long-term success (integration) of an invading species is much more likely in an aquatic system permanently altered by human activity than in a lightly disturbed system (Moyle and Light 1996a). Most prominently, this is due to the fact that human disturbed systems (e.g., reservoirs) resemble one another over broad geographic areas and favor species that are also favored by humans (Gido and Brown 1999). Creating permanent standing waterbodies and/or more constant flow regimes by damming or diverting river flows favors introduced species, many of which are most abundant in lakes and river backwaters in their native range (Moyle 1986).

Dominance of aquatic macrophyte communities in slow flowing and impounded river reaches by exotic species, such as the water hyacinth (*Eichhornia crassipes*) is a common occurrence. With its free-floating habit and rapid growth rate, the hyacinth can form dense surface growths covering large areas of open water, interfering with flow and water transport, disrupting recreation, impeding the access of stock to water, and blocking light penetration (Mitchell and Gopal 1991).

Conversion of rivers to lentic habitat can lead to the proliferation of exotic species of fish, for example tilapia (*Oreochromis mossambicus*) in large dams in Africa, Sri Lanka, and Australia (Arthington and Blühdorn 1994). However, conversion to lake habitat is not always perceived to be bad. For example, the Lake Tanganyika sardine ("kapenta," *Limnothrissa miodon*) was introduced to Lake Kariba. Between the first introduction in the 1960s and late 1990s, it has developed into a thriving fishery producing 25,000 t/yr, with a piscivore *Hydrocynon vittatus*, feeding on the sardine and forming another important fishery (Davies and Day 1998). Although once thought too small and puny to survive turbulent passage through hydroelectric turbines and sluice gates of Kariba Dam, the sardine has successfully invaded Lake Cahora Bassa (a reservoir) in Mozambique, more than 200 km downstream (Davies and Day 1998).

Interbasin Transfers of Water

Although accidental or deliberate movement of propagules (e.g., stocking) are likely to be the most important mechanisms, alteration of flow regimes and the infrastructure associated with it are also major contributors to the spread of introduced and exotic aquatic species. Historical patterns of species distributions, local endemicity, and metapopulation structure of aquatic organisms are largely determined by catchment boundaries and the presence of natural in-stream barriers (e.g., waterfalls) (Meffe and Vrijenhoek 1988, Bunn and Hughes 1997, Pusey and others 1998). Interbasin water transfers can alter natural distribution patterns of aquatic biota and enhance the spread of pests and diseases (as well as presenting serious problems in terms of water balance, water quality and the disruption of significant ecological processes). Such schemes are increasing in popularity as the number of sites suitable for dam construction and the scale of individual decline (Boon 1992).

The South African Orange-Vaal River Project, the Orange-Fish-Sundays River Inter-catchment Transfer Scheme, and the Tugela-Vaal Water Transfer Scheme provide examples of the impacts of interbasin transfers on biological invasions (Cambray and others 1986) (Table 4). The transfer of endemic flora and fauna between catchments has occurred with a variety of consequences (Skelton 1986). Interbasin transfers of schistosomes in the Orange-Vaal Project into rivers previously free of schistosomiasis have been enhanced by temperature changes below large dams that affect the dynamics of both the snail host and parasite populations (Pitchford and Visser 1975). The catfish *Clarias gariepinnus* has invaded the Great Fish River through the intercatchment transfer tunnel from Lake Verwoerd and has become established in the Sundays River system (Skelton 1986), and there has also been some spread of aquatic macrophytes. Four species of fish have been introduced from the Orange River drainage to the Great Fish River drainage via interbasin water transfers, presumably transferred as eggs or larvae.

Uncertainty and the Role of Science

There can be no question that the natural flow regime has a profound influence on the biodiversity of streams, rivers, and their floodplain wetlands (Poff and others 1997, Hart and Finelli 1999). There are clearly several interrelated causal mechanisms operating over different temporal and spatial scales, and no one characteristic of the flow is responsible (Figure. 1). As a consequence, it is often difficult to determine which attributes of the altered flow regime are directly responsible for observed impacts (e.g., is the decline of a fish species due to reduced capacity to migrate under altered peak flows or because of a change in substrate composition of spawning areas, or both?). An obvious constraint to resolving this is the potential lag effect in biological response to flow alteration. In particular, impacts to aquatic biota caused by changes in physical habitat (principle 1) may not directly coincide with actual changes in flow regime because of longer time scales for channel adjustment.

Despite this, there is growing recognition that certain aspects of the flow regime are important for particular ecological processes (e.g., to trigger fish migration and spawning, and rejuvenate floodplains). However, river managers now wish to predict how far these attributes can be altered from their natural state, before an impact occurs. For example, "what will be the impact of reducing a particular flow attribute from a current level of 10% less than natural to 20% less?" Similarly, managers need to be convinced that providing additional environmental flows (e.g., by reducing irrigation allocations at considerable cost) can produce some demonstrable environmental benefit. Our limited ability to predict and quantify the biotic response to flow regulation is a major constraint to achieving ecological sustainability (Bunn 1999, Naiman and others 1995, Richter and others 1997).

Perhaps a greater challenge to resolving this problem is the separation of direct effects of the modified flow regime from impacts associated with land-use changes that often accompany water resource development (e.g., conversion of forest to irrigated agriculture). In writing this review, we often encountered reports of river systems affected by multiple stressors and were unable to definitively separate the impacts of altered flow regimes from those of the myriad of other factors and interactions. How much of an observed decline in species diversity can be attributed directly to modified flow compared with diffuse inputs of nutrients and other contaminants? A similar problem occurs in our attempts to unravel the cause and effect of exotic species on aquatic biodiversity. Is an observed decline in native fish species the result of a modified flow regime or the direct impact of an introduced species (or both)? Alternatively, is the proliferation of exotic species a direct response to the modified flow or the decline in native species (or both)? Ecological science is not yet able to answer these questions, important as they are.

Ecologists still have much to learn about the ecological significance of individual flow events and sequences of events, and descriptive science can take us only so far in unraveling these linkages. The advice from aquatic ecologists on environmental flows might be regarded at this point in time as a series of largely untested hypotheses about the flows that aquatic organisms need and how rivers function in relation to flow regime. To overcome these problems, aquatic science needs to move into a manipulative or experimental phase, either by restoring flows, or taking away flows, and measuring ecosystem response. It is hoped, flow restoration experiments will dominate over flow regulation experiments!

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Extinction Rates in North American Freshwater Fishes, 1900–2010

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Extinction Rates in North American Freshwater Fishes, 1900–2010

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Widespread evidence shows that the modern rates of extinction in many plants and animals exceed background rates in the fossil record. In the present article, I investigate this issue with regard to North American freshwater fishes. From 1898 to 2006, 57 taxa became extinct, and three distinct populations were extirpated from the continent. Since 1989, the numbers of extinct North American fishes have increased by 25%. From the end of the nineteenth century to the present, modern extinctions varied by decade but significantly increased after 1950 (post-1950s mean = 7.5 extinct taxa per decade). In the twentieth century, freshwater fishes had the highest extinction rate worldwide among vertebrates. The modern extinction rate for North American freshwater fishes is conservatively estimated to be 877 times greater than the background extinction rate for freshwater fishes (one extinction every 3 million years). Reasonable estimates project that future increases in extinctions will range from 53 to 86 species by 2050.

Keywords: North America, freshwater fishes, extinction rates, E/MSY, aquatic biodiversity

Understanding the underlying causes of the extinction of modern organisms is, in most cases, relatively simple. Extinction is the antithesis of speciation and a natural outcome of evolutionary change (Darwin 1859). Under natural conditions, including catastrophic events, extinction is one of nature's best ideas: It enables life to adapt to ever-changing environments. A fundamental concern among biologists is that contemporary rates of extinction due to human activities are orders of magnitude greater than background rates evidenced in the fossil record, and these rates appear to be increasing (May et al. 1995, Pimm et al. 1995, 2006). Catastrophic events that caused the five well-known mass extinctions, including the cataclysmic extermination of the dinosaurs, are not responsible for the majority of extinctions in geological history. Rather, 90%–96% of all extinct species variably disappeared during the normal give and take of speciation and extinction over geological time scales (May et al. 1995). In phylogenetic theory, ancestral species may become extinct in the evolutionary transition to new species, or conversely, derived taxa may split from the ancestral taxa and remain extant. Both modes are theoretically plausible under allopatric speciation scenarios (Wiley and Mayden 1985). In the present study, I am not concerned with methodological intricacies; rather, I focus on the human-caused extinction of North American freshwater fishes from the close of the nineteenth century to the present. In the context of human life spans, observations of extinction should be extraordinarily rare. Nonetheless, since 1900, at least 57 species and subspecies of North American freshwater fishes have become extinct, and three unique populations have been extirpated (Miller et al. 1989, Jelks et al. 2008).

> *"Do not tell fish stories where the people know you; but particularly, don't tell them where they know the fish."*
> *—Mark Twain.*

Declining biodiversity and increasing rates of extinction are fundamentally important metrics of natural resource status and are the subjects of intensive investigation. In particular, the mitigation and prevention of biodiversity loss are among the overarching goals of conservation biology (Helfman 2007, Pereira et al. 2010). The threat of extinction may be greatest in freshwater ecosystems, where the proportion of threatened and endangered species is generally greater than that in terrestrial ecosystems (Pimm et al. 1995, Strayer and Dudgeon 2010) and where imperilment levels are similar to those of tropical rain forests (Ricciardi and Rasmussen 1999). Inferences that the rates of contemporary extinction will increase are based on large numbers of organisms considered to be critically endangered worldwide (IUCN 2011), the increasing negative effects of human activities on the Earth's biosphere (Vitousek et al. 1997, Naiman and Turner 2000, McKee et al. 2004, Davies et al. 2006), and the conclusion that such activities will result in higher near-future extinction rates (Pereira et al. 2010, Barnosky et al. 2011).

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North American freshwater fishes: A brief synopsis

North America is geographically defined as Canada, the United States, and Mexico, including the coastal islands off Canada and Alaska but excluding Hawaii and the southern Mexican states of Quintana Roo and Campeche (Jelks et al. 2008). The diversity of fishes is equivalent to that of all other vertebrate groups combined (Nelson 2006); therefore, the number of descriptions of fishes new to science exceeds that of descriptions of new tetrapods each year. At the close of 2010, the cutoff point for this study, 31,769 valid fish species had been described worldwide (William N. Eschmeyer, California Academy of Sciences [retired], personal communication, 28 August 2011). About 43% of the world's fishes are freshwater or diadromous species (Nelson 2006). Comparatively, the freshwater fish diversity of North America is less than those of Africa (about 2945 species), Asia (3533), and South America (4035), but higher than those of Europe (330), Russia (206), and Oceania (260) (Lévêque et al. 2008). North America has the most diverse nontropical freshwater fish fauna in the world (Lundberg et al. 2000). At the end of 2010, the freshwater fish fauna of North America consisted of 53 families, 214 genera, and 1213 species, or about 8.9% of the Earth's freshwater fish diversity (Nelson et al. 2004). Continental fishes primarily consist of obligate freshwater species, *diadromous* fishes (species in which part of their life cycle occurs in the marine realm), and marine fishes that occasionally or regularly enter freshwater during their lives. The tally through 2010 is based on independent counts of species described after 2004, aided by comments from Larry Page (University of Florida Museum of Natural History, personal communication, 14 October 2010).

Patterns of species richness

Until recently, most species of the modern North American fish fauna were considered derived from the mid-Miocene to the late Pleistocene, or about 15–1.5 million years ago (mya) or less (Mayden 1988, Strange and Burr 1997, Smith GR et al. 2002). However, cross-calibration of molecular-clock and fossil data (chronograms) has significantly revised the concepts of lineage ages in fishes. For example, half of the sunfish family's (Centrarchidae) lineages significantly predate the Pleistocene, and the least-derived taxon—the mud sunfish (*Acantharchus pomotis*)—emerged by the early Oligocene, 33.7 mya (Near et al. 2005). The mean age estimates for species lineages in the diverse family Percidae have been pushed back to the Oligocene, from 30.7 to 34.8 mya (Near et al. 2011). These studies suggest that many North American fishes are likely to be far older than was previously recognized.

There is, however, clear evidence for the derivation of species from the late Pleistocene (Near and Benard 2004, Near et al. 2005) to the last 10,000 years for species that evolved after the glaciers retreated (e.g., Hatfield 2001, Taylor et al. 2006). The end of the Pleistocene was demarked by dramatic changes: subsidence of glaciers, rising sea levels, severing of lateral connections between some coastal drainages, and the filling of numerous basins gouged by the giant ice sheets (e.g., the Great Lakes; Hocutt and Wiley 1986). The evolution and biogeography of the North American fish fauna is intimately linked to transitional changes to landforms and their influences on continental watercourses over time (Mayden 1988, Smith GR et al. 2002). Generally, species richness per drainage (or ecoregion) increases from Canada southward, but over two-thirds of species richness occurs east of the Great Continental Divide, especially in the Interior and Appalachian Highlands (Hocutt and Wiley 1986, Mayden 1992). Fishes in the western United States and Mexico exhibit relatively lower species richness per drainage unit but generally have higher endemism and disproportionate numbers of extinct species (Minckley and Douglas 1991, Burr and Mayden 1992).

Rates of faunal documentation and evidence of extinction

Our knowledge of North American fishes is facilitated by a long tradition of faunal study and public access to most river and lake systems. From 1758 to 2010, the average rate of fish descriptions for North America was 4.8 species described per year, but as is evident in figure 1a, the rates varied over time and logically increased as more biologists studied the fauna. From 1970 through 2010, species documentation averaged 6.7 species described per year, which is considered the modern rate of faunal discovery and documentation (figure 1a). The discovery and description of North American freshwater fishes continues unabated, and unlike birds (see Pimm and colleagues' [2006] figure 1), there is no evidence of an asymptote in the rates of species descriptions.

Modern extinctions of North American fishes were first observed at the dawn of the twentieth century, and the trend continues (figure 1b). The exact year of extinction can be difficult to document (Harrison and Stiassny 1999) because of the inherent difficulty of observing an organism when the probability of its detection approaches zero. Among the first fishes observed to be declining (and later to become extinct) were commercially important Great Lakes fishes for which harvest data were kept (McCrimmon 2002). Included in that group is the first fish population to disappear from North America, the Lake Ontario population of the highly valued Atlantic salmon (*Salmo salar*). The year of expiration for six narrow endemics is exactly known because the desiccation of their habitats (four springs and one caldera) was observed. These species included five desert pupfishes (*Cyprinodon* spp.; Contreras-Balderas and Lozano-Vilano 1996) and the last known fish to go extinct in North America, the Alberca silverside (*Chirostoma bartoni*), which vanished when the Alberca caldera temporarily dried in August 2006 (Edmundo Díaz Pardo, Universidad Autonoma de Queretaro, personal communication, 13 September 2007). In many cases, extinction was recognized only in hindsight, and the last year of observation was used to estimate the extinction year (Miller et al. 1989).

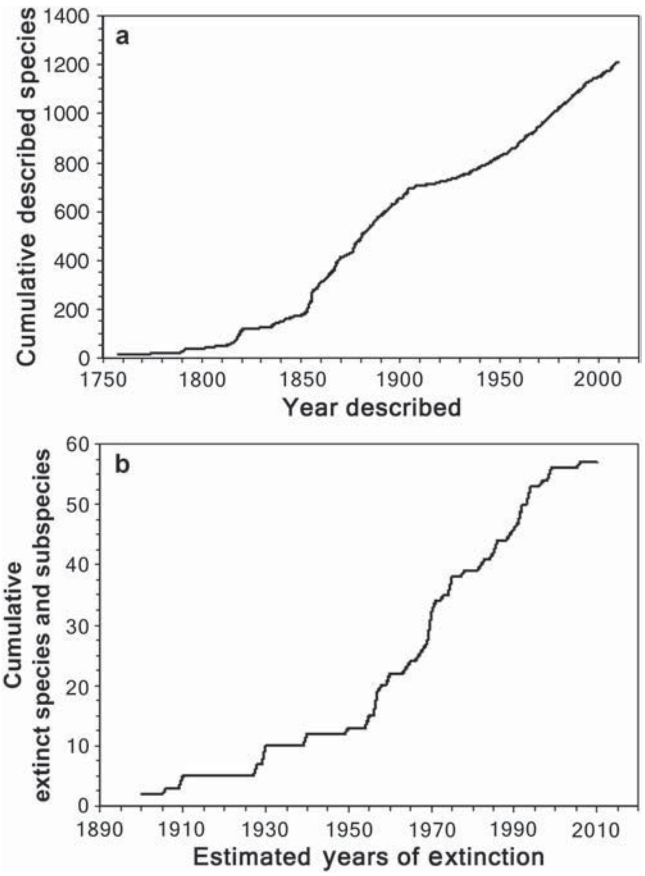

*Figure 1. (a) Cumulative rate of North American fish descriptions from 1758 to 2010 (*n *= 1213 species). (b) Cumulative rate of North American fish extinctions from 1900 to 2010 (*n *= 57 [39 species and 18 subspecies]).*

Data sources, definitions, corrections

The data for this study were derived from the foundational study by Miller and colleagues (1989), which provided the first list of 40 extinct fishes and included the causes and estimated years of their extinction. The conservation assessment by Jelks and colleagues (2008) reduced the number of extinct fishes listed by Miller and colleagues (1989) from 40 to 35 taxa (four fishes were determined to be extant, and one was a synonym), and added 26 new taxa to the list. During data compilation for this report, one fish listed as *possibly extinct* (Jelks et al. 2008), an undescribed species of *Gila*, "carpa gorda de Parras," an endemic known only from desert springs near Parras, Coahuila, Mexico (Contreras-Balderas et al. 2003), was rediscovered from a nearby spring after a 42-year hiatus in observation (Dean Hendrickson, University of Texas at Austin, personal communication, 10 June 2010). Additional data on fish extinction from other continents were downloaded from the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (IUCN 2011).

The total richness of freshwater fishes listed here does not include all species characterized as *freshwater fishes* by Nelson and colleagues (2004). Excluded are 77 marine fishes that are tolerant of variable salinities, because these species do not appear to be dependent on freshwater to complete their life cycles throughout their ranges. A well-known example is the bull shark (*Carcharhinus leucas*). Examples of euryhaline species with populations dependent on freshwater and included as part of the freshwater fauna tallied herein are the Atlantic needlefish (*Strongylura marina*), the opossum pipefish (*Microphis brachyurus*), and the California killifish (*Fundulus parvipinnis*).

The term *extirpated* (meaning that all individuals in a population have been lost) is distinguished from *extinct* (all individuals of a species have been permanently lost). The three categories of *extinct* defined in the conservation assessment of North American freshwater fishes—*extinct in nature*, *possibly extinct*, and *extinct* (Jelks et al. 2008)—are combined herein to simplify the analyses. Three taxa listed as *extinct* by Jelks and colleagues (2008) are actually extirpated populations, but they are retained on the list (table 1) because their ranges and years of extirpation are known and because they are analogous to regionally extinct taxa tracked by the IUCN (Snoeks et al. 2011). The last year of observation and the estimated year of extinction listed by Miller and colleagues (1989) for three species of the minnow genus *Evarra* are corrected to be 1957 and 1970, respectively (Edmundo Díaz Pardo, Universidad Autonoma de Queretaro, personal communication, 13 August 2011). Because the AFS definitions of *possibly extinct* and *extinct* incorporate hiatuses of 20 or 50 years since the last observation of a species, respectively (Jelks et al. 2008), it is possible, even though 12 years have passed, that the tally of twentieth century fish extinctions remains incomplete. I reviewed literature cited by Miller and colleagues (1989) and data compiled by Jelks and colleagues (2008) to determine the last year of observation to estimate the difference in years between the last observation and the estimated year of extinction for the 60 fish taxa.

The Highland splitfin (*Girardinichthys turneri*), a species listed as *extinct* by Jelks and colleagues (2008), was reported to be extant in Lake Zacapu but as *Hubbsinna turneri* (Ramírez-Herrejón et al. 2010). The Lake Zacapu population in Michoacán, Mexico, is recognized as a distinct sister taxon, the Zacapu splitfin (*Girardinichthys ireneae*; Radda and Meyer 2003). Therefore, of the 60 extinct taxa (table 1), 35 are from Miller and colleagues (1989) and 25 are from Jelks and colleagues (2008), including three extirpated populations.

This assessment of North American fish extinctions is a spin-off study of the AFS Endangered Species Committee (ESC) that was active from 2004 to 2008 (i.e., after Jelks et al. 2008). This report is the first of three articles on the extinction patterns in North American fishes that are built on the data developed by Miller and colleagues (1989) and Jelks and colleagues (2008). A summary of data on extinct North American freshwater fishes is at the USGS Web site, as are relevant definitions and other information sources. In the present article, I focus on the current, background, and

Table 1. Extinct North American freshwater fishes as of December 2010.

Family	Scientific name	Common name	Estimated year of extinction
Cyprinidae (minnows)	*Cyprinella lutrensis blairi*[a]	Maravillas red shiner	1960
	Evarra bustamantei[a]	Mexican chub	1983
	Evarra eigenmanni[a]	Plateau chub	1983
	Evarra tlahuacensis[a]	Endorheic chub	1983
	Gila bicolor sp.[b,c]	"High Rock Springs Tui chub"	1989
	Gila crassicauda[a,c]	Thicktail chub	1957
	Gila sp.[b,c]	"Carpa delgada de Parras"	1968
	Lepidomeda altivelis[a]	Pahranagat spinedace	1940
	Notropis aulidion[a]	Durango shiner	1965
	Notropis orca[a,c]	Phantom shiner	1975
	Notropis saladonis[b]	Salado shiner	1992
	Notropis simus simus[a,c]	Rio Grande bluntnose shiner	1964
	Pogonichthys ciscoides[a,c]	Clear Lake splittail	1970
	Rhinichthys cataractae smithi[a]	Banff longnose dace	1982
	Rhinichthys deaconi[a]	Las Vegas dace	1955
	Rhinichthys osculus reliquus[a]	Grass Valley speckled dace	1950
	Stypodon signifer[a]	Stumptooth minnow	1930
Catostomidae (suckers)	*Chasmistes liorus liorus*[a,c]	June sucker	1935
	Chasmistes muriei[a]	Snake River sucker	1928
	Moxostoma lacerum[a]	Harelip sucker	1910
Ictaluridae (North American catfishes)	*Noturus trautmani*[b,c]	Scioto madtom	1957
Salmonidae (trouts and salmons)	*Coregonus johannae*[a]	Deepwater cisco	1955
	Coregonus kiyi orientalis[a]	Lake Ontario kiyi	1967
	Coregonus nigripinnis nigripinnis[a,c]	Blackfin cisco	1969
	Coregonus reighardi reighardi[b,c]	Shortnose cisco	1985
	Oncorhynchus clarkii alvordensis[a]	Alvord cutthroat trout	1940
	Oncorhynchus clarkii macdonaldi[a,c]	Yellowfin cutthroat trout	1910
	Salmo salar[b,c]	Atlantic salmon, Lake Ontario pop	1898
	Salvelinus fontinalis agassizii[a,c]	Silver trout	1930
	Thymallus arcticus[b,c]	Arctic grayling, Great Lakes pop	1935
Atherinopsidae (New World silversides)	*Atherinella callida*[b,c]	Cunning silverside	1957
	Chirostoma bartoni[b,c]	Alberca silverside	2006
	Chirostoma charari[b,c]	Least silverside	1957
	Characodon garmani[a]	Parras characodon	1900
Goodeidae (goodeids)	*Empetrichthys latos concavus*[a]	Raycraft Ranch poolfish	1960
	Empetrichthys latos pahrump[a,c]	Pahrump Ranch poolfish	1958
	Empetrichthys merriami[a]	Ash Meadows poolfish	1953
	Girardinichthys turneri[b]	Highland splitfin	1990
	Skiffia francesae[b]	Golden skiffia	1978
Fundulidae (topminnows)	*Fundulus albolineatus*[a]	Whiteline topminnow	1900
Cyprinodontidae (pupfishes)	*Cyprinodon alvarezi*[b,c]	Potosí pupfish	1994
	Cyprinodon arcuatus[a]	Santa Cruz pupfish	1971
	Cyprinodon ceciliae[b,c]	Villa Lopez pupfish	1991

Table 1. Continued

Family	Scientific name	Common name	Estimated year of extinction
	Cyprinodon inmemoriam[b,c]	Charco Azul pupfish	1986
	Cyprinodon latifasciatus[a]	Parras pupfish	1930
	Cyprinodon longidorsalis[b,c]	La Palma pupfish	1994
	Cyprinodon nevadensis calidae[a]	Tecopa pupfish	1971
	Cyprinodon veronicae[b,c]	Charco Palma pupfish	1997
	Megupsilon aporus[b,c]	Catarina pupfish	1994
Poeciliidae (livebearers)	*Gambusia amistadensis*[a,c]	Amistad gambusia	1973
	Gambusia georgei[a]	San Marcos gambusia	1983
	Priapella bonita[b]	Graceful priapella	1906
Gasterosteidae (sticklebacks)	*Gasterosteus* sp. cf. *aculeatus*[b,c]	"Benthic Hadley Lake stickleback"	1999
	Gasterosteus sp. cf. *aculeatus*[b,c]	"Limnetic Hadley Lake stickleback"	1999
Cottidae (sculpins)	*Cottus echinatus*[a,c]	Utah Lake sculpin	1928
Moronidae (temperate basses)	*Morone saxatilis*[b,c]	Striped bass, St. Lawrence Estuary pop	1968
Percidae (perches)	*Etheostoma sellare*[b,c]	Maryland darter	1988
	Sander vitreus glaucus[a]	Blue pike	1970
Cichlidae (cichlids)	*Cichlasoma urophthalmus conchitae*[b,c]	Mojarra del cenote Conchita	1975
	Cichlasoma urophthalmus ericymba[b,c]	Mojarra de Sambulá	1975

Note: The common names of undescribed taxa are in quotation marks. Abbreviations: sp., species; ssp., subspecies; pop, extirpated population.
[a] 35 extinct fishes (Miller et al. 1989).
[b] 25 taxa added to the list by Jelks and colleagues (2008).
[c] 32 taxa for which the last year of observation is the same as the estimated year of extinction.

near-future extinction rates out to 2050 in the continent's freshwater fish fauna.

Current rates of extinction

Rates of extinction can be estimated indirectly using species–area relationships (May et al. 1995), from models (Ricciardi and Rasmussen 1999), or directly when extinct taxa and associated data are known. All extinct or extirpated fishes treated herein represent modern losses as opposed to extinctions in the geological past (table 1). The rates of extinction fluctuated by decade, with a significant increase in the mean number of extinctions per decade after 1950 (figure 2). The post-1950s increases in extinction probably resulted from indirect effects of the post–World War II baby boom, including demographic shifts from rural to urban areas, increased construction of large and small dams, increased alteration of natural water bodies (e.g., channelization, pollution), and other consequences of economic growth and industrial expansion (CEC 2001, McKinney 2002, De Souza et al. 2003). The recent decline in extinction rates is the fourth decadal decline since 1900, but three of the extinction declines were followed by episodes of increasing or stable extinction rates (figure 2).

The patterns of decadal extinctions in North America roughly paralleled those on other continents, but the number of extinctions across decades was significantly higher in North America than those in all other continents combined (figure 3). Of the estimated 83 extinct fish species and subspecies worldwide (IUCN 2011), North America accounts for 57, Eurasia 19, Africa and Madagascar 5, South America 1, and Oceania 1. Some of these discrepancies clearly relate to the numbers of ichthyologists and the history of faunal investigation in different regions of the world. Other regions with long (or longer) traditions of faunal study exhibit similar overall extinction rates to that of North America—for example, in Europe, 3.4% of 531 species are extinct or possibly extinct (Freyhof and Brooks 2011), and in the Mediterranean basin, 3.2% of 253 species are extinct (Smith KG and Darwall 2006). Around 43% of the 31,769 fish species on Earth are freshwater fishes (Nelson 2006), which equals about 13,661 species, 3% of which would be approximately 410 extinct freshwater species worldwide. This elementary extrapolation based on the North American proportion of extinct fishes suggests that worldwide tallies of extinct freshwater fishes significantly underestimate the actual number suggested by current databases (IUCN 2011)—perhaps by several times.

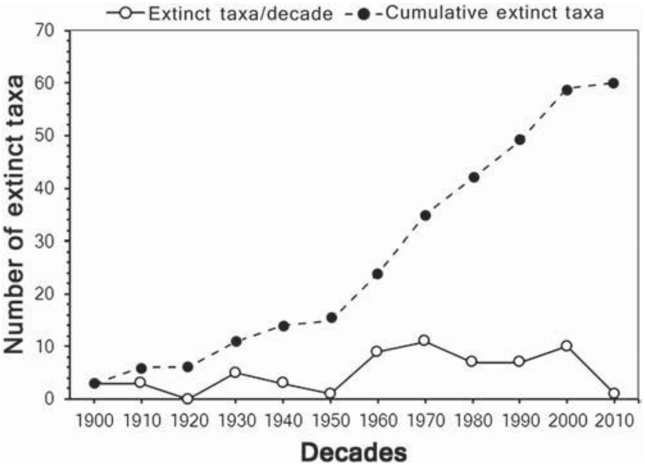

Figure 2. Extinction rates of North American freshwater fishes by decade (*n *= 60). The solid black circles and dashed line represent cumulative extinctions and extirpations from 1898 to 2006. The open circles and solid line represent extinctions by decade (range = 0–11 extinctions per decade; pre-1950s mean = 2.5; post-1950s mean = 7.5;* t*-test for unequal variances,* t*(7) = –6.16, two-tailed,* p *= .0004).

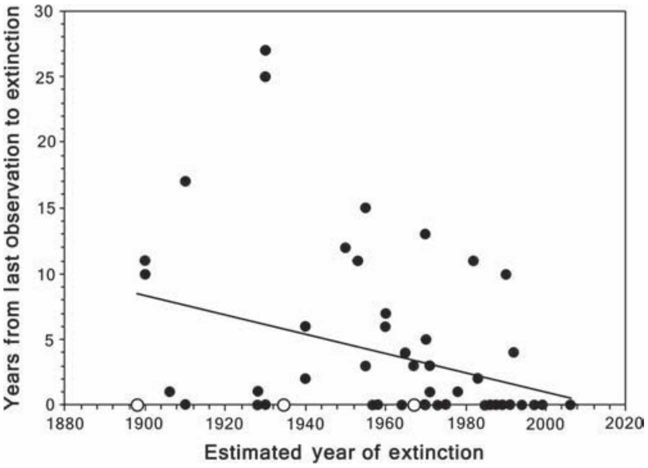

Figure 4. Lag time in years between the last observation of a species and its estimated year of extinction for North American freshwater fishes. Mean lag time = 3.8 years. The closed circles represent extinct species and subspecies, including undescribed taxa. The open circles represent extirpated populations (32 taxa had lag times of 0 years). The fitted black trend line is that described by a simple linear regression (*R^2 *= .0994,* p *< .0001).

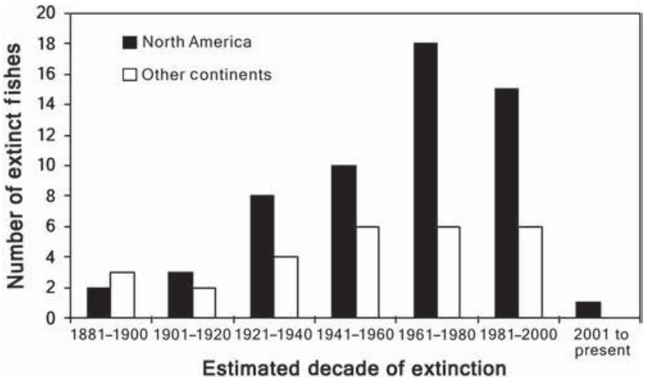

Figure 3. Comparison of extinction rates for freshwater fishes of North America (black bars) and those from other continents (white bars). The other continents and islands include Africa and Madagascar, Eurasia, South America, and Oceania. The data are from the International Union for Conservation of Nature (2011). The categorical differences in decadal proportions between North America and the other continents are significantly different (Fisher's exact test,* p *< .0001).

It has been argued that extinction dates should be classified relative to the strength of evidence supporting their validity, known as *effective extinction dates* (Harrison and Stiassny 1999). Harrison and Stiassny (1999) recommended listing a range of dates when the year of disappearance is not precisely known, and they suggested nine categories of extinction. The AFS definitions of *extinction* explicitly require that searches for missing species be performed by experienced biologists and provides classifications based on different hiatuses in years since the last observation. I elected to compare the last year of observation with the estimated year of extinction for North American fishes. The data indicated that the differences were greatest prior to 1940 and decreased thereafter (figure 4). Some fishes may have been extinct when they were described, although their fate was unknown at that time. For example, a silverside species that was known only from a single site (a narrow endemic), the cunning silverside (*Atherinella callida*), was captured only once, in 1962, and its common name was ironically coined for its ability to avoid detection (Chernoff 1986)—when it was described, it may have already been extinct. Unexpectedly, the last year of observation was the same as the estimated year of extinction for 29 fishes and was the same as the year of extirpation for the three populations (table 1, figure 4). Examples of these fishes include commercially important Great Lakes fishes for which annual catches were tracked (McCrimmon 2002). Also included in this number are fishes that were narrow endemics, for which the years of habitat destruction or introductions of a nonindigenous species were known (Contreras-Balderas and Lozano-Vilano 1996, Hatfield 2001). The largest differences in lag times occurred in the first half of the twentieth century, and the differences generally declined toward the close of the twentieth century (figure 4). The taxa with the three highest lag times were the Parras pupfish (*Cyprinodon latifasciatus*, 27 years), the stumptooth minnow (*Stypodon signifer*, 25 years), and the harelip sucker (*Moxostoma lacerum*, 17 years). The loss of 57 species and subspecies and three unique populations since 1898 is intuitively significant, but only a comparison of modern with background extinction rates (BERs) will enable a robust evaluation of these losses.

Background rates of extinction

In their seminal studies, Pimm and colleagues (1995, 2006) demonstrated the utility of comparing modern extinctions with BERs in birds by estimating the number of extinctions per million species years (E/MSY). This logical approach facilitates comparing modern bird extinction rates with those of other biotas, and the examination of changes in bird extinction rates in the past 500 years. To estimate the E/MSY, the following must be known: the mean species duration interval from origination to extinction (from the fossil record) in millions of years, the total number of extant taxa, the number of modern extinct taxa, and the interval in years in which modern extinctions occurred. Pimm and colleagues (1995, 2006) lacked data for the mean species duration interval for birds, so they substituted data from terrestrial vertebrates (mammals; Pimm et al. 1995, May et al. 1995). They also considered 1 million years as the benchmark interval prior to human impacts.

Pimm and colleagues (2006) specifically posited that around 1.3% of the roughly 10,000 known bird species have become extinct since 1500, which equals a modern to BER of approximately 26 E/MSY (calculated by multiplying the quotient of the mean species duration interval for birds and total bird diversity [$10^6/10^4 = 100$] by the mean annual bird extinction rate [130 extinctions/500 years = 0.26]). When shorter intervals over which extinction occurred (e.g., since 1900) were examined, global extinction rates were as high as 65 E/MSY (Pimm et al. 2006).

For North American freshwater fishes, the mean species duration interval from the fossil record is 3 million years (Stanley 1990), the total number of species is 1213, the time interval over which modern extinctions were examined is 110 years (1900 to 2010), and the number of extinct fish species is 39 (3 of which are undescribed). The modern to BER estimate is 877 E/MSY for North American freshwater fishes—the highest estimate reported for contemporary vertebrates (Pimm et al. 2006, Pereira et al. 2010 [and its supplemental material], Barnosky et al. 2011).

