Case No. 84739

IN THE SUPREME COURT OF THE STATE OF NEVADA

Electronically Filed
Nov 08 2022 04:38 p.m.
Elizabeth A. Brown
Clerk of Supreme Court

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

Appellants,

vs.

LINCOLN COUNTY WATER DISTRICT, et al.

**JOINT APPENDIX**

**VOLUME 15 OF 49**

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September 17, 2019

2019 SEP 18 AM 11:38

*VIA U.S. MAIL*

Micheline Fairbank
Nevada Division of Water Resources
901 South Stewart Street, Suite 2002
Carson City, NV 89701

**RE: Western Elite Environmental, Inc. and Bedroc Limited, LLC**
**In the Matter of the Administration and Management of the Lower White River Flow System**
**Amended Exhibit: BEDROC Ex. No. 23-A**

Dear Ms. Fairbank:

On behalf of Western Elite Environmental, Inc. and Bedroc Limited LLC ("Bedroc"), enclosed for filing please find:

1. Two copies of [amended] BEDROC Ex. No. 23-A: SNWA Assessment of LWRFS July 3, intended to replace BEDROC Ex. No. 23 filed on September 6, 2019

2. A USB Flash Drive providing an electronic copy of the item listed above as well as an Updated Exhibit List in Excel format.

Thank you for your assistance with this matter. Please contact our office with any questions at (775) 786-8800.

Very truly yours,
SCHROEDER LAW OFFICES, P.C.

Lisa M. Gage
Paralegal

LMG:lmg
Enclosures
cc: Clients – *via email without enclosures*

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{P0474785; 1576.00 LMM }

July 3, 2019

Tim Wilson, Acting State Engineer
Nevada Division of Water Resources
901 S. Stewart St., Suite 2002
Carson City, NV 89701

Mr. Wilson,

The Center for Biological Diversity is pleased to submit the attached technical memorandum from hydrologist Dr. Tom Myers, regarding the questions raised by Interim Order 1303.

As the Center has stated from the beginning of this process, our primary concern is ensuring long-term sustainable flows in the Muddy River Springs Area (MRSA) to ensure adequate habitat for the survival and recovery of the federally protected endangered Moapa dace. Protecting the dace is a legal obligation for the Division of Water Resources, in order to ensure compliance with the federal Endangered Species Act, and acting in compliance with NRS 533.370(2) to ensure that water right applications are not "detrimental to the public interest."

Dr. Myers' report contains three primary conclusions:

- The Division should not allow any pumping of the carbonate aquifer if the continued decrease in spring flow in the MRSA is to be avoided.
- The Kane Springs Valley should be managed as a part of the LWRFS.
- Some basin-fill pumping could occur without significantly affecting MRSA spring flow, with a preliminary estimate of 4,000 afa as a sustainable yield.

We appreciate this opportunity for engagement and look forward to further discussions on this issue.

Sincerely,

Patrick Donnelly
*Nevada State Director*
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**Technical Memorandum**

**Groundwater Management and the Muddy River Springs, Report in Response to Nevada State Engineer Order 1303**

**June 1, 2019**

**Prepared for: Center for Biological Diversity**

The Nevada State Engineer (NSE) is planning to establish a plan to conjunctively use groundwater and surface water in the Lower White River Flow System (LWRFS). The NSE has established the LWRFS as the valleys shown in Figure 1, except that only the northern portion of Black Mountains Area would be included. The basis for his planning is the Order 1169 aquifer test results and observations ongoing since the end of the test. The NSE in order 1303 requested that stakeholders provide reports with "further analysis of the historic and ongoing groundwater pumping data, the relationship of groundwater pumping within the LWRFS to spring discharge and flow of the fully decreed Muddy River, the extent of impact of climate conditions on groundwater levels and spring discharge, and the ultimate determination of the sustainable yield of the LWRFS" (NSE Order 1303, p 11). This report addresses the four points the NSE requests stakeholders to address, although in a different order:

1. The report summarizes the Order 1169 aquifer test, specifically regarding groundwater levels throughout the LWRFS and spring flows at Muddy River Springs, and extends the interpretations through the recovery period of 2013 through the present,
2. The report considers the reasons to consider Kane Springs Valley (KSV)as part of the LWRFS (the water level is just five feet higher than in Coyote Springs Valley (CSV), and pumping in KSV could reverse the gradient pulling water from CSV,
3. The report addresses the long-term quantity of water that could be pumped from the LWRFS without harming any Muddy River Springs. (Because of the flat gradient over the 1100 sq miles of the joint management area, there can be no location for pumping within the LWRFS that is safe meaning it would not affect Muddy River Springs),
4. Finally, the report also considers the relationship between alluvial and carbonate wells and how that could affect senior decreed rights to the Muddy River.

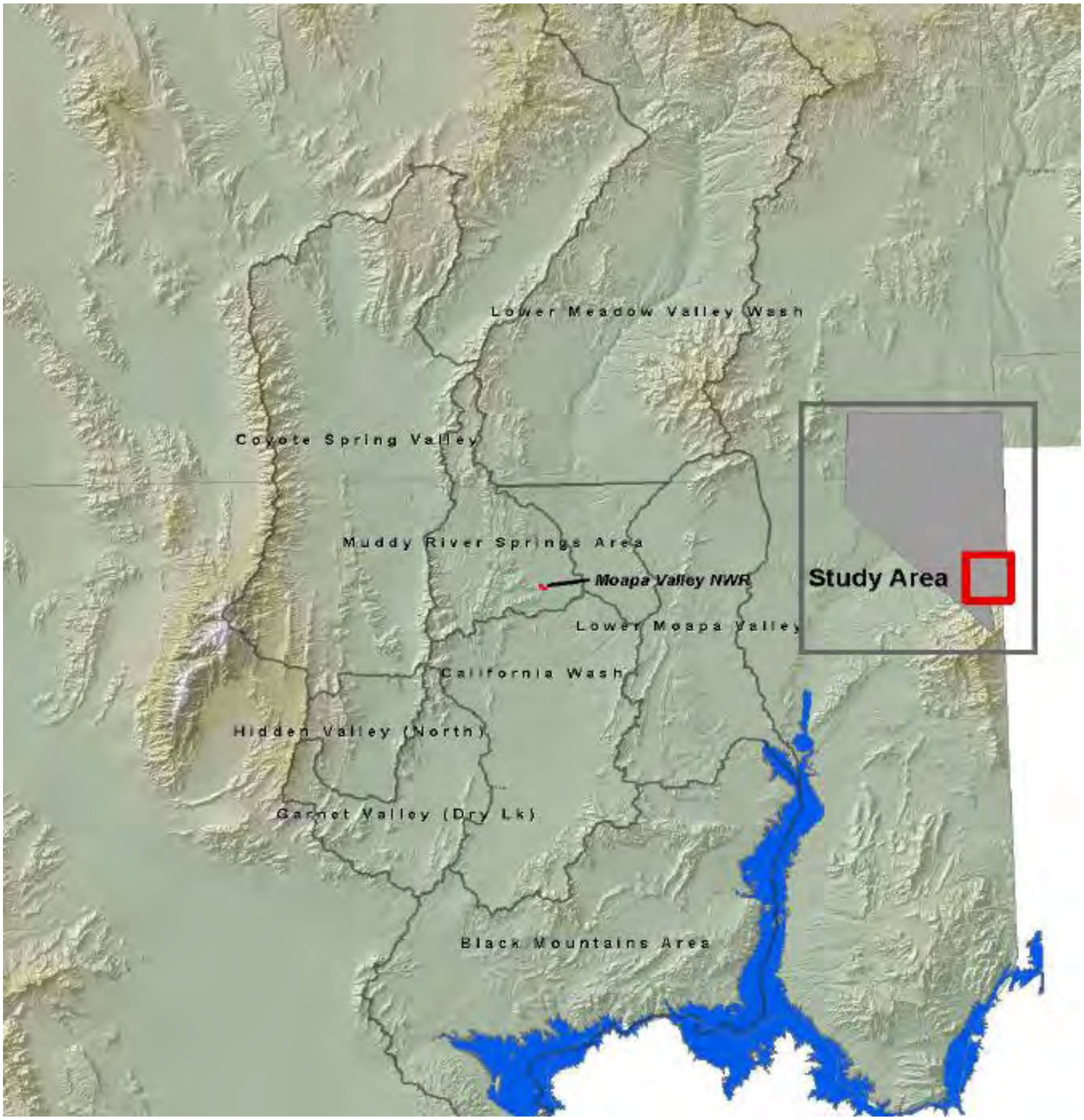


**Figure 1: Study area showing the Lower White River Flow System. Kane Springs Valley is northeast of Coyote Spring Valley. Source: USDOI (2013).**

## Order 1169 Aquifer Test and the Period 2013 to 2019

NSE Ruling 6254 summarizes the finding of the 1169 aquifer test as reported on by various stakeholders including SNWA (2013), US DOI (2013), Myers (2013), and Johnson and Mifflin (2013). The 1169 aquifer test had been required by NSE Order 1169 to determine the effects of developing the carbonate aquifer in CSV. The order had required the participants to pump 8050 acre-feet per year (afa) from wells in CSV for two years. However, for the duration of the test, from November 15, 2010 to December 31, 2012, the total pumpage from the CSI wells and MX-5 well was 11,249 af, or only 5290 afa. During the test period, 79 monitoring and pumping wells (MWs and PWs) monitored water levels throughout the area (Figures 2 and 3). The CSV carbonate PWs lie on the east side of the valley near the boundary with Muddy River Springs Area (MRSA) and basin fill and carbonate MWs lie throughout the valley (Figures 2 and 3). MRSA wells concentrate along a trend along a wash running southeast through the middle of the valley (Figures 2, 3 and 4). The Arrow Canyon wells (Figure 3) are high-producing carbonate wells. The basin fill pumping wells on the southeast portion of MRSA are commonly called the Lewis Well field. The Muddy River Springs also lie in the far southeast portion of MRSA. The clastic rocks just east of the MRSA (Figure 4) may provide a structural boundary that partly controls flow and the location of the Muddy River springs (Johnson and Mifflin 2013).

Southern Nevada is generally very dry and average recharge over the LWRFS is very low (NSE Ruling 6254). But some years can be relatively very wet and the runoff that occurs during those years can cause recharge into washes and into outcrops of conductive rock. The twelve-month moving average of monthly precipitation ranges averages near half an inch but was close to zero in 2002 and approached 1.3 inches in 2005 (Figure 5). These monthly values correspond with an annual average of about 1 inch and 14 inches per year in those years, as reported by USDOI (2013). Several years in the 1990s have monthly average precipitation near an inch. During the aquifer test, the first year, 2011, appears to be slightly wetter than the average and 2012 became dry relative to most years.

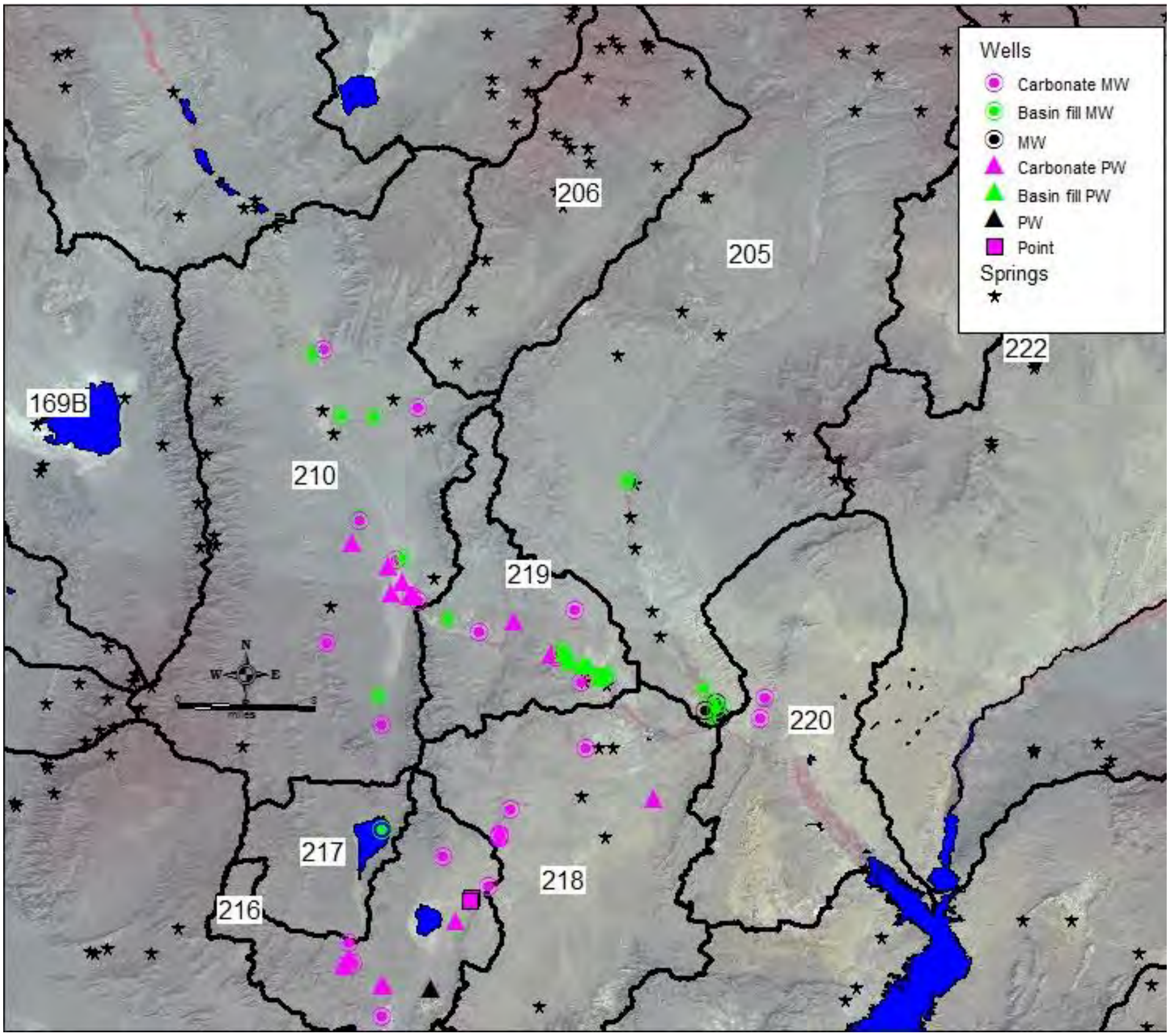


**Figure 2: General layout and type of wells in the Coyote Spring Area. Basin 210 is Coyote Spring Valley, 219 is Muddy River Spring Area, 220 is Lower Moapa Valley, 218 is California Wash, 217 is Hidden Valley, 216 is Garnet Valley, 205 is Lower Meadow Valley Wash, and 206 is Kane Springs Valley. MW is monitoring well; PV is production well. See Figure 3 for the names for some of the wells. Source of well data: NVSE website.**