Several issues merit a brief discussion relative to the comparison of modern extinction rates with BERs. First, the actual species richness of North America freshwater fish fauna is not yet known, as is indicated by the lack of an asymptote in the rate of fish descriptions (figure 1a), and it is possible that not all recent fish extinctions are known. In addition, fishes are not equal entities evolutionarily or with respect to species duration intervals. The latter spans several orders of magnitude, from about 10,000 years ago to the present for fishes that diverged after the last glaciation (Smith GR et al. 2002, Taylor et al. 2006) to over 160 mya for extant archaic fishes, such as the longnose gar (*Lepisosteus osseus*; Grande 2010). The loss of species such as sturgeon or gar would significantly increase the mean duration intervals for freshwater fishes because of the tremendous species durations of these archaic fishes. At least two sturgeon species of *Pseudoscaphirhynchus* are considered critically endangered in Eurasia (IUCN 2011); if one of these sturgeons disappeared, the mean species duration interval for fishes would significantly increase, causing estimates of E/MSY to increase likewise. If evolutionarily old taxa such as sturgeons, paddlefishes, or gars became extinct, it might be appropriate to divide extinct fishes into two groups—archaic and modern bony fishes. The species duration interval estimated for freshwater fishes (Stanley 1985, 1990) is based on Lyellian percentages—proportions of living species within fossil faunas (Stanley et al. 1980). As was noted in Near and colleagues' (2005, 2011) discussions of recent chronogram estimates for centrarchids and percids, the lineage derivation estimates are far older than was previously known, and it is possible that the mean duration interval of one extinction every 3 million years (Stanley 1985, 1990) underestimates, perhaps significantly, the species age for freshwater fishes. If that were true, it would make the E/MSY estimates low, possibly by an order of magnitude. For example, if the mean species duration for freshwater fishes is actually closer to one extinction each 11 million years, the modern to BER estimate for North American fishes would be 3215 E/MSY.

The ability to compare modern extinction rates with BERs facilitates meaningful comparisons of contemporary extinction rates among different biotas (Pereira et al. 2010 [and its supplemental material], Barnosky et al. 2011). Most of the bird extinctions investigated by Pimm and colleagues (2006) were of island species, which are inherently susceptible to extinction because of high endemism; habitat destruction; and the introduction of nonnative organisms, including humans. BERs are compared among world vertebrate groups for the twentieth century in table 2. The E/MSY estimate for freshwater fishes in the twentieth century was nearly twice that of other vertebrate groups. The BER estimated for birds (table 2) is higher than that estimated by Pimm and colleagues (2006) because I used different species duration data for birds (i.e., 2.5 million years; Stanley 1990). As was noted in the "Current rates of extinction" section, the reported extinction rates for freshwater fishes from other continents appear grossly underestimated. If, for example, the continental extinction rate for North America (3.2%) mirrors the extinction rates of freshwater fishes in other continents, the number of extinct fishes for the twentieth century would be around 384 species (instead of 81 in table 2) and the twentieth century BER would be 960 E/MSY.

The continental list of extinct fishes from Africa and Madagascar differs from the data given in the worldwide assessment of extinct fishes by Harrison and Stiassny (1999), in which about 50 haplochromine cichlids from Africa and Madagascar were considered *possibly extinct*. In a recent assessment, Snoeks and colleagues (2011) determined that these species are critically endangered or that their status is data deficient and in need of further study.

Table 2. Comparison of current to background extinction rates for world vertebrates in the twentieth century.

Vertebrate group	Total number of species	Total number of extinct species	Mean species duration	E/MSY
Freshwater fishes	11,997	81[a]	3.0[b]	203
Amphibians	5743[c]	25[a]	1.0	44
Reptiles	8860[d]	11[a]	~2.2[e]	27
Birds	9917[c]	45[c]	2.5[b]	113
Mammals	4853[c]	31[c]	1.7[b]	109

Note: The number of freshwater fishes in 2000 was 43% of about 27,901 total species (Eschmeyer and Fong 2012). Mean species duration is the species life span in millions of years from origination to extinction; when it was not known, it was estimated to be 1.0 E/MSY, which is also considered the benchmark extinction rate prior to human impacts (Pimm et al. 1995). The correct twentieth century background extinction rate for fishes may be over 900 E/MSY (see the "Background rates of extinction" section).
Abbreviations: E/MSY, extinctions per million species years.
[a] IUCN 2011. [b] Stanley 1990. [c] Pereira et al. 2010. [d] Uetz 2000. [e] Stanley 1985.

Predicting extinctions to 2050

Human activities are inexorably linked to fish extinctions, which makes prediction of future extinctions challenging. The primary causes of imperilment and extinction in freshwater fishes are the loss of habitat and the introduction of nonindigenous fishes (Harrison and Stiassny 1999, Jelks et al. 2008). Even with prescient knowledge, it is doubtful that some extinctions resulting from introductions of alien fishes could ever be anticipated. For example, the unlikely introduction of brown bullhead catfish (*Ameiurus nebulosus*) into one of a few lakes on small coastal islands off British Columbia (Hatfield 2001) resulted in the decimation of sympatric populations of distinct sticklebacks (table 1). Likewise, the very remoteness of desert springs seemed to ensure the security of isolated pupfishes, but in hindsight, groundwater pumping was an obvious threat to the persistence of the springs (figure 5; Contreras-Balderas and Lozano-Vilano 1996).

Future extinctions will probably include some of the North American fishes recently classified as *threatened* (190) and *endangered* (280), particularly the 73 endangered species that were identified as *declining* (Jelks and colleagues' [2008] appendix 1). The Southeastern Fishes Council published a list of the 12 most endangered fishes in the southeastern United States (SFC 2008), all of which are vulnerable to extinction in the near future. One of these fishes, the slender chub (*Erimystax cahni*; figure 6), is a minnow that is most recently known only from a few sites in a 13-kilometer section of the Clinch River in northeastern Tennessee. Despite repeated intensive seining and snorkeling surveys focused on the species, it has not been observed since 1996 (SFC 2008). The slender chub is on the knife's edge; we do not know whether it was the last fish to disappear in the twentieth

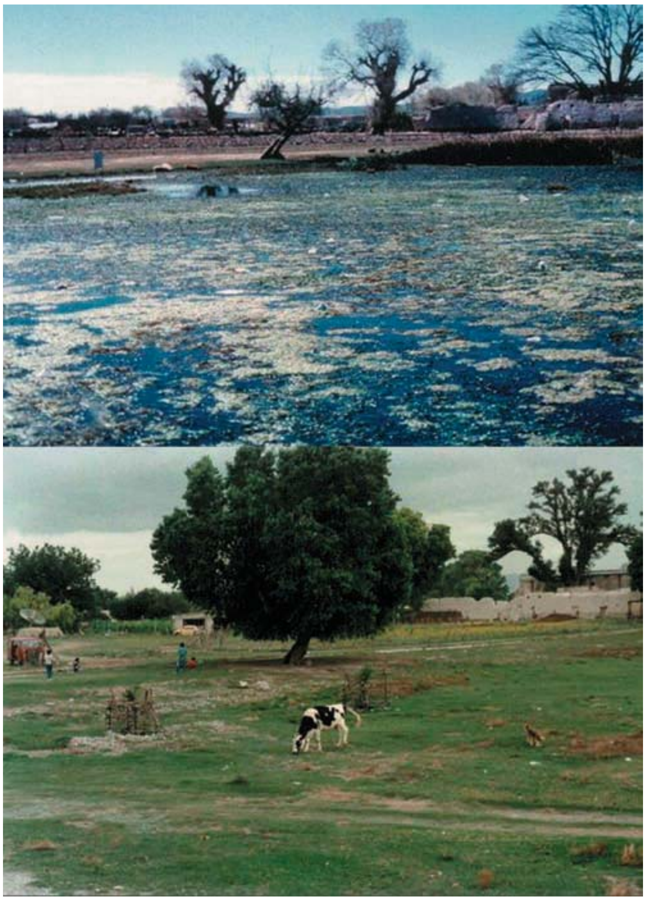

*Figure 5. Potosí Spring, northwest of Galeana, Nuevo León, Mexico, was the only known locality for two narrow endemic fishes, the Potosí pupfish (*Cyprinodon alvarezi*) and Catarina pupfish (*Megupsilon aporus*). The top image is from 1972, and the bottom is from 1995. Groundwater pumping caused the spring to dry in 1994 and two pupfishes to go extinct. Photographs: Salvador Contreras-Balderas (deceased); images courtesy of his family.*

*Figure 6. The slender chub (*Erimystax cahni*), a narrow endemic in the upper Tennessee River drainage that has not been observed since 1996 despite repeated, intensive searches. The slender chub may be the next fish declared* possibly extinct *in North America (adult male, 81.1 millimeter standard length, Clinch River, Hancock County, Tennessee, 29 June 1985). Photograph: Noel M. Burkhead and Robert E. Jenkins, courtesy of the Virginia Division of Game and Inland Fisheries.*

century or whether it made it to the twenty-first century. If it is not found in 5 years, the slender chub could be the next fish to qualify for *possibly extinct* status in North America.

Mexico has a large number of fishes vulnerable to extinction in the near future, primarily because of high levels of endemism. Of the 280 North American fishes identified as *endangered*, 65 were exclusively from Mexico, 70 were from the United States, and 21 were from Canada (Jelks et al. 2008). For example, the Ameca River system, noted for its high levels of endemism, has lost 70% of its native fish fauna (López-López and Paulo-Maya 2001, Pérez-Rodríguez et al. 2009). The family Goodeidae has a large number of endangered and extinct species in Mexico. Of the extant Mexican goodeids, 16 were identified as *critically endangered* and 7 as *endangered* (Domínguez-Domínguez et al. 2005); all are small fishes, and most are narrow or localized endemics exposed to multiple threats. Another nine Mexican fishes were recently categorized as *in danger of extinction* (Schmitter-Soto 2006).

A frequently cited exponential-decay model used to estimate future extinction rates required recent data on the numbers of threatened and endangered species in order to model future extinctions (Ricciardi and Rasmussen 1999) and was therefore unable to estimate the number of future fish extinctions by 2050. Assuming no near-future catastrophic events, different elementary approaches were used to estimate the numbers of extinct fish species by 2050. The number of currently declining endangered fishes (see Jelks and colleagues' [2008] appendix 1) plus the number of currently extinct species equals 113 species. Although it is unlikely that all currently declining endangered fishes would become extinct by 2050, 113 species could be considered the upper limit of extinction in a worst-case scenario. Two elementary extrapolations based on the mean annual extinction rate (MAER) and on the mean annual description rate (MADER) yielded the following estimates: The overall MAER is 0.35 extinct fish species per year (which is more conservative than the post-1950s rate of 0.73 species per year; see figure 2). Beginning with 39 extinct species in 2010, the MAER extrapolation approximates 53 extinct species by 2050 (an increase of 14 species). The MADER extrapolation based on 6.7 species described per year yields 1482 species by 2050. Under the assumption that the continental proportion of extinct fishes remains about 3.2% until 2050, the number of extinct fish species approaches 86 (an increase of 47 species). Therefore, by 2050, the number of extinct fishes is estimated to range from 53 to 86 species, representing an increase of 35.9%–120.5%, with an improbable upper limit of 113 species (a 190% increase).

What is more important to resource managers than estimating the number of future extinctions is identifying which fishes are more likely to become extinct in the near future. Of the endangered fishes listed by Jelks and colleagues (2008), those that are narrow or localized endemics and in proximity to major urban areas, transportation corridors, future energy development, or resource extraction sites or whose ranges are truncated by large impoundments are probably more vulnerable to future extinction because of exposure to multiple stressors (McKinney 2002, McKee et al. 2004).

Conclusions

Each continental fish fauna is a unique, globally important resource of immensurable worth. The North American fish fauna has tremendous recreational and commercial value, as well as aesthetic, scientific, and cultural importance (Helfman 2007, NFHB 2010). In particular, fish represent important sources of protein for individuals at lower socioeconomic levels worldwide (Helfman 2007). With respect to scientific and ecological studies, fishes are especially useful for evaluating environmental change, because biologists know much more about their biology than they do those of other aquatic biotas. Actually, declining fishes represent just the tip of the iceberg regarding losses of freshwater biota and their habitats. Comparatively, mussels and snails are exceptionally imperiled, with BERs an order of magnitude greater than that of freshwater fishes.

The exigent issue regarding these extinctions is not so much the number of missing fishes but the fact that these fishes disappeared in only 110 years (figures 1b and 2). Fish extinction rates are currently 877 times greater than BERs, and since 1900, those rates have fluctuated between 556 and 1042 E/MSY. These BER estimates are low because they do not include infraspecific taxa (extinct subspecies or extirpated populations). Future freshwater fish extinctions in North America are estimated to range from 53 to 86 species by 2050.

Current estimates of the number of extinct fishes from all other continents are significantly lower than decadal extinction rates for North America (figure 3). In most cases, these discrepancies represent gross underestimates of true extinction levels on those other continents. However, recent changes in some of the IUCN (2011) data resulted from increased caution about the accuracy of previously reported extinction estimates, particularly in the African rift lakes, where funding and logistics reduces the ability to intensively sample and where the fauna is taxonomically complex (Snoeks et al. 2011). Based on the continental extinction rate of 3.2% for North America, the worldwide loss of freshwater fishes may exceed 400 species.

After 253 years of faunal discovery and documentation (figure 1a), the freshwater fishes remaining to be discovered are more likely to be narrow or localized endemics, cryptic, and imperiled (Burkhead and Jelks 2000). The number of humans recently increased to 7 billion individuals; the totemic effects of our activities on the Earth's systems and processes are quantifiable at global scales, are observable from space, and include ongoing biodiversity decline and loss as well as worldwide changes to geochemical cycles and increasing climatic variability (Rockström et al. 2009, Pereira et al. 2010 [and its supplemental material], Barnosky et al. 2011). The loss of 3.2% of the continental fish diversity is not trivial and demonstrates that some of our resource practices are detrimental to the persistence of freshwater fishes and likely to that of other aquatic faunas.

Online data on extinct North American freshwater fishes, as well as any potential errata from this report may be found at the USGS–AFS Web site (*http://fl.biology.usgs.gov/extinct_fishes/index.html*).

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Restoration Ecology
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The Disconnect Between Restoration Goals and Practices: A Case Study of Watershed Restoration in the Russian River Basin, California

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Abstract

Over the past two decades, watershed restoration has dramatically increased internationally. California has been at the forefront, allocating billions of dollars to restoration activities through legislation and voter-approved bonds. Yet, the implications of restoration remain ambiguous because there has been little examination of restoration accomplishments and almost no analysis of the political context of restoration. This article addresses these gaps, utilizing a case study of the Russian River basin in Northern California. We identify trends that shed light on both the ecological and the political implications of restoration at a basin scale by examining a database of 787 restoration projects implemented in the Russian River basin since the early 1980s. Although a total of over $47 million has been spent on restoration in the basin, dominant forms of restoration are limited in scope to small-scale projects that focus on technical solutions to site-specific problems. The majority of restoration efforts are devoted to road repair, riparian stabilization, and in-stream structures, accounting for 62% of all projects. These types of projects do not address the broader social drivers of watershed change such as land and water uses. We suggest that restoration can become more effective by addressing the entire watershed as a combination of social and ecological forces that interact to produce watershed conditions.

Key words: **ecological restoration, geographic information systems, Mediterranean-climate streams, post project monitoring.**

Introduction

The amount of public investment in restoration is increasing, accounting for more than a billion dollars annually in the United States alone (Bernhardt et al. 2005). Yet, there is limited understanding of ecological patterns (Kondolf 1995, 1997; Downs and Kondolf 2002) and social implications associated with restoration (Gobster and Hull 2000; Higgs 2003). A recent study compiled coarse-scale data on restoration efforts nationwide (Bernhardt et al. 2005), concluding that little is known about the outcomes of restoration because postproject monitoring and assessment are extremely limited. A growing literature on biophysical monitoring has attempted to address this gap, focusing primarily on site-level analyses of ecological and geomorphic metrics (Harris et al. 2005). However, these measures do not address social aspects of restoration like the institutional context, which many credit as determining where and how restoration is done (Lufkin 1991).

The objective of this article is to better understand how and why restoration occurs the way that it does. The central questions that we address are: (1) Where is restoration happening; (2) How is restoration happening?; and (3) How has the practice of restoration changed over time? In answering these questions, we discover a disconnect between restoration goals and practices that we investigate further in the Discussion and Conclusions by asking: Why does this disconnect exist? and How can it be bridged? Our methods focus on analyzing a database of 787 restoration projects implemented in the Russian River basin, California, over 21 years. Although this article primarily analyzes the long-term dataset, we have also conducted extensive interviews with restoration practitioners and participated in restoration activities throughout the Russian River watershed, which informs our interpretation of the data (Christian-Smith 2006).

In order to understand where restoration is happening, we examine the spatial distribution and landscape attributes of restoration projects using a geographic information system (GIS) database of restoration project locations throughout the basin and available data layers on landscape features such as land use/land cover and lot size. This examination provides insight into the types of landowners who are primarily benefiting from the current practice of restoration and the ecological context in which it occurs. In order to understand how restoration is happening, we devote particular attention to the often overlooked institutional framework—the agencies and organizations involved in funding and implementing restoration. We analyze how policy language and funding priorities are translated into on-the-ground practices,

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focusing on the three agencies most involved in funding restoration activities in the Russian River basin. Finally, in order to understand how the practice of restoration has changed since the early 1980s, we examine trends in the types of projects implemented, their costs, and the organizations involved.

Methods

We employ a case study approach, focusing on an area of concentrated restoration effort and funding for several decades. The Russian River basin is located on the North Coast of California, straddling Mendocino and Sonoma Counties (Fig. 1). It is roughly 80 miles long, drains 1,485 square miles, and has an average annual discharge of 1.6 million acre-feet. Current land uses include timber harvesting, ranching, gravel mining, and intensive agriculture. Approximately 98% of the Russian River basin is privately owned. Although the majority of the basin is characterized by low-density rural development, the southern portion is experiencing a boom in suburban and urban development around the city of Santa Rosa (U.S. Census 2006*a*, 2006*b*).

Over the past three decades there have been several major institutional sources of funding for restoration projects in the Russian River basin. These include the California Department of Fish and Game (CDFG), the U.S. Department of Agriculture (USDA), and the Sonoma County Water Agency (SCWA). These agencies have

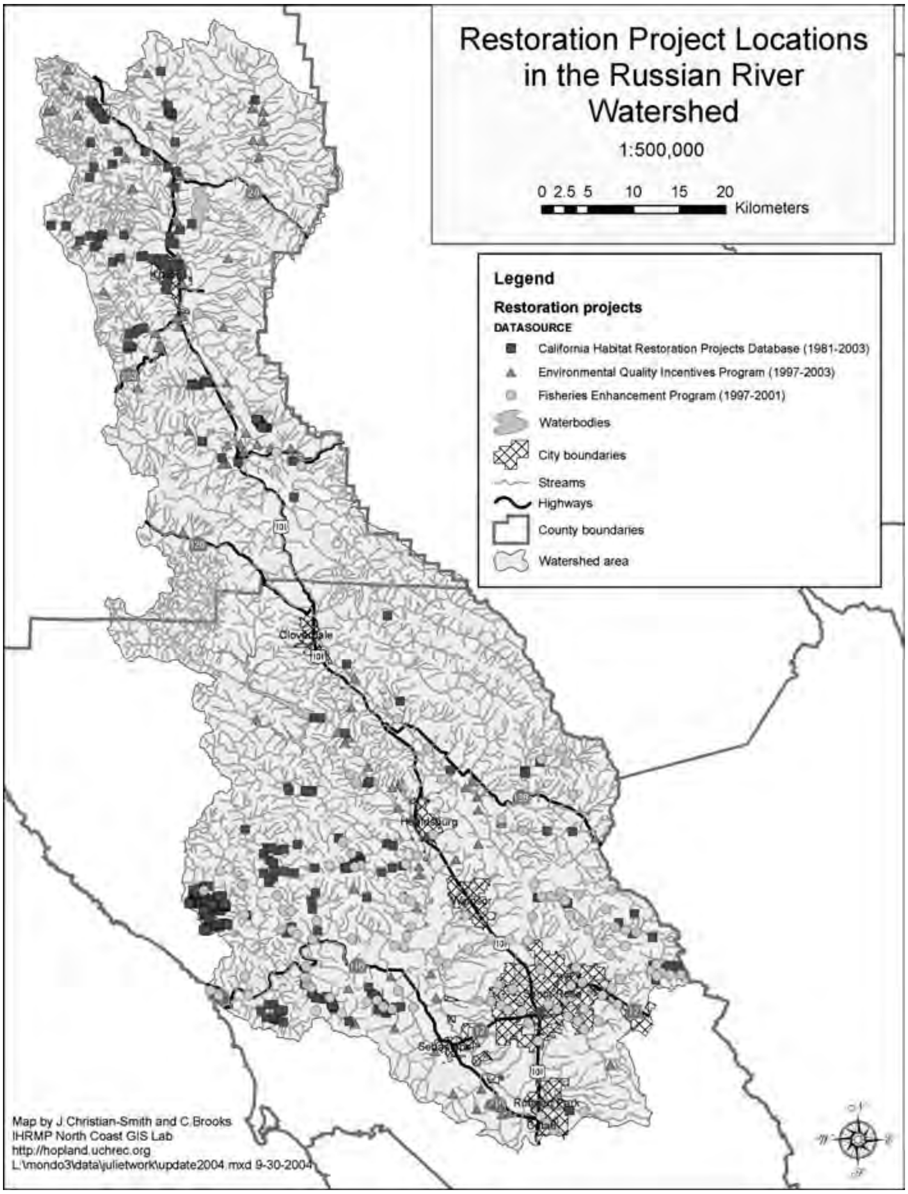

Figure 1. Restoration project locations within the Russian River Basin.

distributed funds for restoration activities from federal sources (Pacific Salmonid Fisheries Act) and state sources (California Senate Bills and voter-approved Propositions) through a variety of grant programs including: CDFG's Fisheries Restoration Grant Program, the USDA's Environmental Quality Incentives Program, and SCWA's Fisheries Enhancement Program. The priorities of these grant programs vary and thus, the characteristics of projects associated with each differ in some interesting ways that will be noted in the Results and Discussion sections.

In order to analyze the spatial distribution of restoration projects at the basin scale, we built upon an existing GIS of the Russian River basin. The first step was to collect and compile geographic coordinates and project details for restoration projects throughout the Russian River basin in an ArcMap database. We gathered GIS data from the CDFG California Habitat Restoration Projects Database describing projects funded through the Fisheries Grants Restoration Program (1981–2003). Second, we gathered and digitized map-based data and associated project information for restoration activities funded by the USDA Environmental Quality Incentives Program (1997–2003). Finally, we gathered and converted AutoCAD data and associated project descriptions describing restoration activities funded by the SCWA Fisheries Enhancement Program (1997–2001). We clipped the combined spatially explicit databases to the boundaries of the Russian River basin.

The resulting database of restoration projects included a total of 787 projects that were implemented in the Russian River basin between 1981 and 2003. Although this encompasses a variety of funding sources, it does not capture many of the smaller projects implemented without agency funding. Therefore, it does not represent the entire universe of restoration projects present in the basin and may bias the outcomes toward larger-scale projects. However, it does provide a comprehensive representation of the types of projects that receive the majority of public funds. The spatial distribution of these projects, along with associated grant programs, is displayed in Figure 1. To determine the randomness of the spatial distribution of restoration project locations in relation to land use classes, we utilized a Monte Carlo simulation that took the empirical probabilities of land uses in the basin and simulated the distribution of the 787 project locations 1,000 times, using a macro script in Excel. We then calculated the z statistic by comparing the means from the observed and simulated distribution of project locations across four major land use categories. The test is considered statistically significant if the difference between the two means is significantly different than zero (as measured by the p value of the z score).

In order to analyze the practice of restoration, we looked at the various kinds of restoration projects that were implemented over time. First, we extracted the "work types" associated with restoration projects from the GIS database to define the most prevalent forms of restoration. Projects that involved more than one practice were categorized based on the practice that received the greatest amount of funding. In addition, we examined how restoration project types, costs, and associated organizations have changed over time. Second, we examined the economic context of restoration by extracting restoration costs from the GIS database and associating these with policy changes and a growing restoration industry (Gustaitis 2004; Baker 2005). Finally, we examined the institutionalization of particular restoration practices by analyzing the policy language and funding priorities of three agencies most involved in restoration activities in the Russian River basin.

Results

Our research reveals distinct patterns in the locations and types of projects that are funded by three major funding institutions in the Russian River basin. The following results demonstrate the prevalence of site-specific, technical approaches (particularly in-stream, riparian, and road-related improvements). Other objectives that are included in restoration goals and policies such as water quality, water quantity, habitat acquisition, and education are not widely addressed by the current practice of restoration in the basin. These results are relevant not only in a regional context but also internationally because an international survey of river restoration across 35 countries documents the prevalence of technical approaches and the implementation at reach or subreach scales (Wheaton et al. 2006).

Where is Restoration Happening?

To examine different landscape attributes associated with restoration project locations, we first looked at land cover and land use. Over half of the restoration projects had associated land use data available from the county tax assessor's office and Landsat TM satellite imagery. Based on this data, from both Sonoma and Mendocino Counties, the majority of restoration projects were located on four land uses classes: timberland, rangeland, rural residential land, and vineyards. "Rangeland" includes land classified by the tax assessor as rangeland or pastureland along with areas without land use data that are classified by Landsat TM satellite imagery as having hardwood/chaparral land cover. "Rural residential" includes land that has one or fewer units per acre. Higher densities are classified as suburban and urban.

Figure 2 displays the percent of restoration projects associated with each of the four most common land use classes and juxtaposes that with the percent of the watershed area in each of the four land use classes. Timberland and rangeland had the highest number of restoration projects associated with each land use class (117 and 116 projects, respectively). However, it is important to note that rangeland occupies a much larger area, accounting for nearly 60% of the total acreage in the Russian River basin, whereas timberland accounts for less than 10% of the total acreage in the basin. The difference between the

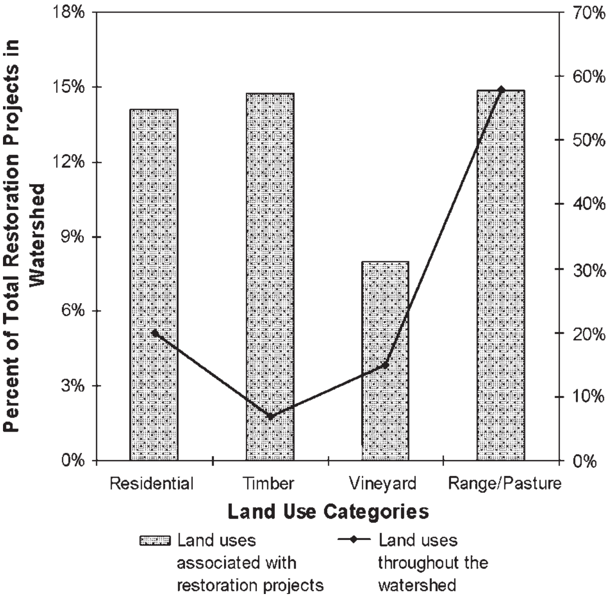

Figure 2. Restoration and land use.

observed and the expected values for residential and vineyard land use classes were not statistically significant (*p* values of 0.26 and 0.42, respectively). The difference between observed and expected values for timber and rangeland land uses was highly significant (*p* values of <0.0001 and 0.003, respectively). Therefore, the real difference in land uses between the restoration project locations and the basin as a whole is due to the over-representation of restoration project points on timberland and the under-representation of restoration project points on rangeland.

Similarly, we examined the distribution of average lot sizes within a 500-m buffer of restoration project locations and compared these to the distribution of average lot sizes throughout the basin. We used five lot size categories: 0–4, 4–14, 14–26, 26–40, and greater than 40 ha. Almost 45% of restoration projects are located in areas with an average lot size of greater than 40 ha. This is not particularly surprising because the basin is dominated by very large, rural properties. However, restoration projects are over-represented on medium to large average lot sizes of 14–40 ha. There are approximately 15% more restoration projects in areas that have average lot sizes of 14–40 ha than would be expected by looking at the distribution of lot sizes across the basin. We theorize that this is associated with the goals of the funding programs and the privatized landscape (Discussion section).

How is Restoration Happening?

Here, we examine the practice of restoration as a physical and political process, beginning with an analysis of how policy language and goals are translated on-the-ground by three primary agencies involved in restoration activities in the Russian River basin. First, the CDFG Fisheries Restoration Grants Program is the dominant funding source in the Russian River basin and in many coastal areas of California. Between 1981 and 2006, CDFG invested over $180 million and supported approximately 2,600 salmonid restoration projects (CDFG 2006). California Senate Bill 271 (Thompson & Ducheny 1997) created the Salmon and Steelhead Trout Restoration Account that provides the CDFG with much of the funding to support projects that improve fish habitat. Section 4 of Senate Bill 271 states restoration goals:

"Projects that restore habitat for salmon and anadromous trout species that are eligible for protection as listed or candidate species under state or federal endangered species acts shall be given top funding priority…Projects may implement instream, riparian, water quality, water quantity, and watershed prescriptions and shall be designed to restore the structure and function of fish habitat" (Senate Bill 271 1997, sections 4b & 4c).

The legislation goes on to define that 65% of the money shall be used for on-the-ground salmon habitat protection and restoration, with 75% of that amount going specifically to "watershed (upslope) and riparian area protection and restoration activities." Only 35% of the money can be allocated to other uses like watershed evaluation, watershed planning, watershed organization support and assistance, public school watershed, and fishery education programs (Senate Bill 271, section 4d 1 & 2).

The Fisheries Restoration Grants Program project solicitation package reiterates that the objective of the program is to fund projects that are consistent with the goal of salmon and steelhead trout conservation and restoration (CDFG 2006). This package includes a list of 22 approved project types like habitat acquisition, upslope restoration, watershed education, flow meters, and other relatively diverse restoration practices. However, an analysis of the 726 funded projects between 2001 and 2006 reveals that there are clear trends in the types of projects approved (Fig. 3). Habitat acquisitions and conservation easements, postproject monitoring and maintenance, water conservation, and water measuring devices are

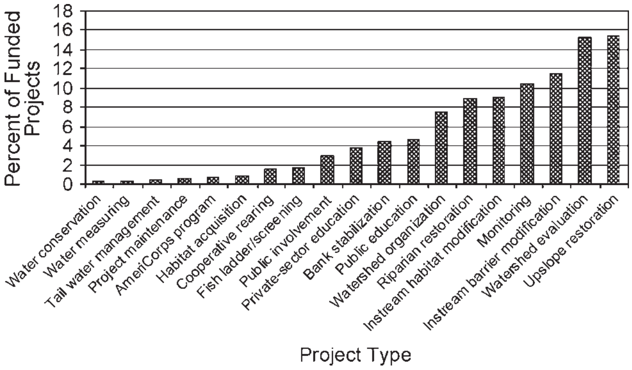

Figure 3. Project types funded by CDFG fisheries restoration grants program, 2001–2006.

among the project types with fewer than 20 funded projects. On the other hand, upslope watershed restoration and watershed evaluation each account for over 100 funded projects.

A closer examination of project descriptions reveals that almost 40% of projects focus on site-specific in-stream and riparian work (this includes projects from several different categories: in-stream barrier modification, in-stream habitat restoration, riparian restoration, and in-stream bank stabilization), 28% of projects are associated with some sort of assessment, and 28% of projects are associated with road improvement (almost all of the projects categorized as upslope restoration are road related). In addition, nearly half of the projects categorized as watershed evaluations and assessments involve inventories of road crossings and sediment production from road surfaces. This clearly illustrates the disconnect between broad policy goals that suggest a wide variety of restoration strategies and the comparatively narrow on-the-ground practices, as 91% of practices can be categorized as assessment, in-stream, riparian, or road repair work.

Second, the USDA's Environmental Quality Incentives Program implemented 499 projects in Sonoma and Mendocino Counties between 1997 and 2002 (Natural Resources Conservation Service 2002). The Environmental Quality Incentives Program Final Rule, issued by the USDA Commodity Credit Corporation (Federal Register 1997) explains that it is a voluntary program for agricultural producers, authorized at $1.3 billion over 7 years. Section 1466.6 of the Final Rule explains that "the participant shall develop and submit a conservation plan for the farm or ranch unit of concern that, when implemented, protects the soil, water, or related natural resources in a manner that meets the purpose of the program, is acceptable to NRCS [National Resource Conservation Service], and is approved by the conservation district. This plan forms the basis for an EQIP [Environmental Quality Incentives Program] contract." Although particular conservation techniques are not specified by the legislation, they are provided in the state of California's approved practices that list over 100 approved practices.

Again, by examining the actual categories of funded projects, a less diversified picture emerges. In Sonoma and Mendocino Counties, the majority of implemented practices involve constructing access roads (9%), fencing (11%), riparian protection (13%), and structures for water control (21%). Many of these measures address sediment production and nonpoint source pollution, which are increasingly being regulated—most recently by the Environmental Protection Agency's new total maximum daily load provisions that specify the maximum amount of a pollutant that a waterbody can receive from point and nonpoint sources.

Finally, the SCWA Fisheries Enhancement Program funded 63 projects in the Russian River basin. The restoration program was funded, in part, through the Pacific Salmonid Restoration Act that the head of the Water Agency played a key role in coordinating and lobbying for in Congress. The specific goals of the program are stated as: (1) to work cooperatively and in conjunction with other federal, state, and local agencies to preserve, enhance, and restore fishery habitats and resources; (2) to develop research programs to study the fisheries within affected watersheds; and (3) to assist the environmental compliance section of the agency in the assessment of impacts, the writing of environmental documents, and permit compliance for the agency for projects which may effect fisheries resources (SCWA 2006). It is the last of these that is particularly interesting because restoration is specifically being linked to mitigation in the program's stated objectives.

Examining the Fisheries Enhancement Program's annual reports from 1997–2001 reveals a clear preference for funding internal agency projects along with surveys, studies, and research—much of which is required to protect endangered species. For instance, a "Fish Rescue Activities" project was awarded $15,000–20,000 during the 1997–1998 funding cycle. An examination of the project description reveals that the agency operates several pumping stations and infiltration ponds for its water supply and distribution network that trap fish (including endangered salmonids). The project paid for labor to capture and release trapped Chinook salmon and steelhead trout back into the Russian River main stem.

In summary, the results presented in Figure 4 show that the most common types of restoration across all three funding sources were riparian improvements (including bank stabilization, invasive plant removal, and riparian revegetation), road improvements (including culvert replacements/removals, road paving, and installing rolling dips), surveys (including field studies of fish habitat and abundance), and in-stream improvements (including altering the channel morphology to meet Rosgen [Rosgen 1994] stream-type classifications, installing structures such as large woody debris, and barrier removal). Less common in practice are activities related to education, water conservation, and upland restoration.

How Has the Practice of Restoration Changed Over Time?

Finally, we examine how the proportion of different project types changed between 1981 and 2003. The results

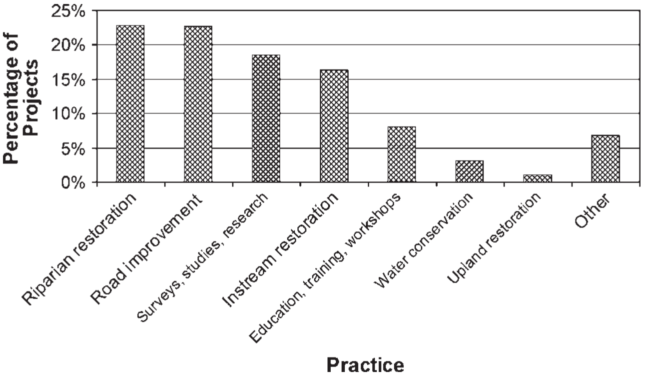

Figure 4. Restoration project practices.

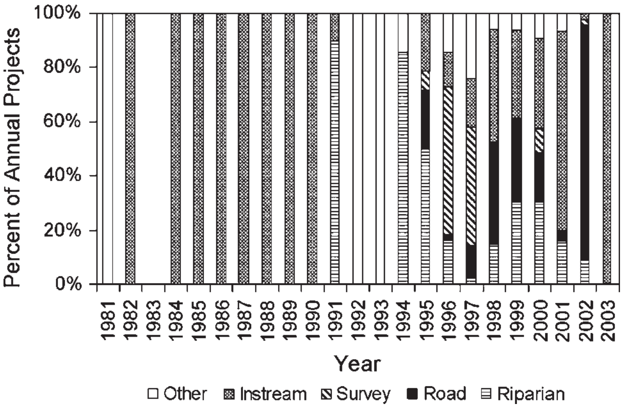

Figure 5. Restoration practice, 1981–2003.

show that restoration practice has shifted over time from primarily in-stream work through the 1980s to include a higher proportion of riparian- and road-related work in the 1990s and 2000s (Fig. 5). Major changes in practice can be seen at several time points. In 1991, riparian-related restoration activities became important (accounting for 90% of the annual projects), though they have since declined in prevalence. In 1995, both road-related work and surveys began to be common practices. Although the survey and research work dropped off after 2001, road-related work has persisted. In 2002, road-related work accounted for nearly 80% of all projects.

Along with changing practices, there have also been changing costs associated with restoration activities. The total investment in restoration has, predictably, increased over time (Fig. 6). Still, there has been considerable fluctuation and some substantial increases. Most markedly, between 1997 and 1998, the total cost of restoration activities rose from below $1 to $8 million, and from 2002 to 2003, costs jumped from just below $3 million to nearly $16 million. The per project cost of restoration has also increased from an average of almost $19,000 in 1981 to a little over $700,000 in 2003.

With the increased funding, there have been an increasing number of institutions and organizations associated with restoration activities. The organizations involved with restoration significantly increased in 1998 from a handful of agencies to over 20 different entities. Interestingly, between 1998 and 2003, the character of these organizations changed from primarily federal and state agencies along with local nonprofits to an increasing number of private restoration, design, and engineering firms including Pacific Watershed Associates, Bioengineering Associates, Prunuske and Chatam, Dragonfly Stream Enhancement, Forest Soil and Water Inc., Doyle and Company, and Watershed Science. This growing "restoration industry" (Gustaitis 2004; Baker 2005) specializes in particular types of work, primarily engineering-oriented solutions at a site scale.

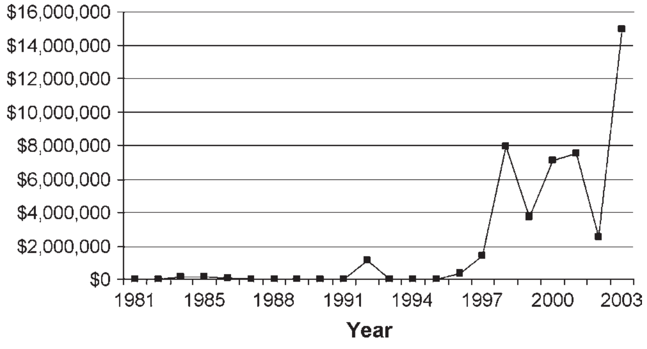

Figure 6. Total investment in restoration, 1981–2003.

Discussion and Conclusions

Our results illustrate where and how hundreds of restoration projects were done over a 20-year period in the Russian River and compare these outcomes with the intended goals of restoration as articulated by the agencies involved in restoration statewide. The resulting disconnect between restoration goals and outcomes on the ground points to a restoration implementation crisis that requires new directions in order to bridge the gap between intension and practice.

In terms of where restoration happens, the over-representation of restoration project points on timberland and the under-representation of restoration projects on rangeland may be attributed to the focus of several granting programs on restoring upstream salmonid spawning habitat, which is often timberland in the Russian River basin. Two of the main restoration funding programs are interested in fisheries restoration and thus are more focused on spawning regions that are found in higher elevations of the basin. These steep uplands have lower population densities and larger parcel sizes. In addition, landownership in the basin is almost completely private and therefore conducting restoration requires finding willing landowners, gaining the legal right to access property through landowner agreements, and establishing trust and cooperation to ensure the restoration project is implemented correctly and maintained. There can be diminishing returns when attempting to work with many small property owners. Thus, large, rural landowners who are primarily engaged in agriculture and timber extraction benefit most from the current pattern of restoration.

When looking at the entire database, the most common restoration practices in the Russian River basin include: riparian, road, and in-stream improvements, which together account for 62% of the projects in the database. Some surveys and research were conducted, but the funding source that provided almost all of the support for these activities terminated in 2001. The focus on stream and road improvements can be explained, in part, by the emphasis on the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 1998), which past restoration grant recipients refer to as the "Bible" of stream restoration. Section VI of the manual (Project Planning and

Organization) defines five fish habitat restoration categories: (1) upslope improvements; (2) riparian and bank stability improvements; (3) in-stream habitat improvements (with the stipulation that "Rosgen's stream classification system…provides a basis for evaluating instream structure suitability"); (4) artificial propagation; and (5) watershed stewardship programs. Although there is diversity in the restoration practices outlined, the implementation section is much narrower in scope. Section VII (Project Implementation) covers only in-stream large woody debris and boulder structures (pp. 1–46), fish passage structures (pp. 47–61), and bank stability structures (pp. 62–97) with dozens of design drawings depicting plan views and cross sections. There is little to no guidance regarding upslope improvements, watershed stewardship, education, and land and water conservation—despite that the Department of Fish and Game itself has prioritized water quantity as one of the key "limiting factors" for salmonid survival in the basin (CDFG 2002).

A panelist discussing restoration on the 16 March 2006 edition of the National Public Radio program *Forum* remarked that although road repair and barrier removal projects may not be their top priority in terms of restoring the ecological processes of a stream or bringing back a fishery, the funding is there for this type of work and therefore they "have to get on the boat." Indeed, although the California Salmonid Stream Habitat Restoration Manual defines upslope restoration as improving road drainage, road or trail obliteration, reforestation, or changes in land management (section VI, p. 3), in practice, it is almost exclusively road repair.

Our results demonstrate the increasing costs associated with these types of repairs and show that the total number of restoration projects has increased over time resulting in a greater expense to the public. Examining changing environmental legislation reveals significant incentives and regulatory action to encourage or require restoration like California Senate Bill 271 that passed in 1997, providing substantial funding for restoration in the area. As a response to this increased funding for restoration, a growing restoration industry has emerged that specializes in technical restoration practices. As the results indicate, road improvement has become one of the most prevalent practices in recent years. The design and implementation of road improvements were initially popularized in California by the private firm, Pacific Watershed Associates. One of the founders of the firm was quick to point out that they only work on technical matters of road improvements and do not discuss larger watershed issues (Hight 1998).

Equally significant are those practices that are *not* well represented, which include education for the public and school children, land and water conservation projects to address harmful activities beyond the riparian zone, and upland projects that are focused on changing land use patterns or activities beyond the riparian zone. Therefore, although the goals of restoration are broad, addressing watershed-scale ecological processes and social issues, the actual practice of restoration is primarily restricted to repairing streams and re-routing sediment at specific sites. Why does this disconnect exist? How can it be bridged?

We suggest that the disconnect between restoration goals and practice is closely related to a lack of attention to the social, political, and economic drivers of watershed degradation. Water quantity and flow levels in the Russian River are examples of a larger, and critical, watershed issue that is currently not being addressed by the practice of restoration. In the summer of 2007, the Water Resources Control Board mandated reductions of water use by municipalities and agriculture in the Russian River basin (Rose 2007). This request was made because there was not enough water in existing reservoirs to provide adequate flows for salmon migration and could result in a violation of the Endangered Species Act. Restoring stream flow during the dry season, when almost no rain falls in the basin and demand for water is at its peak, is critical for salmon recovery and requires that the practice of restoration addresses water quantity as listed in the agencies' programmatic goals for their restoration programs. Water quantity in streams is currently not part of the restoration efforts in upland streams, with the exception of the recent efforts by the Mattole Restoration Council and Sanctuary Forest in Humboldt County, California. There, restoration practitioners are tackling the issue of water quantity by working with water attorneys to draft "forbearance" agreements where riparian water rights holders forebear their summer water rights in exchange for off-stream reservoirs (McKee, unpublished report).

Similarly, in the Russian River basin, the Salmon Coalition is exploring ways to provide incentives for altering the use of historic rights in order to improve stream flows in areas designated as critical for salmon recovery. These efforts are currently not seen as "restoration projects" per se and therefore have not received restoration dollars, yet they are critical for salmonid survival. In conclusion, real solutions will only be found when restoration looks beyond the stream to address the entire watershed as a combination of social and ecological forces that interact to produce watershed conditions. Bridging the disconnect between restoration goals and practices will require better coordination of agencies involved in restoration to focus on larger, watershed-scale concerns.

Implications for Practice

- Restoration must address the social and ecological forces that interact to produce watershed conditions in order to create sustainable ecosystems and equitable policies.
- More research needs to be done on the root causes of environmental degradation, and these causes should be understood within a social context, particularly in terms of policy mandates and economic incentives that motivate particular land and water uses.

- Funding should be targeted at modifying the social drivers of environmental degradation by focusing on more transformative changes at a basin-scale, particularly in terms of land and water conservation and management, policy, and education.
- Restoration practices must also include efforts to protect upland habitat from harmful activities beyond the riparian zone associated with land use. Reducing sprawl and agricultural conversion in the uplands would both reduce the demand on water and protect remnant upland habitat.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum 1983 (NAVD 83).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Symbols

Abbreviation or Symbol	Meaning
AGU	Agricultural unit
BLM	Bureau of Land Management
CH_{sw}	Channelized surface water component to ET_t along washes and rivers from sources outside the study area
CRFS	Colorado Regional Ground-Water Flow System
DMV	Dense meadowland vegetation
DSV	Dense shrubland vegetation
DWV	Dense woodland vegetation
E	Rate of water evaporation
E_n	Available energy
ET	Evapotranspiration
ET_{gs}	Ground- and surface-water discharge from ET
ET_t	Estimated total evapotranspiration
G	Subsurface heat flux
GW	Ground-water component of ET_{gs}
GW_t	Ground-water component of ET_t
H	Sensible-heat flux
H_b	Sensible heat calculated using the Bowen-variant method
H_e	Sensible heat calculated using the eddy covariance method
MWV	Moderate woodland vegetation
MSAVI	Modified soil-adjusted vegetation index
MSV	Moderate shrubland vegetation
NAIP	National Agriculture Imaging Mapping Program
NPS	National Park Service
NPU	Non-phreatophytic unit
OWU	Open water unit
PL	Annual local precipitation
PL_{GW}	Ground-water components of local precipitation
PL_{SW}	Surface-water components of local precipitation
R_n	Net radiation
SP_{SW}	Channelized surface water component of SWt from springs and seeps
SP_{GW}	Recycled ground water component of GWt from springs and seeps
SW_t	Surface-water component of ETt
SWReGAP	Southwest Regional Gap Analysis Program
UF_{GW}	Ground-water underflow component to ETt
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
λ	Latent heat of vaporization for water
λE	Latent-heat flux (or evaporative flux)
λE_b	Latent-heat calculated using the Bowen-variant method
λE_e	Latent-heat calculated using the eddy covariance method

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By Guy A. DeMeo, J. LaRue Smith, Nancy A. Damar, and Jon Darnell

Abstract

Rapid population growth in southern Nevada has increased the demand for additional water supplies from rural areas of northern Clark and southern Lincoln counties to meet projected water-supply needs. Springs and rivers in these undeveloped areas sustain fragile riparian habitat and may be susceptible to ground-water withdrawals. Most natural ground-water and surface-water discharge from these basins occurs by evapotranspiration (ET) along narrow riparian corridors that encompassed about 45,000 acres or about 1 percent of the study area.

This report presents estimates of ground- and surface-water discharge from ET across 3.5 million acres in 12 hydrographic areas of the Colorado Regional Ground-Water Flow System. Ground-and surface-water discharge from ET were determined by identifying areas of ground- and surface-water ET, delineating areas of similar vegetation and soil conditions (ET units), and computing ET rates for each of these ET units. Eight ET units were identified using spectral-reflectance characteristics determined from 2003 satellite imagery, high-resolution aerial photography, and land classification cover. These ET units are dense meadowland vegetation (200 acres), dense woodland vegetation (7,200 acres), moderate woodland vegetation (6,100 acres), dense shrubland vegetation (5,800 acres), moderate shrubland vegetation (22,600 acres), agricultural fields (3,100 acres), non-phreatophytic areas (3,400,000 acres), and open water (300 acres).

ET from diffuse ground-water and channelized surface-water is expressed as ET_{gs} and is equal to the difference between total annual ET and precipitation. Total annual ET rates were calculated by the Bowen ratio and eddy covariance methods using micrometeorological data collected from four sites and estimated at 3.9 ft at a dense woodland site (February 2003 to March 2005), 3.6 ft at a moderate woodland site (July 2003 to October 2006), 2.8 ft at a dense shrubland site (June 2005 to October 2006), and 1.5 ft at a moderate shrubland site (April 2006 to October 2006). Annual ET_{gs} rates were 3.4 ft for dense woodland vegetation, 3.2 ft for moderate woodland vegetation, 2.2 ft for dense shrubland vegetation, and 1.0 ft for moderate shrubland vegetation. Published annual rates of ET_{gs} were used for the other ET units found in the study area. These rates were 3.4 ft for dense meadowland vegetation, 5.2 ft for agricultural fields, and 4.9 ft for open water. For the non-phreatophytic ET unit, ET_{gs} was assumed to be zero.

Estimated ground- and surface-water discharge from ET was calculated by multiplying the ET_{gs} by the ET-unit acreage and equaled 24,480 acre-ft for dense woodland vegetation, 19,520 acre-ft for moderate woodland vegetation, 12,760 acre-ft for dense shrubland vegetation, 22,600 acre-ft for moderate shrubland vegetation, 680 acre-ft for dense meadowland vegetation, 16,120 acre-ft for agricultural fields, 1,440 acre-ft for open water, and 0 acre-ft for the non-phreatophytic ET unit. Estimated ground-water and surface-water discharge from ET from each hydrographic area was calculated by summing the total annual ET_{gs} rate for ET units found within each hydrographic area and equaled 1,952 acre-ft for the Black Mountains Area, 6,080 acre-ft for California Wash, 4,090 acre-ft for the Muddy River Springs Area, 11,510 acre-ft for Lower Moapa Valley, 51,960 acre-ft for the Virgin River Valley, 16,168 acre-ft for Lower Meadow Valley Wash, 5,840 acre-ft for Clover Valley, and 0 acre-ft for Coyote Spring Valley, Kane Springs Valley, Tule Desert, Hidden Valley (North), and Garnet Valley. The annual discharge from ET_{gs} for the study area totals about 98,000 acre-ft.

Introduction

Rapid population growth and development in southern Nevada has increased demand for additional water supplies. Numerous applications have been submitted to the Nevada State Engineer requesting water rights in rural areas to meet the projected water supply needs for Nevada. Water from springs and rivers in these undeveloped areas sustain riparian habitat that supports numerous species of plants and animals. Some species, such as the Moapa dace, are federally listed as a threatened and endangered species (U.S. Fish and Wildlife Service, 1996). Water is naturally discharged from these areas by surface-water outflow, subsurface outflow, and evapotranspiration (ET).

The U.S. Geological Survey, in cooperation with the National Park Service, Bureau of Land Management, and U.S. Fish and Wildlife Service, conducted a study during 2003–06 to quantify discharge through ET processes for 12 hydrographic areas in the southern part of the Colorado Regional Ground-Water Flow System (fig. 1). The Colorado Regional Ground-Water Flow System (CRFS) is part of a major ground-water flow system within the Great Basin Regional Aquifer System that encompasses much of eastern and southern Nevada, parts of southeastern California, northwestern Arizona, and western Utah (Harrill and Prudic, 1998). Discharge from this regional flow system is by phreatophytic ET from numerous valleys (discharge areas), spring discharge, and surface-water flow into Lake Mead. A large unknown component of the CRFS water budget is the amount of discharge that occurs as ET.

Purpose and Scope

This report documents the methodology and presents estimates of ground-water and surface-water discharge by ET from 12 hydrographic areas in the CRFS (referred to as the study area). Descriptions of the approach include remote-sensing techniques used to determine acreage and density of vegetation, selection of study sites, instrumentation, and methods used to estimate discharge by ET processes.

Description of the Study Area

The study area encompasses more than 3.5 million acres in southern Nevada, southwest Utah, and northwest Arizona and includes 12 hydrographic areas[1]: Clover Valley (HA 204), Kane Springs Valley (HA 206), Lower Meadow Valley Wash (HA 205), Tule Desert (HA 221), Coyote Spring Valley (HA 210), Virgin River Valley (HA 222), Muddy River Springs Area (HA 219), Hidden Valley (North) (HA 217), Garnet Valley (HA 216), California Wash (HA 218), Lower Moapa Valley (HA 220), and the part of the Black Mountains Area (HA 215) north of the Las Vegas Valley and Lake Mead shear zones (fig. 1). The study area has numerous valleys and mountains, many of them north–south trending, that range between 5 to 15 mi wide and 10 to more than 20 mi long. The valley floors range in altitude from less than 1,500 ft in the south to more than 4,000 ft in the north with the highest mountain peaks exceeding 7,000 ft.

The study area is characterized by hot summers and mild winters; however, precipitation and temperature do vary according to altitude. Based on four weather observation sites located in the study area with 30-years of record, the average maximum and minimum annual air temperature was 109°F at Overton, Nevada and about 20°F at Caliente, Nevada, respectively. Data from the same weather stations and periods of record indicate that the average annual precipitation ranges from slightly more than 5 in. at Overton and Logandale, Nevada, to just less than 10 in. at Caliente, Nevada (fig. 2).

Upland and high-altitude terrain primarily receive water from local precipitation (as rain or snow) that will evaporate, sublimate, runoff as channelized surface water into washes and rivers, be transpired by upland vegetation, or infiltrate the soil and may eventually recharge the ground-water system. Lowland terrain receives water from multiple ground- and surface-water sources. Ground water in these lower lying areas is supplied by local precipitation, diffuse ground-water underflow, or as recycled water from springs and seeps. Surface water is supplied by local precipitation, channelized surface water from springs and seeps, and channelized surface water along washes and rivers that originate outside the study area. Ground water is evaporated from bare soils or is transpired by phreatophytes and riparian vegetation. Surface water is evaporated from washes, rivers, and reservoirs, or transpired from riparian vegetation along the banks of washes and rivers. Only a few acres are classified as agricultural fields. These fields are dispersed throughout the study area and located within the riparian areas along washes and rivers.

The study area contains two main washes and two rivers: Meadow Valley Wash, Beaver Dam Wash, the Virgin River, and the Muddy River. All these drainages are long and narrow, sustain various plants and fauna, and provide habitat for local wildlife. Meadow Valley Wash receives runoff from higher terrain as well as discharge from several seeps and springs before joining with the Muddy River east of Moapa, Nevada. Beaver Dam Wash receives runoff from the Clover Mountains in the northeast part of the study area and also receives spring discharge just above Littlefield, Arizona (pl. 1). Beaver Dam Wash flows into the Virgin River about 0.5 mi above Littlefield, Arizona (Beck and Wilson, 2006; pl. 1).

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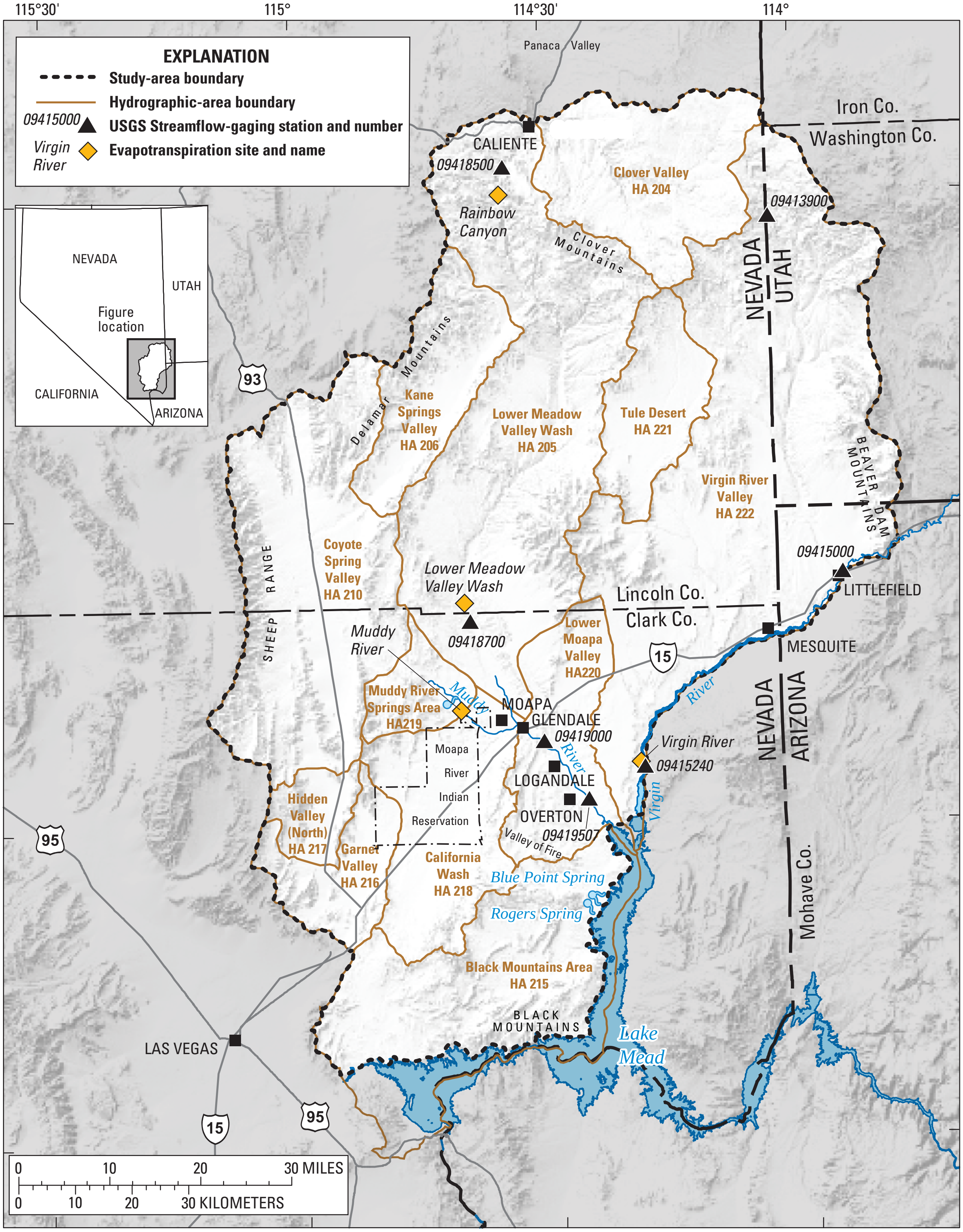
[1] Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Cardinalli and others, 1968; Rush, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities.



Base from U.S. Geological Survey digital data, 1:100,000, 1988.
Universal Transverse Mercator projection, Zone 11. Shaded-relief
from 30-meter Digital Elevation Model; sun illumination from
northwest at 30 degrees above horizon.

Figure 1. Hydrographic areas in the study area, southern Nevada and adjacent areas in Utah and Arizona.

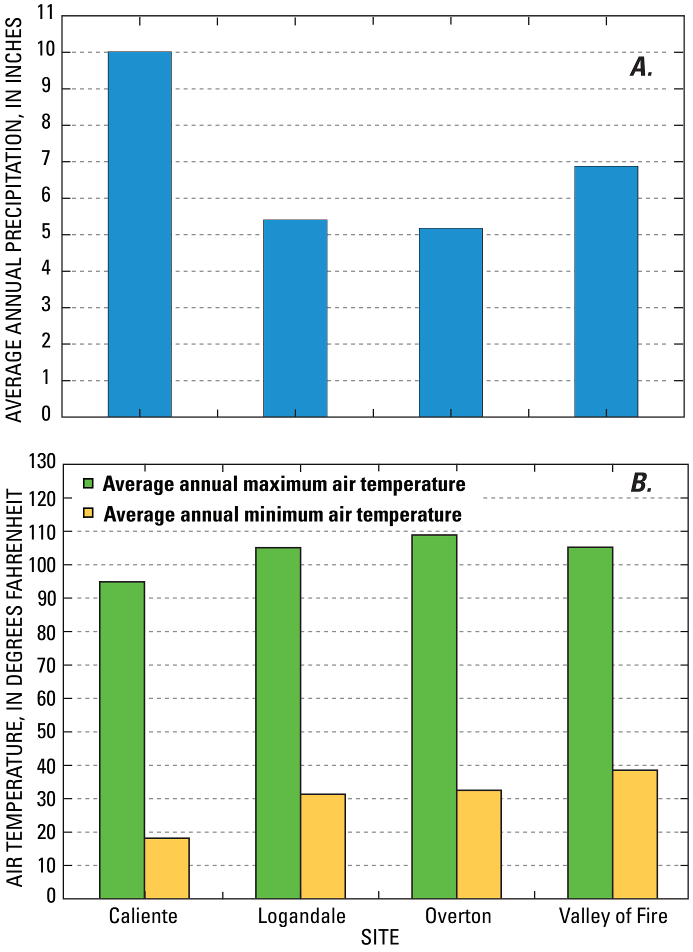


Figure 2. Thirty-year average annual precipitation and 30-year average annual maximum and minimum air temperature in and around the study area, southern Nevada and adjacent areas in Utah and Arizona. (Data from Western Regional Climate Center, 2006).

The Virgin River originates from rain and melted snow in Zion National Park, Utah, and flows southeasterly across southwest Utah. Flow in the river is augmented by springs in Beaver Dam Wash just above Littlefield in northwest Arizona, and continues flowing into southern Nevada before discharging into Lake Mead (pl. 1). The Virgin River supplies water to the Virgin River floodplain which supports a large riparian vegetation community.

The Muddy River originates from a system of regional springs and tributaries (Eakin, 1964) in the Muddy River Springs area (fig. 1; pl. 1). The Muddy River supports a large riparian vegetation community along the reach of the river before discharging into Lake Mead. Ground water also is discharged into Lake Mead from Rogers and Blue Point springs (fig. 1; pl. 1).

Dominant vegetation in the lower altitudes of the study area includes xerophytes such as creosote, yucca, Joshua trees, and saltbrush and at higher altitudes, Pinyon pine and juniper trees. Xerophytes have a shallow root zone and obtain water primarily from local precipitation.

A variety of phreatophytes and riparian vegetation such as mesquite (*Prosopis*), saltcedar (*Tamarix Ramosa*), meadowgrasses, rabbitbrush (*Chrysothamnus viscidiflorus)*, big sage, arrowweed (*Pluchea sericea*), cottonwood (*Populus fremontii*) and willow trees (*Chilopsis)* grow along washes and rivers where the depth to water is within about 40 ft of the surface. About 3,000 acres of agricultural fields, primarily alfalfa, are located along the Virgin River, Meadow Valley Wash, Beaver Dam Wash, and the Muddy River. These fields are irrigated by surface-water diversions, where some water is consumed by ET, and the remainder is either re-diverted back to the source or returned by ground-water infiltration.

Evapotranspiration

Total ET is defined in this study as the annual volume of water lost from an area to the atmosphere. Components that contribute to total ET are surface water, ground water, and local precipitation. The surface-water ET component includes transpiration from riparian vegetation along the banks of washes and rivers and evaporation from open-water surfaces. The ground-water ET component includes transpiration of diffuse underflow from phreatophytes where the water table is 40 ft or less, transpiration from recycled spring water from riparian vegetation near springs and seeps, and evaporation of water from bare soil surfaces where the water table is at or near land surface. This process can be expressed as:

$$ET_t = SW_t + GW_t \quad , \tag{1}$$

where

ET_t is total ET,
SW_t is the surface-water component to ET_t, and
GW_t is the ground-water component to ET_t.

The surface- and ground-water components can be expanded to include their various subcomponents:

$$SW_t = P_{LSW} + SP_{SW} + CH_{SW} \tag{2}$$

$$GW_t = P_{LGW} + SP_{GW} + UF_{GW} \quad , \tag{3}$$

where

P_{LSW} is the surface-water component of local precipitation,

SP_{SW} is channelized surface water from springs and seeps,

CH_{SW} is channelized surface water along washes and rivers from sources outside the study area, and

P_{LGW} is the ground-water component of local precipitation.

SP_{GW} is recycled ground water from springs and seeps, and

UF_{GW} is the ground-water underflow component.

If local precipitation is expressed as the sum of local surface- and ground-water precipitation subcomponents, then:

$$P_L = P_{LSW} + P_{LGW} \quad , \tag{4}$$

where

P_L is local precipitation,

then total ET (ET_t) can be expressed as:

$$\begin{aligned} ET_t &= P_L + (SP_{SW} + CH_{SW}) + (SP_{GW} + UF_{GW}) \\ &= P_L + SW + GW \quad , \end{aligned} \tag{5}$$

where

SW and GW are the total surface- and ground-water components minus their components of local precipitation.

ET_t and P_L can be measured or calculated from micrometeorological data collected in the field. The sum of SW and GW is equal to the difference of ET_t and P_L, and herein referred to as ET_{gs}. ET_{gs} can be expressed as

$$ET_{gs} = ET_t - P_L = SW + GW. \tag{6}$$

The location at which ET_{gs} occurs is not necessarily the same location as the source of the water. For example, ground water can be discharged from a regional spring as spring flow, and then channeled some distance away before infiltrating down into the shallow water table where it is later transpired by the local phreatophytes.

The annual volume of discharge by ET_{gs} was estimated by mapping areas of similar surface and vegetation cover and multiplying the area of the mapped cover by a representative annual ET_{gs} rate. This method is similar to those described by Walker and Eakin (1963) and Laczniak and others (1999). Values of ET_{gs} were either estimated from data collected at field sites or compiled from the literature.

Evapotranspiration Units

Areas of similar land cover are defined as unique ET units. ET units are areas of similar plant type, density, and vigor. ET rates are correlated well with these vegetation characteristics (Ustin, 1992; Laczniak and others, 1999; Nichols, 2000; and Reiner and others, 2002). Eight ET units were identified in this study (table 1, pl. 1): dense meadowland vegetation (DMV; 200 acres), dense woodland vegetation (DWV; 7,200 acres), moderate woodland vegetation (MWV; 6,100 acres), dense shrubland vegetation (DSV; 5,800 acres), moderate shrubland vegetation (MSV; 22,600 acres), agricultural unit (AGU; 3,100 acres), non-phreatophytic unit (NPU; 3,400,000 acres), and open water unit (OWU; 300 acres). More than 99 percent of the study area is occupied by xerophytes, identified as NPU, that subsist on soil moisture from local precipitation and do not contribute to ground-water or surface-water discharge.

Prior to delineating ET units, the extent of discharge areas were delineated using the National Agriculture Imaging Program (NAIP) database, Southwest Regional Gap Analysis Program (SWReGAP) data (Kepner and others, 2005), and field reconnaissance. These areas encompass the spatial extent of phreatophytic and riparian vegetation, and open-water areas where the potential ET_{gs} is greater than zero. Discharge areas typically are mapped in early to mid-summer because color contrasts in the vegetation are highest due to maximum water availability to plants.

ET units were delineated using the modified soil-adjusted vegetation index (MSAVI; Qi and others, 1994). The MSAVI uses selected reflectance bands of Landsat Thematic Mapper satellite data (100 by100 ft pixel resolution; obtained June 21, 2003) that respond to the photosynthetic activity of the vegetation. The MSAVI has an advantage over other vegetation indexes in areas of sparse vegetation because it removes soil influences from the vegetation index at sparse plant cover. MSAVI values are dimensionless and range from -1 to 1. For this study, values were scaled from 0 to 1. Values less than 0 were set equal to 0. MSAVI reflectance values between 0.01 and 0.07 represent areas of non-phreatophytic vegetation or bare soils which have the lowest potential for ET. Values of MSAVI reflectance that were greater than 0.55 correspond to vegetation with the highest potential for ET (such as meadow grasses; table 1). MSAVI reflectance values less than zero represent areas of open water because of the absence of photosynthetic activity (table 1). Open-water areas contributing to evaporation were determined from satellite data and were at least 100 by 100 ft in size. All other open-water areas either did not contribute to total ET or were accounted for in other ET components such as rivers and washes. ET units representing areas of agricultural vegetation (AGU) were identified and delineated manually using the NAIP data.

Table 1. Evapotranspiration units determined from the modified soil-adjusted vegetation index in the study area, southern Nevada and adjacent areas in Utah and Arizona.

[ET, evapotranspiration. MSAVI, modified soil-adjusted vegetation index. N/A, not applicable]

ET-unit identifier	ET unit	MSAVI value (dimensionless)	ET-unit area (acres)	General description of ET unit
DMV	Dense meadowland vegetation	0.55 and greater	200	Primarily meadow grasses with some tall reedy and rushy marsh plants; perennially flooded; water table at or just below surface.
DWV	Dense woodland vegetation	0.28–0.55	7,200	Primarily dominated by trees, including mixed trees, grasses and shrubs; water table greater than 10 feet below land surface; soil typically dry.
MWV	Moderate woodland vegetation	0.20–0.28	6,100	Primarily mixed trees, with grasses and shrubs; water table greater than 15 feet below land surface; soil typically dry.
DSV	Dense shrubland vegetation	0.15–0.20	5,800	Primarily shrubs, sparse grasses, sparse trees; water table greater than 15 feet below land surface; soil dry.
MSV	Moderate shrubland vegetation	0.07–0.15	22,600	Sparse shrubs and grasses: water table greater than15 feet below land surface; soil dry.
AGU	Agricultural fields	N/A	3,100	Primarily alfalfa; depth to water table unknown.
NPU	Non-phreatophytic vegetation that do not use ground water	0.01–0.07	3,400,000	Primarily dry bare soils and xerophytes; water table typically greater than 20 feet below land surface.
OWU	Open water areas	0	300	Washes, rivers, and springs.

Site Selection and Instrumentation

Micrometeorological stations were instrumented at four sites representative of dense and moderate woodland, and dense and moderate scrubland ET units. Sites were located on the Virgin River floodplain (dense woodland), along the Muddy River (moderate woodland), in Rainbow Canyon (moderate shrubland), and in Lower Meadow Valley Wash (dense shrubland) (fig. 1, pl. 1, and table 2**)**. Site selection was based on field reconnaissance, preliminary ET-unit characteristics, and upwind fetch. Generally, fetch refers to the distance that air travels from the boundary of the surface of interest to the instruments and implies a homogeneous mix of vegetation, soils, surface water, or some combination thereof. The acceptable minimum fetch allowed in this study was 1:100 (1 m in instrument height above measuring surface to 100 m to the boundary of the environment of interest; Weeks and others, 1987).

Data collection for the study began in February 2003 and ceased in September 2006. Equipment was installed at each site for a minimum of 1 year, except for the Lower Meadow Valley Wash site, which was in operation for only 6 months because of technical difficulties. Sites were not installed at the same time but there were periods when data collection did overlap. Missing data resulted from various technical or weather related problems.