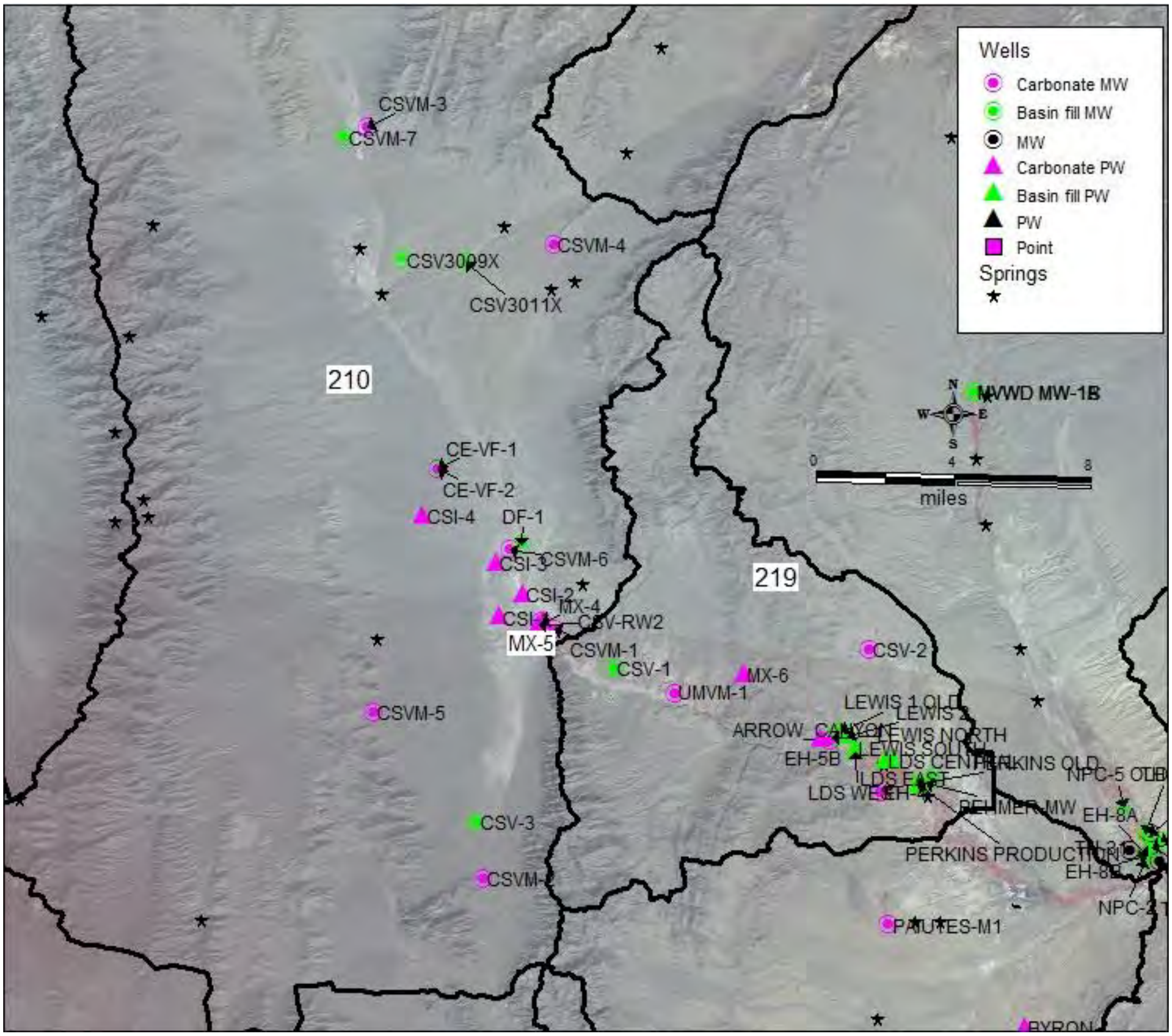


**Figure 3: Detailed well layout and names for Coyote Spring Valley (210) and Muddy River Springs Area (219). Source of well data: NVSE website.**

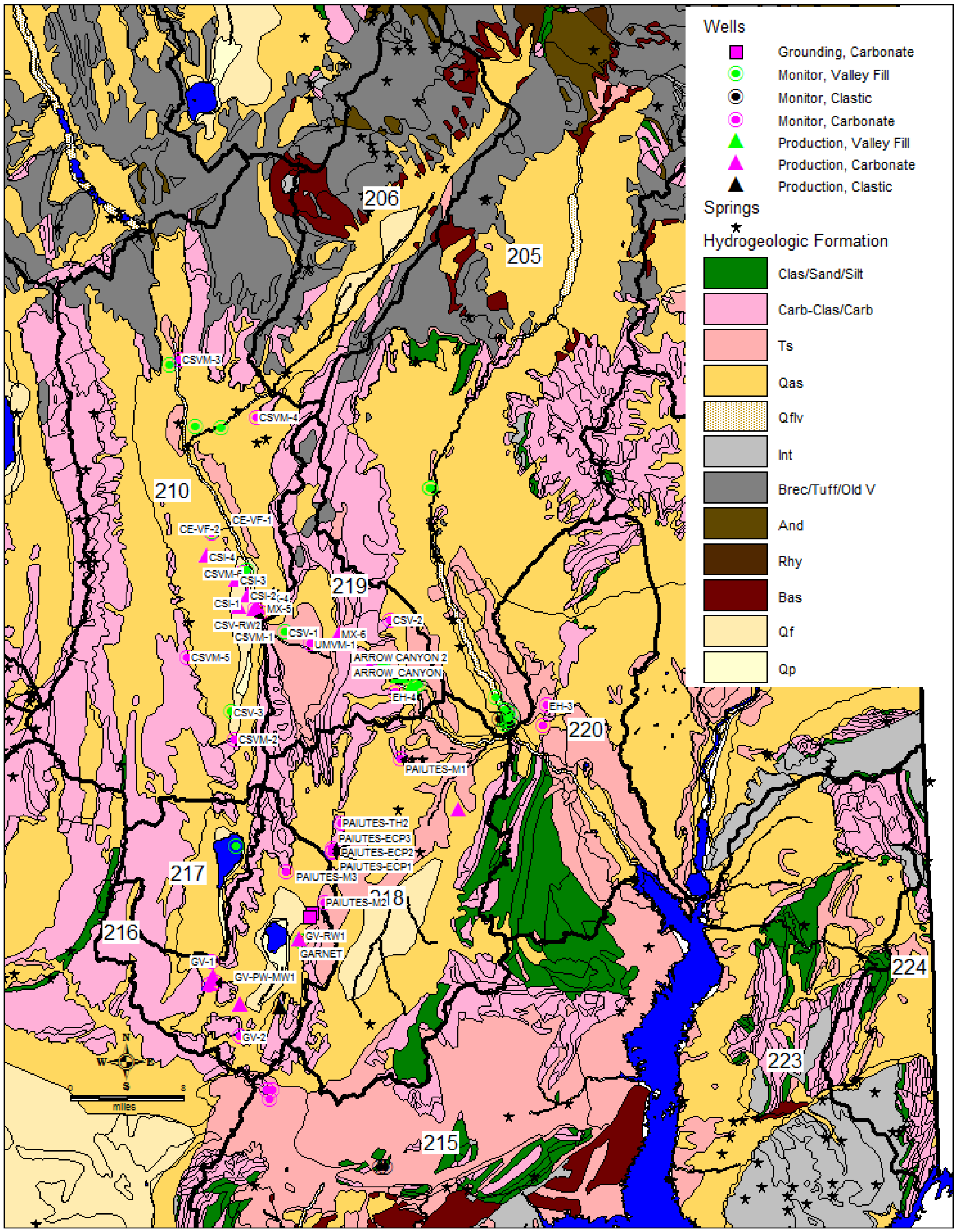


**Figure 4: Lower White River Flow System wells and hydrogeology.**

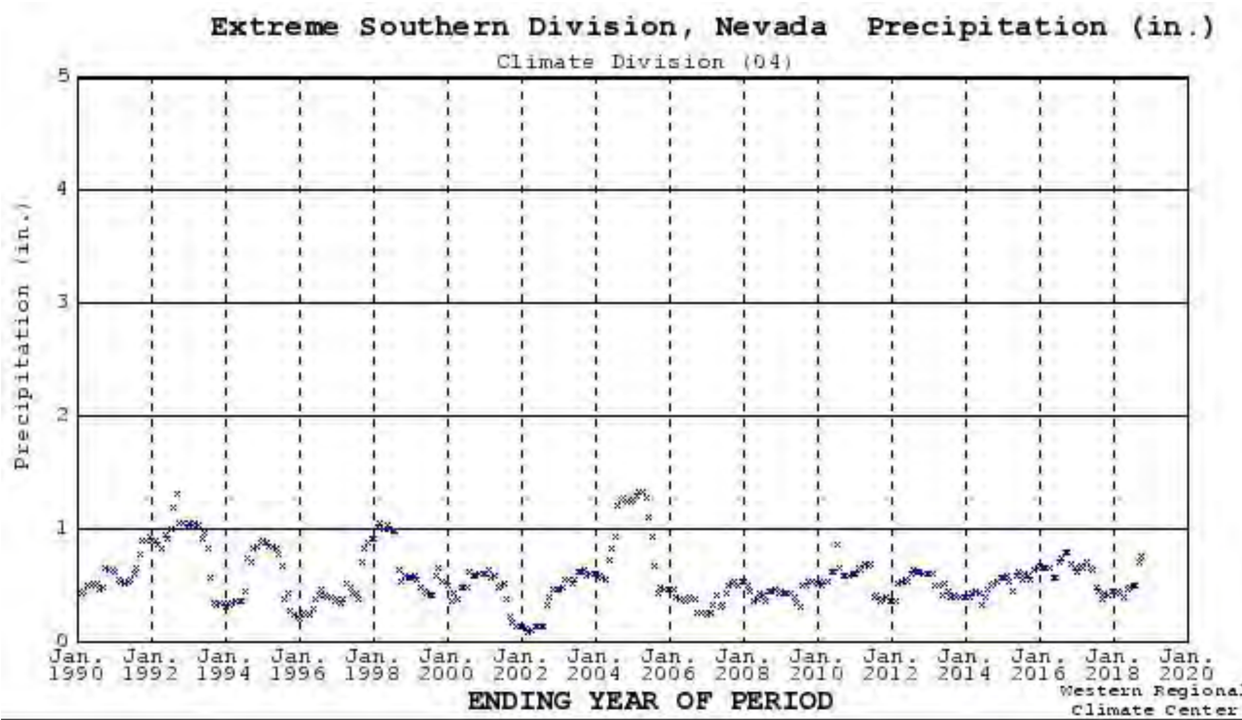


**Figure 5: Twelve-month running average of precipitation for the southern zone of Nevada. Data from the Western Regional Climate Center, https://wrcc.dri.edu/spi/divplot2map.html**

The NSE found that even the reduced pumping completed during the aquifer test satisfied its goals and that pumping in CSV caused impacts north in CSV "at least to Kane Springs Valley, south to Hidden Valley and Garnet Valley, and southeast to Muddy River Springs Area and California Wash" (NSE Order 6254, p 20-21). There was no monitoring for the test in Kane Springs Valley, so it is not possible to assess whether the impacts extended into that valley. USDOI (2013) concluded the impacts covered 1100 square miles. NSE summarized that groundwater level declines attributable to MX-5 pumping ranged from less than one foot in northern CSV to more than two feet in central CSV to more than a foot in central MRSA and California Wash (NSE Order 6254, p 21). The following paragraphs detail the water levels before, during, and after the aquifer test.

Carbonate MWs in central and southern CSV have varied in parallel since the early 2000s (Figure 6). The trend has been downward except for the increase during the wet period around 2005. All the carbonate MWs in central and southern CSV decreased more than two feet during the pump test period and all have recovered less than half the pump-test decrease by 2019 (Figure 6). The lack of recovery indicates the increased gradient, caused by the 2-foot drawdown, does not draw substantially more water from beyond the boundaries of the high-transmissivity area. Drawdown in northern CSV was much less (not shown). Basin fill well groundwater levels in the southern portion of CSV have also trended downward since the late

1990s, with an exception being during the wet period around 2005 (Figure 7). Well CSV3011M water levels increased from its installation in 2008 until the aquifer test. Well DF-1, a basin fill well in the middle of southern CSV, has water levels about 200 feet higher than other wells in the area.

Carbonate MWs in the MRSA also show a long-term downward trend commencing in the 1990s with an uptick in 2005 (Figure 8). USDOI (2013, p 11) identified several wet year responses in the groundwater levels, including in 1992, 1993, 2005, and to a lesser degree in 1998 and 2011. The small seasonal fluctuation may relate to pumping in the basin fill (Id.), which would reflect the connection between aquifers. The 1169 aquifer test accelerated the decline in the MWs in the MRSA with a decrease of as much as 2.5 feet. Recovery since the decline was as much as a foot in the first year, but levels have remained steady since.

Basin fill MWs in the Lewis Field portion of the MRSA have been steady since the 1990s except for a three-foot decline in the Lewis North MW (Figure 9). Lewis South and Lewis 1 Old have declined a couple feet since the 1990s, but with an almost ten-foot seasonal variation. Seasonal variation in Lewis North was much less. All wells in the Lewis Field portion of the MRSA exhibited a substantial drawdown of several feet during and for two years after the pump test (Figure 9).

Basin fill MWs near the springs have declined, other than the uptick in 2005, since the 1990s much more than the Lewis Field wells (Figure 10). The decline accelerated through the aquifer test period, although, in contrast to the carbonate wells, these basin fill wells have mostly recovered since the aquifer test. Seasonal variations are as much as ten feet. The downward trend probably reflects the trend in the carbonate wells, the source for most basin fill water. Recovery however could be due to decreased pumpage in the Lewis Field, as discussed below.