The Virgin River floodplain ET site is typified by a dense population of 20 to 30-ft tall saltcedar trees with lesser amounts of mesquite, pickleweed, and arrowweed. This site was located about 8 mi northeast of Overton, Nevada, at an altitude of about 1,200 ft (fig. 1; pl. 1). The floodplain at the site is about 0.62 mi wide and extends several miles north/south, and is comprised of fine-grained sand. The height of the data collection platform was about 30 ft above land surface, raising the instrumentation above the tree tops. Depth to ground water varied from 13 to 15 ft during the site's operation (February 2003–March 2005; table 2). This site was instrumented to collect data for the Bowen-ratio method of calculating ET (fig. 3*A*).

The Muddy River riparian ET site was located about 100 ft from the river surrounded by a dense grove of 10 to 15-ft tall mesquite trees growing in soil composed mostly of silty clays. The Muddy River site is in lower Moapa Valley about 7 mi from the town of Glendale, Nevada at an altitude of about 1,650 ft. Flow in the Muddy River originates from Muddy River Springs, which are about 2.5 mi northwest of the site (fig.1; pl. 1). The Muddy River riparian area is about 980 to 1,300 ft wide and extends from just north of the Muddy River Springs southward to the Moapa River Indian Reservation. The riparian area primarily consists of groves of dense mesquite trees mixed with cottonwood trees, palm trees, and various species of vines. Depth to ground water at this site varied from 14 to 23 ft during the site's operation (July 2003–October 2006; table 2). This site was instrumented to collect data for the Bowen-ratio method of calculating ET (fig. 3*B*).

The Rainbow Canyon site was located about 10 mi south of Caliente, Nevada, and about 200 ft east of Meadow Valley Wash at an altitude of about 4,100 ft. The canyon is north-south trending and very narrow, with a width of less than 0.25 mi. The site is dominated by rabbitbrush and sage that stand about 3 ft tall in gravelly soil. The gravelly soils made it difficult install a well at this site and as a result the depth to ground water is unknown. This site was instrumented to

Table 2. Characteristics of evapotranspiration sites in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; MSV, moderate shrubland vegetation; DSV, dense shrubland vegetation]

Site name	ET-unit identifier	Latitude	Longitude	Altitude (feet)	Depth of water table below land surface (feet)	Period of data collection [total days]	Number of days of ET data
Virgin River	DWV	N36° 35' 15.01"	W114° 19' 42.21"	1,200	13 – 15	02-02-03 – 03-09-05 [766]	521
Muddy River	MWV	N36° 41' 27.50"	W114° 41' 16.30"	1,650	14 – 23	07-30-03 – 10-19-06 [1,177]	917
Rainbow Canyon	MSV	N37° 31' 13.38"	W114° 34' 59.52"	4,100	[1]15 – 20	06-18-05 – 10-19-06 [488]	487
Lower Meadow Valley Wash	DSV	N36° 51' 00.17"	W114° 39' 57.20"	1,900	[2]16	04-11-06 – 10-19-06 [191]	191

[1] Estimate.

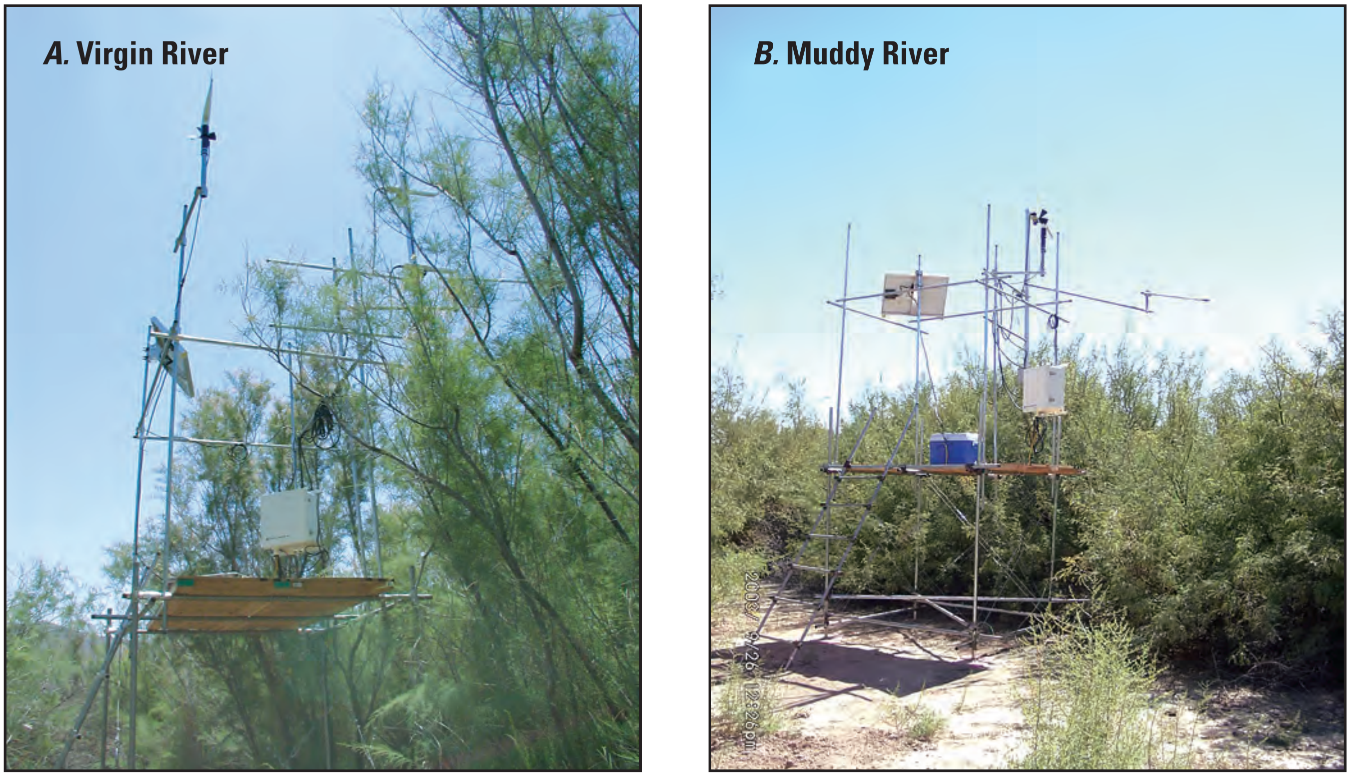
[2] Less than 1 foot change in water level.

collect data for the eddy-covariance method for calculating ET (fig. 3*C*) and was in operation from June 2005 to October 2006.

The Lower Meadow Valley Wash site was located about 15 mi north of Moapa, Nevada, at an altitude of about 1,900 ft. The site was in a narrow canyon, less than one-half mile across, in a riparian meadow with soils composed of fine-grained sand with some clay. Depth to ground water varied from 16 and 16.5 ft below land surface during the data collection period. The sites vegetation community was diverse and complex with an assortment of saltcedar, mesquite, and cottonwood trees lining the wash on the eastern and far southern edges of the area, xerophytes, mainly creosote and saltbrush, dominating the west edge, and a homogeneous community of arrowweed plants in an irregularly shaped patch (980-ft north-south by 229-ft east-west) in the center of the area. Obtaining an adequate fetch was a challenge at this site due to the mixed vegetation and limited area. This site was instrumented to collect data for the eddy-covariance method of calculating ET (fig. 3*D*). The ET sensors were placed as close to the center of the arrowweed community as possible. At the time of installation in March 2006, the arrowweed plants were about 3.5 ft tall and the ET sensors were placed about 3.5 ft above average vegetation height. This installation allowed for adequate fetch from the south (direction of prevailing wind); however, it was thought that fetch from the east-west direction might be insufficient. As data were collected ET rates were higher than expected and on August 7, 2006, adjustments were made to sensor height by lowering them to 1.5 ft above average vegetation height in an attempt to better account for the fetch from all directions. This adjustment resulted in an even higher ET rate.

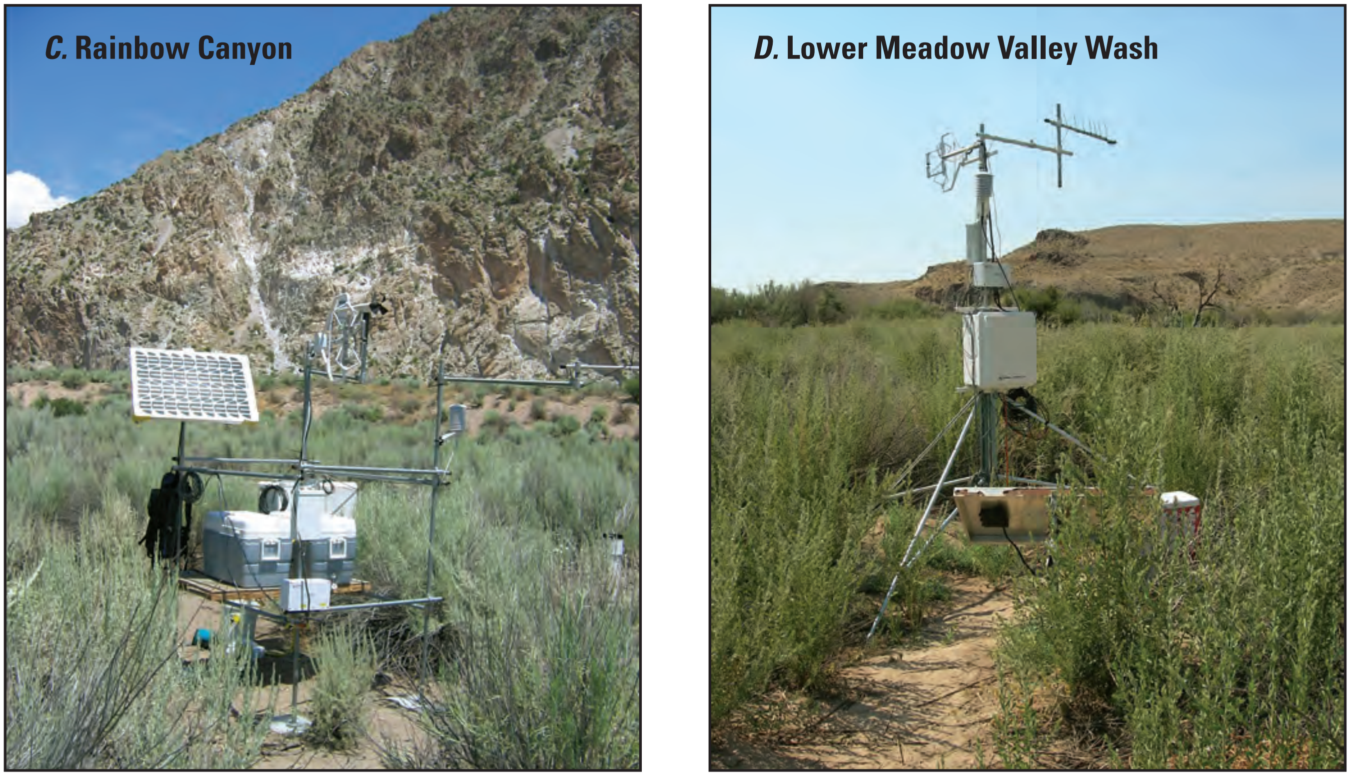
The micrometeorological station at the Lower Meadow Valley Wash site was only in operation from April 11 to October 19, 2006, due to technical difficulties. This time period spans the annual growing season when the majority of the ground- and surface-water discharge from ET occurs. Daily ET rates from the Muddy River site were used as surrogates for missing data from the Lower Meadow Valley Wash site for the periods January 1 to April 11, 2006, and October 20 to December 31, 2006. This substitution was assumed reasonable because the micrometeorological stations were in close proximity and during these periods transpiration is at or near annual minimums.

Between September 2004 and August 2005, about twice the average annual amount of rain (12.74 in.) was recorded in Moapa, Nevada. Precipitation data for Moapa (gauge ID 3264) are available from the Clark County Regional Flood Control District, Nevada, at http://acequia.ccrfcd.org/rainfallhistory/loadrainfall.aspx?Year=2004 for 2004 and at http://acequia.ccrfcd.org/rainfallhistory/loadrainfall.aspx?Year=2005 for 2005. Severe flooding occurred in Meadow Valley Wash, Beaver Dam Wash, and the Virgin River Valley from November 2004 to January 2005. During this period, only the Virgin River and Muddy River sites were in operation; sensors at the Rainbow Canyon and Lower Meadow Valley Wash sites had not yet been installed. The Virgin River site was inaccessible due to the flooding which resulted in a permanent loss of data after March 9, 2005. The Muddy River site also received substantial amounts of rain during that period—more than 11 in. at Muddy River Springs—and although flooding was relatively minor, access to the site was difficult. As a result, data were lost at the Muddy River site from May to September 2005. All other periods of missing data were the result of equipment problems.



Photograph taken by Guy De Meo, U.S. Geological Survey, 2003.

Photograph taken by Guy De Meo, U.S. Geological Survey, 2003.



Photograph taken by Timothy Olsen, U.S. Geological Survey, 2005.

Photograph taken by Jon Darnell, U.S. Geological Survey, 2006.

Figure 3. Evapotranspiration sites at (*A*) Virgin River, (*B*) Muddy River, (*C*) Rainbow Canyon, and (*D*) Lower Meadow Valley Wash in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Evapotranspiration Calculations

ET is a process by which water from the Earth's surface is transferred to the atmosphere. The transfer requires energy to change water from a liquid to a vapor state. This relation between water loss and energy consumption is the basis for many of the energy-budget methods used to estimate ET. ET, as used in this report, includes evaporation from open water and soil and transpiration from plants. Micrometeorological instruments were used at field sites to collect the necessary parameters to derive energy fluxes used in the determination of ET.

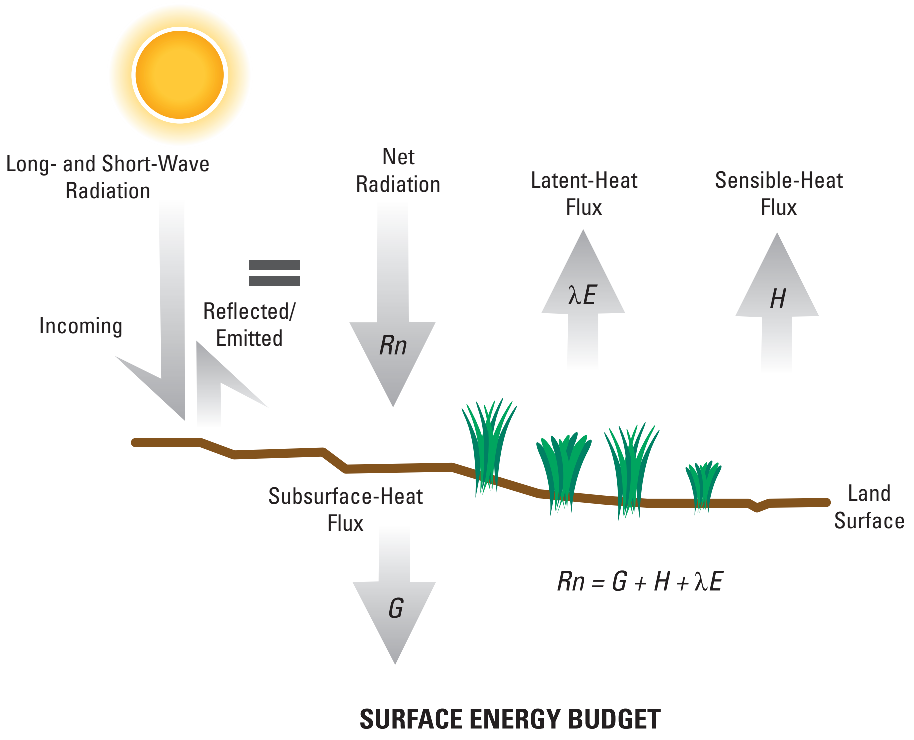


Figure 4. Energy budget of the surface of the Earth.

Energy Budget and Methods

Energy at the surface of the Earth can be described by an energy budget that balances the incoming and outgoing energy fluxes (fig. 4). Assuming that energy use by biological processes and storage of heat by the vegetation are negligible, the energy budget for conditions typical of the study area can be expressed as

$$R_n = G + H + \lambda E \quad , \qquad (7)$$

where

R_n is net radiation (energy per area per time),
G is subsurface-heat flux (energy per area per time),
H is sensible-heat flux (energy per area per time), and
λE is latent-heat flux (energy per area per time)
  where
    λ is the latent heat of vaporization for water (energy per mass), and
    E is the rate of water evaporation (mass per area time).

Net radiation (R_n) is the primary term in the energy budget and is the algebraic sum of incoming and outgoing long- and short-wave radiation. Subsurface-heat flux (G) represents how much energy the soil or water column gains or loses during a given period. Net radiation (R_n) and subsurface-heat flux (G) can be measured or computed in the field. The difference between R_n and G is the energy available at the surface of the Earth. Sensible-heat flux (H) is the energy exchanged between the atmosphere and the surface. When H is positive, the surface of the Earth is heating the atmosphere; when negative, the atmosphere is heating the surface. Latent-heat flux (λE) is the energy used to evaporate or transpire water from soil, open water, and plants. In this study, the Bowen-ratio (Bowen, 1926) and eddy-covariance (Dyer, 1961) methods were used to determine the energy-budget fluxes and calculate ET. Although both methods determine R_n and G using the same instrumentation, H and λE are calculated differently.

Energy-Budget Closure

According to the principal of conservation of energy, the sum of all components of the energy budget is zero and is referred to as energy-budget closure. The achievement of closure is used to assess the measurement accuracy of the individual components of the energy budget. The better the closure, the better the confidence is in the field measurements. To measure relative balance of closure, Duell (1985), calculated the ratio of sensible-heat flux (H) and latent-heat flux (λE) to the available energy ($E_n = R_n - G$) times 100. When this ratio is 100 percent then all of the E_n is accounted for in H and λE and the energy budget is closed. When closure is less than 100 percent, E_n is greater than H and λE indicating that either latent- and (or) sensible-heat flux are being underestimated by the equipment. When the closure is greater than 100 percent, then H and λE are greater than E_n and are being overestimated by the equipment.

Bowen-Ratio Method

Sensible-heat flux (*H*) and latent-heat flux (λE) involve turbulent transfer coefficients of heat and vapor that are difficult to determine, and as a result, neither *H* nor λE can be solved directly. In 1926, Bowen developed the Bowen-ratio method to solve the energy budget by taking the ratio of sensible-to latent-heat flux ($H/\lambda E$). This approach solves for *H* and λE by using all components of the energy budget, resulting in a complete balance or closure of the budget (Laczniak and others, 1999). By using this method, ET can be calculated from measurable micrometeorological data.

Eddy-Covariance Method

The eddy-covariance method is based on the principal that turbulent eddies can vertically transport sensible and latent heat (Brutsaert, 1982). Estimates of sensible-heat flux (*H*) and latent-heat flux (λE) are determined by using instrumentation that makes rapid measurements of fluctuations in vertical wind speed, water vapor, and air temperature over short intervals of time. Unlike the Bowen ratio, all energy-budget components are calculated independently. This computational independence of *H* and λE frequently results in difficulties achieving energy-budget closure; however, this approach to measuring energy fluxes can provide a more accurate representation of *H* and λE because they are not forced to balance. In this study, corrections for temperature-induced fluctuations in air density (Webb and others, 1980) and for the sensitivity of oxygen (Tanner and Greene, 1989) were used in the calculations of latent-heat flux.

Bowen-Variant Method

Sometimes energy-budget closure is not achievable with the eddy-covariance method due to unavoidable placement of instrumentation in the environment. Poor closure is a consequence of either over- or under-estimating the sensible- and latent-heat fluxes. The eddy-covariance method assumes that sensible- and latent-heat fluxes are over- or under-estimated equally (Moore, 1976). To compensate for this assumption, German (2000) took the ratio of *H* to λE estimated with eddy-covariance sensors and calculated the same fluxes using a variant of the Bowen ratio (Sumner, 2001). The sensible- and latent-heat flux can be expressed as

$$\lambda E_b = \frac{R_n - G}{1 + \dfrac{H_e}{\lambda E_e}} . \tag{8}$$

$$H_b = \lambda E_b \frac{H_e}{\lambda E_e} \tag{9}$$

where

λE_e is the latent heat calculated using the eddy-covariance method,
R_n is net radiation,
G is subsurface-heat flux,
H_b is the sensible heat calculated using the Bowen-variant method,
H_e is the sensible heat calculated using the eddy-covariance method, and
λE_b is the latent heat calculated using the Bowen-variant method.

Micrometeorological Data

Micrometeorological data collected at all sites included net radiation, subsurface-heat flux, subsurface soil temperature, and soil-water content. Additionally, at sites instrumented for applying the Bowen-ratio method, air temperature and relative humidity were measured at 1.6 and 4.9 ft above the average canopy height of the vegetated surface of interest (fig. 5*A*). Sites used for the eddy-covariance method required a sonic anemometer to measure three-dimensional wind speeds and a krypton hygrometer (mounted about 5 ft above the average canopy height) to determine water vapor density used to calculate sensible- and latent-heat flux (fig. 5*B*). The following instrumentation was installed and supporting data were collected at each site: a two-dimensional anemometer to measure wind speed and direction, a shallow well with a submersible pressure transducer to measure fluctuations in ground-water level, and a volumetric precipitation gage to collect bulk rainfall. At the Rainbow Canyon site, gravelly soils prevented the installation of the shallow well so the ground-water level was unknown. Data to determine Bowen-ratio values were measured at 10- or 30-second intervals and averaged over 20 minutes. Data to determine the eddy-covariance values were measured at 0.1-second intervals and also averaged over 20 minutes. For all instrumented sites, the 20-minute data were stored and retrieved for processing every month.

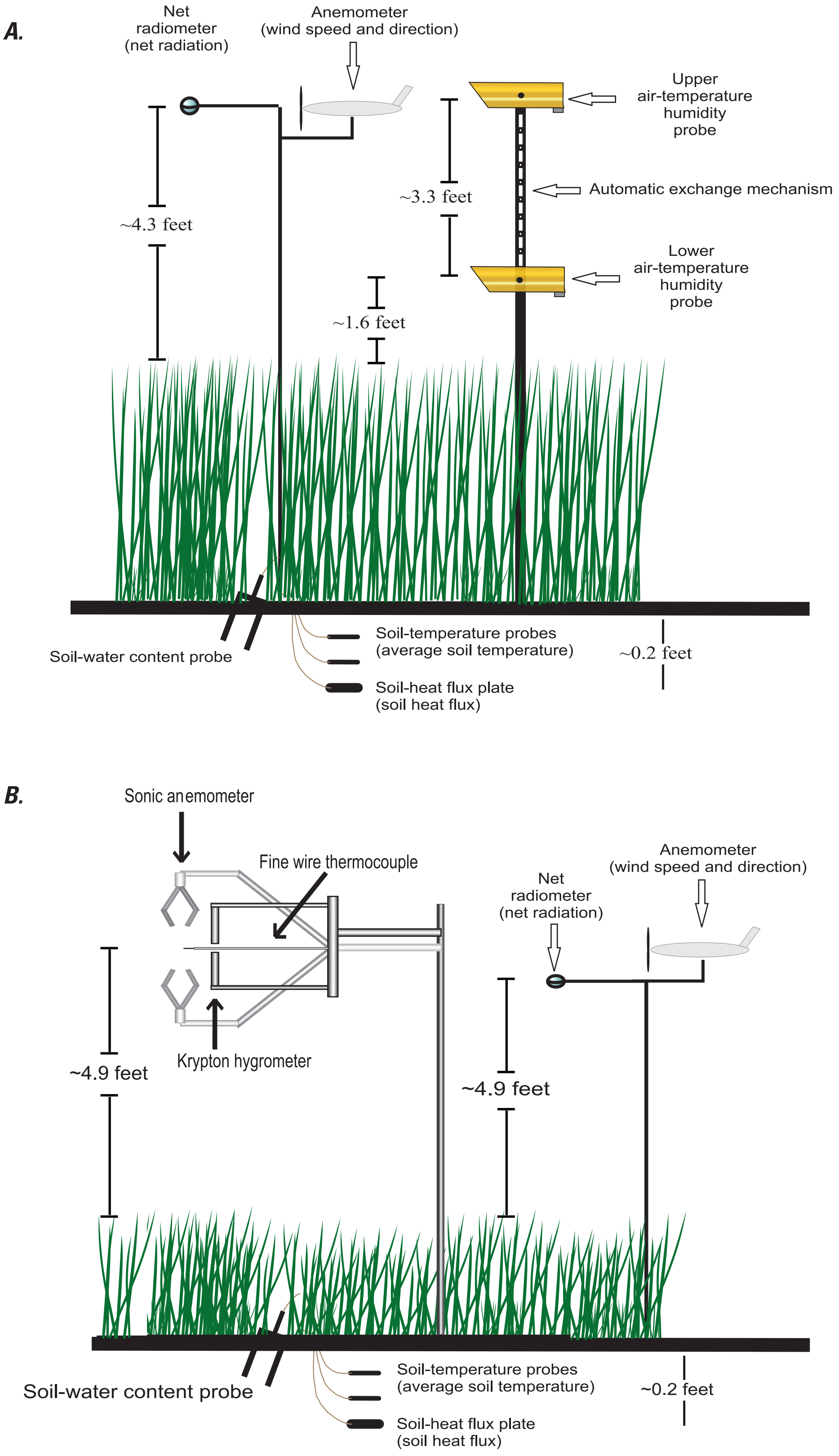
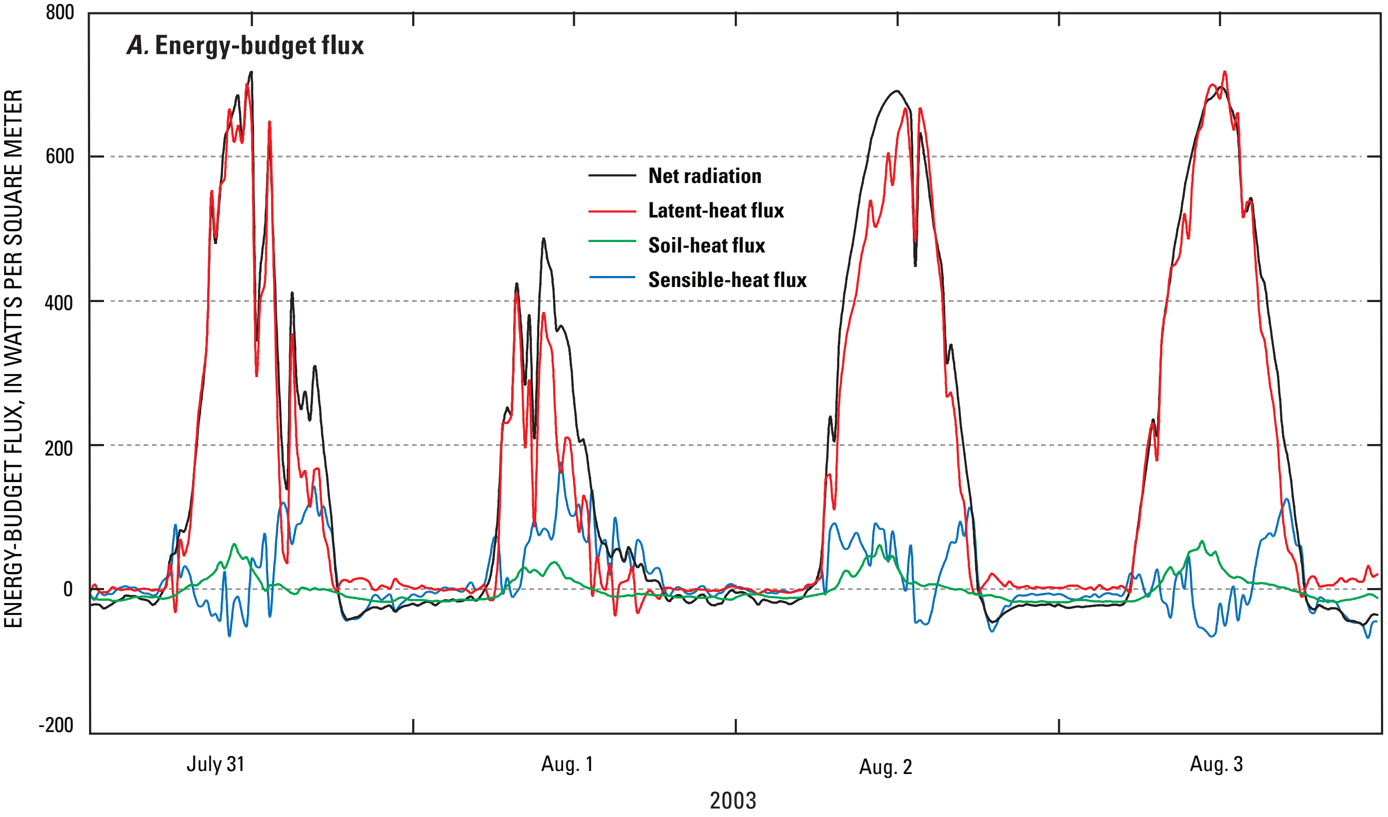


Figure 5. Instrumentation used to measure micrometeorological data for the (*A*) Bowen-ratio and (*B*) eddy-covariance methods.

Daily and Annual Total Evapotranspiration

The stored micrometeorological data were used to calculate the energy budget, 20-minute ET, daily ET, and annual ET. The data-reduction process included (1) determining the 20-minute averaged individual components of the energy budget (net radiation, subsurface-heat flux, latent-heat flux, and sensible-heat flux; fig. 6*A*), (2) calculating 20-minute ET values from the latent-heat flux, (3) summing the 20-minute ET values over a 24-hour period to obtain daily ET rates (fig. 6*B*), and (4) whenever possible, calculating average daily ET values using two or more years of data (fig. 6*C*).



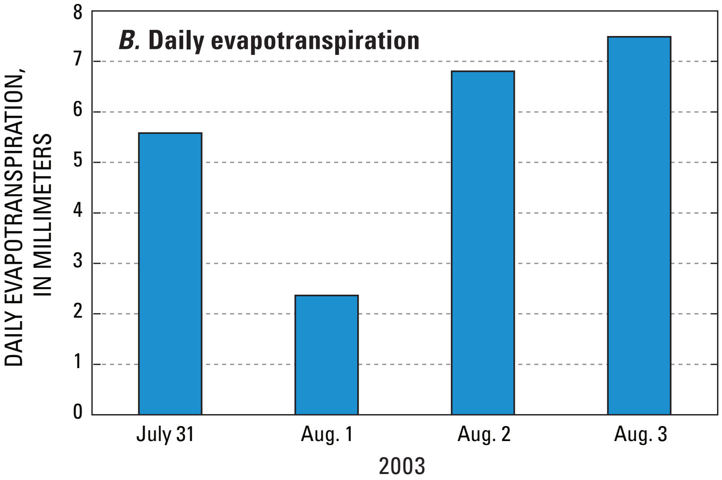


Figure 6. Example of (*A*) 5-day energy-budget flux at Muddy River site, July 31–August 3, 2003, (*B*) daily evapotranspiration for the Muddy River site July 31–August 3, 2003, and (*C*) daily evapotranspiration collected at the four sites, southern Nevada, and adjacent areas in Utah and Arizona, July 31–August 3, 2003.

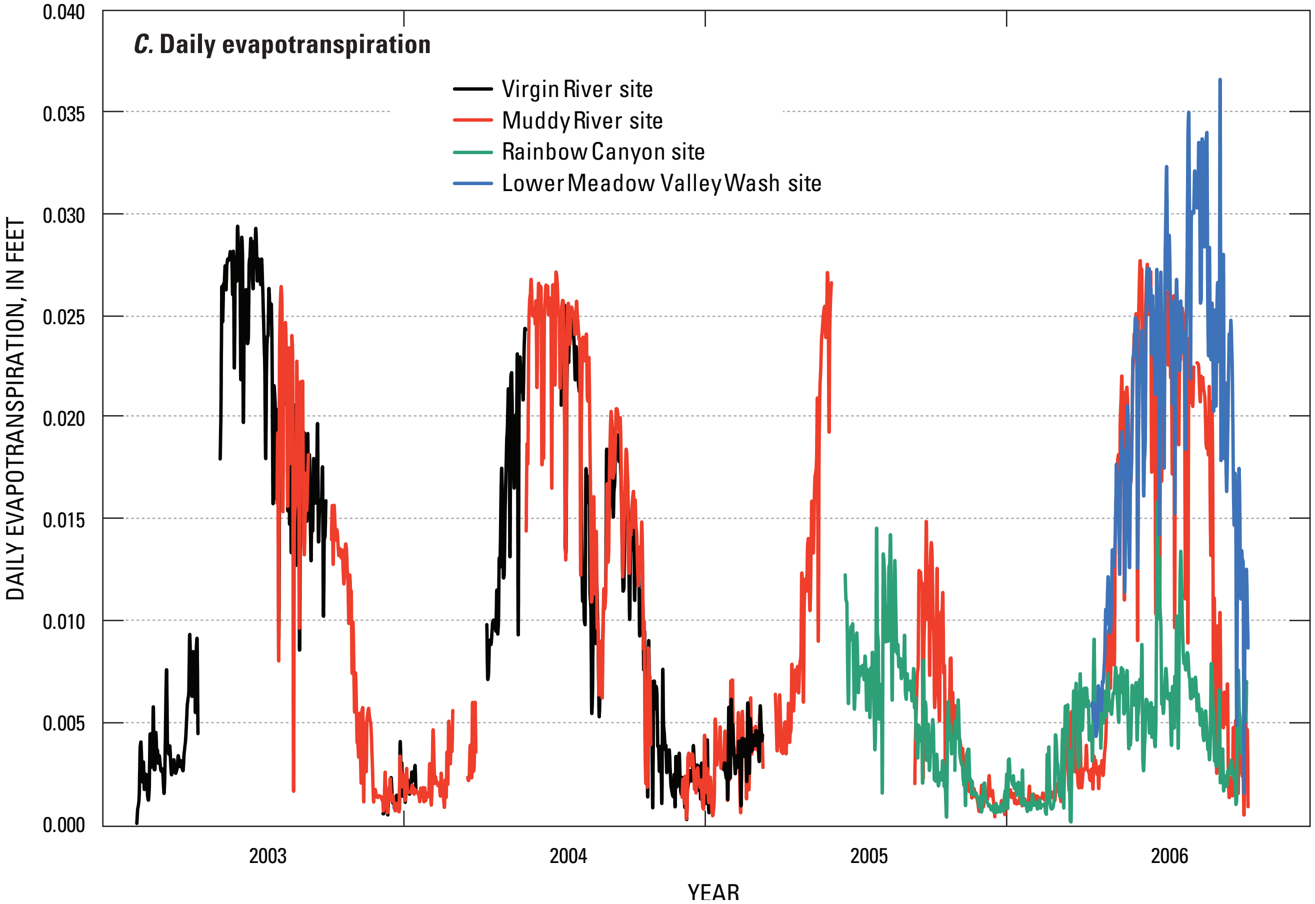


Figure 6.—Continued.

ET rates can vary from year to year and from one day to the next in response to rapidly changing weather conditions. Annual ET rates sometimes have to be estimated due to periods of missing or inaccurate data, or varied weather conditions. To correct for data gaps and to obtain an annual average ET rate, the entire record of available ET from the Virgin River site, Muddy River site, and Rainbow Canyon site were used to determine the average daily ET rate, which then can be summed to determine the annual ET rate (fig. 7). Average daily ET values were calculated for each calendar day from each year that data were available for that day. Some days had available data from only 1 year while others days had available data for as many as 4 years at the Muddy River site. This approach could not be used at the Lower Meadow Valley Wash site because data were only collected from April 12, 2006 to October 19, 2006.