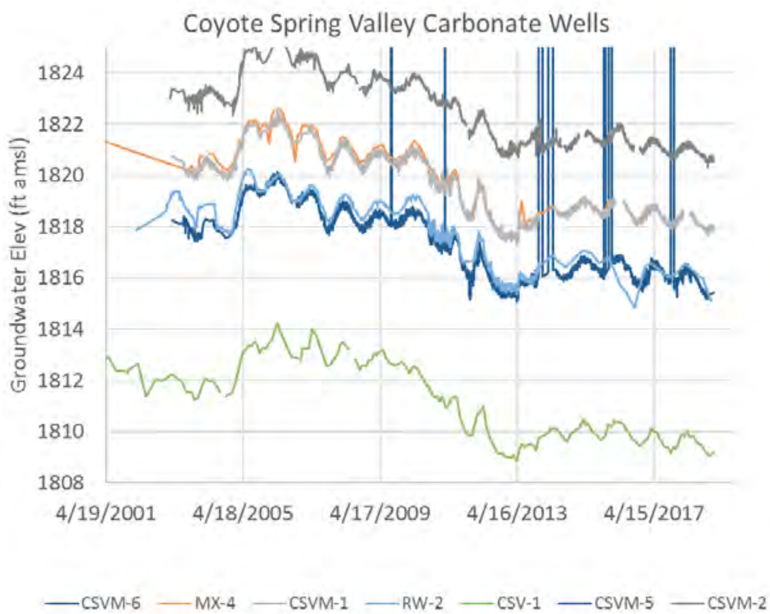


**Figure 6: Hydrograph of carbonate monitoring wells in Coyote Spring Valley, through the Order 1169 pump test and to 2019. Source of data-NSE web page.**

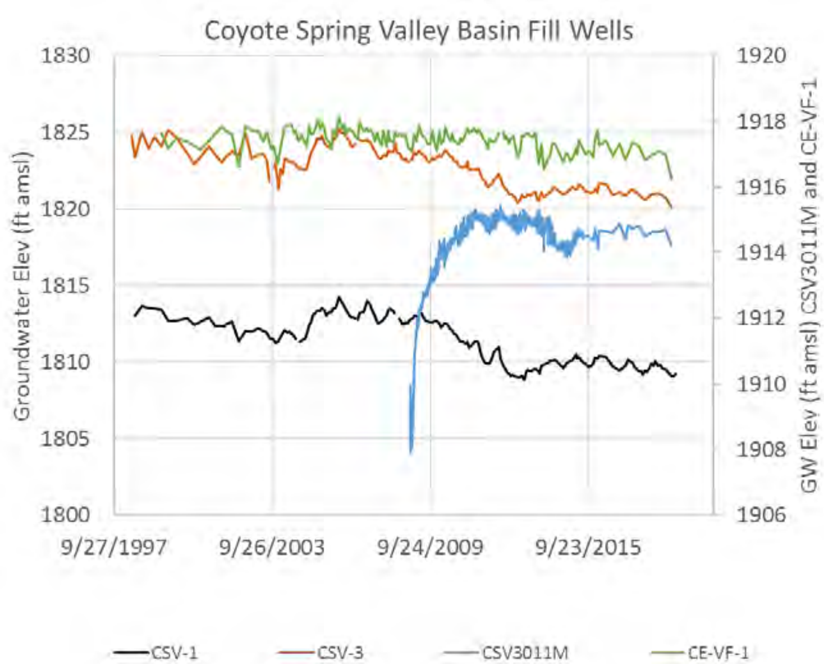


**Figure 7: Hydrograph of basin fill monitoring wells in the south half of Coyote Spring Valley. Source of data - NSE web page.**

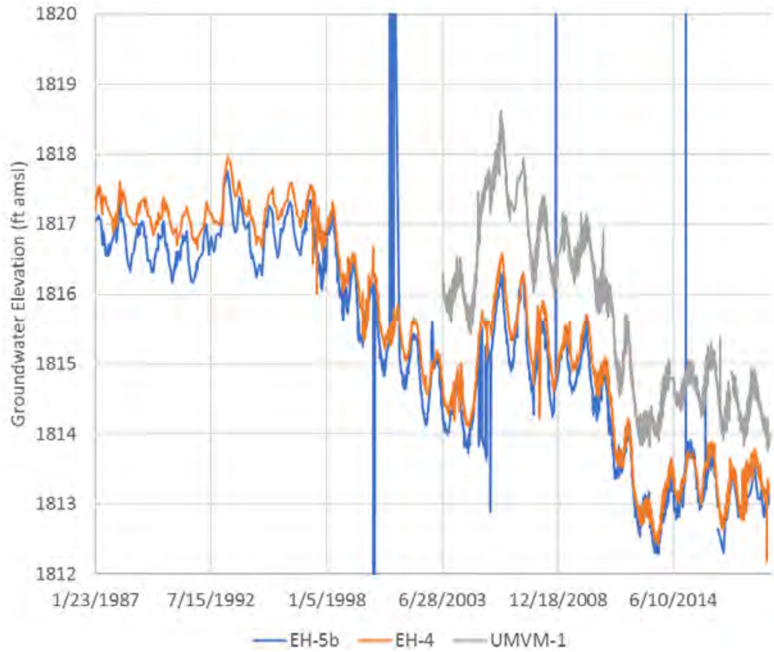


**Figure 8: Muddy River Springs Area carbonate monitoring wells.**

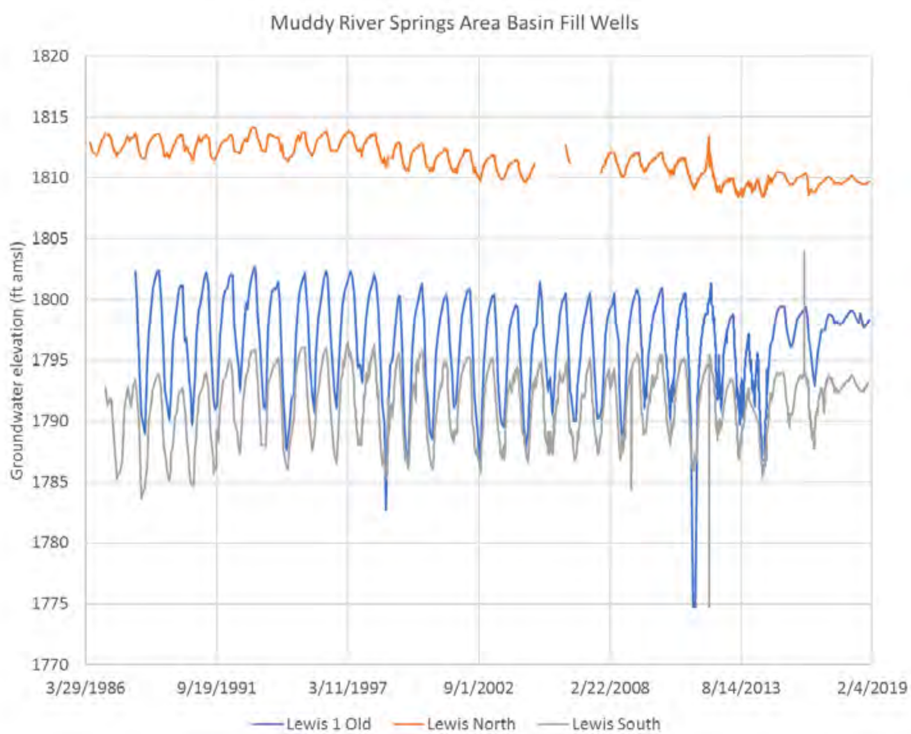


**Figure 9: Hydrographs of basin fill wells in the Lewis Field portion of the Muddy River Springs Area. Perforations are from 28 to 68 feet bgs for Lewis North and are unknown for the other wells. Source of data - NSE web page.**

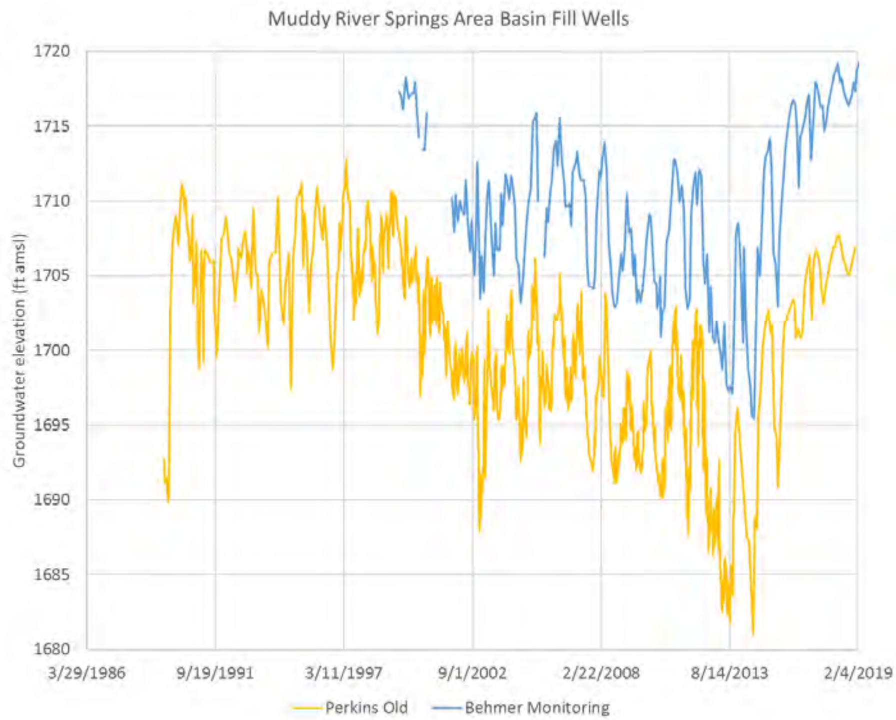


**Figure 10: Hydrographs of basin fill wells in the Muddy River Springs portion of the Muddy River Springs Area. The Perkins Old well is screened from 20 to 60 ft bgs. Source of data -NSE web page.**

The groundwater levels recorded at the end of the pump test throughout the CSV and MRSA show the very flat potentiometric surface from midway up CSV through the MRSA. The groundwater gradient through the area affected by the pump test is very flat because of the likely very high transmissivity from about the southern half of Coyote Spring Valley through the Muddy River Springs and further downstream to the Lower Moapa Valley (Figure 11). The groundwater elevation ranges from about 1815 ft above mean sea level (amsl) at CSVM-6 almost three miles northwest of MX-5 to about 1814 at UMVM-1 about 4 ½ miles southeast of MX-5. Interestingly, the groundwater elevation is 1817 at CSVM-1 which is very near MX-5, which itself is at 1813. In other words, there is a small rise in the potentiometric surface of the carbonate aquifer southeast of MX-5. The minor groundwater divide may be slightly southwest of the direct flow path, thereby partly bounding the divide. During pumping, water levels throughout this highly transmissive aquifer responded as if the aquifer water is a pond with water level changes transmitted quickly throughout.

Carbonate water levels in northern CSV are several tens to almost 400 feet higher than near the southeast portion of CSV, but the water levels did decline during the aquifer test (USDOI 2013). The groundwater level in MW CSVM-4, in CSV but near the southern end of Kane Springs Valley, is just six feet lower than well KMW-1 (206 S11 E64 06CACC1) further north in Kane Springs Valley. This suggests the high transmissivity carbonate rock extends into that valley.

Carbonate groundwater levels drop almost 250 feet between the MRSA and the southeast portion of the Lower Meadow Valley Wash valley. The carbonate groundwater levels in the MRSA are several tens of feet above the levels in the basin fill, which drives upward flow into the basin fill. Both observations support the idea of a flow impedance in the carbonate aquifer near the southeast boundary of MRSA which could be a major cause of the springs.

Basin fill water levels in Coyote Spring are substantially higher than the carbonate water levels. Most apparent is CE-VF-2 for which the water level is more than 50 feet lower in the carbonate (Figures 2 and 11). Basin fill well DF-1 groundwater levels exceed 2000 ft amsl while underlying carbonate wells have levels 200 feet lower. Because of the aridity of the area and because of the likely confining unit between the aquifers, it is unlikely the higher basin fill levels reflect substantial recharge to the carbonate. Rather it suggests a hydrologic disconnect. Groundwater levels in basin fill wells CSVM3009M and DF-1 have been trending upward, with no signal from the aquifer test; this also indicates there is no connection between carbonate and basin fill.

Downgradient in the Muddy River Springs Area, the carbonate water levels exceed those in the basin fill, which reflects the discharging springs in the area. In the Lower Meadow Valley Wash area, outside of the pump test study area, at wells MW-1 there is a substantial upward gradient from depth in a very thick basin fill aquifer.

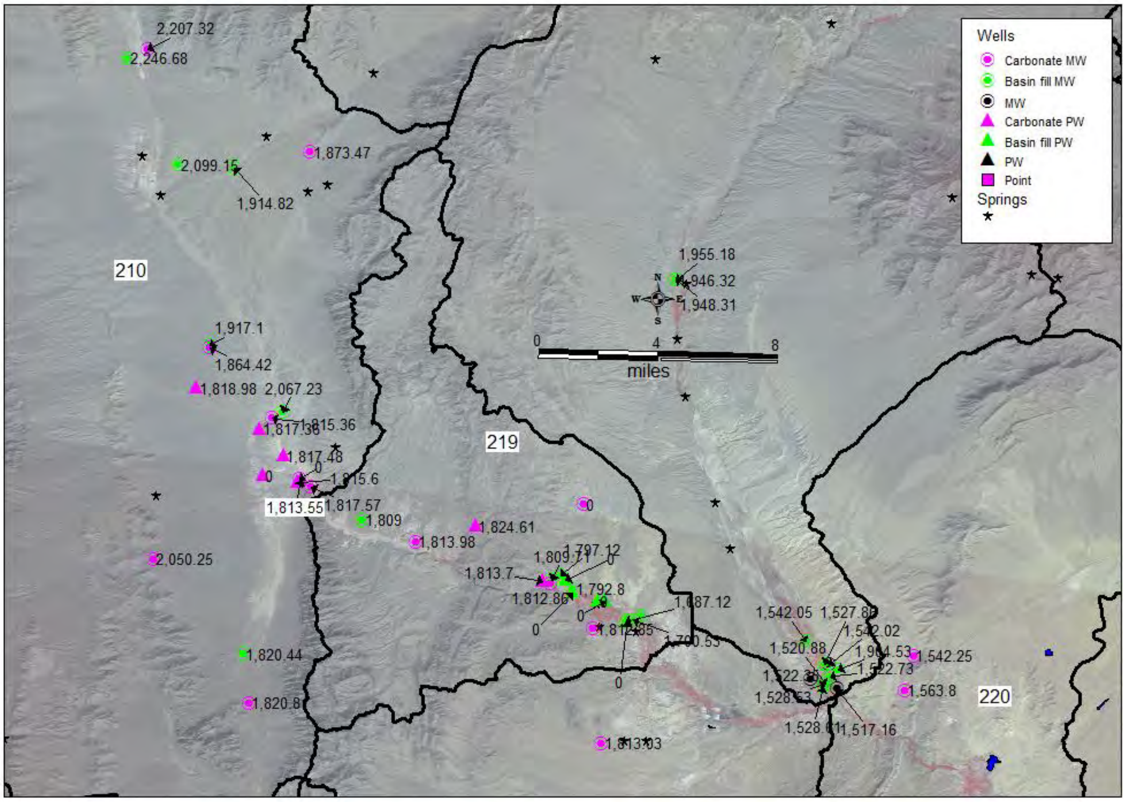


**Figure 11: Groundwater level at various wells throughout the study area. See Figure * for the well names. The label 0 means either the data is not available or the well is a production well and the water level is very low.**

A profile of the carbonate groundwater levels through CSV and MRSA at the beginning and ending of the aquifer test demonstrates the flatness of the potentiometric surface in the high transmissivity zone through the area and how the response decreases to the north (Figure 12). For almost 20 miles, the carbonate water level is between 1820 and 1813 feet amsl. During the aquifer test, the level consistently dropped about 2 feet. The small rise at CSVM-1 may reflect a slightly higher groundwater ridge south in CSV, as seen at well CSVM-2 where the groundwater levels exceed 1820 feet amsl about five miles south of the profile line (Figure 11). This slight rise suggests there is no flow south from CSV but the groundwater levels in southern CSV did decline during the aquifer test.

Further north at CSVM-4, the groundwater level change was less than a foot. Groundwater levels at well CSVM-4 are also several tens of feet higher than further south. As noted, groundwater levels rise about six feet into Kane Springs. Even further north, carbonate groundwater levels are about 200 feet higher and there was little effect from the aquifer test. Transmissivity is probably lower in northern CSV as reflected by the steeper gradient. Inflow to CSV from Pahranagat or Delamar Valley flows through the lower transmissivity area to reach southern CSV and well MX-5.

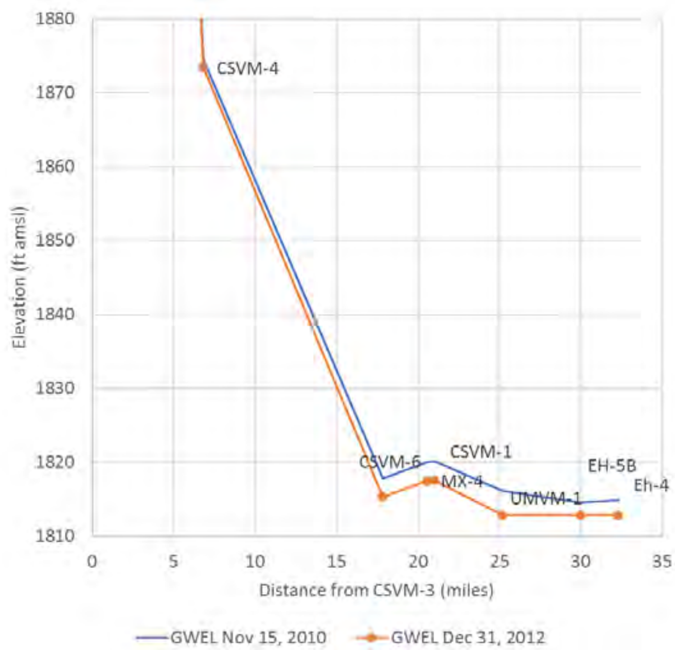


**Figure 12: GW elevation from northern Coyote Spring Valley to well EH-4 at the beginning and end of the Order 1169 pump test.**

The changes in groundwater levels in the carbonate aquifer manifests in the Muddy River Springs Area (Figure 13) spring flows. Pederson Springs and Warm Springs West provide most of the flow to one of the channels that is tributary to the Refuge Stream, which is then tributary to the Muddy River Channel (Figure 13). The Pederson Springs are the highest elevation springs on the site.

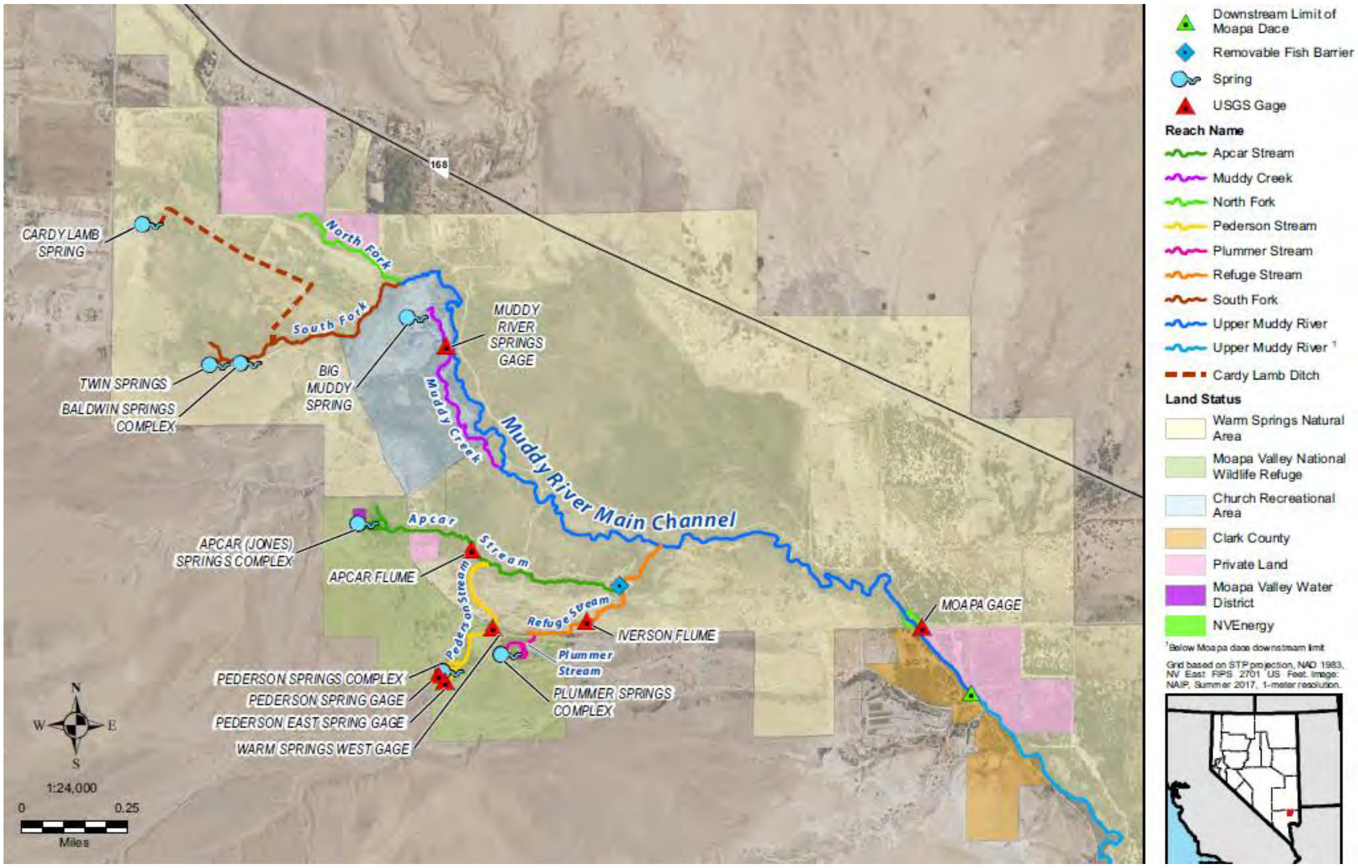


**Figure 13: Muddy River Springs area. Source, SNWA (2018) Figure 2-1.**

Discharge from the Warm Spring West decreased from about 4.0 cfs to as low as 3.4 cfs between the 1990s and mid-2000s, then after an uptick in flows in the wet period in 2005 (Figure 14) and during the Order 1169 pump test dropped to almost 3.2 cfs (Figure 14). It has recovered only to a little more than 3.4 cfs since 2012. At the Pederson springs, flow is about half of what it was in the mid-2000s, with much of the decrease occurring during the Order 1169 pump test (Figure 15). Flows recovered some after the test, but for about four years flows have been steadily low. At the Pederson Springs East gage, flows had fluctuated around 0.2 cfs prior to the pump test during which the flow decreased to about 0.14 cfs (Figure 15). The flow has not recovered at these springs.

USDOI (2013) determined that the flow rate at Pederson Springs had declined about 63% and at Pederson East Spring about 45% during the test. Flow at Warm Springs West (Figure 14) declined about 9% during the test. USDOI (2013) correlated spring flows to carbonate groundwater level drawdown and found that if the rate of drawdown observed during the aquifer test continued, Pederson Spring, the highest elevation spring in the MRSA, would have gone dry in 1.5 years. USDOI also estimated that Pederson East Spring would have gone dry in another 2.5 to 3 years if pumping continued. In other words, if the trend observed on Figure 15 had continued, the springs would be dry. Flow at Jones and Baldwin Springs (Figure 13) declined about 4%. Curiously, the flow at Muddy Springs increased by 19% per year, possibly due to decreased evapotranspiration (ET) resulting from a fire in July 2010.

USDOI also estimated that 80 to 90% of the groundwater pumped during the aquifer test was drawn from groundwater storage (USDOI 2013, p 4) which means that the groundwater system is far from being in equilibrium, which occurs when inflow (recharge and groundwater flow from adjoining basins) equals the outflow. Although several ecologically important springs had their flow reduced substantially during the aquifer test, those flow reductions represent only a small portion of the outflow from the LWRFS. Continued pumping at those rates would have continued to decrease spring flow as the pumping removed additional groundwater storage and decreased the groundwater level controlling discharge from the springs. Even after pumping ceases, groundwater discharge would continue to reduce as it is diverted to replenish the groundwater storage (make up drawdown).

The discharge before the aquifer test was spring discharge and existing pumpage. As pumpage increased, the spring discharge would decrease until the sum equals the inflow. Because of the extremely flat gradient through the carbonate system, the pump test has essentially reset steady state conditions. A major recharge event may eventually allow some temporary recovery, as was seen in 2005, but the ongoing pumping would resume the drawdown trend.

The limited recovery in carbonate groundwater levels and springs indicates there is a steady state inflow to the system. Inflow from upstream would not increase due to drawdown in CSV because the controlling gradient is quite high due to the drop from Delamar and Pahranagat Valley into CSV. Between Hoyt Spring in Pahranagat Valley and MW CSVM-3, a distance of 11.47 miles, the water level drops from 3195 to 2207 ft amsl for a gradient of 0.0163. This assumes the water level in Hoyt Springs is that of the carbonate aquifer. Between Delamar Valley and Coyote Spring Valley, the gradient would be the difference in water level between well 182 S07 E64 19ACDB1 at about 3480 ft amsl and CSVM-3 over 20 miles, or be 0.012. Between groundwater levels in Kane Springs Valley at well 206 S11 E64 06CACC1 at 1878 ft amsl and CSVM-4 at 1873 ft amsl over about 6 miles, the gradient is about 0.00016. The flat gradient through the Coyote Spring Valley apparently extends into Kane Springs Valley, so it is possible that some flow could be induced from Kane Springs Valley by pumping in CSV.

The drawdown in the MRSA alluvial wells suggests that lowering the water levels in the carbonate is decreasing the inflow from below into the alluvium. Spring flow has decreased but it is doubtful this has been sufficient to decrease secondary recharge.

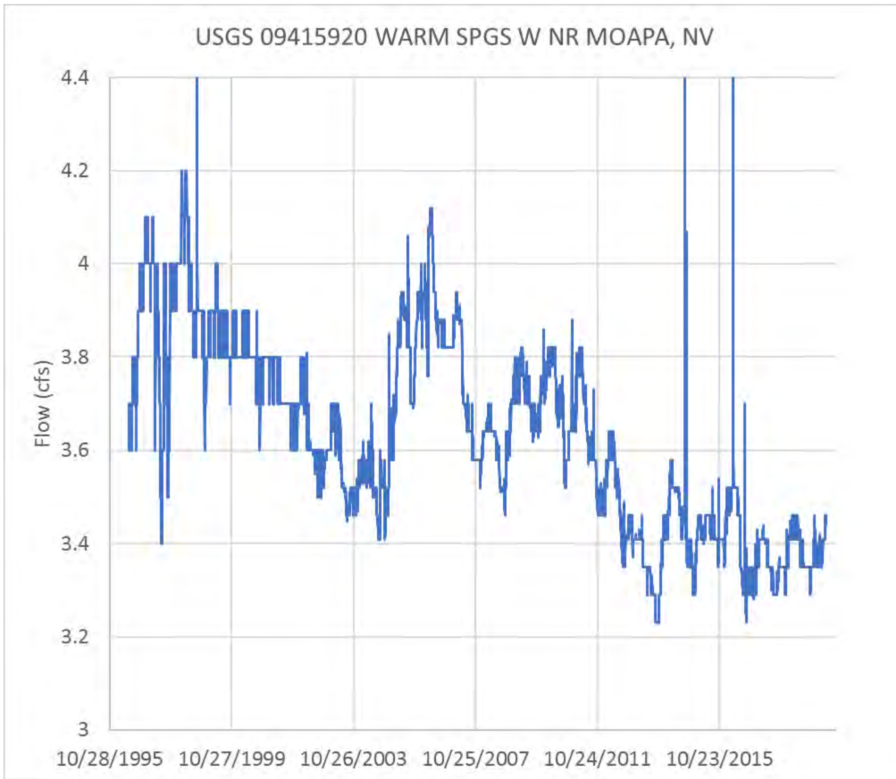


**Figure 14: Daily flow at Warm Springs W near Moapa.**

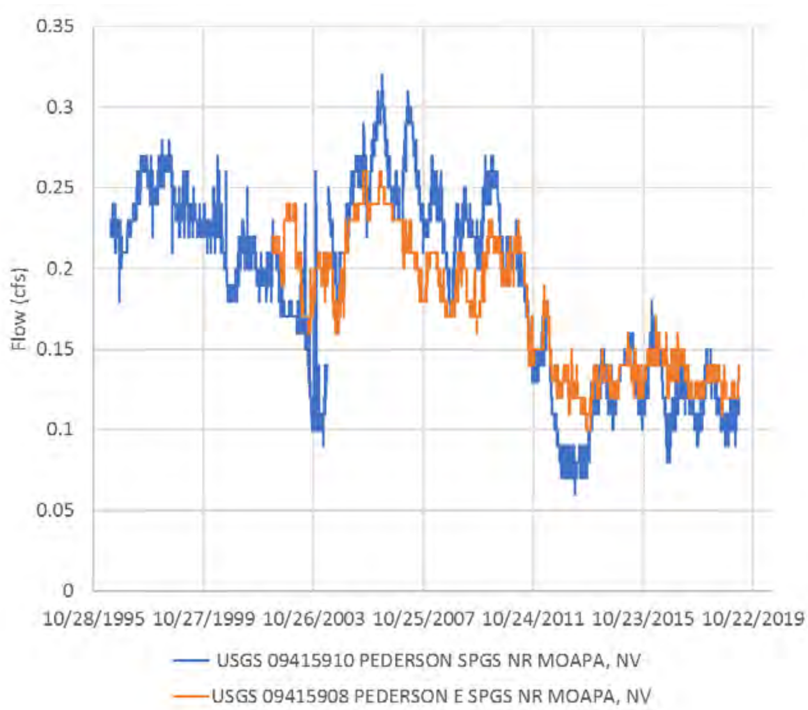


**Figure 15: Daily flow at the Pederson gages**

**Boundary of the Lower White River Flow System**

NSE Order 1303 requests the reports filed in response to the order address the "geographic boundary of the hydrologically connected groundwater and surface water systems comprising the Lower White River Flow System" (NSE Order 1303, p 13). The NSE has already outlined reasons for including CSV, MRSA, Garnet Valley, Hidden Valley, a portion of the Black Mountains Area, and the Lower Moapa Valley. The analysis herein and the analyses of USDOI (2013), SNWA (2013), Myers (2013), and NSE Order 5462 found a large high transmissivity area within the carbonate aquifer of these areas and basin fill aquifers within CSV, MRSA and Lower Moapa Valley that should be managed as one basin.