At the Rainbow Canyon and Lower Meadow Valley Wash sites, the riparian areas were very narrow limiting the available fetch needed to determine the energy-budget and estimate ET. The accuracy of ET estimates was assessed by comparing the averaged 20-minute closure values at these two sites on July 2 and on August 20, 1996, spanning the hours from 0700 to 1600 PST. These dates were selected for comparison because vegetation were very productive and ET likely was at or near annual maximum. Additionally at the LMVW site, July 2 is representative of the lower sensor height while August 20 is representative of the raised sensor height. Average closure at the Rainbow Canyon site was about 100 and 90 percent on July 2 and on August 20, respectively. Average closure at the Lower Meadow Valley Wash site was about 128 and 168 percent on July 2 and on August 20, respectively. The Rainbow Canyon site achieved good closure indicating that all the sensors were sampling air from the same environment and that fetch was not much of an issue during these periods. At the Lower Meadow Valley Wash site, however, closure was poorer indicating that the measured sensible-heat and latent-heat flux were greater than the measured available energy suggesting that fetch was an issue before and after the adjustments were made to the instruments.

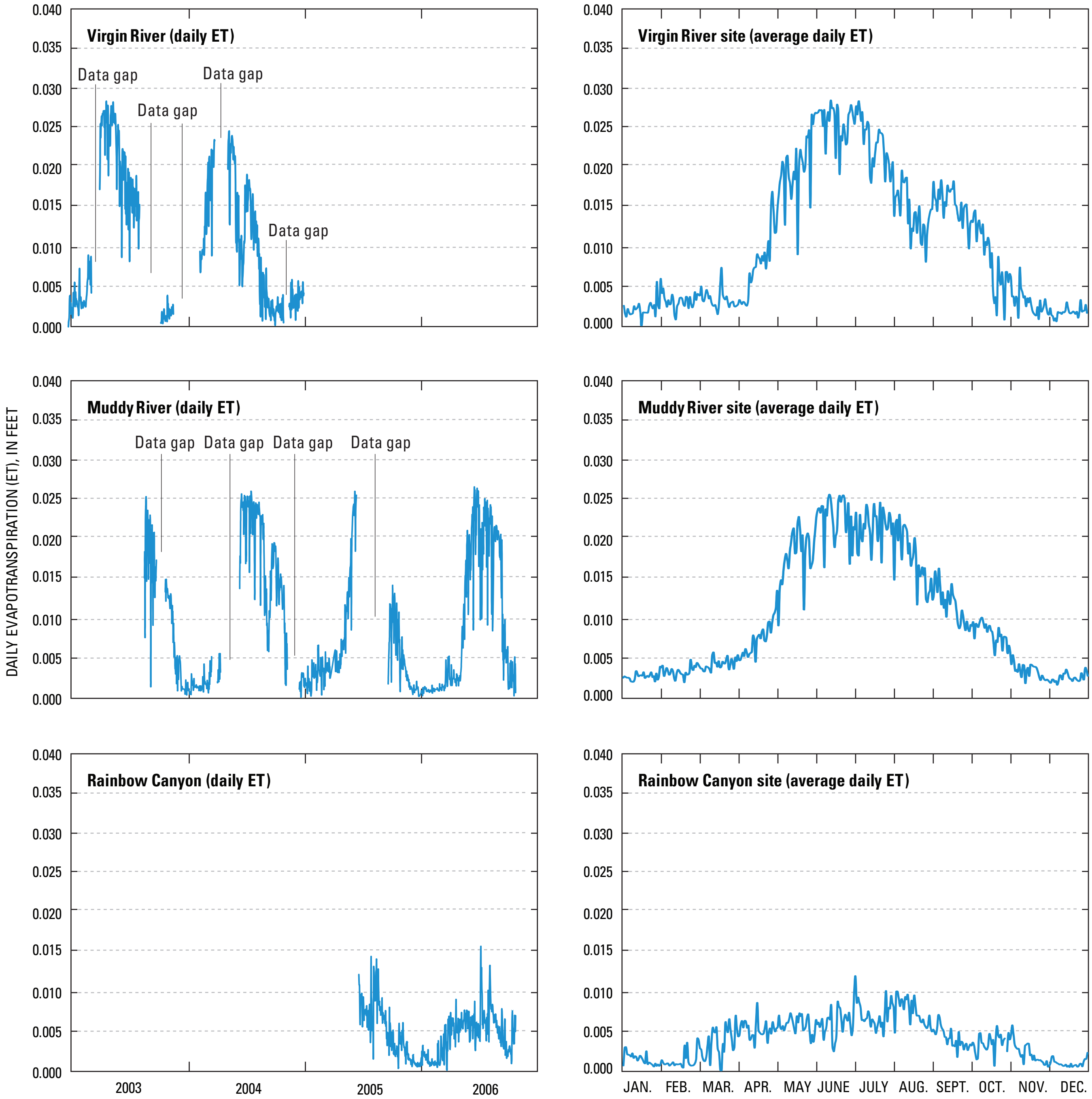


Figure 7. Collected daily evapotranspiration for the Virgin River site from February 2003 to March 2005, the Muddy River site from July 2003 to October 2006, and from the Rainbow Canyon site from June 2005 to October 2006 and the corresponding average daily evapotranspiration for each site calculated from the collected daily evapotranspiration in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Bowen-variant approach (eq. 8 and 9) was applied to provide additional estimates of ET rates for comparison against the eddy-covariance results. Figure 8 displays the Bowen-variant ET rates (Y-axis) plotted against the eddy-covariance ET rates (X-axis) for both the Rainbow Canyon and Lower Meadow Valley Wash sites. The closer the slope of the ET trend line and the Y=X line the better agreement between the Bowen-variant and eddy covariance ET rates. The slope of the trend line at the Rainbow Canyon site is closer to the Y=X line than at the Lower Meadow Valley Wash site (fig. 8).

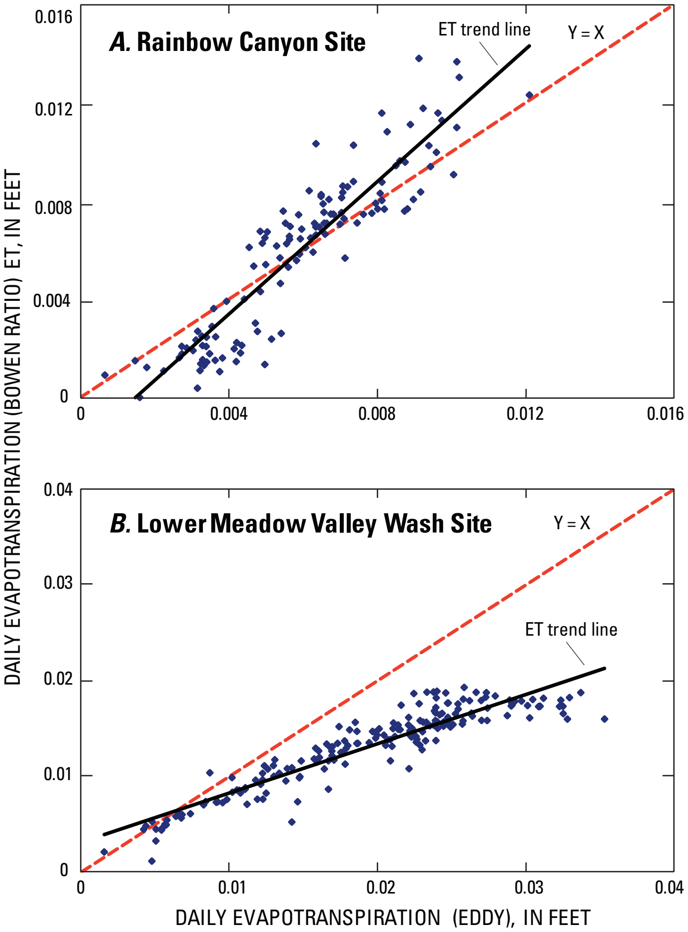


Figure 8. Regression of daily evapotranspiration calculated with the Bowen-variant and eddy-covariance methods using sensible- and latent-heat fluxes from the eddy-covariance equipment at the Rainbow Canyon site from June 19, 2005, to October 19, 2006, and the Lower Meadow Valley Wash site, from April 12 to October 18, 2006, southern Nevada.

This suggests that there is better agreement between the eddy covariance and the Bowen-variant ET rates at the Rainbow Canyon site than at the Lower meadow Valley Wash site. The estimated total annual ET rates at Lower Meadow Valley Wash site were 4.1 and 2.8 ft from the eddy-covariance and the Bowen-variant methods, respectively. At the Rainbow Canyon site, the estimated total annual ET rate was 1.5 ft for both methods (table 3). These results also suggest that fetch may have been a problem at the Lower Meadow Valley Wash site along with rapid growth of vegetation during the time of data collection. The Bowen-variant ET rate of 2.8 ft was the rate used to determine the total annual ET for Lower Meadow Valley Wash.

From January 1 to April 11, 2006 and October 20 to December 31, 2006, data were not collected at the Lower Meadow Valley Wash site. Daily ET rates from the Muddy River site were used as proxy data. During the first period of missing data (January 1–April 11, 2006) daily ET from the Muddy River site for the same period were used. However, during the second period of missing data (October 20–December 31, 2006) daily ET from October 20 to December 31, 2005 were used because data were not being collected at either site. These daily ET substitutions were assumed reasonable because the sites were in close proximity to one another and substitutions were made during the time of year when transpiration of ground- and surface- water discharge from vegetation are at or near annual minimums (fig. 9).

The total annual ET rates for the four ET sites ranged from a minimum of 1.5 ft at Rainbow Canyon which was a moderate shrubland site to 3.9 ft at the Virgin River which was a dense woodland vegetation site (fig. 10; table 4). The total annual ET rate for the Virgin River site determined in this study was in the same range (2.5–4.7 ft) as the ET rate for a similar type site on the Virgin River reported by Devitt and others (1998) and slightly higher than the range of values (2.5–3.5 ft), reported for the same area by Weeks and others (1987).

Table 3. Annual evapotranspiration rate from the eddy-covariance and Bowen-variant methods at Rainbow Canyon (June 2005–October 2006) and Lower Meadow Valley Wash (January–December 2006) sites, southern Nevada.

ET site name	Annual evapotranspiration rate (feet)	
	Eddy covariance	Bowen-variant method
Rainbow Canyon	1.5	1.5
Lower Meadow Valley Wash	4.1	2.8

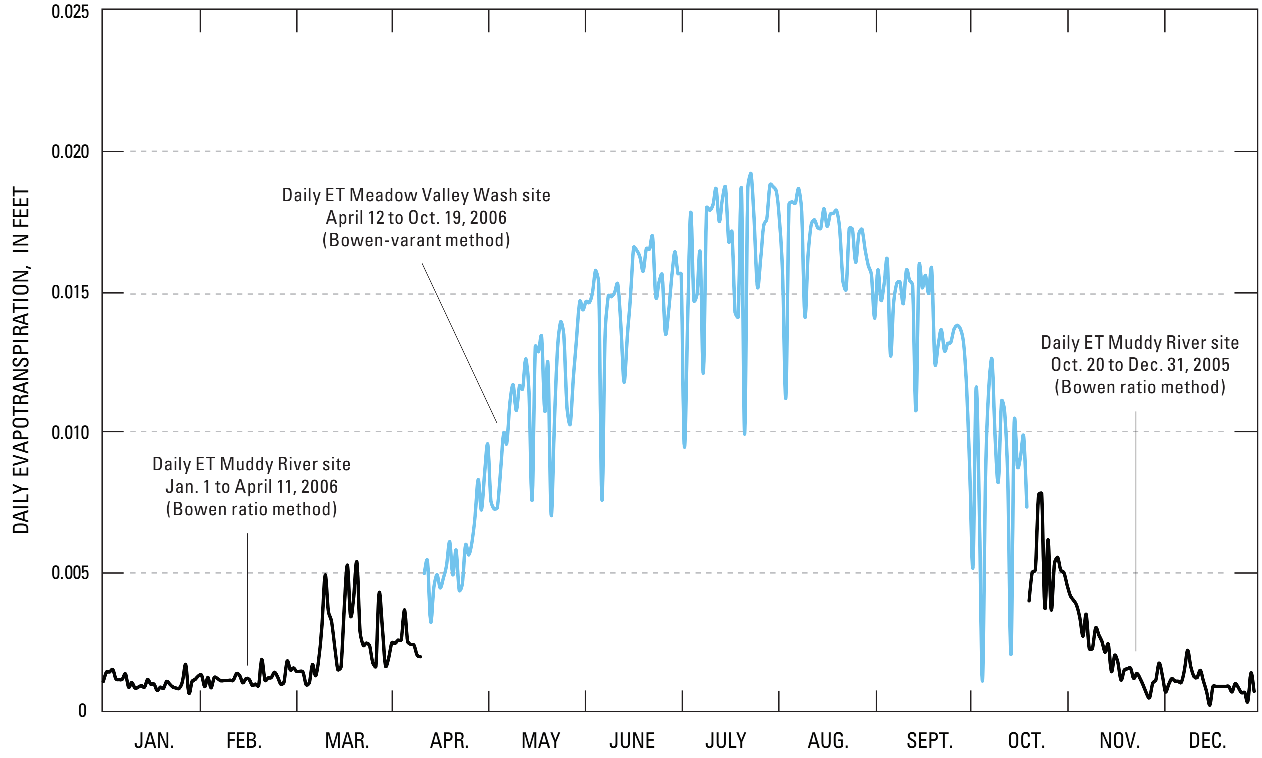


Figure 9. Daily evapotranspiration at the Lower Meadow Valley Wash site with data substituted from the Muddy River site January 1 to April 11, 2006, and October 19 to December 31, 2005, southern Nevada.

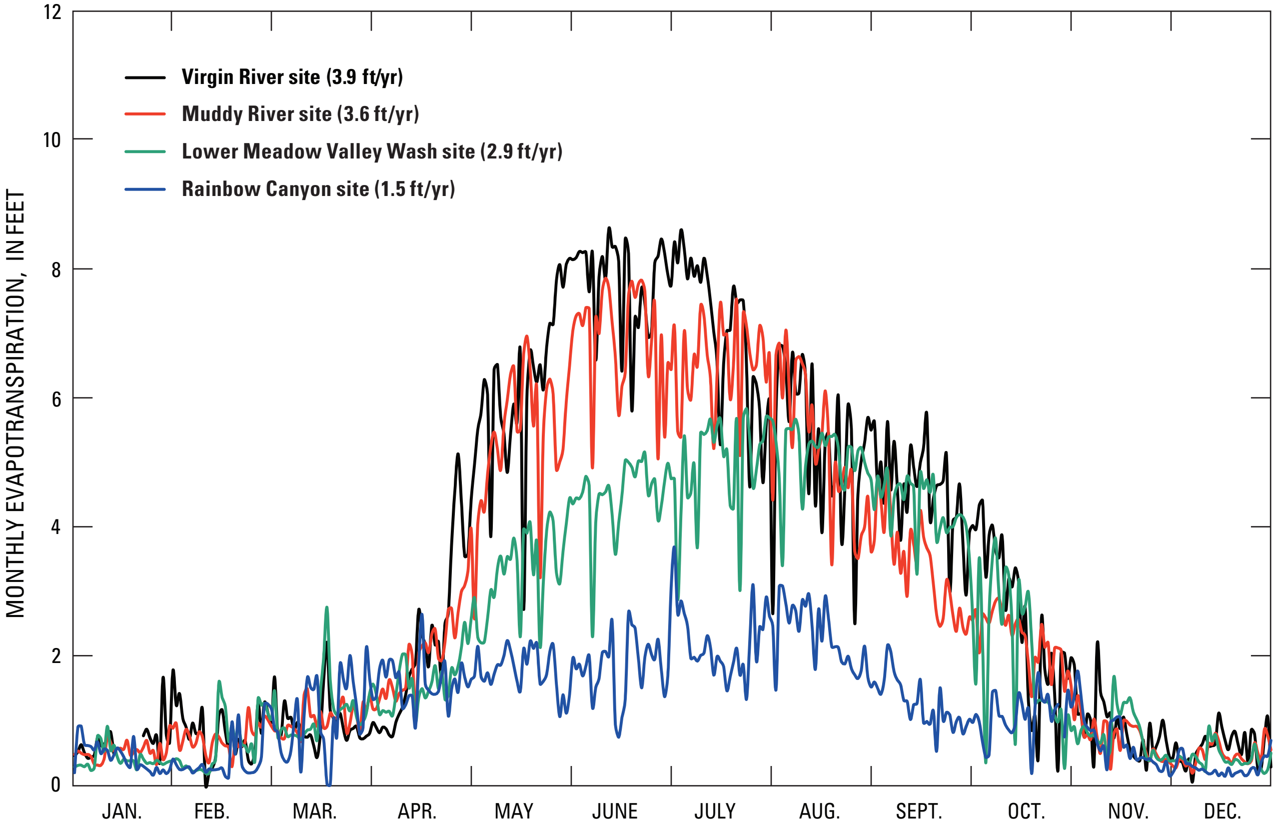


Figure 10. Monthly evapotranspiration for Virgin River, Muddy River, Lower Meadow Valley Wash, and Rainbow Canyon sites in the study area, southern Nevada and adjacent areas in Utah and Arizona.

Table 4. Annual total evapotranspiration rate, measured precipitation, and annual ground- and surface-water ET rate from sites in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. ET_{gs}, ground- and surface-water discharge from ET. ET_t, estimated total evapotranspiration rate. **ET-unit identifier:** DWV, dense woodland vegetation; MWV, moderate woodland vegetation; MSV, moderate shrubland vegetation; DSV, dense shrubland vegetation]

Site name	ET-unit identifier	Annual ET_t rate (feet)	Annual precipitation (feet)	Annual ET_{gs} rate (feet)
Virgin River	DWV	3.9	0.5	3.4
Muddy River	MWV	3.6	.4	3.2
Rainbow Canyon	MSV	1.5	.5	1.0
Lower Meadow Valley Wash	DSV	2.8	.6	2.2

Estimates of Annual Ground- and Surface-Water Discharge from Evapotranspiration

A combined estimate of ground-water and surface-water discharge from ET along narrow riparian areas for 12 selected hydrographic areas of the CRFS was computed from estimates of total annual ET. The approach used in this study assumes that all ground water and surface water discharged across the study area is evaporated or transpired locally from within seven of the eight identified ET units (pl. 1). Although springflow is not directly accounted for in this approach, it is considered part of the ET component on the assumption that it is evaporated or recycled back into the ground-water or surface-water system and is eventually evaporated or transpired. As estimated, total annual ET includes any precipitation falling onto the study area that is evaporated or captured by the ground- or surface-water system to be evaporated or transpired. Total annual ET is adjusted to remove any water contributed by local precipitation prior to computing discharge.

Estimated rates of ET_{gs} were determined from micrometeorological stations located in four of the eight ET units identified in the study area. These four sites were considered to be essential for understanding the magnitude of ground-water and surface-water discharge because they were located in areas that were representative of vegetation with higher ET rates or were representative of the larger ET units found in the study area. Published annual ET discharge rates from similar ET units were used for computation in the other three ET units contributing to discharge in the study area.

Micrometeorological stations were installed in very dense saltcedar trees (DWV unit Virgin River site), in moderately dense mesquite trees (MWV unit Muddy River site), in dense arrowweed (DSV unit Lower Meadow Valley Wash site), and in moderately dense rabbitbrush and sage (MSV unit Rainbow Canyon site). The total annual ET_{gs} rate for these ET units ranged from 3.4 ft for DWV to 1.0 ft for MSV (table 4). Published rates of ET_{gs} used in this study are the DMV unit (3.4 ft) from Laczniak and others (1999), and the OWU (4.9 ft) and the AGU (5.2 ft) from the Bureau of Reclamation (2005) (table 5). The annual ET_{gs} rate for the OWU is an average of open water evaporation values for different reaches of the Lower Colorado River (Davis Dam to Parker Dam and Parker Dam to Imperial). The annual ET_{gs} rate for the AGU is the consumptive use of water by ET from alfalfa.

The amount of surface- and ground-water discharged from each ET unit was calculated by multiplying the annual ET_{gs} rate by the ET unit acreage (table 5). The ET unit with the greatest annual discharge was the DWV unit at 24,480 acre-ft and the ET unit with the least amount was the DMV unit at 680 acre-ft. The difference between the discharge volumes of these ET units was due to the difference in their size because both had the same ET_{gs} rate. The area of the DWV unit is 36 times larger than the DMV unit.

Estimates of annual ET_{gs} discharge were determined for each of the 12 hydrographic areas. This was accomplished by first determining the acreage of each ET unit for each hydrographic area (fig. 1; table 6). The acreages were then multiplied to the ET_{gs} rate that corresponds to that ET unit to determine the discharge for each ET unit within the hydrographic area. The discharge of each ET unit, within the hydrographic area, was summed together giving the total annual discharge for each hydrographic area (table 7). The annual ET_{gs} discharges were 1,952 acre-ft from the Black Mountains Area, 6,080 acre-ft from the California Wash, 4,090 acre-ft from the Muddy River Springs Area, 11,510 acre-ft from the Lower Moapa Valley, 51,960 acre-ft from the Virgin River Valley, 16,168 acre-ft from the Lower Meadow Valley Wash, 5,840 acre-ft from Clover Valley, and 0 acre-ft from Coyote Spring Valley, Kane Springs Valley, Tule Desert, Hidden Valley (North), and Garnet Valley. The total amount of annual discharge from ET_{gs} for the study area is 97,600 acre-ft.

Table 5. Evapotranspiration unit acreage, annual ground- and surface-water evapotranspiration rate, and annual ground- and surface-water ET discharge for all evapotranspiration units within the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; AGU, agricultural unit; MSV, moderate shrubland vegetation; OWU, open water unit]

ET-unit identifier	ET-unit area (acres)	Annual ET_{gs} rate (feet)	Annual ET_{gs} discharge (acre-feet)
DMV	200	[1]3.4	680
DWV	7,200	3.4	24,480
MWV	6,100	3.2	19,520
DSV	5,800	2.2	12,760
MSV	22,600	1.0	22,600
AGU	3,100	[2]5.2	16,120
OWU	300	[2]4.9	1,440

[1] Data from Laczniak and others (1999).

[2] Data from Bureau of Reclamation (2005).

Table 6. Area of ET units (in acres) for each of the 12 hydrographic areas in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003–06.

[ET, evapotranspiration. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; MSV, moderate shrubland vegetation; AGU, agricultural unit; OWU, open water unit]

Hydrographic area	ET unit identifier, in acres							
	NPU	MSV	DSV	MWV	DWV	DMV	AGU	OWU
Black Mountains Area	320,000	1,000	200	100	0	0	0	40
California Wash	200,000	1,200	200	200	200	0	600	0
Muddy River Springs Area	60,000	1,450	300	300	300	0	0	0
Lower Moapa Valley	160,000	1,450	600	700	700	0	700	100
Virgin River Valley	1,000,000	8,700	3,300	3,600	4,900	100	1,300	150
Lower Meadow Valley Wash	600,000	6,500	800	900	700	0	500	10
Clover Valley	230,000	2,300	400	300	400	100	0	0
Coyote Spring Valley	420,000	0	0	0	0	0	0	0
Kane Springs Valley	140,000	0	0	0	0	0	0	0
Tule Desert	120,000	0	0	0	0	0	0	0
Hidden Valley (North)	50,000	0	0	0	0	0	0	0
Garnet Valley	100,000	0	0	0	0	0	0	0

Table 7. Estimates of annual discharge from ground- and surface-water evapotranspiration for each ET unit in each hydrographic area in the study area, southern Nevada and adjacent areas in Utah and Arizona, 2003-06.

[ET, evapotranspiration; ET_{gs}, ground- and surface-water evapotranspirarion. **ET unit identifier:** DMV, dense meadowland vegetation; DWV, dense woodland vegetation; MWV, moderate woodland vegetation; DSV, dense shrubland vegetation; MSV, moderate shrubland vegetation; AGU, agricultural unit; OWU, open water unit]

Hydrographic area	Annual ET_{gs} discharage, in acre-feet								Total annual ET_{gs} discharge (acre-feet)
	NPU	MSV	DSV	MWV	DWV	DMV	AGU	OWU	
Black Mountains Area	0	1,000	440	320	0	0	0	192	1,952
California Wash	0	1,200	440	640	680	0	3,120	0	6,080
Muddy River Springs Area	0	1,450	660	960	1,020	0	0	0	4,090
Lower Moapa Valley	0	1,450	1,320	2,240	2,380	0	3,640	480	11,510
Virgin River Valley	0	8,700	7,260	11,520	16,660	340	6,760	720	51,960
Lower Meadow Valley Wash	0	6,500	1,760	2,880	2,380	0	2,600	48	16,168
Clover Valley	0	2,300	960	960	1,360	340	0	0	5,840
Coyote Spring Valley	0	0	0	0	0	0	0	0	0
Kane Springs Valley	0	0	0	0	0	0	0	0	0
Tule Desert	0	0	0	0	0	0	0	0	0
Hidden Valley (North)	0	0	0	0	0	0	0	0	0
Garnet Valley	0	0	0	0	0	0	0	0	0
Total	0	22,600	12,760	19,520	24,480	680	16,120	1,440	97,600

Environmental Influences on Ground- and Surface-Water Discharge from Evapotranspiration

Hydrographic and atmospheric conditions can affect ET measurements and may influence the total annual discharge rates determined for ET_{gs}. Of particular concern in the study area were potential influences on ET_{gs} discharge from ground- or surface-water inflow to support riparian vegetation along the Virgin River, from agricultural areas that were, at one time, populated with natural vegetation, and from areas of limited fetch.

Influence of Ground- and Surface-Water Flow along the Virgin River

A simple water budget was computed along the Virgin River between the USGS streamflow-gaging stations at Littlefield, Arizona (09415000) and near Overton, Nevada (09415240) to evaluate the general influence of ground- or surface-water flow that supports riparian vegetation contributing to ET_{gs} discharge (table 8; pl. 1). The average annual streamflow was calculated for the Littlefield and Overton gaging stations between January 1, 2003, and December 28, 2004. The 2-year average annual streamflow at the Virgin River at Littlefield, Arizona and Virgin River near Overton, Nevada was 102,000 and 72,000 acre-ft, respectively. The difference (or loss) in streamflow between these two gaging stations was 30,000 acre-ft. The ground- and surface-water discharge was calculated for this specific reach of the river, between the two gages, by determining the acreage of riparian vegetation between the two gages using the ET unit data and multiplying the ET_{gs} rate for the Virgin River site. This computation resulted in an annual ground- and surface-water discharge of about 31,000 acre-ft between the two gages. The ground- and surface-water discharge is about 1,000 acre-ft more than the lost streamflow between the two gages. This result suggests that most, if not all, of the lost streamflow between these two gages can be accounted for by ET.

Table 8. Characteristics of U.S. Geological Survey streamflow-gaging stations for the Virgin River at Littlefield, Arizona, and Virgin River near Overton, Nevada, January 1, 2003, through December 28, 2004.

[**Altitude:** Datum is National Geodetic Vertical Datum of 1929. **Latitude/Longitude:** Datum is North American Datum of 1927 in degrees, minutes, and seconds]

Site No.	Site name	Altitude (feet)	Average channel discharge (acre-feet)	Latitude	Longitude
09415000	Virgin River at Littlefield, Arizona	1,764	102,000	36° 53' 30"	113° 55' 25"
09415240	Virgin River near Overton, Nevada	1,230	72,000	36° 34' 59"	114° 19' 27"

Influence of Agricultural Areas

Across the study area, about 3,000 acres of agricultural fields have replaced natural vegetation. The total annual ET_{gs} rate of 5.2 ft for AGU is significantly higher than the total annual ET_{gs} rate (1.0–3.4 ft) for natural vegetation ET units. To estimate the influence on ET_{gs} discharge from the replacement of natural vegetation by agricultural fields, discharge was recalculated for AGU areas using the rate from a natural vegetation ET unit. Across the study area, most of the agricultural unit replaced vegetation in the DWV unit. Therefore, by using the DWV unit ET_{gs} rate rather than the AGU ET_{gs} rate, the total study area discharge decreased about 6,000 acre-ft, from 98,000 to 92,000 acre-ft. This resulted in a change in total ground- and surface-water discharge by about 1 percent.

Influence of Fetch

ET rates in the study area were possibly affected by limited fetch (Stannard and others, 2004) because much of the 45,300 acres of riparian vegetation occurs in narrow corridors. Analysis of satellite imagery showed that about 33 percent of the vegetation borders the outer 200 ft of the riparian corridors. The effects of limited fetch are uncertain because remote-sensing techniques do not account for environmental influences along the boundary of narrow riparian corridors such as depth to water and weather conditions. For example, ET could decrease because vegetation near the edge of the riparian areas might become stressed due to a combination of lack of water and hot, dry air from the surrounding desert. On the other hand, if ample water were available, the advection of hot dry air could increase ET (this is referred to as an oasis effect).

Sensitivity of ET discharge due to limited fetch was evaluated by reducing the acreage around the outer edge of the riparian areas by removing 1 and then 2 pixels or 0.02 square acres and 0.05 square acres, respectively. The process reduces the total area around the riparian areas by about 18 percent for 1 pixel and 33 percent for 2 pixels. A 33 percent decrease in acreage for the riparian areas decreases the estimated total ET discharge for the study area by about 8 percent—from about 98,000 to 91,000 acre-ft. While fetch effects may have significant impacts at isolated locations, the overall change in ET discharge for the study was not significantly influenced by limited fetch.

Limitations to Estimates of Ground- and Surface-Water Discharge from Evapotranspiration

The estimated discharge by ET_{gs} is limited by the (1) assumptions inherent in the energy budget, (2) small number of sites used to estimate ET and precipitation, (3) short time duration that field sites were in operation, (4) application of published annual ET discharge rates measured prior to this study, (5) instrumentation bias, (6) missing data for at the Virgin River and LMVW sites due to flooding, and (7) accuracy of the delineated ET units.

Summary

The U.S. Geological Survey, in cooperation with the National Park Service, Bureau of Land Management, and U.S. Fish and Wildlife Service conducted a study to quantify the amount of ground- and surface-water discharged by evapotranspiration processes in 12 hydrographic areas in the southern part of the Colorado Regional Ground-Water Flow System.

In various locations in the study area, ground water that is discharged from springs combines with surface water from outside the study area making it difficult to determine the original source of the water. Water from these various sources is transpired by crops, phreatophyte and riparian vegetation, and evaporated from open-water surfaces. This study quantified annual ET discharge from diffuse ground-water and channelized surface-water (expressed as ET_{gs}) by (1) delineating and classifying the study area into eight ET units primarily based on information from multi-spectral satellite imagery and Southwest Regional Gap Analysis Program data, (2) estimating ET rates at four micrometeorological stations located in representative ET units or using published ET rates for similar environments, and (3) estimating the volume of annual ground- and surface-water discharged from ET by summing the products of ET unit acreage and ET rate for each ET unit.

The eight ET units identified in the study area include: dense meadowland vegetation, dense woodland vegetation, moderate woodland vegetation, dense shrubland vegetation, moderate shrubland vegetation, agricultural fields, non-phreatophytic, and open water. Field sites were installed in four ET-unit areas: dense woodland vegetation, moderate woodland vegetation, dense shrubland vegetation, and moderate shrubland vegetation. Two of the sites collected data for use with the Bowen-ratio method of calculating ET and two of the sites collected data for use in the eddy-covariance method of calculating ET.

Sites that collected data for the Bowen-ratio method were installed in a dense grove of saltcedar trees along the Virgin River floodplain and in an area of dense mesquite trees along the Muddy River. Sites that collected data for the eddy-covariance method were installed in Lower Meadow Valley Wash—one in Rainbow Canyon just south of Caliente, Nevada, and one just north of Moapa, Nevada. Local precipitation from each site was subtracted from the total annual ET rate to obtain the ET_{gs} rate for that ET unit. The annual ET_{gs} rate was multiplied by the acreage of the ET units across the study area to estimate the total annual discharge from ET_{gs}.

The energy flux used to estimate ET was calculated using two energy-budget approaches—the Bowen-ratio and the eddy-covariance methods. In addition, a variant of the Bowen-ratio method was applied at two sites using data collected for the eddy-covariance method. Data for these methods were collected at four micrometeorological sites placed in selected vegetated environments (ET units) for varying periods. The annual ET_{gs} rates for individual ET units ranged from 1.0 to 5.2 feet and the annual ET_{gs} discharge for the 12 hydrographic areas in the study area ranged from 0 to about 52,000 acre-feet. The annual discharge from ET_{gs} across the study area was about 98,000 acre-feet.

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A Regional Interbasin Groundwater System in the White River Area, Southeastern Nevada[1]

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Abstract. A regional interbasin groundwater system including thirteen valleys in southeastern Nevada is generally identified on the basis of preliminary appraisals of the distribution and quantities of the estimated groundwater recharge and discharge within the region, the uniformity of discharge of the principal springs, the compatibility of the potential hydraulic gradient with regional groundwater movement, the relative hydrologic properties of the major rock groups in the region, and, to a limited extent, the chemical character of water issuing from the principal springs. The principal findings are: (1) Paleozoic carbonate rocks are the principal means of transmitting groundwater in the interbasin regional system—the regional transmissibility provisionally is estimated to be about 200,000 gal/day/ft; (2) estimates of recharge and discharge show wide discrepancies in individual valleys, but hydrologic balance with recharge and discharge estimates of about 100,000 acre-ft/yr obtains within the thirteen-valley region; and (3) the discharge of the Muddy River Springs, the lowest of the three principal spring groups, is shown to be highly uniform, which is consistent with their being supplied from a large regional groundwater system. The relation between this regional system and others in eastern and southern Nevada is now under study by the Geological Survey. (Key words: Hydrologic systems; hydrology (limestone); springs; groundwater)

INTRODUCTION

Reconnaissance appraisals of the groundwater resources of various valleys in Nevada have been made for several years. One of the assumptions on which these studies originally were predicated was the generally accepted concept that most hydrologic systems were more or less co-extensive with the topographically closed basins in the Basin and Range province. As studies for various areas were completed, it became evident that groundwater systems in certain valleys of eastern and southern Nevada extended beyond the limits of the particular valley. Some valleys have a much larger spring discharge than could be sustained by local recharge, and other valleys have deep water levels that preclude an annual groundwater discharge by evapotranspiration comparable with probable local recharge. If these observations are correct, a multivalley regional groundwater system is required to satisfy the general hydrologic equation that inflow equals outflow.

This report describes the general features of a regional groundwater system in a part of the Basin and Range province in southeastern Nevada. Although the scope of the report is limited by the reconnaissance nature of the investigations on which it is based, virtually all components of the hydrologic system are evaluated.

Location and extent of the region. The region discussed includes the area within the drainage divides of six valleys drained by the White River in Pleistocene time and seven adjacent but topographically separated valleys. It is in southeastern Nevada and lies within lat 36°40′ and 41°10′N and long. 114°30′ and 115°45′W. It includes parts of Clark, Elko, Lincoln, Nye, and White Pine counties (Figure 1). From its north end in southern Elko County, the region extends southward to include the upper Moapa Valley, a distance of about 240 miles. Its maximum width is about 70 miles near lat 38°N. The region includes an area of about 7700 square miles.