Information presented herein suggests that Kane Springs Valley should be added to the LWRFS. Because water levels in that basin are just a few feet higher than in adjoining portions of CSV, the gradient between them is very low. Pumping in Kane Springs Valley that decreases that gradient would decrease flow into CSV in a time frame likely measured in less than a few years. I base the time frame estimate on the rapid response observed in the aquifer in CSV and the assumption that a carbonate aquifer extending into Kane Springs Valley would also have a high transmissivity. Because of the very low perennial yield in Kane Springs Valley and lack of inflow to the valley from upgradient valleys, pumpage in Kane Springs Valley could reverse the gradient and draw water from CSV. Considering how fast MX-5 pumping manifest through the carbonate aquifer, a decreased flow into or reversed flow from the high transmissivity portion of the CSV carbonate aquifer would also spread through the system and lower the groundwater levels. It would have a significant effect on water rights through the LWRFS. Lowering the water table in CSV could increase the gradient between CSV and Kane Springs and draw a small amount of groundwater into the CSV. Because groundwater at the source in Kane Springs is limited, inducing flow from Kane Springs Valley is not a sustainable means of increasing the available water in LWRFS. Kane Springs should be managed as part of LWRFS.

Groundwater levels in northern CSV were several hundred feet higher than in southern CSV and there was no apparent effect of the drawdown reaching MW CSVM-3. Transmissivity in northern CSV is likely lower than further south. There is no evidence of an impedance caused by a fault structure isolating north CSV because a fault would prevent groundwater from flowing south through CSV. The pump test did not propagate to that point during the test but there is no evidence suggesting it would not do so if the pumping continued. Developing groundwater in this area would intercept groundwater flowing into southern CSV and have the same effect as diverting from Kane Springs Valley; it would decrease flow to the springs and downgradient water rights.

The ultimate source of groundwater for the LWRFS is upgradient in Pahranagat and Delamar Valley. Recharge in each of these valleys could combine with interbasin flow from upstream to provide the inflow to CSV. Groundwater developed upstream, especially in Delamar, Dry Lake or Cave Valleys, would ultimately decrease flow to CSV. The only question is timing. Once depletions upstream reach CSV, they will manifest as a loss of flow to the LWRFS. The inflow of approximately 47,900 afa will begin decrease[1]. As shown by the Order 1169 aquifer test, this reduced flow will propagate through the system and manifest as reduced carbonate water levels and spring flows. The Judge Esty order[2] properly requires that the NSE not grant any water rights above CSV in order to protect water rights and spring flows in the LWRFS in perpetuity.

The White River Flow System above CSV does not have to be added to LWFRS boundary in order to manage it properly. Developing groundwater in the LWRFS will not propagate impacts north of CSV.

**Long-term Quantity of Water that Could be Pumped from LWRFS**

One limit on pumping water in the LWRFS are the impacts caused by that pumping on spring flow necessary to support the Moapa Dace and water rights to flow from the springs and in the Muddy River. The recovery plan for the Moapa Dace requires that existing instream flow and historical habitat be protected in three of five channels supported by springs in order to reclassify the dace. The five channels are Apcar, Baldwin, Cardy Lamb, Muddy Spring, and Refuge (Figure 13) (USFWS 1996, p 33, 34). According to the recovery plan, all five must be protected for delisting. USFWS does not specify a required flow rate for each channel, but a Memorandum of Agreement (MOA) signed by Southern Nevada Water Authority, Coyote Springs Investment, Moapa Valley Water District, and the Moapa Valley Paiute Tribe, established trigger ranges for flows at Warm Springs West. Figure 16, sourced from the NSE

[1] The DEIS groundwater model (SNWA 2009) simulated that all flow went from Delamar Valley to Pahranagat Valley and then to CSV (as shown in a data file accompanying the original reference: folder/file deis groundwater model/simulation files/3_Detailed_Results/Interbasin-Flow-Tables/IBF_rev2_1b_NoAction.xls). The estimated flow was 41,900 afa. The value did not vary due to project development. There was also 1900 afa flow from Kane Springs Valley to CSV. NSE Ruling 6167 concluded that inflow from Tikaboo South Valley to CSV is 4100 afa. This brings the total inflow to 47,900 afa. In his presentation on LWRFS of July 24, 2018, the NSE estimated inflow equaled 47,502 afa. He also estimated CSV LWRFS recharge at approximately 3000 afa, so the total supply is 50,500 afa, which the NSE stated was "50,000 afa or less" (NSE July 24, 2018 LWRFS Presentation, p 41).

[2] White Pine County and Consolidate Cases, Et al, v Jason King, P.E., Nevada State Engineer, State of Nevada Division of Water Resources. In the Seventh Judicial District Court of the State of Nevada in and for the County of White Pine. Case No. CV1204049. The ruling required the NSE to recalculate "appropriations from Cave Valley, Dry Lake and Delamar Valley to avoid over appropriation or conflicts with downgradient, existing water rights". (NSE Ruling 6446, p 109)

July 24, 2018 presentation regarding the LWRFS, describes the trigger ranges and pumping limitations for the MOA. Warm Springs West is on the Pederson Stream which is not listed as one of the channels for protection in the recovery plan but does contribute to the Apcar Channel (Figure 13). Warm Springs West flows almost dropped to 3.2 cfs during the aquifer test (Figure 14).

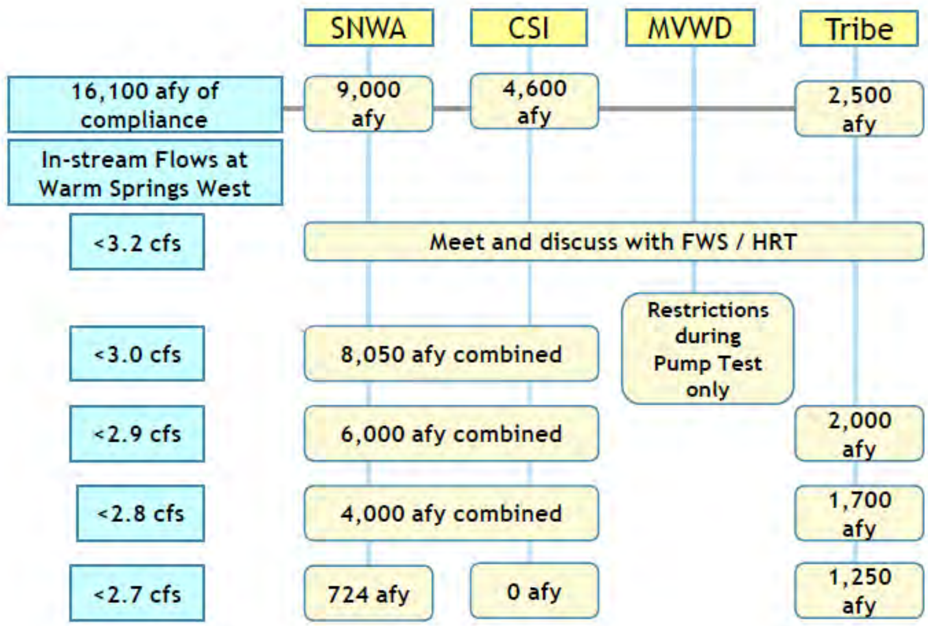


**Figure 16: Description of trigger flows and pumping limits for those trigger flow for the Memorandum of Agreement described in the text.**

The 1920 Muddy River Decree has total rights of 37,000 afa, as noted by NSE Order 1169. There are other stream and spring rights listed in the hydrographic abstract that could be in addition to Muddy River Decree rights.

The best way to determine the effect of pumping on the LWRFS is to consider the water balance of the system that feeds the Muddy River Springs. Ignoring local recharge which is probably to basin fill, the inflow through CSV is about 50,500 afa. The Muddy River Springs represent most of the outflow from the area, although estimating that ouflow is complicated by the irrigation in the area and ET from the basin fill. The gaging station Muddy River near Moapa (#9416000) is downstream of and therefore includes flow for all area springs (Figure 13) but the gaging station description notes irrigation diversions above the gage. Based on the gage, discharge from the LWRFS had been estimated to be about 36,000 afa from springs that supply the MRSA (Eakin 1964, p 24). However, none of the recorded flows since 1943 have been that high (Figure 17). From about 1943 to 1960, the recorded flow was just less than 34,000 afa. After 1960, the flow rate decreased to less than 24,000 afa. After the wet year in 2005, it began to increase again to over 30,000 afa in 2012.

Trends at the Muddy River gage are likely due to surface and groundwater development upstream from the gage, including diversion of up to 9.2 cfs to the Reid-Gardner electrical generating station which began in 1968 (USFWS 1996). Decreasing spring flow likely began in the 1990s with carbonate pumping. The increase just after 2005 may be due to the high precipitation year and after 2010 could be due to the decreased ET after a fire in 2010 (Figure 17). Flows have been relatively constant at about 30,500 afa since 2014. Notwithstanding the portions of the decree satisfied by diversions upstream of the gage, flow at the gage has not been meeting the requirements of the Muddy River Decree because the flow has been less than 37,000 afa (Figure 17).

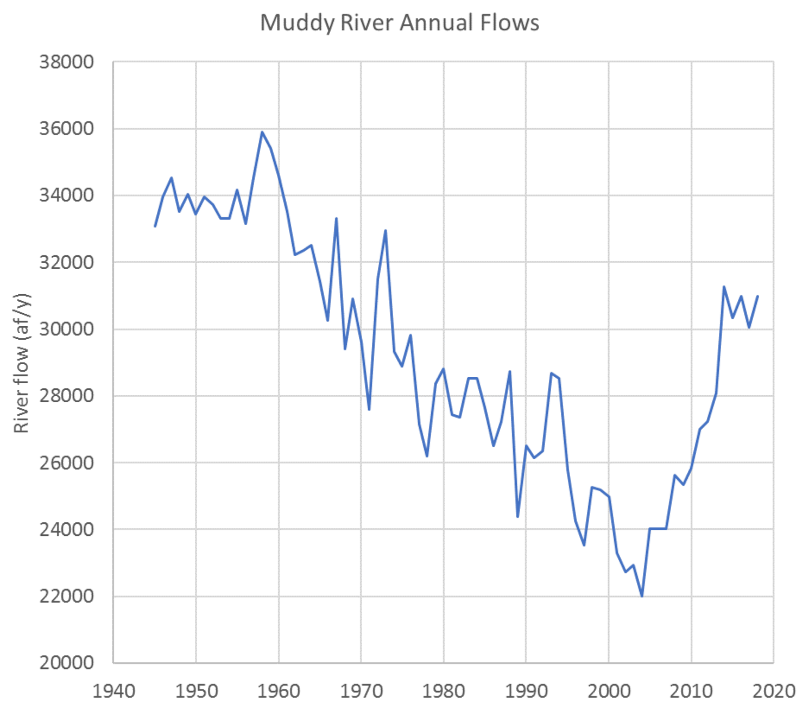


**Figure 17: Annual flows (cfs) at the Muddy River near Moapa, NV gage (09416000)**

Pumpage since 2000 has been from variable sources. Monthly pumpage varied from 500 to 1600 af/mnth between 2000 and 2010, with the 12-month average ranging from 800 to a little more than 1000 af/mnth (Figure 18), which converts to annual pumping from about 9600 to 12,000 afa. Total carbonate pumping increased from about 400 to 600 af/mnth, or 4800 to 7200 afa between 2000 and 2010, so there was a decrease in alluvial pumping in MRSA (Figure 18). There was a substantial jump in pumping between 2010 and 2012 due to the 1169 aquifer test. After the test and especially since 2014, total pumping has decreased to just over 8000 afa with carbonate pumping being most of it. Alluvial pumping has dropped to close to zero since 2015 (Figure 19).

Carbonate pumping in CSV first began in 2005, so flow in the carbonate system upstream from the springs has only been pumped for 14 years. MRSA carbonate pumping has been steady or slightly decreasing with ranges from 100 to 400 af/mnth (Figure 19). Production is primarily from the Arrow Canyon wells. During the aquifer test, CSV carbonate pumping dominated the pumping from the carbonate aquifer. Since the aquifer test, CSV carbonate pumping has been about half that in MRSA.

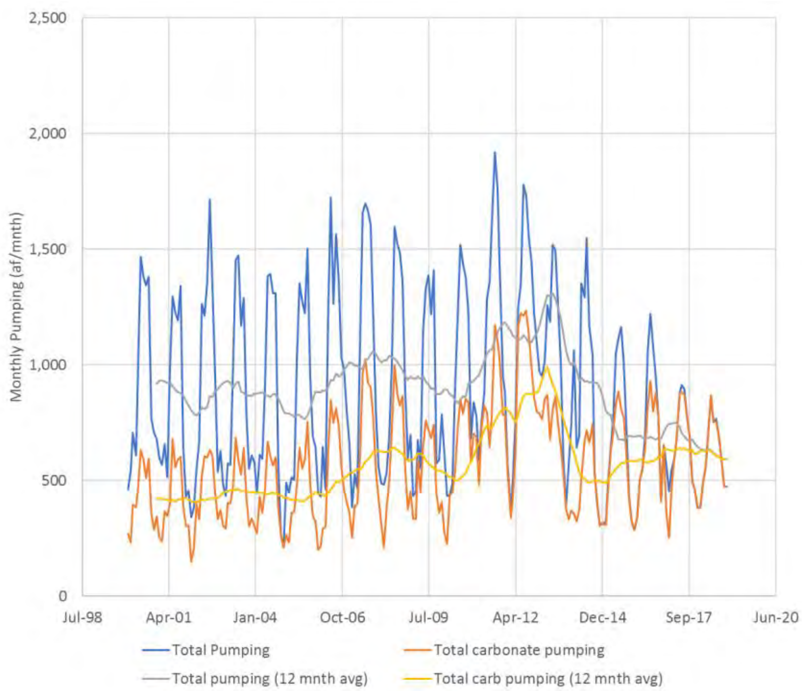


**Figure 18: Total pumping and total carbonate pumping, by month and by 12-month moving average, for the study area. Data from NSE Web page.**

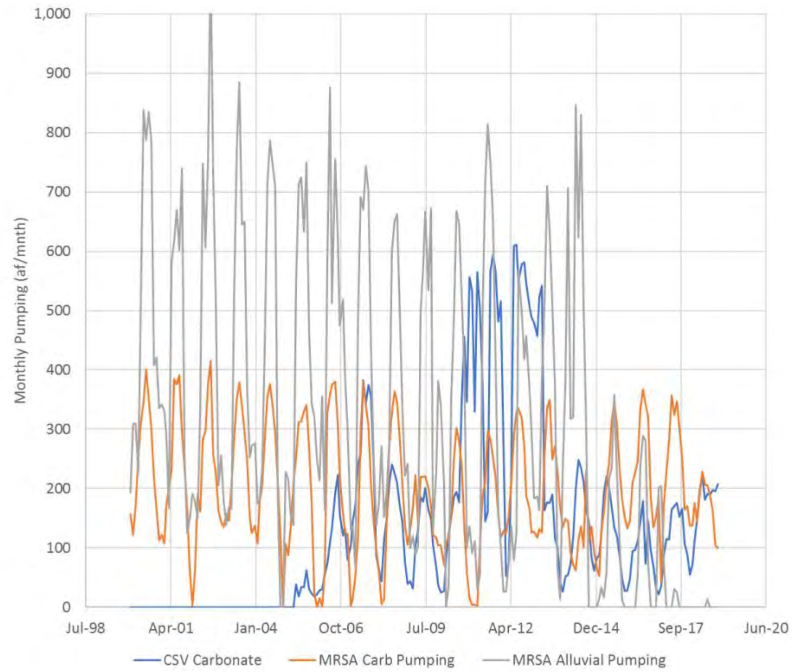


**Figure 19: Carbonate pumping for Coyote Spring Valley and the Muddy River Springs Area. Source of data: NSE web page.**

Prior to the pump test, the trend for water levels in most carbonate monitoring wells had been for them to decrease except during brief wet periods. This may be seen by plotting the carbonate groundwater levels with carbonate pumping, as done by the USDOI (Figure 20). Groundwater levels began to decrease as carbonate pumping commenced. Carbonate spring flow also began to decrease with pumping in the mid-1990s, also except during very wet years. The trend has been for the flows to decrease. At Warm Springs West, flow had been near 4.0 cfs in the 1990s and now is near 3.4 cfs, having recovered about 0.1 cfs since the aquifer test (Figure 14). Smaller, higher altitude springs are flowing at a little more than half of their 1990s flow.

Carbonate pumping as it occurred in the 1990s caused spring flow and groundwater levels to decline; total pumping was less than 10,000 afa and carbonate pumping was less than 5000 afa. Excepting those downstream of the springs, the basin fill wells were not experiencing a water level decline even with the alluvial pumping of near 5000 afa.

It is therefore apparent that any carbonate pumping removes water from the springs. Prior to the pump test, the small amount of carbonate pumping was causing a small but measurable decrease in spring flow. The decrease would occasionally be partially countered by extremely wet years, such as in 2005. As noted above, the majority of carbonate pumping was removed from storage, so the flow decreases would continue into the future as the storage recovers.

The conclusion therefore is that the NSE should not allow any carbonate pumping in the LWRFS to prevent further decreases and to allow recovery in the flow to Muddy River Area Springs. Pumping carbonate water intercepts spring flow and upward flowing groundwater recharge to the basin fill. With carbonate pumping, it is only a matter of time before the spring flow on which the Moapa dace depends decreases significantly or is completely lost. The next section addresses the potential for basin fill pumpage.

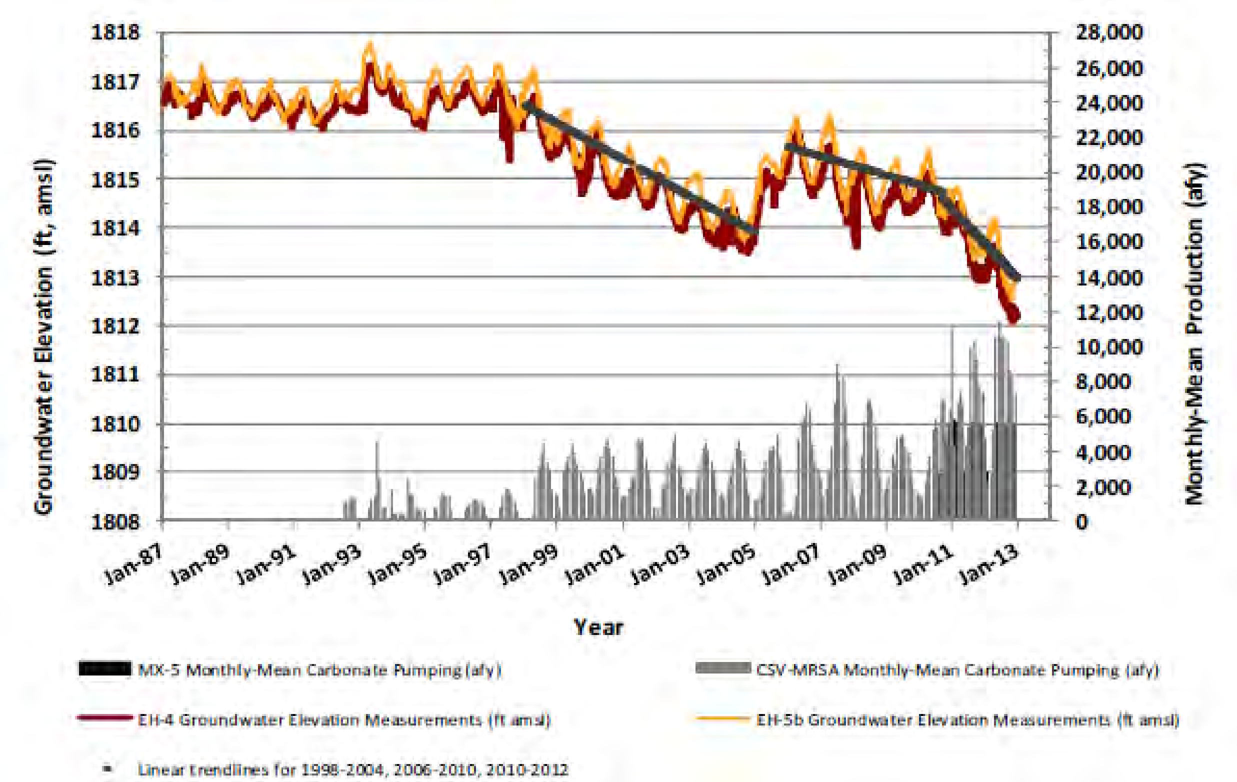


**Figure 20: Trends in carbonate water levels at MWs EH-4 and EH-5b with carbonate pumping in Coyote Spring Valley and Muddy River Springs Area. Source: USDOI (2013) Figure 1.2.**

**Relation between Carbonate and Basin Fill Wells and the Potential for Conjunctive Use**

The pumping and water level relations discussed in the previous section suggest that some water can be pumped if sourced from the basin fill aquifer. Except in the far southeast portion of MRSA, basin fill groundwater levels did not decline due to carbonate pumping. This is probably because carbonate water discharging into the basin fill supports the basin fill aquifer. Secondary recharge, probably including both direct spring flow and irrigation recharge, supports the basin fill water levels. Some basin fill pumping could be acceptable in MRSA because alluvial groundwater is partly secondary recharge from the springs. As secondary recharge, the water has already been used in the spring channels most important for the dace. The existing levels of pumping in MRSA basin fill, about 4000 afa, is probably acceptable.

Although there is no basin fill pumping in CSV, it is possible that some basin fill pumping there could be sustainable. The evidence for this is that basin fill water is likely disconnected from the carbonate and not responsible for substantial recharge. That basin fill water levels increased during the aquifer test exemplifies that. Prior to allowing basin fill pumping, it is essential to determine where the basin fill groundwater discharges. If ultimately it supports carbonate groundwater, it should not be pumped.

NSE Order 1303 requests reports address “effects of movement of water rights between alluvial wells and carbonate wells on deliveries of senior decreed rights to the Muddy River” (NSE Order 1303, p 14). This suggests that reports consider the change in the point of diversion from one to the other aquifer. As noted previously, carbonate pumping would eventually dry the Muddy River Springs, but carbonate groundwater flow also supports basin fill water through direct discharge from the carbonate to the basin fill and secondary recharge of springflow into the basin fill. The long-term decline of flow in the Muddy River indicates there is a limit to the amount of even basin fill groundwater that can be pumped without affecting Muddy River flows.

**Conclusion**

The Order 1169 pump test made apparent that there is a broad highly transmissive carbonate aquifer underlying CSV, MRSA, Garnet Valley, Hidden Valley and California Wash. The aquifer is interconnected so much among basins that it is necessary to manage groundwater through all basins as if they were part of a whole basin. The primary conclusion of this analysis is that the NSE not allow any pumping of the carbonate aquifer if the continued decrease in spring flow in MRSA is to be avoided. This conclusion results from the direct correlation of carbonate pumping and carbonate water level and spring discharge decline. Because the spring flow is directly responsible for Muddy River flows, preventing any additional carbonate pumpage is also necessary for protecting downstream water rights.

Another conclusion is that Kane Springs Valley should be managed as part of LWRFS. This conclusion results from the flat carbonate water level extending into that valley and the likelihood that water pumped from Kane springs Valley would quickly contribute to the depletion of the carbonate aquifer in CSV and MRSA.

A third conclusion is that some basin fill pumping could occur without significantly affecting the spring flow. A preliminary estimate is the pumping that occurred prior to significant carbonate pumping, or about 4000 afa. It is probably not possible to increase that pumpage by transferring carbonate rights to basin fill wells because of the observed long-term decline in Muddy River flows.

**References**

Johnson C, Mifflin M (2013) Summary of Order 1169 Testing Impacts, per Order 1169A. Mifflin and Associates, Inc.

Myers T (2013) Technical Memorandum, Comments on Carbonate Order 1169 Pump Test Data and the Groundwater Flow System in Coyote Springs and Muddy River Springs Valley, Nevada. Prepared for Great Basin Water Network.

SNWA (Southern Nevada Water Authority) (2018) Assessment of Environmental Conditions Related to Moapa Dace in the Lower White River Flow System. Las Vegas, Nevada, 55 p.

SNWA (Southern Nevada Water Authority) (2013) Nevada State Engineer Order 1169 and 1169A Study Report. Las Vegas, Nevada, Doc. No, WMP-ED_0001, x p.

US DOI (US Fish and Wildlife Service, Bureau of Land Management, National Park Service) (2013) Test Impacts and Availability of Water Pursuant to applications Pending Under Order 1169.

USFWS (US Fish and Wildlife Service, Region 1) (1996) Recovery Plan for the Rare Aquatic Species of the Muddy River Ecosystem, First Revision. Portland OR

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**Technical Memorandum**

**Groundwater Management and the Muddy River Springs, Rebuttal in Response to Stakeholder Reports Filed with Respect to Nevada State Engineer Order 1303**

**August 16, 2019**

**Prepared for: Center for Biological Diversity**

The Nevada State Engineer (NSE) is planning to establish a plan to conjunctively use groundwater and surface water in the Lower White River Flow System (LWRFS) under Order 1303. The NSE has established the LWRFS as the valleys shown in Figure 1, except that only the northern portion of Black Mountains Area would be included, and excluding Lower Meadow Valley Wash and Lower Moapa Valley. The bases for this planning are the Order 1169 aquifer test results and observations ongoing since the end of the test. The NSE requested reports from stakeholders be filed by July 3, 2018. This technical memorandum is a review and rebuttal of those stakeholder reports, as requested by the NSE.

Throughout the rebuttal, I contrast the reviewed reports to the evidence I prepared for the submission by the Center for Biologic Diversity (CBD) (Myers 2019). This rebuttal also endorses the letter provided by the Great Basin Water Network in its last section. I organize the reports by stakeholder.