Topographic setting. Figure 2 shows the locations of the principal valleys and ranges in the region. Of the thirteen valleys, Long, Jakes, Cave, Dry Lake, and Delamar valleys are topographically closed. Garden Valley surfici-

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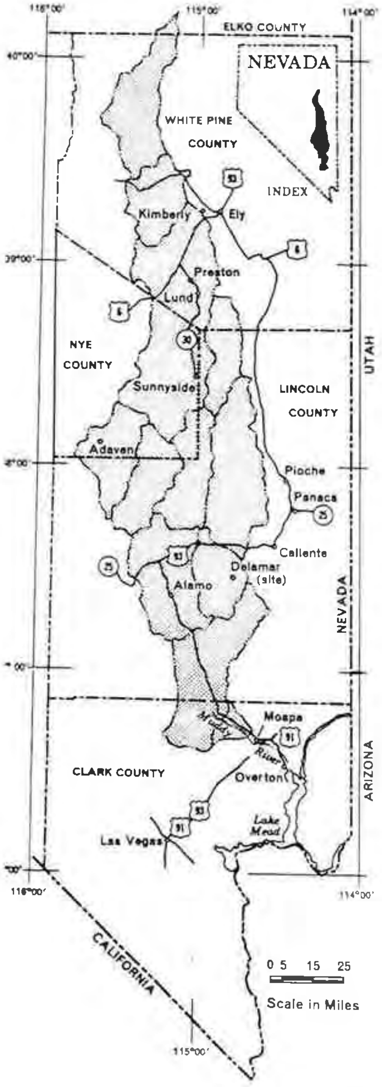
[1] Publication authorized by the Director, U. S. Geological Survey.



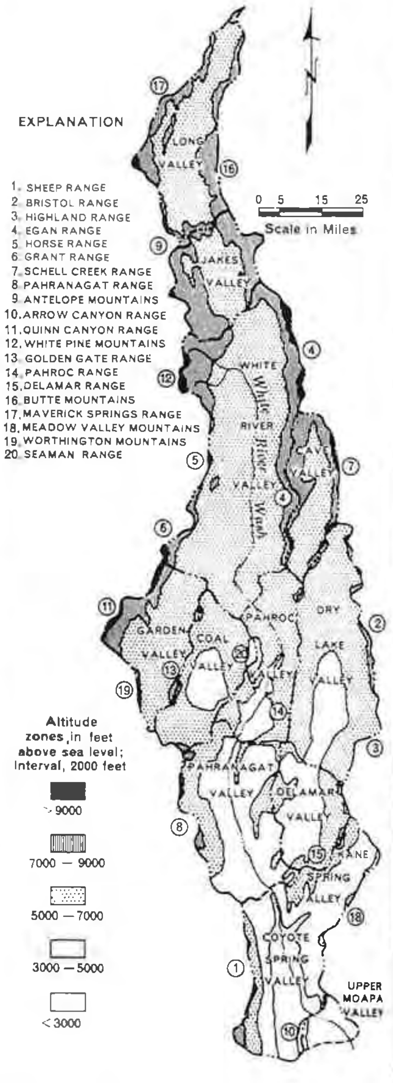


Fig. 1. Location of regional interbasin groundwater system described in this report.

Fig. 2. General topography of the area of this report.

ally may drain into Coal Valley but together they form a topographically closed unit. The remaining six valleys were drained by the Pleistocene White River, then a tributary to the Colorado River system. The six valleys are White River, Pahroc, Pahranagat, Kane Spring, Coyote Spring, and upper Moapa.

This region of mountains and valleys generally has a southward gradient (Figure 2). Along the White River Wash the altitude decreases from about 5500 feet in the latitude of Lund to about 1800 feet in the vicinity of the Muddy River Springs in a channel distance of about 175 miles. The average gradient along the Wash is about 21 feet per mile. The White River Wash forms an axial topographic low between Garden and Coal valleys on the west and Cave, Dry Lake, and Delamar valleys on the east.

The mountains generally are 2000 to 4000 feet higher than the floors of the adjacent valley (Figure 2). The crests of the ranges commonly exceed 8000 feet above sea level and locally exceed 10,000 feet in the north part of the area. In the south part of the area the crests of the ranges exceed 8000 feet above sea level only locally and commonly are less than 7000 feet in altitude.

THE REGIONAL GROUNDWATER SYSTEM

The regional groundwater system includes both the rocks and the groundwater of the defined area. It includes the areas of recharge and discharge, storage and transmission of water, and geologic units that control the occurrence and movement of water. Semiperched groundwater in the mountains and in the valley fill of at least some valleys contributes to the regional system but is not emphasized herein.

The identification of this regional groundwater system is based upon (1) the relative hydrologic properties of the major rock groups in the area of consideration; (2) the regional movement of groundwater as inferred from potential hydraulic gradients; (3) the relative distribution and quantities of the estimated recharge and discharge; (4) the relative uniformity and long-term fluctuation of the discharge of the principal springs; and (5) the chemical quality of the water discharged from the principal springs. Much of the available data pertinent to the analysis is included in Tables 1, 4, 5, and 6 and on Figures 4 and 6. These elements are discussed in the following sections.

Geologic setting. The rocks provide the framework in which groundwater occurs and moves. Groundwater may occur in interstitial openings, in fractures, or in solution openings in the rocks. The openings may have been formed at the time the rocks were deposited or at a subsequent time by fracturing, weathering, or solution. The distribution and nature of these openings may relate generally to other physical and chemical characteristics of formations or groups of rocks. Thus, the general nature and distribution of the rocks in the region permit some inferences regarding the occurrence and movement of groundwater.

A number of geologic studies in parts of the area of this report have been made. For present purposes, the reconnaissance geologic map of Lincoln County [*Tschanz and Pampeyan*, 1961], the reconnaissance geologic map of Clark County [*Bowyer et al.* 1958], the general geologic map accompanying the guidebook to the geology of east-central Nevada [*Boettcher and Sloan*, 1960] for White Pine and parts of northeastern Nye counties, and unpublished information from F. J. Kleinhampl for segments of the region in northeastern Nye County have been most useful with reference to the areal geology of the region. For the White Pine County part of the region many of the papers in the guidebook to the geology of east-central Nevada [*Boettcher and Sloan*, 1960] are of much value.

Although not known to crop out within the area of this report, Precambrian rocks are exposed in the northern Egan Range east of Long Valley, in the Schell Creek Range [*Young*, 1960], along the east side of Cave Valley and northward, and in the Mormon Mountains [*Tschanz and Pampeyan*, 1961] east of Coyote Spring Valley and may be inferred to underlie all the region of this report.

A thick section of Paleozoic rocks was deposited throughout and beyond the area. Locally, the stratigraphic thickness of the Paleozoic rocks exceeds 30,000 feet [*Kellog*, 1963, p. 685]. Clastic rocks occur principally in the upper and lower parts of the section. Carbonate rocks, which comprise more than half of the section, are generally found in the central part of the Paleozoic section.

Lower Triassic marine deposits are noted by

EXPLANATION

Valley fill

Principally clay, silt, sand, and gravel; locally may include fresh-water limestone or evaporite; consolidated to unconsolidated. Deposited under subaerial, stream or lacustrine environments. Lower Tertiary deposits involved in deformation; upper Tertiary and Quaternary deposits moderately deformed, locally. Sand and gravel deposited in stream channels and alluvial fans transmit water freely; fine-grained deposits, where saturated, transmit water slowly but contain a large volume of water in storage

TERTIARY AND QUATERNARY

Volcanic rocks

Principally volcanic tuff and welded tuff or ignimbrite, but include other volcanic rock types and locally sedimentary deposits. Generally transmits water slowly, but locally highly fractured welded tuff may yield water readily. In mountains differential transmissibility, bedding planes, or fracture systems result in semiperched ground water which supplies many small springs. Where saturated transmits water slowly but contain a large volume of water in storage

TERTIARY

▥ Paleozoic rocks undivided

Principally limestone and dolomite. Secondary fracture or solution openings result in transmission of substantial quantities of water, at least locally. In gross where saturated, store a large volume of water. Principal regional aquifer.

Include some shale, sandstone, and quartzite which generally act as a barrier to ground-water movement. Locally, however, fractured or weathered zones transmit some water

PALEOZOIC

Fig 3 Generalized geology of the region. Adapted from *Bowyer et al.* [1959] for Clark County; *Tschanz and Pampeyan* [1961] for Lincoln County; F. Kleinhampl (private communication, 1963) for parts of Nye County, and *Boettcher and Sloan* [1960] for remaining area

EXPLANATION

Area of evapotranspiration of ground water

4600

Playa and approximate altitude, in feet, above sea level

Lund Spring (5595)

Data point, name, and approximate altitude of water level above sea level

30

Data point and serial number. Points described below include name or well number followed by depth to water and by altitude of water level. For oil tests, only total depth (T.D.) of well given

1.—Well 21N/59-18d2; 88; 6000
2.—Well 21N/58-33b1; 68; 6000
3.—Well 20N/58-14a1; 117; 6000
4.—Oil test, Summit Springs Unit no. 1; T.D. 11453
5.—Illipah Creek
6.—Oil test, Hayden Creek Unit no. 1; T.D. 5117
7.—Well 14N/61-10c1; 280; 5760
8.—Ellison Creek
9.—White River
10.—Oil test, County Line Unit no. 1; T.D. 4850
11.—Emigrant Springs; 5415
12.—Morman Spring; 5300
13.—Butterfield and Flag Springs; 5275
14.—Well 5N/60-25a1; 25; 5100
15.—Well 8N/64-30c1; 331; 5800
16.—Well 5N/64-14a1; 214 (dry); < 5385
17.—Well 3N/64-20b1; 317; 4820
18.—Well 2N/64-3b1; 664; 4350
19.—Well 1N/64-24a1; 398; 4300
20.—Well 4N/61-36c1; 90; 4970
21.—Well 3N/62-8c1; 217; 4835
22.—Well 3N/62-35b1; 252; 4770
23.—Well 2N/63-31b1; 800 (dry); < 4125
24.—Well 2S/61-23d1; 302 (dry); <3900
25.—Well 2N/59-22b1; 250 (dry); < 4775
26.—Well 4N/59-6d1; 9; 5340
27.—Well 3N/58-15b1; 235; 5040
28.—Well 3N/57-16c1; 33; 6150
29.—Well 1S/57-3a1; 570; 5020
30.—Well 6S/63-12a1; 900 (dry); <3700
31.—Well 4S/61-15b1; 670; 3700
32.—Well 5S/60-6c1; 380; 4025
33.—Well 3S/60-24d1; 187; 3815
34.—Well 4S/60-2a1; 105; 3870
35.—Hiko Spring, altitude 3890
36.—Crystal Springs, altitude 3805
37.—Ash Springs, altitude 3610
38.—Upper Pahranagat Lake
39.—Maynard Lake
40.—Well 10S/62-14a1; 416; 2175
41.—Coyote Spring, altitude 2575
42.—Well 13S/63-25a1; 330; 1875

Fig. 4. Location points of selected data in the area of this report.

Stokes [1960, Figure 2] near Currie, Nevada, and near Wah Wah, Utah, about 70 miles north and 90 miles southeast of Ely, respectively. *Nolan et al.* [1956, pp. 68–70] described the nonmarine Newark Canyon Formation of Early Cretaceous age, which occurs in the vicinity of Eureka, Nevada, 70 miles west of Ely. To the southeast in northwest Arizona and adjacent areas, substantial sections of Mesozoic rocks occur. *Stokes* [1960, p. 121] indicates that southeastern Nevada was generally above sea level for most of Mesozoic time. At least in late Mesozoic time, parts of the area were being eroded and had exterior drainage.

Nonmarine sedimentary rocks of Eocene age in and adjacent to the White River Valley have been described by *Winfrey* [1960], who named them the Sheep Pass Formation. Their aggregate thickness is 3220 feet. As tentatively outlined [*Winfrey*, 1960, Figure 3], the basin in which they were deposited extended from about T5N to T11N in the southern White River Valley and from Cave Valley on the east to beyond the White Pine Mountains on the west. Contemporaneous deposits have not been described elsewhere in the region, although the Horse Spring Formation of Eocene (?) age in the Muddy Mountains, south of Coyote Spring Valley, may be equivalent in age [*Winfrey*, 1960, p. 133].

During middle Tertiary time an extensive and thick section of volcanic rocks was laid down in eastern Nevada. *Cook* [1960, Figure 1] indicates that an extensive ignimbrite province included much of the area of this report. To some extent nonmarine sediments, such as the lacustrine limestone and cobble conglomerate in the Pahroc Range reported by *Tschanz* [1960, p. 204], are interbedded locally with the volcanic rocks. The thickness of the volcanic rocks varies substantially from place to place, but *Dolgoff* [1963, p. 878] estimates a thickness of over 3000 feet for the volcanic sequence in the Pahranagat area.

Continental deposits overlie the Tertiary volcanic rocks in the present valleys. Commonly these are fine grained lacustrine or playa deposits that grade laterally to coarser fractions toward the source areas in the mountains. The Muddy Creek Formation of Pliocene (?) age [*Longwell*, 1928, pp. 90–96] is partly exhumed in Moapa Valley. *Longwell* [1928, p. 94] suggested that a thickness of 1700 feet for the Muddy Creek Formation was not excessive in the central part of the basin. Somewhat similar fine grained deposits are exposed along parts of the White River Channel. Their maximum thickness is not known. In White River Valley the County Line oil test (point 10, Figure 4) penetrated 1475 feet of 'valley fill' as reported by *McJannett and Clark* [1960*a*, p. 245], who infer that part of this valley fill is of Pliocene (?) age. Obviously, as the deposits were laid down in basins or valleys, the thickness should be variable, ranging from a feather edge at the margins to a substantial thickness in the central parts of the valleys.

Quaternary deposits include gravel, sand, silt, and clay laid down in stream-channel, alluvial-fan, and playa environments. White River, when it was a through-flowing stream in late Pleistocene time, probably removed more material than it deposited in the lower parts of the valleys in which it flowed. The depth and extent of dissection are greatest in the southern or downstream valleys.

Most of the mining districts have areas of exposed intrusive rocks, and *Bauer et al.* [1960, p. 223] discuss some of the intrusive rocks in the Robinson Mining District west of Ely. *Adair and Stringham* [1960, Figure 1] show the location of five intrusive igneous bodies or dike groups adjacent to the White River Valley. Two areas are in the White Pine Mountains, and three areas are in the Egan Range.

The rocks have been faulted, fractured, and displaced in a complex way and in varying degrees within the region during several periods of structural activity.

Occurrence of groundwater. For the purposes of this report the several stratigraphic units discussed briefly in the previous section can be grouped broadly on the basis of apparent gross hydraulic properties.

Three groups are shown on Figure 3. The relative hydraulic properties are noted in the explanation. Not shown are Precambrian and intrusive rocks that have negligible fracture permeability. These rocks probably provide a lower limit to groundwater circulation, not otherwise limited, at depth. Where these rocks are exposed and are continuous with depth, they also should form a barrier to the lateral movement of groundwater.

Fracture and solution openings in the Paleozoic carbonate rocks locally store and transmit substantial quantities of groundwater. The great thickness of Paleozoic carbonate rocks in this region tends to favor a regional hydraulic continuity, even though the Paleozoic rocks have been subjected to several periods of substantial faulting.

The occurrence of groundwater in carbonate rocks is demonstrated by the widespread distribution of many large springs associated with Paleozoic carbonate rocks throughout eastern Nevada. For example, most of the flow of Crystal Springs in Pahranagat Valley (Figure 4) issues in the bottom of pools and adjacent seeps from valley fill. However, part of the flow of Crystal Springs issues directly from carbonate rocks, which are exposed and also underlie the adjacent valley fill. The other principal springs, such as Ash and Hiko springs in Pahranagat Valley, the large springs in upper Moapa Valley, and Hot Creek, Mormon, and Lund springs in White River Valley, issue from points at or near contacts with carbonate rocks and valley fill.

Groundwater occurs in carbonate rocks at depth, as in the Deep Ruth, Kelinske, and Starpointer shafts in the Robinson Mining District (L. Green and M. Dale, oral communication, 1964). These shafts are about 1 mile east of Liberty pit, shown on Figure 4. Groundwater also occurs in carbonate rocks in the Bristol Mine in the Bristol Range (Paul Gemmill, private communication, 1964). Fresh water was reported [*McJannett and Clark*, 1960*b*, p. 249] in 'cavernous zones' of the Joana Limestone (Lower Mississippian) at depths of 4058 to 4097 feet below land surface in the Hayden Creek oil test (data point 6, Figure 4). This interval is roughly 3000 feet lower than the floor of Jakes Valley, which is about 5 miles northeast of the test well.

The clastic rocks included in the Paleozoic group in Figure 3 tend to act as barriers to groundwater movement compared with carbonate rocks. However, fractured clastic rocks do store and transmit some groundwater at least locally, as in the Pioche district.

The older Tertiary sedimentary rocks, such as the Sheep Pass Formation of *Winfrey* [1960], are generally consolidated and are believed to have little primary permeability. Locally they are faulted, which may provide secondary fractures through which some water may be transmitted to springs, such as in T11N, R62E in the Egan Range where that formation is exposed. Where such rocks underlie the valley floor and are saturated, they may contain a considerable volume of groundwater in storage, even though the average permeability is small.

The Tertiary volcanic rocks generally have low permeability. These rocks ordinarily are rather fine grained, and the extent to which they may transmit groundwater is possibly controlled by the degree to which closely spaced fractures occur in them. Where these rocks are welded or more or less glassy, fractures may be somewhat open and locally transmit groundwater freely. A well north of Lathrop Wells in southern Nevada is known to be capable of producing several hundred gallons of water per minute from the welded tuff (Winograd, private communication, 1963). Commonly, however, semi-perched groundwater in fracture systems in the Tertiary volcanic rocks supplies the water for numerous small springs in the mountains, such as those in the southern Butte Mountains, in the Quinn Canyon Range along the west side of Garden Valley, and in the Delamar Range along the northwest side of Kane Spring Valley. Where these rocks are beneath the valleys and are saturated, substantial quantities of groundwater may be stored in them. The extent to which they may transmit groundwater is rather a function of the cross-sectional area through which the water may move and the hydraulic gradient than of the unit permeability, which generally is very low.

The partly consolidated or cemented fine-grained valley fill of Pliocene(?) and Pleistocene age generally yields water slowly. However, Coyote Spring in Coyote Spring Valley yields a modest supply of water, at one time nearly half a cubic foot per second, from a combined development of a tunnel and several wells in fine-grained valley-fill deposits. Brownie Spring in Pahranagat Valley yields about 1 cubic foot per second from a tunnel in consolidated conglomerate. Where saturated, the fine-grain valley fill is capable of storing large quantities of water. The unconsolidated sand and gravel deposits of the younger valley fill and in alluvial fans are capable of transmitting water freely. The sand and gravel deposits of the younger valley fill commonly have the highest unit permeability of any unconsolidated deposits in the region. The large-capacity irrigation wells in the White River, Pahranagat, and upper Moapa valleys are developed in these deposits.

Groundwater movement. The hydraulic gradients between springs and selected wells, and, more generally, the regional topographic

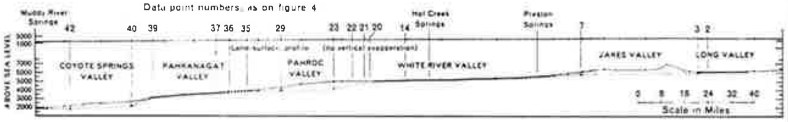


Fig. 5. Diagrammatic profile showing relation of water level to land surface along longitudinal axis of the area.

gradient, indicate the general direction of potential lateral groundwater movement in the regional system. Actual movement is dependent upon the hydraulic conductivity of the rocks.

The principal springs, which are the major points of discharge from the regional system, are on or adjacent to the White River Wash, and the altitudes of their orifices decrease southward. Thus, in White River Valley, Preston Big Spring issues at an altitude of 5680 feet above sea level and Hot Creek Springs, about 40 miles south, issues at an altitude of 5175 feet above sea level (Figure 4). In Pahranagat Valley from north to south, Hiko, Crystal, and Ash Springs issue at altitudes of about 3890, 3805, and 3610 feet, respectively. In upper Moapa Valley, the closely grouped Muddy River Springs issue between altitudes of 1800 and 1780 ft.

Compared with the low parts of adjacent topographically closed valleys of the regional groundwater system, the White River Wash is generally considerably lower at equivalent latitudes (Figure 4). The playa of Cave Valley is about 5975 feet above sea level. Due west in White River Valley the Wash altitude is less than 6200 feet. In Coal Valley the playa is at an altitude of about 4950 feet, whereas due east the White River Wash altitude is about 4800 feet. In Dry Lake Valley the playa altitude is slightly less than 4600 feet. At the latitude of the central part of that playa, the White River Wash is about 440 feet. The Delamar Valley playa is about 4400 feet above sea level, and upper Pahranagat Lake due west is about 1000 feet lower.

In all the above valleys plus Garden Valley, which surficially drains to Coal Valley, water levels are several hundred feet or more below the respective playas. Representative known, reported, or inferred low water-level altitudes for Cave, Dry Lake, Delamar, Garden, and Coal valleys, respectively, are 5800, 4300, 3700 ?), 5020, and less than 1775 feet (points 15, 19, 30, 29, and 25 on Figure 4). The altitudes of these water levels are higher than known or inferred altitudes of water levels along White River Wash at or south of the equivalent latitudes. Most of these water levels are considered to represent semiperched groundwater in valley fill. As such, it is inferred that water levels in the carbonate rocks underlying the several wells would be at somewhat lower altitudes. Even so, the potential gradient and movement from the adjacent valleys apparently is toward the trough occupied by the White River Wash.

For Jakes and Long valleys, lying north of White River Valley, the valley floors are at altitudes of 6295 and 6050 feet, respectively, and are higher than White River Valley. The lowest known water-level altitude beneath the playa of Long Valley is about 6000 feet, and in Jakes Valley the water level is unknown but is estimated to be as much as 400 feet below the playa surface. A potential though low southward gradient through the carbonate rocks toward White River Valley apparently exists, as the altitude of the water level in a well (point 7, Figure 5) in northern White River Valley is about 5780 feet and at Preston Springs, about 12 miles farther south, is about 5680 feet.

Outcrops of Paleozoic carbonate rocks at or adjacent to most of the springs are at altitudes lower than other Paleozoic carbonate rocks at or north of the latitude of the respective outcrops within this region. For example, in White River Valley the carbonate-rock outcrops adjacent to Lund Spring (Figures 3 and 4) are at a lower altitude than other carbonate-rock outcrops at or north of that latitude in White River, Jakes, or Long valleys. The carbonate-rock outcrops from which Hot Creek Springs issue are also at lower altitudes than any others at or north of that latitude in White River, Jakes, Long, and Cave valleys.

Similarly, the Paleozoic carbonate rocks from which Crystal Springs issues in Pahranagat

Valley are at a lower altitude than other outcrops of carbonate rocks north of that latitude. This same relation applies to the Paleozoic carbonate rocks exposed adjacent to the Muddy River Springs. This repetitive association of large springs with areas of topographically low outcrops of Paleozoic carbonate rocks demonstrates their close association and supports the inference of the regional movement of groundwater.

The regional potential groundwater surface is not everywhere defined by a smooth surface. On the contrary, limited data suggest that the water surfaces have local hydraulic discontinuities resulting from barrier effects or from other causes.

The profile in Figure 5 shows the land-surface and water-level altitudes along the approximate longitudinal axis of the region. It follows the general alignment of the White River wash southward from the latitude of Preston Springs. The upper line of the profile shows land surface with the vertical and horizontal scales the same, to illustrate the small proportion of relief in the region as a whole. The lower profile shows the land surface and water levels at a vertical exaggeration 10 times the horizontal scale for the purpose of more readily showing the local divergence of water level from land surface. As can be seen from the lower profile, the water-level gradient is near and parallel to the land-surface gradient in the White River, Pahranagat, and upper Moapa valleys, the areas of principal spring discharge. Elsewhere, the gradient locally may be steeper than the land surface, as is indicated in the north end of Pahroc and Coyote Springs valleys, and in other sections the gradient is less than that of the land surface, as in the central and southern parts of Pahroc and Coyote Spring valleys.

At the north end of Pahroc Valley and the south end of White River Valley the depth to water in the valley fill along White River Wash in 4 wells (points 20, 21, 22, and 23, Figure 4) increases progressively from about 90, to 217, to 252, and to more than 800 feet below land surface. The land-surface gradient in this segment of the wash is about 14 feet per mile, and the distances between the wells are 3, 4.5, and 6 miles, respectively. Thus, the indicated water-level gradient between the upstream pair of wells (points 20 and 21) is about 56 feet per mile, between the middle pair of wells (points 21 and 22) is nearly 22 feet per mile, and between the downstream pair of wells (points 22 and 23) is over 100 feet per mile. Several miles northwest of the upstream well (point 20) the water-level gradient is parallel to and within about 10 feet of land surface. The steepening of the water-level gradient in the valley fill in this section of the White River Wash is inferred to reflect a relatively abrupt change of head in the groundwater in the underlying carbonate rocks. This change or difference in head may be associated with faulting in the carbonate rocks, which results in a barrier effect to the movment of groundwater across the fault, or with an increase in the relative capacity to transmit water in the Paleozoic carbonate rocks downstream from this section.

A somewhat similar discordance in altitude of water levels occurs in the valley fill southward from Maynard Lake (point 39, Figure 4). The reported depth to water in the well (point 40) in northern Coyote Spring Valley was 416 feet, or at an altitude of 2175 feet. The well is about 8 miles south of Maynard Lake. The indicated water-level gradient between Maynard Lake and the well is about 117 feet per mile. This gradient too is considered to reflect a relatively steep apparent water-level gradient of the groundwater in the underlying Paleozoic carbonate rocks in the vicinity of Maynard Lake gap. The most likely cause here is a barrier effect resulting from faulting in the vicinity of the Maynard Lake gap. *Tschanz and Pampeyan* [1961] show a prominent fault complex crossing White River Wash just south of Maynard Lake, which could provide the necessary local barrier effect to southward groundwater movement.

In central Pahroc Valley, the well (point 23) was dry at a depth of 800 feet, or at about an altitude of 4125 feet, as noted above; the altitude of Hiko Spring, 31 miles southwest along the Wash, is about 3890 feet. The indicated gradient is less than 8 feet per mile. However, the water-level altitude in the carbonate rocks is probably somewhat lower than in the overlying valley fill in the vicinity of the well. Thus, the inferred water-level gradient in the carbonate rocks between these two points may be even less than the above indicated gradient of 8 feet per mile.

In Coyote Spring Valley, the indicated hy-lraulic gradient between the two wells (points l0 and 42) is about 13.5 feet per mile. This ower gradient is in contrast with the steep radient near the north end of the valley, as vas also the case in Pahroc Valley. Between he southern well (point 42) and Muddy River prings the difference in altitude of water level s about 75 feet in a distance of about 10 miles. The apparent gradient is about 7.5 feet per nile. Again the inference is that the water-level radient in the underlying carbonate rocks is robably somewhat less than that in the valley ll for most of the length of the valley. The bove information suggests that a general radient in the carbonate rocks in this region nay be less than 8 feet per mile. Thus, the rela-ive altitudes of the principal springs, wells in ey locations, and regional topography support he inference of regional groundwater gradient o the south.

Recharge of groundwater. Table 1 sum-narizes the estimates of recharge to and of dis-harge from the groundwater system. These stimates were derived mainly in the reports eferred to in the table.

Precipitation provides the principal source of ater for recharge to the regional groundwater ystem. The direct measurement of recharge is ot feasible, nor perhaps even possible, over an rea of any great size. However, the general rela-onships that potential recharge increases with ncreased precipitation and that precipitation enerally increases with altitude have been used make estimates of long-term average annual echarge. The average annual recharge to roundwater from precipitation in a valley has een estimated empirically for the reconnais-ance investigations by a technique that seem-ngly produces reasonable estimates for most reas of Nevada. Briefly, precipitation zones dicated by *Hardman and Mason* [1949, p. 10] re taken to be approximately represented by titude zones on the 1:250,000-scale topo-aphic maps. The successively higher zones have igher average annual precipitation and ac-ordingly are considered to have a higher per-ntage of the precipitation recharging the oundwater reservoir. The values generally as-med are shown in Table 2.

Obviously, recharge is not uniformly dis-ibuted either over the area or in time. However, average precipitation is greatest in the mountainous areas at altitudes of 7000 feet and higher. Much of the precipitation in the mountains occurs as snow, which accumulates during the winter and melts in the spring. This process is favorable for accomplishing recharge. In general, then, most of the recharge from precipitation is probably centered in and adjacent to the several principal mountain ranges.

The general relations of increased precipitation with altitude and the seasonal distribution of precipitation are shown by the average monthly and annual precipitation for Kimberly, Adaven, Alamo, and Overton (Table 3). Station locations are shown on Figure 1.

Winter precipitation usually results from general storms that originate in the north Pacific. Summer precipitation occurs as high-intensity showers resulting mainly from southeast storms and local convectional storms. This relationship results in a pattern in which most of the precipitation occurs during the winter half of the year but with a secondary summer maximum in July and August. The summer maximum tends to be more pronounced in the southern part of the region.

The distribution of water runoff from the mountains also permits some inferences of the distribution and manner of recharge to the groundwater system. For mountain areas of otherwise similar characteristics, proportionally large runoff suggests little recharge by deep infiltration in bedrock in the mountains, and small runoff suggests proportionally large recharge by deep infiltration in the bedrock. Also, substantial runoff from the mountains suggests that recharge by infiltration from streamflow on the valley fill may be significant.

Records are not available to demonstrate the magnitude and distribution of streamflow throughout this region, but a general description of the streamflow conditions provides illustrative support.

The present-day White River is a headwater remnant of the ancestral White River (Figures 1 and 4). The White River formerly was a throughflowing stream that surficially drained the White River, Pahroc, Pahranagat, Coyote Spring, Kane Spring, and upper Moapa valleys to the Colorado River. It was a prominent stream as late as late Pleistocene time. Probably, too, in extremely rare and most favorable con-

TABLE 1. Summary of Hydrologic Information Relative to the Regional Groundwater System

Valley or Area (1)	Area, mi² (2)	Estimated Average Annual Recharge from Precipitation, acre-ft (3)	Estimated Average Annual Discharge of Groundwater by Evapotranspiration, acre-ft (4)	Estimated Discharge from Principal Springs, acre-ft (5)	Probable Principal Means of Discharge U–Underflow Sp–Springs ET–Evapotranspiration (6)	Lowest Water Level: Location and Reported Depth below Land Surface, ft (7)	Lowest Water Level: Approximate Altitude Above Sea Level (8)	Lowest Water Level: Water in A–alluvium T–Tertiary Volcanics (9)	References (10)
Cave Valley	365	14,000	Few 100		U	8N/64-30c1 330	5,800	A(?)	*Eakin* [1962, pp. 2, 12, 13, 14]
Coal Valley	455	2,000	Minor		U	2N/59-22b1 250 (dry)	<4,750	A(?)	*Eakin* [1963*b*, pp. 14, 18, 19]
Coyote Spring and Kane Spring valleys	950	2,600	Few 100		U	13S/63-25a1 332	1,875	A(?)	*Eakin* [1964, pp. 20, 22, 25]
Delamar Valley	385	1,000	Minor		U	6S/63-12a1 900	3,700	A–T(?)	*Eakin* [1963*a*, pp. 13, 17, 18]
Dry Lake Valley	900	5,000	Minor		U	2N/64-3b1 664	4,350	A–T(?)	*Eakin* [1963*a*, pp. 13, 17, 18]
Garden Valley	490	10,000	2,000		U	1S/57-2a1 570	5,020	A–T(?)	*Eakin* [1963*b*, pp. 14, 18, 19]
Jakes Valley	430	17,000	Minor		U	...	?	...	Columns 2 and 3 computed in same manner as for other valleys. Value in column 3 is based on topographic maps now available and differs somewhat from value given by *Maxey and Eakin* [1949, p. 41]
Long Valley	650	10,000	2,200	51 cfs	U	21N/58-35b1	6,000	A	*Eakin* [1961, pp. 22, 23, 31, Fig. 2]
Upper Moapa Valley (Muddy River Springs)	75	Minor	2,300	*36,000 35 cfs	Sp, ET	River	1,660	A	*Eakin* [1964, pp. 4, 6, 22, 24]
Pahranagat Valley	790	1,800	25,000	†25,000	ET, Sp	Maynard Lake <5	3,115	A	*Eakin* [1963*c*, pp. 18, 20]
Pahroc Valley	510	2,200	Minor		U	2S/61-23d1 350	3,950	A–T(?)	*Eakin* [1963*c*, pp. 13, 19, 21, Fig. 3]
White River Valley	1,620	38,000	34,000	†37,000	ET, U	5N/60-25a1 25	5,100	A	*Maxey and Eakin* [1949, pp. 12, 41, 44]. Estimates in columns 3 and 5 differ slightly from Maxey and Eakin figures, owing to minor differences in computations.
Totals (rounded)	7,670	101,000	‡65,000	98,000					

* Average of about 33,700 acre-ft occurs as flow in Muddy River; remainder of about 2,300 acre-ft is consumed locally by evapotranspiration.

† Nearly all subsequently consumed by evapotranspiration within valley.

‡ Includes about 5,000 acre-ft of evapotranspiration of groundwater largely unrelated to major spring discharge.

TABLE 2. Assumed Values for Precipitation and Per Cent Recharge for Several Altitude Zones in Area of This Report

Precipitation Zone, in.	Altitude Zone, ft	Assumed Average Annual Precipitation, ft	Assumed Average Annual Recharge to Groundwater, % of average precipitation
Less than 8	below 6000	variable	negligible
8 to 12	6000 to 7000	0.83	3
12 to 15	7000 to 8000	1.12	7
15 to 20	8000 to 9000	1.46	15
More than 20	more than 9000	1.75	25

litions, through streamflow may have occurred since Pleistocene time. The position of the ancestral White River is marked by a wash or trench along the topographical axis of the White River, Pahroc, Pahranagat, Coyote Spring, and upper Moapa valleys. The wash is incised from a few to several hundred feet below the adjacent valley surfaces. Perennial flow presently occurs only from the White Pine Mountains and downstream from the principal springs in the White River, Pahranagat, and Moapa valleys. The principal present-day flow occurs in the downstream part of the ancestral river. Here Muddy River flows from Muddy River Springs near the head of Moapa Valley through Moapa Valley to Lake Mead (Figure 1). Otherwise, flow occurs along limited sections of the wash only after high-intensity storms or very favorable snowmelt conditions.

The present-day White River and its principal tributary, Ellison Creek, drain a part of the east side of the White Pine Mountains. The White River flows from these mountains at a point about 5 miles northwest of Preston Springs. During periods of high flow or when evapotranspiration is at a minimum, the streamflow may extend to the south end of White River Valley, a distance of about 50 miles, in part sustained by flow from the several springs along the floor of the valley. However, during much of the year streamflow from the mountains is small and is dissipated by diversion for irrigation and evapotranspiration before it reaches the Nye County line. At times of minimum streamflow the channel may be dry only a short distance downstream from where the stream leaves the mountains. The streamflow reportedly [*Maxey and Eakin*, 1949, p. 15] has been as much as 75 cfs (cubic feet per second) during the spring freshet, although commonly the streamflow is about 2 cfs during the summer season in the vicinity of Preston. *Maxey and Eakin* [1949, Table 1] list a number of measurements on the White River, made during the period 1908–1943.

Most of the streams having sufficient flow to be utilized for irrigation head in the ranges bordering the west side of Jakes, White River, and Garden valleys. The streamflow is derived largely from the seasonal snow accumulation. Peak flow occurs with the spring runoff, and low flow is partly supplied from small mountain springs.