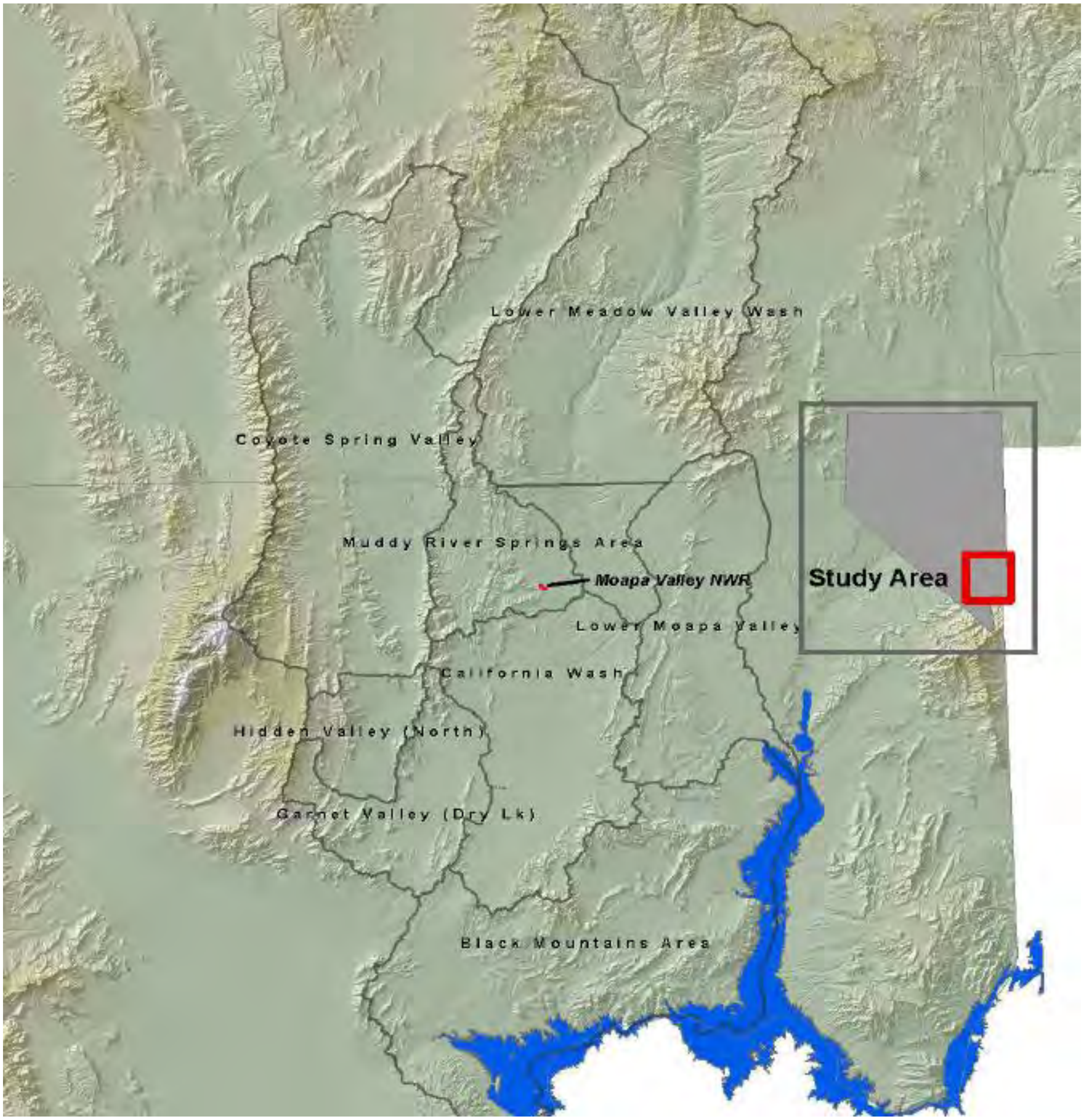


*Figure 1: Study area showing the Lower White River Flow System. Kane Springs Valley is northeast of Coyote Spring Valley. Source: USDOI (2013).*

**Rebuttal to Coyote Springs Investment Report**

Coyote Spring Investment (CSI) submitted a report prepared by Stetson Engineers (Stetson 2019) in support of its claim that up to 5280 acre-feet/year (af/y) can be pumped from Coyote Spring Valley (CSV) without harm to the Muddy River Springs Area (MRSA) (Stetson 2019, p 60).

The evidence presented by Stetson is faulty as presented herein and does not support the claim.

Stetson compares drawdown calculated using a Theis analysis of pumping all water from CSV from the MX-5 well on water levels at the Muddy River springs (Stetson 2019, p 7-12). Stetson claims that pumping could not cause drawdown as substantial as seen at the springs, which experience more drawdown than predicted using Theis. However, two of the assumptions that go into a Theis analysis, as properly listed by Stetson (p 8), that of an aquifer with infinite extent and no boundary effect, cannot be applied to the actual groundwater system here. Faults and unsaturated carbonate blocks, referenced by Stetson elsewhere in its report, provide a boundary that limits the size of the aquifer. As noted by Stetson, drawdown in aquifers with high transmissivity expands fast, and would encounter the boundary quickly. Boundaries limit the aquifer from which water can be drawn so drawdown is higher than predicted with Theis. Water is drawn to the well from all directions but the system between the pumping wells and springs is a relatively narrow interbasin connection through the Arrow Canyon Range, through which the discharge essentially squeezes, which could multiply the drawdown by many times over that estimated using the Theis solution.

Stetson (2019, p 47) incorrectly implies there is no effect of the aquifer test on water levels at EH-4 and that the response is due to climate effect: "What is most evident from the water level graphs is the long-term climatic impact of drying from 1998 through 2004, wetting in 2004 and 2005, drying from 2006 through 2013, and stable water levels from 2013 through 2018" (Stetson 2019, p 47). Stetson refers to its Figure 18 which compares water levels at EH-4 (the water level graphs referred to in the quote) to pumping in CSV and MRSA. Despite its claims in the previous quote, the lower half of Stetson Figure 18 shows clearly a decline at EH-4 with pumping in MRSA with the exception of an upward jump during the wet 2005 period. The decline steepens during the aquifer test period. Although Stetson claims the levels since 2013 are stable, it neglects to consider that precipitation during the period between 2014 and 2018 has trended upward.

Stetson's interpretation of CSVM-1 in its Figure 19 is mostly correct, except for the period since the pump test. CSVM-1 water levels recovered about a foot between 2013 and 2014 which appears to correspond to substantial decrease in CSV pumping. As CSV pumping recovered to pre-pump test rates, CSVM-1 water levels began a slight decrease of about half a foot up to 2019, even though the precipitation had increased as shown on Stetson's Figure 1.

Stetson finds that wells CSVM-2, -3, -4, -5 and CE-VF-2 "do not show a response to pumping" in either CSV or MRSA (Stetson 2019, p 48). Myers (2019) found similar results except I found minor decreases of up to half a foot at CSVM-5. Stetson's explanation that the lack of response is "due to barriers to flow created by normal (extensional) faults that impede groundwater flow in the east-west direction" (Id.) is incorrect. The wells in question lie north of the pumping so barrier to east-west flow would have no effect. Myers (2019) explained the decreasing response with distance north of MX-5 as being due to the higher ground level and to the aquifer becoming less transmissive to the north, not due to an impedance to east-west flow.

Stetson claims pumping at CSI-2 did not affect Warm Springs West (WSW) flow during the last three quarters of 2018 (Stetson 2019, p 52) and references its Figure 21. That figure also shows that MRSA pumping has decreased, which affects water levels at EH-4 which the spring discharge correlates with. Also, Stetson Figure 21 does show a minor flow decrease but the measurements are reported only at 0.1 cfs intervals and Stetson's scale goes way beyond the bounds that the flow data is reported. In more detail, Myers (2019) Figure 14 shows a substantial fluctuation, but flows that are mostly less than 3.4 cfs, a decrease from levels exceeding 3.4 cfs subsequent to the aquifer test. In other words, Myers' figure shows that spring discharge has been decreasing ever since it recovered from the pump test.

Stetson (2019) argues in its section 3 that Kane Springs Valley (KSV) should not be part of the LWRFS, but provides evidence that clearly supports KSV's inclusion and fails to present evidence showing there is no connection. The hydrogeology map presented by Stetson as Figure 8 shows that volcanic rock forms the boundary of KSV (206) and CSV and that carbonate rock forms the boundary between CSV and KSV. Also, at no point did Stetson consider groundwater levels between CSV and KSV or whether drawdown in CSV would draw water from KSV. Myers (2019) showed the groundwater elevation difference between valleys was minimal.

In section 4, Stetson (2019) develops water budgets for LWRFS and CSV. First, Stetson estimates recharge for CSV using three recharge methods, (Maxey and Eakin 1949, Nichols 2000, and Epstein 2004). The Nichols and Epstein methods are based on methodology of Maxey and Eakin (1949) in that recharge is estimated as a coefficient applied to a precipitation interval within the basin. Stetson's application of the methods is incorrect and shows a misunderstanding of the methodology.

Maxey and Eakin (1949) assumed that outflow from a basin, including groundwater evapotranspiration (GWET), spring flow, and interbasin outflow, would equal recharge and interbasin inflow to that basin. They analyzed 13 basins for which they could estimate the outflow because GWET is easier to estimate than any other flux in the method and for which they could assume interbasin outflow was minimal. They estimated precipitation by elevation using a precipitation map developed by Hardman (1936). The precipitation estimates were by zone, as Stetson shows in its Table 2 (precipitation zones <8 in/y, 8 to 12 in/y, 12 to 15 in/y, 15 to 20 in/y, and >20 in/y). Maxey and Eakin developed the coefficients shown in Stetson Table 2 by trial and error. By precipitation zone, the coefficients are 0, 0.03, 0.07, 0.15, and 0.25, respectively. This means the precipitation falling in the <8 in/y zone would be assumed to not become recharge whereas 25% of that falling in the >20 in/y zone would become recharge within the basin. For example, if 10,000 af falls in the >20 in/y zone, 2500 af of it would be assumed to become recharge within the basin. Several distinguishing points about the method are essential:

- The recharge occurs within the basin, not necessarily at the point the precipitation falls. The method does not consider geology, and it is obvious that precipitation runs off granitic and much volcanic rock but infiltrates carbonate rock. Runoff from granitic rock may become mountainfront recharge whereas infiltration into carbonate rock is recharge in place. An inherent assumption is that the basins have a relatively similar ratio of pervious to impervious geology. However, recharge may be much higher than expected by precipitation zone in an all carbonate basin.
- The method depends on the map used to estimate the precipitation intervals. Just like a regression analysis, the results only hold for dependent and independent values drawn from the same population of data. It is not appropriate to use M-E coefficients with PRISM-estimated rainfall as described (Stetson 2019, p 33-34). As shown in its comparison among methods, using PRISM precipitation yields a much higher estimated recharge. Being “more scientifically sophisticated” (Stetson 2019, p 38) does not make an estimate using most recent PRISM data more accurate because it was not made using the same precipitation estimates used to derive the coefficients.
- Because the M-E method was derived using outflow estimates and precipitation zones for entire basins, it is inappropriate to estimate recharge for small subbasins. Stetson inappropriately divided the Sheep Range portion of CSV into 15 zones in which to estimate recharge, introducing a level of granularity to the analysis which does not exist in the model. Its’ estimated recharge of 5280 af/y is therefore not accurate.

Stetson develops a water budget for the LWRFS (Stetson Table 8) and states that “This report recommends and supports an initial estimate of groundwater available for appropriation should be based on capturing *all evapotranspiration* and groundwater outflow from the LWRFS.” (Stetson 2019; emphasis added). Contrary to Stetson’s assertion, the availability of all evapotranspiration (ET) from groundwater for appropriation is not supported in the report. First, capture of *all* ET is not possible. There is no evidence that all ET from the extensive LWRFS groundwater system that supports functioning ecosystems could feasibly be captured—as Stetson 2019 asserts. Second, the CSI report makes no showing that *any* of the estimated amount of evapotranspiration in the LWRFS (Stetson 2019, Appx. C, chart “LWRFS ET (AFY)”) is “available” for capture. DeMeo et al. (2008), which is relied on by Stetson (2019, Appx. C), shows that the estimated ET in the hydrographic areas in the LWRFS supports functioning ecosystems consisting of various native vegetation types including both dense and moderate meadowland, woodland, and shrubland vegetation as well as agriculture (Figure 2).

**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 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 | 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 |

*Figure 2: Annual evapotranspiration (af/y) for hydrographic areas in southeast Nevada. Source: DeMeo et al (2008) Table 7*

Stetson also ignores that the capture of any significant amount of ET from the LWRFS could cause significant impacts to native vegetation and soils in areas across the LWRFS as well as to spring flow. For example, loss of vegetation and drying of soils would make them more vulnerable to erosion by water and wind creating impacts to air and water quality as well as habitats. Loss of ET in riparian areas or near springs and seeps could devastate those habitats.

Stetson claims that up to 5280 af/y could be pumped from the west side of CSV because of recharge in the Sheep Range and the unsaturated carbonate rock preventing a connection with flow to MRSA (Stetson 2019, p 57). The amount is the estimated recharge from the Sheep Range, which was shown to be incorrect in the bullet above. It also does not account for where that water discharges which means there is not a means of capturing this discharge from ET.

Thus, the CSI/Stetson proposal to include all ET as available water to be captured in the LWRFS is unsupported and should be rejected.

Stetson also presents a water budget for CSV that included inappropriate fluxes (Stetson 2019, Table 9). They claim ET in CSV is 1000 af/y and reference Thomas et al (2001). That reference does not show where in CSV that ET would occur. Figure 2 shows that DeMeo et al (2008) estimated ET from CSV is 0.

Stetson make an accurate statement about pumping from the aquifers in CSV or MRSA: "All groundwater pumping, regardless of which aquifer it is pumped from, will eventually affect the flow of the Muddy River or subflow out of the LWRFS" (Stetson 2019, p 58). This is a correct statement, and Stetson claims it is all a matter of timing. As shown by the aquifer test, pumping anywhere south of the middle of CSV has a rapid effect on spring flow and, pumping also affects flow from the alluvial aquifer to the river, although the effect is delayed.

Stetson (2019) does not at any point consider the effect of pumping on the spring flows necessary for the dace.

**Rebuttal to Moapa Band of Paiutes Report**

Moapa Band of Paiutes submitted a report prepared by Cody Johnson and Marty Mifflin of Mifflin Associates (Johnson and Mifflin 2019). They use this report to suggest there is much more water available for development, especially in the west portion of California Wash (CW). Johnson and Mifflin (2019) make the following conclusions based on their analysis of data completed for the NSE Order 1303.

> (1) the LWRFS designation and Order 1303 are responses to a flawed conceptual model based on conflated climate and pumping effects, because widespread water-level declines associated with Order 1169 pumping of MX-5 were mistakenly attributed entirely to pumping rather than to the superposition of local, fracture-controlled pumping responses with regional, climate-driven decline;
> (2) the LWRFS as drawn by the State Engineer ignores hydrochemical and hydrodynamic divides that suggest the existence of two separate capture zones influencing groundwater flow through the five designated basins;
> (3) ~40,000 afy of south-flowing groundwater may be the flux within the Las Vegas Valley capture zone south and southwest of the MRSA;
> (4) pumping from California Wash has little to no impact on the MRSA and much more groundwater is available in California Wash than previously assumed;
> (5) the State Engineer should supplement and extend the LWRFS concept to an analysis domain based on regional-spring capture zones, as delineated by the best available science; and
> (6) if the long-term drought trend evident in climate records persists, no amount of pumping curtailment will restore or maintain high-elevation spring flows, curtailment of pumping in sustainable locations will serve no purpose and thus mitigation measures, including curtailment, will not likely prove effective in protecting senior-rights holders in the Muddy River and Moapa dace habitat from continued drought impacts. (Johnson and Mifflin 2019, p 35)

The conclusions are erroneous because the data and analysis does not support them. This section rebuts these conclusions.