Throughout the area streamflow may occur for short periods after high-intensity storms, most of which probably occur during the summer months. On the whole all streamflow is dissipated within the area by evaporation, transpiration, and recharge, except for minor amounts generated by high-intensity storms either in Coyote Spring or Kane Spring valleys, which occasionally results in runoff through Arrow Canyon into the Muddy River in upper Moapa Valley.

TABLE 3. Average Monthly and Annual Precipitation for Adaven, Alamo, Kimberly, and Overton, Nevada, for Period of Record

Station	Period of Record	Altitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Adaven	1949-1962	6250	1.32	1.48	1.40	1.01	0.81	0.43	0.86	1.20	0.50	1.02	0.81	1.20	12.19
Alamo	1922–1960	3610	0.62	0.66	0.70	0.58	0.47	0.16	0.67	0.72	0.26	0.56	0.43	0.51	6.34
Kimberly	1931–1958	7230	1.55	1.50	1.55	1.32	1.32	0.66	0.90	0.83	0.68	0.89	0.81	1.51	13.30
Overton	1940–1962	1220	0.51	0.48	0.41	0.24	0.15	0.05	0.20	0.38	0.29	0.17	0.11	0.60	4.22

The nature of the bedrock in the mountains apparently affects the runoff in the area. Locally, the Paleozoic carbonate rocks, which transmit water readily, seemingly receive recharge from precipitation that otherwise would become runoff in the mountain canyons. Thus, Illipah Creek (point 5, Figure 4) seems to be smaller than one might expect from the altitude and area of its drainage basin. Perhaps a more surprising example is the near lack of perennial runoff into the valley for the well-watered Egan Range.

The distribution of present-day perennial and seasonal runoff is closely associated with the distribution of the higher mountain ranges and generally supports the concept that the greater average precipitation is associated with the higher mountain ranges.

Average annual runoff from the mountains of the region is estimated to be about 80,000 acre-feet, as computed by the altitude-runoff method described by *Riggs and Moore* [1965]. Of this amount, about 70% is estimated to be generated in the northern half of the region. Thus, the distribution of runoff indicates that the northern part of the area is relatively well watered. This indication in turn suggests that the potential for recharge from streamflow also is relatively favorable in the northern part of the region.

Discharge of groundwater. The principal natural discharge of groundwater is from the three groups of springs in the White River, Pahranagat, and upper Moapa valleys. The discharge of the springs in the White River and Pahranagat valleys subsequently is lost from those valleys, largely by evapotranspiration, including the water utilized for irrigation. In upper Moapa Valley most of the spring discharge leaves the valley as streamflow in the Muddy River. The combined average discharge of these three groups of springs is estimated to be about 08,000 acre-feet a year (Table 1). Additionally, discharge of groundwater by evapotranspiration in the other valleys, which is not associated with the principal springs, is estimated to be nearly 5000 acre-feet a year and largely occurs in Long, Garden, and Cave valleys.

The springs of the three groups generally are known to have relatively uniform flow. Some variation of flow undoubtedly occurs, but the occasional measurements of discharge made at most of the springs are not adequate to define minor variations. In White River Valley, the Preston Springs–principally Big, Arnoldson, Cold, and Nicholas–have been measured at regular weekly intervals sufficiently to demonstrate a relatively constant flow characteristic. Preston Big Spring (discharge about 8.5 cfs) has been * measured at about weekly intervals during the periods March to August 1936, September to November 1948, April to November during 1949, 1950, and 1951, and from May to September 1952. Arnoldson Springs (discharge about 3.5 cfs) and Nicholas Springs (discharge about 3.0 cfs) have been measured at about weekly intervals from September 1948 to September 1952. These records indicate that the minimum discharge is only about 10% less than the maximum.

Arnoldson, Nicholas, and Cold springs also were measured at about weekly intervals from March to August 1936. These measurements also indicated nearly constant flow. During this period the flows of Arnoldson (3.8 cfs) and Nicholas (2.7 cfs) springs were somewhat different than the flows during the later period of measurement, apparently the result of changing the outlet level of one of the springs. However, the combined flow of the two springs for both periods was almost identical. These data suggest a highly uniform flow of the springs. The best record to indicate the long-term springflow characteristics, however, is the gaging record of the Muddy River near Moapa. The gaging station is within 2 miles of the Muddy River springs, which supply most of the flow of the Muddy River. With appropriate adjustments, that record can be used to represent the discharge of the springs.

The streamflow of the Muddy River, near Moapa, has been recorded for the periods July 1913 to September 1915, May 1916 to September 1918, June 1928 to October 1931, April to July 1932, and from October 1944 to the present. The streamflow record at this station represents the actual discharge of the springs, except as follows: (1) streamflow at the station may be higher than spring discharge during periods of local runoff, particularly from high-intensity rains within the immediate drainage area; and (2) streamflow at the station is lower than spring discharge when water is diverted above the gaging station for irrigation, and when evapotranspiration between the station and the springs depletes the flow at the gaging station site.

A partial adjustment for the effect of overland runoff, during the period 1944–1962, was made by *Eakin* [1964, p. 23]. This adjustment resulted in a residual flow that, in effect, was entirely derived from spring discharge. The mean, median, and adjusted mean monthly and annual discharges for 25 complete water years of record through 1962 are given in Table 4.

Recently *Eakin and Moore* [1964] further analyzed the record of discharge of the Muddy River to evaluate the characteristics of the flow of the springs supplying the river. Corrections for evapotranspiration losses between the springs and gaging station virtually eliminated the seasonal variation shown by the month-to-month variations of mean streamflow at the gaging station. January characteristically is the month having the minimum average temperature and rate of evapotranspiration. Accordingly, the mean annual discharge of the springs supplying Muddy River is thus closely represented by the mean January discharge (49.8 cfs) recorded at the gaging station.

The analysis indicated a high degree of uniformity of spring discharge. The minimum annual mean discharge was about 90% of the maximum year. However, the small range in annual mean discharge apparently is significant in that the variations appear to be orderly and to occur, with considerable time lag, in response to variations in precipitation and consequent recharge. Both the high degree of uniformit of discharge and the small variations in annual mean discharge are compatible with the expected character of discharge from a regional groundwater system.

Relation of estimated groundwater recharge to discharge. The estimates of recharge to and discharge from the regional system shown in Table 1 agree closely for the region as a whole: the estimated recharge is 104,000 acre-feet a year, and the estimated discharge is 103,000 acre-feet a year. The estimates are considered reasonable and represent the magnitude of water naturally entering and leaving the regional system. The close agreement in the numerical values is considered to be coincidental rather than to indicate a high order of accuracy in the estimating techniques.

Although the regional estimates agree closely, there is wide divergence in the estimates for particular valleys. For example, in the White River and upper Moapa valleys the estimates of spring discharge are 37,000 and 36,000 acre-fee respectively. The estimate of recharge (38, acre-feet) from precipitation within the su ficial drainage area of White River Valley approximates the estimate for spring discharge, but the estimated recharge from precipitation in the local drainage area of upper Moapa Valley is negligible.

Figure 6 shows the distribution of the estimated recharge to and discharge from the regional groundwater system and a generalized representation of the regional flow system. From the figure it is seen that about 78% of the recharge is estimated to occur in the 4 northern valleys, and about 62% of the discharge is estimated to be from the springs in

TABLE 4. Monthly Discharge of Muddy River, near Moapa, for 25-year Period Ending September 30, 1962

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Year
25-year mean	46.1	48.7	49.5	49.8	49.7	48.1	46.8	45.0	43.2	43.4	44.2	44.4	46.5
25-year median	46.5	48.0	49.3	49.3	49.2	47.6	46.5	45.4	43.4	43.9	43.3	44.4	46.7
Mean adjusted for effect of local surface-water runoff	46.0	48.2	49.5	49.8	49.4	48.0	46.8	44.9	43.2	43.0	53.5	44.4	46.

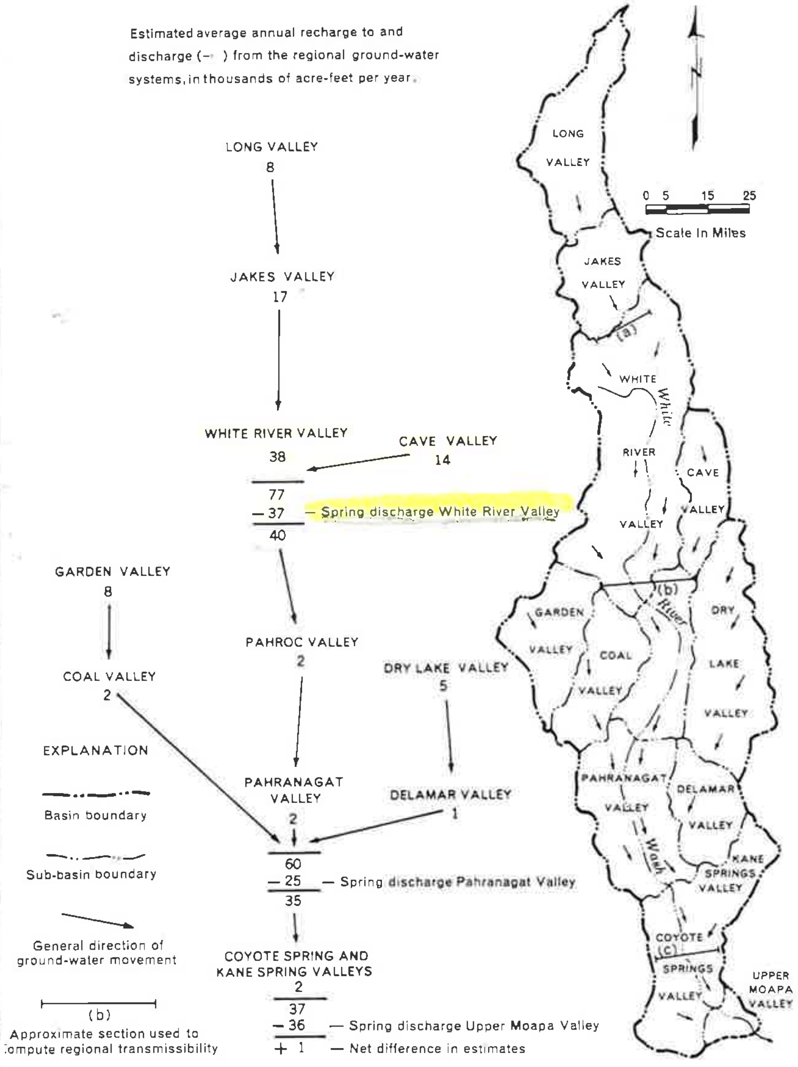


Fig. 6. Generalized flow pattern and estimated average annual recharge to and discharge from the regional groundwater system.

the Pahranagat and upper Moapa valleys in the southern part of the region.

Thus, the general balance between the overall estimates of recharge and discharge suggests a regional system within the 13-valley area. Further, the gross distribution of recharge and discharge infers a generally southward movement compatible with the regional movement indicated by the potential hydraulic gradient discussed in the previous section.

Regional transmissibility of the Paleozoic carbonate rocks. Transmissibility, one of the hydraulic properties of an aquifer, is usually determined by pumping tests under controlled conditions. Values so obtained are then used to compute the quantity of groundwater flow through a specified segment of aquifer. Wells are not available in this region to obtain transmissibility data of the carbonate rocks.

However, the generalized flow pattern and natural recharge-discharge relations shown on Figure 6, together with the hydraulic gradients discussed in the previous section on movement and generally shown in the profile on Figure 5, can be used to estimate the regional transmissibility of the Paleozoic carbonate rocks. The formula used is

$$T = Q/0.00112\,IW \qquad (1)$$

where T is the transmissibility in gal/day/ft; Q is the underflow in acre-feet per year; I is the hydraulic gradient in feet per mile; W is the effective width of the aquifer in miles, through which southward flow occurs; and the constant 0.00112 is a factor to convert gallons per day to acre-feet per year.

Three general sections were selected to estimate transmissibility: (1) a section near the north end of White River Valley through which most of the underflow occurs from Long and Jakes valleys; (2) a section near the south end of White River Valley through which most of the underflow occurs from White River and Cave valleys; and (3) a section in central Coyote Spring Valley through which most of the underflow occurs from Pahranagat and Delamar valleys. Gradients used are the indicated regional minimums, as discussed in the section on groundwater movement. Locally, actual gradients may be only a foot or two per mile or as much as several hundred feet per mile where controlled by barriers.

The estimated transmissibilities for the thre sections were computed by using equation 1 and the values are listed in Table 5. Thes values suggest that a first approximation of the regional transmissibility of the Paleozoic carbonate rocks is on the order of 200,000 gal/day/ft. The value is not large considering the substantial thickness of the Paleozoic carbonate rocks. However, as the actual transmission of groundwater in the carbonate rocks is localized largely in fracture or solution zones, local transmissibility values undoubtedly are much higher, perhaps 10 times or more, than the indicated average regional value. On the other hand, large areas of carbonate rocks that have little or no fracturing and solution openings transmit very small amounts of water.

Chemical quality of water in the regional system. The chemical character of groundwater in part reflects an interaction between the water and the rocks through which it passes. Chemical analyses of water from several of the principal springs in the region are listed in Table 6. As these springs represent most of the discharge for the regional system, chemical constituents are a composite of the variations and concentrations that ordinarily may be found in the system. Locally, higher or lower concentrations of individual constituents and total dissolved constituents undoubtedly occur.

The water from the springs in the White River and Pahranagat valleys characteristically is a calcium-magnesium bicarbonate type, and the dissolved-solids concentration ranges from 246 to 343 ppm (parts per million). Water from the Muddy River Springs in upper Moapa Valley has about twice the dissolved-solids concentration (614 and 620 ppm) and is of a mixed type.

In a complex hydrologic system with many

TABLE 5. Three Estimates of Transmissibility in the Regional Groundwater System

Section	Underflow (Q) from Figure 2, acre-ft/yr	Estimated Effective Width (W), mi	Computed Gradient, ft/mi	Estimated Transmissibility, gpd/ft
(a)	25,000	15	6.4	230,000
(b)	40,000	25	8	180,000
(c)	35,000	15	8	260,000

TABLE 6. Chemical Analyses for Selected Springs in the Regional Groundwater System (in ppm)
(Analyses by U. S. Geological Survey)

†Springs	Date of Collection	Temperature, °F	SiO_2	Fe	Ca	Mg	Na	K	*HCO_3	SO_4	Cl	F	NO_3	B	Dissolved Solids (sum of determined constituents)	Hardness as $CaCO_3$: Calcium, Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific Conductance, μmhos at 25°C	pH
									White River Valley										
Preston Big	6-23-62	61	20	0.01	43	22	1	3.2	193	39	15	0.4	3.0	0.1	254	196	38	417	7.9
Lund	6-23-62	65	11	...	56	25	0.5	0.8	281	11	8.0	0.1	3.0	0.0	257	242	12	438	8.0
Lund	4-16-63	59	12	0.01	48	28	3.8	1.0	275	12	2.8	0.1	3.2	0.1	246	235	9	408	8.1
Butterfield	5-27-49	..	46	..	40	23	2.0		178	27	18	...	...		283	194	...	...	...
Hot Creek	6-23-62	88	28	...	60	22	29	5.3	288	45	8.9	1.0	0.4	0.0	342	238	2	540	8.0
Hot Creek	4-16-63	80	28	0.01	60	24	24	5.1	300	43	9.0	1.0	0.6	0.1	343	248	2	548	7.6
									Pahranagat Valley										
Hiko	3-10-62	80	33	...	44	23	29	7.2	260	36	11	0.5	1.2	0.1	313	206	0	494	8.0
Crystal	4-15-63	81	28	0.00	45	23	23	5.2	272	27	8.0	0.5	1.1	0.2	295	209	0	484	8.0
Ash	3-9-62	88	31	...	39	18	32	6.8	231	34	9.7	0.5	1.2	0.1	286	172	0	443	8.1
									Upper Moapa Valley										
‡Warm	4-15-63	90	31	0.00	65	28	99	10	288	171	60	2.4	2.3	0.3	614	279	43	985	7.7
‡Iverson's	9-12-63	89	29	0.00	70	26	101	11	274	179	64	2.3	2.2	0.3	620	280	55	964	7.5
Muddy River gaging station near Moapa	3-9-62	71	32	...	71	33	125	14	303	216	75	2.4	1.5	0.4	719	313	65	1,090	8.2

* CO_3 reported as 0 in all analyses except that for Butterfield Springs.
† See Figure 5 for location.
‡ Part of Muddy River Springs

and precipitation and resultant groundwater recharge alone may be insufficient to maintain a hydraulic divide in these sections. The effectiveness of these divides cannot be determined at this time. However, the prominent structural trends parallel to these ranges probably act as barriers or partial barriers to groundwater movement across those alignments. Provisionally, then, it is assumed that the principal structural trends are sufficient to maintain hydraulic divides in these mountains.

Very little recharge occurs in the low Meadow Valley Mountains. The degree of influence of these mountains on groundwater movement in the carbonate rocks in this area is not known but might very well be almost negligible. Groundwater in the carbonate rocks occurs at higher altitudes, both in the region of this report and northeastward in the Meadow Valley area. However, in the Meadow Valley area the estimates of recharge from precipitation and discharge by evapotranspiration are in relative agreement [*Rush*, 1964, pp. 20–24]. This agreement suggests that if the Meadow Valley area contributes groundwater that ultimately discharges from the Muddy River Springs, then the quantity is only a small proportion of the total discharge of the springs.

In contrast, the combined estimated recharge from precipitation in the area considered to be supplying this regional groundwater system is in reasonable agreement with estimates of discharge from the springs only if the Muddy River Springs are included with those in Pahranagat and White River valleys. For the present, then, information favors the theory that most of the water supplying Muddy River Springs is derived from within the boundaries of the regional groundwater system as described in this report.

CLOSING STATEMENT

The regional interbasin groundwater system here described reasonably explains several otherwise anomalous occurrences of large natural spring discharge in 'dry' areas and of very deep water levels in valleys where at least limited natural discharge of groundwater by evapotranspiration ordinarily would be expected. The identification of this regional system is provisional in that it is based largely on indirect methods and limited data. However, the gross nature of the regional system is conside be valid.

Other regional or multivalley ground systems potentially may occur elsewhere in Basin and Range province, especially with principal area of carbonate deposition in zoic time, which is the area sometimes re to as the Paleozoic miogeosynclinal ar eastern and southern Nevada, parts of W Utah, and possibly in southern Idaho.

West of the area of this report, inte studies are being completed on interbasin ment in Paleozoic carbonate rocks in and jacent to the Nevada Test Site by the Geo cal Survey. Further, additional data are obtained relating to the location and exte regional groundwater systems, in conju with the regular investigations under th operative program of the Geological Surv Nevada.

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* order if we dont
have this

interrelated subsystems, the causes of many of the chemical variations of the groundwater naturally would be obscure. However, the analyses of water from springs in the White River Valley show a reasonable uniformity of composition for water that probably has been derived from nearby areas and has moved largely through carbonate rocks, but which includes some water that has moved partly in volcanic and sedimentary rocks. If the hypothesis of the regional system is approximately correct, most of the water supplying the springs in Pahranagat Valley should be derived from a considerable distance beyond the immediate surface drainage area; that is, several tens of miles at least. The concentration of water from these springs might remain relatively low if the water moved almost entirely in carbonate rocks. The analyses of water from Hiko, Crystal, and Ash springs shown in Table 6 are indeed low, ranging from 286 to 313 ppm of dissolved solids.

The dissolved-solids concentration of the water from two of the springs in upper Moapa Valley is about 2 times that of the other two groups of springs. Much of the increase is due to an increase in sodium, sulfate, and chloride ions. Calcium is moderately higher, but magnesium is nearly constant in the water from all the springs. This general increase in concentration is more or less to be expected for water issuing from a position in the regional system relatively removed from most areas of discharge. The moderate degree of concentration suggests that circulation in the regional system is comparatively active.

Boundaries of the regional groundwater system. In the preceding discussion the general boundary of the White River regional system has been represented as being approximately coincident with the outer topographic divides of the appropriate valleys. In basin and range hydrology, mountains usually are assumed to be hydraulic barriers. Ordinarily few data are available to demonstrate this assumption as a fact, but one or more of several factors provide the basis for this generally correct assumption. These factors include the following:

1. The consolidated bedrock forming the mountains is virtually impermeable. Secondary openings due to surficial fracturing or weathering, which rarely extend to depths of more than a few hundred feet, may transmit groundwater, but the lateral movement of water closel conforms to the general slope of the land surface.

2. The major structural trend commonly about parallel to the principal topographic ax of the range. Ordinarily, faults and structura alignments tend to act as barriers to groundwater movement across or at right angles t them.

3. The mountains characteristically receiv much greater average precipitation than do th adjacent valleys; greater precipitation provide a greater potential for recharge. If greater recharge occurs per unit area, other things bein equal, a hydraulic high (or divide) will b maintained between the areas of lesser or n recharge.

4. Surface water divides are coincident wit the topographic divides, which suggests that th groundwater divide is also aligned with th topographic divide.

The position of the hydraulic boundary of th regional groundwater system is indicated a only a few locations. For example, in the Egar Range, the water-level altitude in the we (point 7, Figure 4) 12 miles north of Presto Springs in White River Valley is about 578 feet. Northeastward about 11 miles, the water-level altitude in the Alpha Shaft is reported t be 6108 feet [*Maxey and Eakin,* 1949, p. 41] Eastward about half a mile, the water-leve altitude in the Liberty Pit is maintained b pumping at an altitude of about 6475 fee Drill holes on the east side of Liberty Pit ar reported to have water-level altitudes rangin from about 6860 to 6960 feet. Groundwater i carbonate rocks was encountered in the nearb Deep Ruth and Kelinske shafts. About 2 mile east the water-level altitude in the Kimberl Pit is somewhat below 6600 feet, and adjacen altitudes in drill holes range from about 661 to 6822 feet. The above-water-level informatio for the Robinson mining district area was reported by L. Green and M. Dale of the Kennecott Copper Company (private communicatio 1964). About 3½ miles southeast of the Kimberly Pit, Murry Springs, which provide th municipal water supply for the City of Ely issue at an altitude of about 6600 feet. Finally several miles east in the floor of Steptoe Valley he water level is within a few feet of land urface, which is at an altitude of about 6375 eet. This mountain area is geologically and tructurally complex, and water levels have een affected somewhat by mining operations. owever, the generalized information indicates hat a hydraulic divide is several hundred feet igher than the water level in either White iver or Steptoe valleys and is within perhaps mile of the topographic divide.

Limited water-level information also indiated the position of the hydraulic divide at the orth end of the Bristol Range. The water-level ltitude at a well (point 17, Figure 4) in Dry ake Valley is about 4820 feet; about 8 miles ast the water-level altitude in the Bristol Mine, s reported (oral communication, 1964) by Paul emmill (formerly of Combined Metals Reuction Company), is about 5675 feet. Still rther east in the next valley, about 4 miles ortheast of Bristol Mine, the water-level altiude in a well is about 5610 [*Rush,* 1964, Table 5]. Groundwater in the Bristol Mine occurs in aleozoic carbonate rocks, and, according to emmill, the level apparently fluctuates to some xtent with variations in recharge. The groundater encountered in the wells is in valley fill nd may be under a higher head than in the nderlying carbonate rocks. Nevertheless, the ater-level altitude in the Bristol Mine indiates a hydraulic divide close to the topographic ivide in the Bristol Range.

The Pahranagat and Sheep ranges form the est side of Pahranagat and Coyote Spring alleys, respectively. Recharge from precipitaion in these mountains, although limited, probbly maintains a hydraulic divide along the ountain alignment. Data on water levels in he Paleozoic carbonate rocks in these mounains are not available. However, the altitude of he water level in a well (point 32, Figure 4) in he valley fill is about 4025 feet, or about 220 eet higher than Crystal Springs, about 3½ iles to the east in Pahranagat Valley. This ltitude suggests that the gradient of groundater in the underlying carbonate rocks may lso be generally from the Pahranagat Range oward the White River Wash to the east. Somehat similarly, the semiperched groundwater upplying Coyote Springs in Coyote Spring alley is considered to be derived from recharge n the Sheep Range to the west and moves through the older valley fill toward the White River Wash. As the recharge area is necessarily at a higher altitude than the spring area, it may be assumed to be at an altitude high enough to provide a hydraulic barrier in the carbonate rocks in the Sheep Range.

The Delamar Range and Meadow Valley Mountains form the east sides of Delamar and Kane Springs valleys. Some groundwater is perched in the Tertiary volcanic rocks and supplies several small springs in the Kane Spring Valley side of the Delamar Range. Near the townsite of Delamar (Figure 4), some water initially was developed at several small seepages from limestone and granite [*Carpenter,* 1915, p. 67] and was insufficient for the requirements. That these springs were derived from perched groundwater is suggested strongly by the fact that, according to Carpenter, the mine at Delamar was totally dry to a depth of 1400 feet. The altitude of the bottom of the mine is not known but apparently was of the order of 5300 feet. West of Delamar, in the lower part of Delamar Valley, the apparent water-level altitude may be below 3700 feet, based on reports that a well (point 30, Figure 4) was dry at a depth of 900 feet. East of Delamar, water levels in the floor of Meadow Valley Wash are at an altitude of about 3800 feet. The meager recharge in the Delamar Range and the presence of relatively impermeable Paleozoic clastic and Tertiary volcanic rocks are probably sufficient to maintain a hydraulic divide between Meadow Valley Wash and Delamar Valley, even though the divide may be much below the level of Delamar mine in that area.

More generally, on the basis of substantial recharge potential, it may be inferred that the Butte Mountains and Egan, Schell Creek, Bristol, and Highland ranges, which form the eastern boundaries of Long, Jakes, White River, Cave, and Dry Lake valleys, respectively, are probably aligned with the east side hydraulic boundaries of those valleys. Similarly, the Maverick Springs, Ruby, and the White Pine mountains and Grant and Quinn Canyon ranges are probably aligned with the west side hydraulic boundaries of Long, Jakes, White River, and Garden valleys.

Some sections of these east- and west-side groups of mountains, such as the Antelope Mountains and Horse Range, are relatively low,

Groundwater

Detecting Drawdowns Masked by Environmental Stresses with Water-Level Models

by C.A. Garcia[1], K.J. Halford[2], and J.M. Fenelon[3]

Abstract

Detecting and quantifying small drawdown at observation wells distant from the pumping well greatly expands the characterized aquifer volume. However, this detection is often obscured by water level fluctuations such as barometric and tidal effects. A reliable analytical approach for distinguishing drawdown from nonpumping water-level fluctuations is presented and tested here. Drawdown is distinguished by analytically simulating all pumping and nonpumping water-level stresses simultaneously during the period of record. Pumping signals are generated with Theis models, where the pumping schedule is translated into water-level change with the Theis solution. This approach closely matched drawdowns simulated with a complex three-dimensional, hypothetical model and reasonably estimated drawdowns from an aquifer test conducted in a complex hydrogeologic system. Pumping-induced changes generated with a numerical model and analytical Theis model agreed (RMS as low as 0.007 m) in cases where pumping signals traveled more than 1 km across confining units and fault structures. Maximum drawdowns of about 0.05 m were analytically estimated from field investigations where environmental fluctuations approached 0.2 m during the analysis period.

Introduction

The volume of aquifer system that can be characterized with aquifer tests is controlled by the distance at which drawdown can be detected. Drawdown detection typically is limited to distances of less than 1 km, because environmental water-level fluctuations frequently exceed the maximum displacement from pumping (Risser and Bird 2003).

Environmental fluctuations in measured water levels are described here as nonpumping (natural or anthropogenic) stresses on the aquifer system. These fluctuations include short-term, seasonal, and long-term stresses such as barometric pressure, tidal signals, natural and artificial recharge, and surface-water stage changes and diversions. Barometric pressure and tidal signals acting on the aquifer system can induce water-level changes of more than 0.3 m during periods of less than a few days (Fenelon 2000). Individual recharge events also can cause episodic water-level rises that exceed 0.5 m over a few days (O'Reilly 1998). Recharge likewise can induce long-term rising trends of more than 1 m/year that affect detection of small pumping signals (Fenelon 2000; Elliott and Fenelon 2010). Stage changes of a fully penetrating river can cause daily and event-based fluctuations in local groundwater levels (Criss and Criss 2011).

Environmental fluctuations from recharge responses, surface water stage changes, or any other external stress can be modeled explicitly by using water levels from background wells that are affected by these environmental stresses (Halford 2006; Criss and Criss 2011). A useful background well is one in which water levels are affected by tidal potential, imperfect barometric coupling between the atmosphere and water table, and all other stresses that affect water levels in observation wells excluding pumping. Although the need for background water levels to characterize environmental fluctuations has long

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been recognized (Stallman 1971), trends and corrections characterizing environmental fluctuations typically have been estimated qualitatively.

One method to reduce drawdown obscurity by environmental fluctuations is to interpret water-level changes from long-term (i.e., years) pumping of water-supply wells (Gonthier 2011; Harp and Vesselinov 2011). Long-term pumping can generate substantial drawdown over time, which will exceed environmental fluctuations during the period of analysis. Despite the utility of this method, using years of water-level changes from pumping of supply wells is an opportunistic approach that generally cannot be applied to aquifer tests.

Alternatively, environmental fluctuations have been distinguished from drawdown by modeling and directly removing barometric and tidal effects from measured water levels (Erskine 1991; Rasmussen and Crawford 1997; Toll and Rasmussen 2007). However, this approach does not remove environmental fluctuations caused by regional trends such as long-term recharge and is difficult to automate because all significant stresses that affect water levels other than pumping are not simulated explicitly.

The above approach was expanded upon by modeling and removing all nonpumping stresses from the water-level record (Halford 2006). Environmental fluctuations caused by barometric pressure and tidal signals, and regional trends captured in background water levels are modeled prior to pumping, projected forward during pumping and recovery periods, and removed from measured water levels. This approach requires antecedent monitoring periods that are more than three times longer than the pumping and recovery period in order to capture short and long-term environmental trends (Halford 2006). Considering recovery periods are often six times longer than pumping periods (Neville and van der Kamp 2012), this approach rapidly becomes unreliable where pumping periods exceed a week.

This paper describes and tests a method presented by Halford et al. (2012) for estimating observation-well drawdown response to aquifer-test stress where (1) environmental fluctuations mask the pumping signal, and (2) the period of record is limited. Drawdown is distinguished from environmental fluctuations by analytically simulating all water-level stresses (nonpumping and pumping) simultaneously during the period of record. Simultaneous modeling of environmental fluctuations and pumping signals overcomes the limitations of long-term interpretation and antecedent water-level monitoring. This approach draws on previous approaches where all environmental fluctuations are simulated and the pumping signal is modeled analytically using Theis (1935). Changes in pumping rates, multiple pumping wells, and lithologic variability are simulated by transforming multiple pumping schedules into water-level changes with Theis (1935). Transmissivity and storage coefficient are curve fitting parameters and are not interpreted as aquifer properties because the underlying assumptions of the Theis solution frequently are not met.

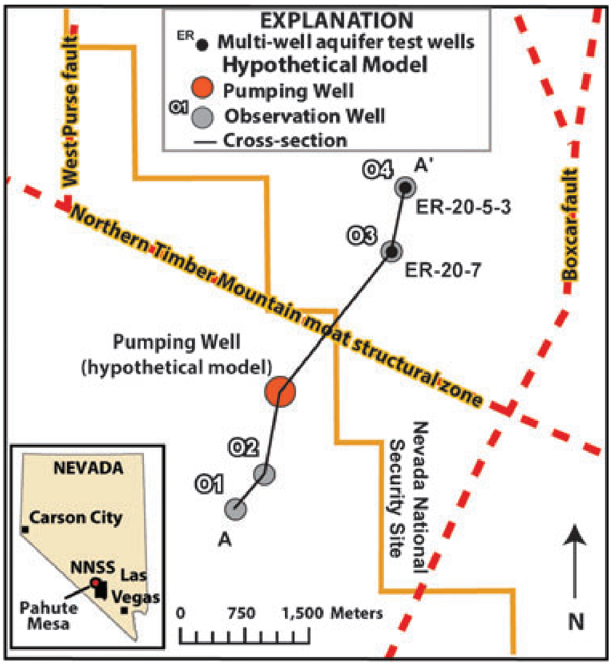

Figure 1. Location map showing Pahute Mesa wells and hypothetical pumping and observation locations.

The described method was tested using "known" drawdowns generated from a hypothetical aquifer test that was simulated with a three-dimensional MODFLOW model. The utility of the approach also was demonstrated using a real aquifer test. The hypothetical model was conceptually based on the complex hydrogeology at the Nevada National Security Site (NNSS) at Pahute Mesa whereas the real aquifer test was conducted in a deep fractured volcanic rock aquifer at Pahute Mesa. The hypothetical model demonstrated that the drawdown estimation approach described here can closely match known drawdowns.

Pahute Mesa Study Area

Pahute Mesa is located in southern Nevada, within the NNSS (Figure 1). The aquifer system beneath Pahute Mesa comprises layered sequences of volcanic rocks that have been faulted into distinct structural blocks (Warren et al. 2000). Rhyolitic lavas or welded ash-flow tuffs such as in the Benham and Topopah Springs Aquifers, respectively, comprise aquifers. Bedded and nonwelded, zeolitized tuffs typically comprise confining units (Blankennagel and Weir 1973; Prothro and Drellack 1997; Bechtel Nevada 2002). More than a half dozen faults with offsets in excess of 200 m have been mapped previously in Pahute Mesa (McKee et al. 2001) and additional faults are mapped as well drilling continues (e.g., National Security Technologies, LLC 2010).

Distant drawdown detection from multiwell aquifer tests is necessary to quantify the hydraulic properties of the stratigraphic and structural features on Pahute Mesa so that radionuclide migration can be evaluated (Laczniak et al. 1996). The depth to water exceeds 600 m and sparsely distributed wells (generally more than 1 km apart) penetrate more than 1 km of a complex, volcanic rock-dominated, hydrogeologic system (Fenelon et al. 2010). Environmental water-level fluctuations are substantial beneath Pahute Mesa because of the thick unsaturated zone and high pneumatic and hydraulic diffusivity of the volcanic rocks.

Methodology

The drawdown estimation approach was tested using hypothetical and real aquifer test applications. A three-dimensional MODFLOW model was used to generate "known" drawdowns in response to a hypothetical aquifer test. Environmental noise was then added to the known drawdowns in order to create a hypothetical water level where the pumping signal was masked. Known and unknown drawdowns from hypothetical and real aquifer tests, respectively, were detected using the drawdown estimation approach presented here by analytically simulating hypothetical and real measured water levels.

Drawdown Estimation

Drawdowns in response to aquifer testing are estimated by analytically simulating all nonpumping and pumping water-level stresses simultaneously. These water-level models are calibrated to measured water levels during the entire period of aquifer-test data collection. Environmental fluctuations are modeled using input series of barometric pressure, tidal potential, and long-term recharge. Additional input series of water levels from background wells are included to capture environmental fluctuations from recharge responses or any other external nonpumping stress. Pumping signals are modeled by transforming pumping schedules into water-level responses using the Theis solution. Drawdown is computed as the summation of all Theis solutions and residual differences between measured and modeled water levels.

Measured water-level fluctuations are modeled analytically by summing multiple pumping and nonpumping stresses affecting the water-level record. All water-level stresses or components (WLC) are summed to compute a simulated water level (SWL) (Halford et al. 2012):

$$\mathrm{SWL}\,(t) = C_0 + \sum\nolimits_{i=1}^{n} \mathrm{WLC}\,(t)_i \tag{1}$$

where t is time, C_0 is a constant [L], n is the number of components, and WLC_i is the ith water-level component in units of the modeled water level.

WLC include raw environmental fluctuations such as barometric pressure and computed components such as tide signals (Harrison 1971), moving averages of raw and computed nonpumping components, and pumping signals generated from the Theis solution (Halford et al. 2012). Nonpumping components are often transformed with multiple, moving averages to capture different signal frequencies. More than a half dozen water-level components frequently are created from a single input series because a broad range of averaging periods are more likely to simulate the environmental fluctuations.

A moving-average is applied to ith WLC at time, t, with:

$$\mathrm{WLC}\,(t)_i = a_i V_i\,(t + \phi_i) \tag{2}$$

where a_i is the amplitude multiplier of the ith component in units of the modeled water level divided by units of the ith component, ϕ_i is the phase-shift of the ith component [T], and $V_i(t + \phi_i)$ is the value of the moving average of ith component at time $t + \phi_i$ in units of ith component. A WLC that was transformed with a moving average is adjusted by changing amplitude (a) and phase (ϕ) in Equation 2. Raw input series can be added as WLCs by assigning a moving average interval of 0 days. Summing multiple, moving averages of an input series is similar to the neural network approach (ASCE 2000).

Pumping schedules are transformed into water-level responses with the Theis (1935) solution. Water-level change or drawdown, s [L], from pumping is simulated with:

$$s\,(t) = \frac{Q}{4\pi T} W\,(u) = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right), \tag{3}$$

where t is the time since pumping commenced, Q is the pumping rate [L^3/T], T is the transmissivity [L^2/T], $W(u)$ is the exponential integral solution, u is dimensionless time, r is the radial distance from the pumping well [L], and S is the storage coefficient [dimensionless]. Variable-rate pumping schedules (Figure 2) and multiple pumping wells can be simulated by superimposing multiple Theis solutions in time and space, respectively (Halford et al. 2012). Similar to the amplitude and phase shift of a moving average, a pumping signal generated with the Theis solution is adjusted by changing transmissivity (T) and storage coefficient (S) in Equation 3.

Transformation of step-wise pumping schedules into water-level changes at observation wells with superimposed Theis solutions (Equation 3) are discussed hereafter as Theis models. The term Theis model is introduced because superimposed Theis solutions typically are used as a transfer function to characterize the hydraulic properties of an aquifer system. In this approach, T and S are fitting parameters that do not necessarily represent hydraulic characteristics of the aquifer system. This is because homogeneity assumptions of the Theis solution are violated in hydrogeologically complex aquifer systems.

Water-level responses to pumping in hydrogeologically complex systems can be approximated well by applying multiple Theis models to a single pumping schedule. Pumping signals propagate through complex aquifer systems at different rates. Relatively faster and slower components of signals are approximated by the Theis models with correspondingly higher and lower hydraulic diffusivities. For example, fracture and matrix flow affect signal propagation in a dual-porosity system. Faster and slower signals, thus can be approximated by adjusting T and S parameters when generating pumping signals with the Theis solution. The summation of multiple pumping signals generated from a single

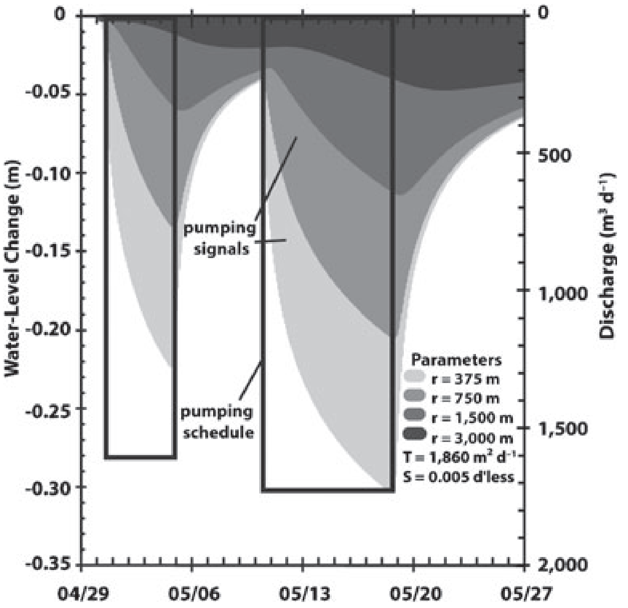

Figure 2. Water-level changes from a pumping schedule that were simulated with superimposed Theis solutions at multiple radial distances.

pumping schedule can successfully simulate the water-level response from pumping in a complex non-Theis-like system.

Water-level models must be calibrated to reliably differentiate small pumping signals from environmental fluctuations. Differences between simulated and measured water levels are minimized with the parameter estimation tool PEST (Doherty 2008). Amplitude and phase or transmissivity and storage coefficient of each component series are adjusted. Sum-of-squares differences between simulated and measured water levels, or residuals, define the measurement objective function,

$$\mathrm{SS}\,(x)_{\mathrm{MEAS}} = \sum\nolimits_{i=1}^{\mathrm{nobs}} (\mathrm{SWL}\,(x)_i - \mathrm{MWL}_i)^2 \qquad (4)$$

where x is the vector of parameters being estimated, nobs is the number of observations that are compared, $\mathrm{SWL}(x)_i$ is the ith simulated water level, and MWL_i is the ith measured water level. Although the sum-of-squares error serves as the measurement objective function, root-mean-square (RMS) error:

$$\mathrm{RMS} = \sqrt{\frac{\mathrm{ss}\,(x)_{\mathrm{MEAS}}}{\mathrm{nobs}}} \qquad (5)$$

is reported in the analyses presented here because RMS is more comparable to water-level measurements.

Drawdown estimates are the summation of all calibrated pumping signals minus residuals. Residuals represent a composite of all water-level fluctuations that were not modeled with environmental- and pumping-component series. These fluctuations are predominantly random residuals during nonpumping periods but may contain components of the pumping signal during pumping periods that are not explained by the Theis solution.

Water levels are modeled and drawdowns were estimated with SeriesSEE, an Excel Add-In for viewing, cleaning, filtering, processing, and analyzing time-series data (Halford et al. 2012). Water-level records and components should be cleaned and filtered prior to simulating water levels. Water levels to be modeled, component time series, and period of analysis are defined interactively and viewed in Excel workbooks. Water levels are simulated with a FORTRAN program that is called from Excel. Parameter estimates, water-level components, simulated water levels, and water-level differences are imported automatically into the modeling workbook following parameter estimation by PEST. Parameters are estimated and water-level model results are evaluated iteratively until the user deems the fit to be adequate.

Hypothetical Model

The reliability of differentiating environmental fluctuations and pumping responses with the drawdown estimation approach was tested with a numerically simulated hypothetical aquifer test, for which drawdowns were known because they were simulated. This hypothetical system was designed with some degree of hydrogeologic complexity. The hydrogeologic framework was conceptualized as layered sequences of hydrostratigraphic units that were offset vertically more than 500 m across a major fault (Figure 3). The fault was simulated as an interface where hydrostratigraphic units were juxtaposed; the fault was not assigned unique hydraulic properties. This hypothetical sequence is similar to the vertical distribution of units that were mapped in cross sections beneath Pahute Mesa (National Security Technologies, LLC 2010).

The hypothetical aquifer system was simulated with a three-dimensional MODFLOW model (Harbaugh 2005). The three-dimensional model grid was rotated about the x-axis so the hydraulic-conductivity distribution coincided with model layer orientation (Figure 3). Therefore, with the layers conceptually flipped to the vertical position, the horizontal dimension was represented by columns and layers and the vertical dimension was represented by rows (Halford and Yobbi 2006). The model grid extended vertically from 0 to 1300 m above sea level, where the upper row of the model was the water table, and the 1300-m thickness was divided into uniform, 10-m thick rows. Temporal changes in the saturated thickness of the aquifer were not simulated because the maximum drawdown near the water table was small relative to the total thickness.

The model grid was divided into 144 columns, with the uniform part of the cross section (Figure 3) subdivided into 90, 50-m wide columns from 0 to 4500 m. The model domain extended laterally, beyond the cross section in Figure 3, and an additional 20,000 m in both directions where each additional column was 1.25 times wider than the previous column.

Symmetry was assumed about the cross section so only half of the hypothetical aquifer system was simulated explicitly. The cross section in Figure 3 was the plane of symmetry and was projected into the page. Layer 1 was half the 50-m thickness of layer 2 because of this plane

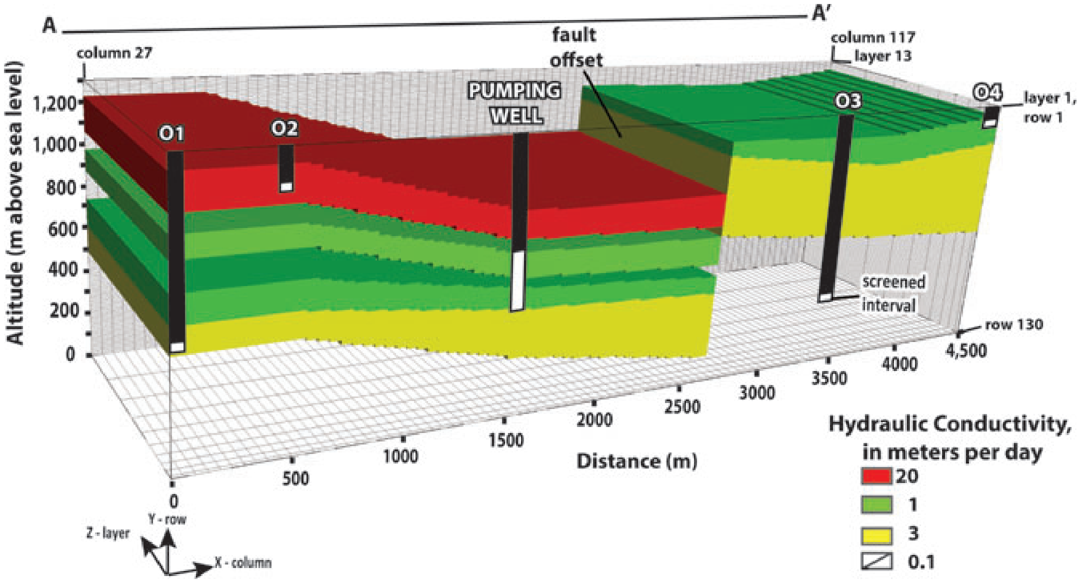

Figure 3. Cross section A-A′ (Figure 1), model grid, hydrogeologic framework, hydraulic-conductivity distribution, observation wells, and pumping well for hypothetical aquifer system. Colored areas represent aquifers and uncolored areas represent confining units.

of symmetry. Each additional layer was 1.25 times wider than the previous layer until the cross section projected more than 100 km into the page (only the first 13 layers are shown in Figure 3). All lateral boundaries were extended beyond 100 km so that simulated drawdowns were not affected by no-flow boundary conditions.

Hydraulic conductivity was distributed in layer 1 from 0 to 4500 m as shown in the cross section (Figure 3). The vertical distribution of hydraulic conductivity at 0 and 4500 m was extended left and right of the visible section to the model edges. Horizontal-to-vertical anisotropy of 1 was assigned. A uniform value of 0.02 was assigned for specific yield and 5×10^{-6}/m was assigned for specific storage.

A hypothetical aquifer test was simulated and analyzed during a 5-month period that was divided into five stress periods. The pre-pumping, pumping, recovery, pumping, and recovery periods were 23, 10, 10, 10, and 97 days, respectively. Pumping rates were 1500 m^3/d during the two 10-day pumping periods. The screened interval of the pumping well was simulated as a high-conductivity zone where water was removed from the uppermost cell and flow was apportioned across the interval within MODFLOW (Halford 2000).

Drawdowns simulated at four locations with the MODFLOW model, ranging between 1 and 3 km from the pumping well, were selected for further analysis (Figure 1). Water levels responded distinctly in observation wells O2 and O1 (Figure 4), which are 1 and 1.5 km, respectively, from the pumping well (Figure 3). Dampened responses occurred in observation wells O3 and O4 (Figure 4), which are 2.2 and 3 km, respectively, from the pumping well (Figure 3). A major fault that offsets the aquifers and confining units lies between the pumping well and observation wells O3 and O4 (Figure 1). These four simulated pumping responses will be referred to herein as known drawdowns.

Hypothetical water levels at each observation well were created to emulate a real water-level response to pumping and test the drawdown estimation approach. Recognizing that known drawdowns represent pumping stresses only, hypothetical water levels were created using a combination of known drawdowns and measured environmental fluctuations. Measured water levels in background well UE-20n 1 (USGS National Water Information System) are assumed to be unaffected by real pumping beneath Pahute Mesa during the hypothetical model simulation period, and therefore, were assumed representative of environmental fluctuations only. Hypothetical water levels were created by adding measured water levels in background well UE-20n 1 to each known drawdown from November 1, 2010 to March 1, 2011 to imitate a real water-level response to pumping (Figure 5). The sum of water levels from well UE-20n 1 and known drawdowns are herein referred to as "measured" water levels that represent both pumping and nonpumping stresses.

Results

Hypothetical Model Application

The reliability of differentiating drawdowns from environmental fluctuations with the drawdown estimation approach was tested by analytically simulating "measured" water levels where drawdowns were known (numerically simulated) (Figure 6A). Simulated water levels were created in the analytical model by combining water-level components representing environmental fluctuations and the pumping signal during the same period that the hypothetical aquifer test occurred.

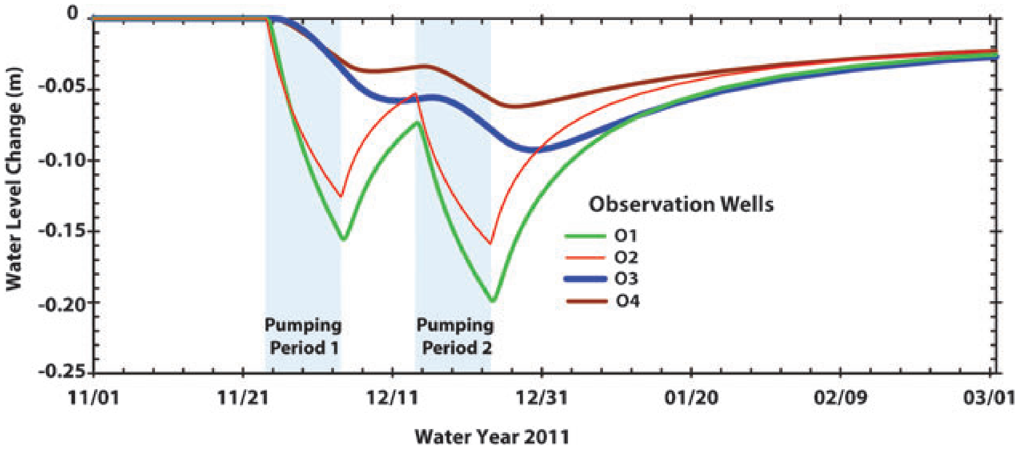

Figure 4. Known drawdown (numerically simulated pumping signals) observed at four locations (Figures 1 and 3) within the model domain.

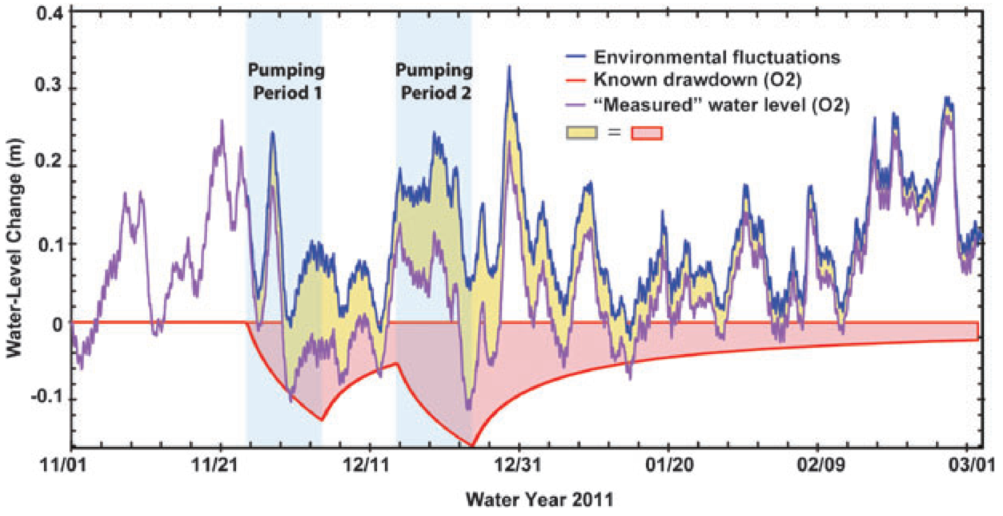

Figure 5. Known (numerically simulated) drawdown at model location O2 (Figure 1), environmental water-level fluctuations in Pahute Mesa background well UE-20n 1, and the hypothetical "measured" water level at location O2 (known drawdown + environmental fluctuations).

Environmental water-level fluctuations were analytically simulated with component series including raw series and moving averages of barometric pressure and background water levels measured at Pahute Mesa background well PM-3-1 (located >12 km northwest of UE-20n 1; USGS National Water Information System, 2011), and computed dry- and gravity-earth tide components. Background well PM-3-1 penetrates similar volcanic units and is likely affected by similar environmental stresses as well UE-20n 1. Therefore it was assumed to sufficiently represent a combination of environmental fluctuations affecting the "measured" water levels, which were derived from well UE-20n 1.

Drawdown in well O2 was approximated with two Theis models in the analytical water-level model, because a single Theis model could not replicate the "known" pumping signal. Well O2 is screened in an aquifer that is separated by a confining unit from the aquifers that are penetrated by the pumping well (Figure 3). The need for two Theis models that conceptually approximate fast and slow aquifer responses can be anticipated where complex hydrogeology occurs. Differences between simulated and "measured" water levels were minimized by estimating 39 calibration coefficients during the period from November 1, 2010 to March 1, 2011 (Table 1; Figure 6).

Physical significance should not be attributed to any of the calibration coefficients, especially T and S in the Theis models (Table 1). Known transmissivity that was specified in the numerical groundwater-flow model ranges between 3400 and 4400 m^2/d left of the fault offset (Figure 3). Estimates of T in the two Theis models were less than 200 m^2/d (Table 1). This considerable difference between calibration coefficients in Theis models and the known, complex hydraulic property distribution illustrates why hydraulic properties should not be interpreted directly from a water-level model.

Differences between analytically estimated and known (numerically simulated) drawdowns in well O2

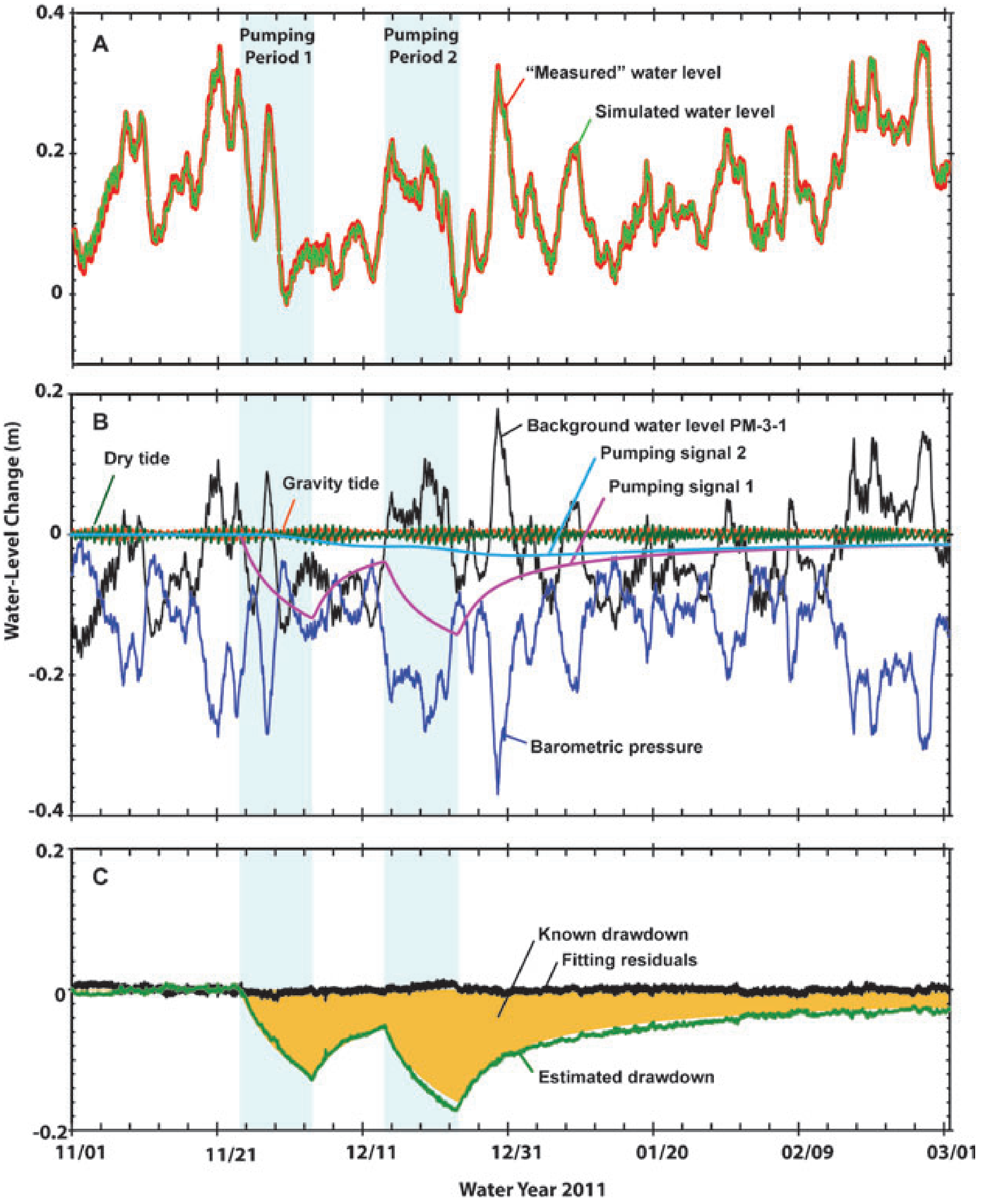

Figure 6. (A) "Measured" and analytically simulated water levels; (B) component time series; and (C) known (numerically simulated) drawdowns, analytically estimated drawdowns, and analytical fitting residuals in well O2 (Figure 1).

averaged 0.005 m and maximum drawdowns differed by 6% (Figure 6C, Table 2). Analytically estimated drawdowns more than 1 month after pumping ceased were within 0.007 m, on average, of the known drawdowns.

Drawdown also was estimated in wells O1, O3, and O4 with the analytical approach presented here (Figure 7, Table 2). The same environmental-fluctuation and pumping components were used in each approach as specified for well O2. Differences between analytically estimated and known drawdowns in wells O1, O3, and O4 averaged 0.008, 0.012, and 0.006 m, respectively. Root-mean-square fitting and prediction errors averaged 0.004 and 0.011 m, respectively, for wells O1, O3, and O4.

RMS errors of fit were consistent between observation wells and appear unrelated to the magnitude of drawdown (Table 2). Fitting errors were constant between observation locations (0.004 m) whereas maximum drawdown estimates varied by up to 0.14 m. This indicates that residual differences from the fit are driven by the measured environmental fluctuations rather than the drawdown magnitude or distance from the pumping well.

The prediction error (RMS error of prediction, Table 2) ranged between 1.75 and 3.5 times the modeled water-level fitting error (RMS error of fit, Table 2). On average, the prediction error shown here was about 2.5 times the fitting error. Similar results were found when known drawdowns were added to measured environmental fluctuations from two alternative background wells to compute "measured" water levels and estimate drawdown (data not shown). Considering results shown here and

Table 1
Component Time Series and Calibration Coefficients Used to Model Water Levels in Observation Well O2

		Calibration Coefficients		
Component	**Time Series[1,2]**	**Amplitude (m)**	**Phase Shift (d)**	**Moving Averaging Interval[3] (d)**
Offset	—	0.01	—	—
Series	Background water level	0.59	−0.003	0
Series	Background water level	0.22	0.004	0.042
Series	Background water level	0.13	0.03	0.083
Series	Background water level	0.27	0.009	0.125
Series	Background water level	−0.15	−0.38	0.25
Series	Background water level	0.25	−0.40	0.5
Series	Background water level	−0.55	0.009	1
Series	Barometric pressure	−0.18	−0.01	0
Series	Barometric pressure	0.06	−0.06	0.042
Series	Barometric pressure	0.18	0.03	0.083
Series	Barometric pressure	−0.07	−0.28	0.125
Series	Barometric pressure	0.18	−0.18	0.25
Series	Barometric pressure	−0.01	−0.17	0.5
Series	Barometric pressure	−0.52	0.03	1
Series	Barometric pressure	0.029903	0.62	2
Tide	Computed gravity	0.00005	0.08	—
Tide	Computed dry	−0.00003	0.006	—
		Transmissivity[4] (m^2/d)	**StorageCoefficient[4] (–)**	**Radius (m)**
Theis	Pumping signal	199	0.007	1,000
Theis	Pumping signal	176	0.10	1,000

Note: Component series include moving average transforms of background water levels and barometric pressure, earth tides (gravity and dry), and pumping signals generated with Theis models. Components were calibrated from November 1, 2010 to March 1, 2011.

[1] Raw time series.

[2] Background water levels and barometric pressure measured at Pahute Mesa well PM-3.

[3] Units are the same as the raw time series.

[4] Estimated values are fitting parameters that have no physical basis.

those determined with alternative well data, prediction errors were about 2.5 times the fitting errors on average and less than four times the fitting errors overall.

Nearly all differences between known and analytically estimated drawdowns result from noise in data sets, not use of the drawdown estimation approach. Known drawdowns that were sampled directly from the MODFLOW model results could be replicated with analytical Theis-generated pumping signals alone (no environmental fluctuations) with RMS prediction errors within 0.0005 m (not shown because signals appear identical). This is much less than the 0.007 m prediction error for well O2 between analytically estimated and known drawdowns where environmental fluctuations had been added to the known drawdowns (Table 2).

Maximum known and analytically estimated drawdowns agreed within 0.02 m in the four hypothetical wells. These small deviations are within the accuracy of the numerical solution of the hypothetical aquifer test. The hypothetical model, known drawdowns, measured barometric pressures, and measured water levels are available as supporting information.

Aquifer Test Application

The utility of the drawdown estimation approach was demonstrated using a real aquifer test conducted in a deep fractured volcanic rock aquifer at Pahute Mesa (Halford et al. 2010). Drawdown in distant observation well ER-20-5-3 was estimated in response to pumping in well ER-20-7 (Figure 1). Well ER-20-7 produced about 17,500 m^3 of water from the Topopah Spring aquifer during two pumping periods from September 14 to17 and 21 to 24, 2010 (Figure 8). Drawdown was estimated in observation well ER-20-5-3, which is screened in the Calico Hills zeolitic composite unit that is vertically offset by more than 100 m across a fault structure. Pumping and observation wells are 0.8 km apart (Figure 1) and penetrate different structural blocks.

The modeled fitting period was from August 10, 2010 to November 24, 2010. Multiple moving averages of barometric pressure and background water levels from well PM-3, and computed dry and gravity tides were used to model environmental fluctuations. The background well was nearly 8 km northwest of the pumping well, ER-20-7 (Halford et al. 2010). The pumping signal was analytically generated with two Theis models of the pumping schedule (Figure 8). Simulated water levels matched measured water levels with a RMS error of less than 0.003 m during the fitting period. Using fitting-to-prediction error comparisons from hypothetical model results, the drawdown prediction error is likely less than 0.01 m.

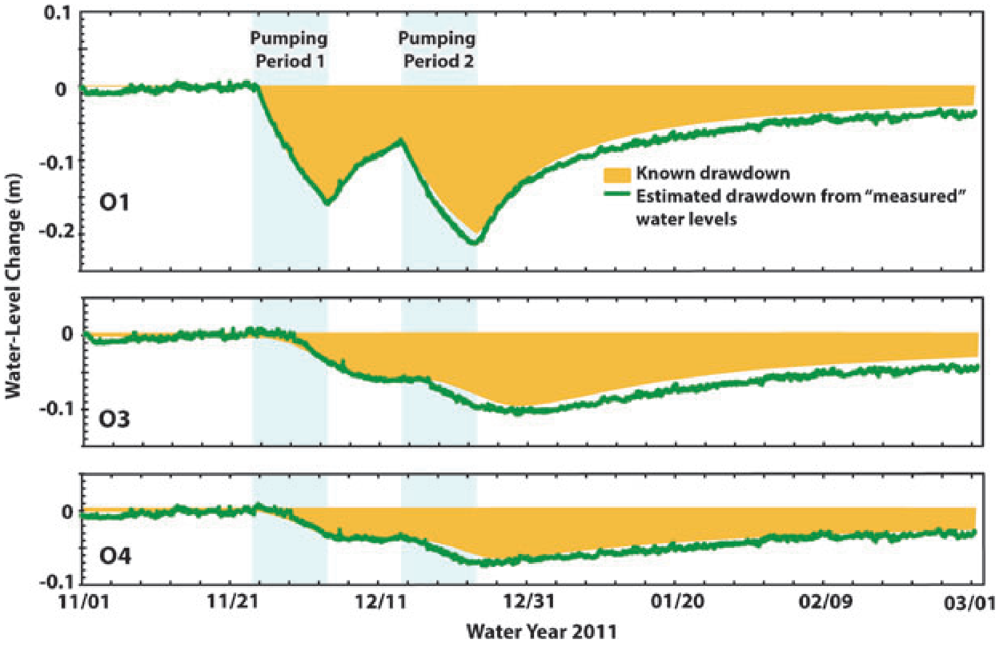

Figure 7. Known (numerically simulated) and analytically estimated drawdowns in observation wells O1, O3, and O4 (Figure 1). Drawdowns were estimated from "measured" water levels.

Table 2

Analytically Simulated Water-Level Fit and Comparison Between Known and Estimated Drawdown at Four Locations

		Difference[2] (m)		Maximum Drawdown (m)	
Model Location	**RMS Error of Fit[1] (m)**	**RMS Error of Prediction**	**Mean**	**Known**	**Estimated**
O1	0.004	0.010	0.008	0.20	0.21
O2	0.004	0.007	0.005	0.16	0.17
O3	0.004	0.014	0.012	0.09	0.11
O4	0.004	0.008	0.006	0.06	0.07

[1] RMS error describing analytical model calibration of simulated to "measured" water levels during the period of record, November 1, 2010 to March 1, 2011.

[2] Difference between known (numerically simulated) and analytically estimated drawdown during pumping and recovery periods only, November 24, 2010 to March 1, 2011. Positive mean differences indicate underprediction.

A maximum drawdown of about 0.05 m was estimated where environmental fluctuations exceeded 0.2 m over a day. Drawdown estimates in additional observation wells within 0.7 km of the pumping well and in wells >3 km away from the pumping well (Halford et al. 2010) corresponded with drawdown estimates in well ER-20-5-3 and ranged from <0.015 to 0.05 m. Consistent distance-drawdown responses in all wells within a 3 km radius of the pumping well indicate that the ER-20-7 drawdown estimates are plausible.

Conclusions

The analytical drawdown estimation approach described here is shown to be reliable for estimating distant observation well response to aquifer-test stress where (1) environmental noise masks the pumping signal, and (2) the antecedent monitoring period is limited. With this approach, environmental water-level fluctuations caused by natural stress on the aquifer system, and the pumping signal from aquifer testing are analytically simulated simultaneously and distinguished from one another during pre-pumping, pumping, and recovery periods in order to estimate drawdown. Environmental fluctuations primarily are simulated with barometric pressure, background water-level, and computed dry- and gravity-tide components. Pumping signals are generated with Theis models, where step-wise pumping records of discharge are transformed into water-level changes using multiple superimposed Theis solutions. This approach closely approximated drawdowns that were numerically simulated with a complex three-dimensional, hypothetical model and reasonably estimated drawdowns from an aquifer test conducted in a complex hydrogeologic system.

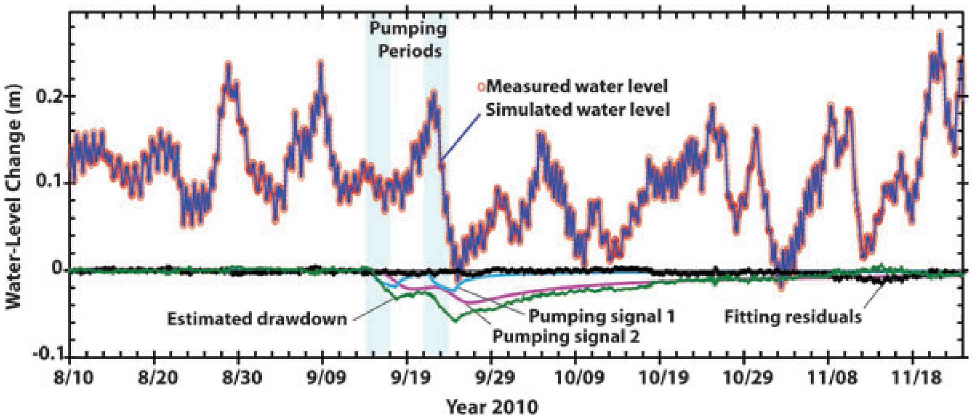

Figure 8. Measured and analytically simulated water levels, pumping signals, analytical fitting residuals, and analytically estimated drawdown in well ER-20-5-3 from pumping well ER-20-7 (Figure 1).

Drawdown responses to pumping that were numerically simulated with a complex three-dimensional MODFLOW model were closely approximated using the analytical drawdown estimation approach. Known (numerically simulated) drawdowns were analytically estimated within volcanic aquifers penetrating the same unit as the pumping well, in aquifers separated from the pumping well by tuff confining units, and in aquifers and confining units separated and vertically displaced from the pumping well by a major fault. Known drawdowns were added to the water-level record measured in a real background well, which represents environmental fluctuations only, in order to create hypothetical "measured" water-level records.

Differences between known and analytically estimated drawdowns result almost exclusively from noise in the measured time series. Pumping signals generated with Theis models could match hypothetical model output with RMS errors of prediction (differences between known and estimated drawdowns) of less than 0.0005 m. These RMS errors of prediction increased by more than 10 times when matching hypothetical "measured" water-level records where known drawdowns were obscured by environmental fluctuations. RMS errors of prediction for noiseless drawdowns were insignificant relative to drawdowns estimated from hypothetical "measured" water-level records.

Fitting errors between measured and analytically simulated water levels approximate the error associated with estimating drawdown during an aquifer test. RMS errors of prediction averaged less than three times the fitting errors between simulated and measured water levels. This facilitates estimating the overall measurement error, which is necessary for interpreting aquifer-test results with a highly parameterized, groundwater-flow model.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. File structure for hypothetical model (Hsieh and Winston 2002).
Figure S1. MODFLOW (MF) and water-level modeling (WLM) subfolders for the hypothetical model.
Figure S2. DFLOW, Batch, and Array files for the hypothetical model.
Figure S3. Hydraulic conductivity arrays for the hypothetical model.
Figure S4. Hydrographs of simulated "known" drawdowns for several observation points from the hypothetical model. These hydrographs were created from observation well results.
Figure S5. Water-level model files and input time-series data including continuous water levels in background wells, known drawdowns, barometric pressure, and pumping schedules for analysis of hypothetical model results.
Figure S6. Additional water-level models for hypothetical model results.
Figure S7. Water-level model files and input time-series for analysis of the Pahute Mesa (PM) ER-20-5-3 drawdown response to pumping well ER-20-7 in the Pahute_Mesa_Ex.zip file.

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