Johnson and Mifflin attempt to claim groundwater level trends can be explained as a response to drought with a few very poorly referenced statements and a series of groundwater level hydrographs. They claim that the longer records "indicate the drought trend began about 1999" (Johnson and Mifflin 2019, p 6) with a reference to their Figure 4 which shows groundwater levels at EH-4 as well as an estimated level adjusted for Arrow Canyon Pumping. They do not explain how the levels were adjusted or provide a reference explaining it. The adjusted groundwater level trend purportedly shows how the water level would have changed without pumping. From 2011 through 2015, they adjust for the aquifer test as well. Johnson/Mifflin use this analysis to claim that groundwater levels are on a major drought-induced downward trend. It is difficult to assess this without an explanation, but the coincidence of drought starting with pumping makes the conclusion suspect. It also does not comport with precipitation data; precipitation data, see Myers (2019) Figure 5, does not reveal a substantial drought spanning the period since 1999.

Johnson/Mifflin consider trends of wells in the Black Mountains Area and Garnet Valley by stating: "Superimposed on generally linear declines since 2006 are widespread but diminishing-with-distance effects from the Order-1169 pumping of MX-5, evidence as far south as the Apex area" (Johnson and Mifflin, p 6). Their Figures 5 and 6 supposedly support their assessment. A linear decline shown on the graphs apparently is intended to be the natural, drought-induced decline, without any analysis supporting that claim. BM-DL-2 in the Black Mountains and GV-1 in Garnet Valley each show a better than 1-foot decline during the pump test. Compared with the declines closer to MX-5, this is a substantial and about what would be expected at that distance. Johnson/Mifflin make no effort to show the rest of the decline is not in fact due to other pumping in the carbonate aquifer. They make similar unsupported claims regarding well MX-4 in CSV and TH-2 in California Wash (Johnson and Mifflin Figures 7 and 8).

Johnson/Mifflin incorrectly attributes the long-term decline in groundwater levels to being a response to a climate-driven trend, with pumping superimposed on that climate-driven decline, and also claims that other Order 1169 reports ignore climate (p 14). At no point does Johnson/Mifflin analyze the climate record and document their assertion that drought commenced in the 1990s at a time coincident with the commencement of pumping through the area. Myers (2019) Figure 5 shows no evidence for a 20-year drought during the period since 1990. Johnson/Mifflin argue that the large water level increases in 2006 refute the idea that "water-level changes in California Wash, Coyote Spring Valley, the Muddy River Springs Area, and Hidden and Garnet valleys have been observed as 'nearly identical'" (p 14). They argue the "cessation of pumping somewhere could not have caused water levels to rise over 1 foot at CSVM-4 in northern Coyote Spring Valley and 3 feet at GV-1 in southern Garnet Valley beginning in later 2004 because there was no cessation of pumping" (p 15). They are refuting a point no one made. Most of the Order 1169 reports that address the subject accept that a wet year caused these water level increases in 2004-2006 (for example, FWS 2019). This is a case of a hugely wet year being imposed on a long-term pumping-caused decline in water levels rather than the other way around as claimed by Johnson/Mifflin. Recharge in the LWRFS is event driven as described by Myers (2019, p 4), meaning it is effective only during extremely wet years, rather than as a long-term average flux as is usually considered in Nevada when considering water rights appropriations.

Johnson/Mifflin claims that flow at WSW declined by 0.6 cfs between 2000 and 2015 and compared with EH-4 decreases, this would be about 0.6 cfs in four feet of decline (p 30). They claim that if the "drought-induced trend" continued, the spring would go dry in 100 years (p 31). They claim this would occur whether or not pumping is curtailed in up-gradient areas (Id.). This claim is unsubstantiated because there is no evidence that most of the declines were drought induced.

Johnson/Mifflin claim the aquifer test is responsible for a 0.3 cfs decrease at WSW (p 31) and suggest there is a similar decrease at the Iverson Flume. Iverson was downstream of WSW until 1999 when the flow at Iverson was considered separate from rather than combined with that at WSW. However, the graphs of flows at Iverson (Johnson/Mifflin Figure 26) shows a hydrograph that fluctuates between about 4.2 and 4.7 cfs from 2010 until 2017. There is no discernible aquifer test effect, contrary to the label on the figure and Johnson/Mifflin's assertions. The aquifer test impact is not discernible at Iverson Flume because the spring contributing to this flume is at a lower elevation so a change in head due to the aquifer test is likely to be much less than the change at the level of head above the WSW spring orifice. Even if the effective head decreases the same amount as at the higher spring, it would be a much smaller percent of the total head above the orifice. The effect of groundwater level decreases at EH-4 could be much different on the flows for the two different spring orifices, with the effect at Iverson being much less.

Johnson/Mifflin Figure 26 shows a substantial decrease at Iverson Flume through about 2018, resulting in the flow decreasing below 4.2 cfs before it recovered. This could represent a delayed response to changes at EH-4. Groundwater levels at EH-4 reached an all-time low point on November 9, 2018 of 1812.18 ft amsl. Whether this caused the low flow at Iverson is not certain.

Johnson/Mifflin continue their analysis of spring flow by claiming that WSW and Iverson streams have been decreasing at 0.3 and 0.7% per year, respectively, since October 2009 when the Refuge Stream was rerouted (p 32). This claim that there is a downward trend suffers from the fact that that assuming a linear flow decrease is not supported by the actual hydrographs for either spring (Johnson/Mifflin, Figure 27). The hydrograph fluctuates around the downward-sloping line labeled "trend" (Id.). This is especially obvious for WSW; for example, from 2013 through early 2015, all points plot beneath the line while from 2009 through 2011 most plot above the line. The hydrograph for WSW shows the sharper decrease during the aquifer test and then a stabilizing after the aquifer test. Their figure is also misleading in that it shows several points higher than 3.6 cfs in the 2014 through 2016 period but the daily flow data base shows just a few points whereas almost all flows since 2011 are less than 3.6 cfs, with a couple of short-term exceptions; Myers (2019) Figure 14 shows several observations greater than 4.0 cfs, which are probably due to short-term events, such as runoff. Myers' figure based on daily flow data shows no observations of 3.8 cfs, which are shown on the Johnson/Mifflin figure.

Discharge from Big Muddy Spring, probably Muddy River Springs on Myers (2019) Figure 13, increased by 1 cfs from 2010 through 2014 after which it increased by more than 12% (Johnson and Mifflin 2019, p 32). They claim that the flow increases during the aquifer test and increase after the test "demonstrates climate-dominance rather than pumping as a forcing agent for water-level change within the MRSA, and perhaps a complete absence of Order-1169 pumping effect in Big Muddy Spring" (p 32). But Johnson/Mifflin fail to note that a fire in 2010 burned over 600 acres and that this caused a decrease in annual evapotranspiration of about 1000 af/y (SNWA 2019, p 5-2, -3 and Figure 5-1). This much-decreased ET would have had a much larger effect on these springs than pumping upstream.

Johnson/Mifflin conclude that the only pumping effects can be seen at WSW with no evidence of impact at other MRSA springs (p 32). Their conclusion is due to poor analysis of water level trends and reliance on an assumption that a drought had been occurring since the 1990s with one year of exception. What they fail to consider by stating the peak pumping rates show no indication that pumping "the Arrow Canyon Wells have any significant effect" (p 32) is that much of the pumping has removed water from storage. The very high transmissivity, or hydraulic diffusivity, allows a large-scale small decline in water levels that represents the removal of groundwater from storage. The discharge rates do not quickly recover because of the storage loss over a very large area does not allow the well levels to recover quickly.

In Appendix 1 of Johnson/Mifflin (2019), the authors present an analysis suggesting that the flow from the LWRFS to Las Vegas Valley is 40,000 af/y, but the report includes unreviewable information and a failure to consider whether that much water is available to flow toward Las Vegas Valley. The analysis is a Darcy's Law calculation with transmissivity estimated based on a report published for a pump test at a well along the proposed flow path. The reference Mifflin and others (1992) is unpublished so it is not possible to review whether the transmissivity as calculated is relevant to this situation. For example, the authors assume horizontal transmissivity and rely on the relationship of effective transmissivity equal to the square root of the product of transmissivity in perpendicular directions. No evidence provided supports the 10:1 ratio of maximum to minimum horizontal transmissivity. Even if the 1992 pump test transmissivity is accurate, the value chosen for the most transmissive direction could be much too high. The 40,000 af/y estimate for flow from LWRFS to the Las Vegas Valley should be given no credence because it is highly dependent on undocumented and unverified assumptions.

Appendix II of Johnson/Mifflin (2019) presents a claim the "fluxes of two tributary groundwater regimes are attributed to about 2 decades of regional climate" (Johnson and Mifflin 2019, p 43). Their first argument is that the "Muddy River is nourished by two proximal but distinct spring flow regimes as revealed by 30-year monitoring records" (p 43). They compare annual flow at Big Muddy Spring , which they consider to be a proxy for a northern-regime discharge, to groundwater levels at EH-4, which they consider a proxy for a southern-regime discharge. Based on the specified gauge id number 09415900, they are using USGS gage Muddy Spring at LDS Farm near Moapa, NV. Figure 3 shows Figure 1 from Johnson/Mifflin Appendix II. The evidence is misleading because the flows presented in Figure 3 are not just spring discharge but include flood flows and irrigation diversions. The following is the USGS description of the "Remarks" and "Extremes" (https://waterdata.usgs.gov/nv/nwis/wys_rpt/?site_no=09415900&agency_cd=USGS)

> REMARKS - Regulation for irrigation purposes occurs 0.1 mi upstream. 10/01/2013-09/30/2014: Records good except for estimated daily discharges, which are poor. 10/01/2014-09/30/2015: Records good except for estimated daily discharges, which are poor. 10/01/2015-09/30/2016: Records fair except estimated daily discharges, which are poor. 10/01/2016-09/30/2017: Records fair except for estimated discharges, which are poor.

> EXTREMES FOR PERIOD OF RECORD - Maximum discharge, 41 $ft^3/s$, Feb. 23, 2002, gage height, 2.18 ft; the gage was submerged by backwater and over bank flow from Muddy River on Sep. 26, 2014, gage height 10.11 ft; discharge unknown; maximum gage height, 2.57 ft, Apr. 6, 2015; minimum daily, 5.9 $ft^3/s$, May 10, 1993, May 25, 2009.

Johnson/Mifflin do not account for the irrigation diversions that occur upstream from the site. Also, the fact the maximum discharge was 41 cfs indicates the channel could be periodically affected by high flows. Both diversions and flood events could account for the variability shown in Figure 3.

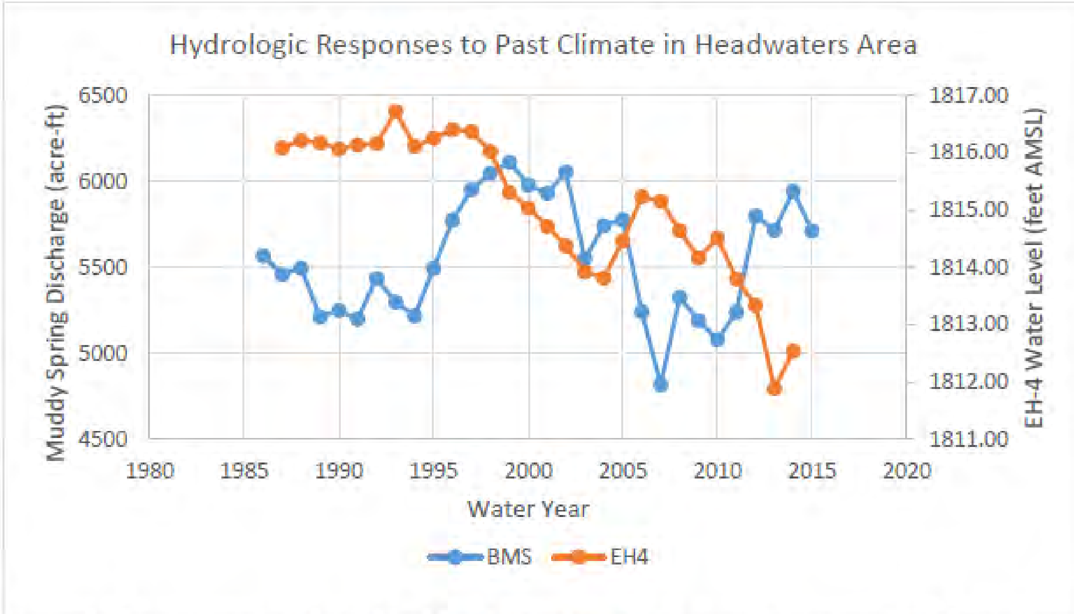


Figure 1. Average spring (April 16 –May 15) water levels in monitoring well EH-4, and annual discharge of Big Muddy Spring (BMS). EH-4 water levels are a proxy for southern-regime discharge, while Muddy Spring is proportional to northern-regime discharge [file SouthernLagComparison.xlsx, sheet 'ShowBMS_EH4']

*Figure 3: Snapshot of Johnson and Mifflin (2019) Appendix II Figure 1.*

Johnson/Mifflin claim that the groundwater which combines to form the Muddy River is influenced by both northern and southern climate regimes. This claim is reasonable especially considering that, as they state, the northern part of the White River Flow System lies hundreds of kilometers north of the Muddy River Springs. They also claim that the largest spring, the Muddy Spring, responds to past northern climate regimes as reflected by the historic base flow of the Humboldt River but do not substantiate that claim. Their Figure 2 purportedly shows the relationship between northern climate and Muddy Spring flows (Figure 4). Other than claiming the "climate index time-series dating to 1912" contains the explanatory variable set that determines discharge at Big Muddy Spring, there is no explanation or evidence of this relationship. Apparently, they used a multiple regression of lagged flows at the Humboldt River Palisade gage to explain flows at the springs. This is shown in their Figure 4. The regression coefficients correspond to lags from 12 to 22 years which is the basis for their conclusion that climate in the upper Humboldt River basin causes flows 12 to 22 years later (p 44) at the Muddy River. The northern portions of the WRFS bound the southern portions of the upper Humboldt River watershed, so conceivably there is some connection such as a similarity in climate. However, Johnson/Mifflin fail to consider three critical factors.

First, the data base is very limited and the authors did not consider whether earlier flows at Palisade could correlate better with MRS. Second, they do not provide significant statistics for the regression coefficients, so there is no explanation or evidence for why this lag was chosen.

Third, they also do not discuss whether they accounted for irrigation diversions above the Palisade gage, which would have decreased the flow, or mine dewatering discharges, which increased the flow substantially for a few years. These anthropogenic impacts could have had a large effect on the regression analysis.

Johnson/Mifflin do not discuss the physical connection that would allow climate in the upper Humboldt River to control flows at Muddy River Springs at a 12- to 22-year lag. The watersheds are separated by a groundwater divide, so clearly they are not claiming that water crosses the topographic and groundwater divides to affect the White River flows. Possibly, climate in the northern half of the WRFS correlates with flows in the Humboldt River, but they do not test this even though there are climate statistics that could be used for regression analysis.

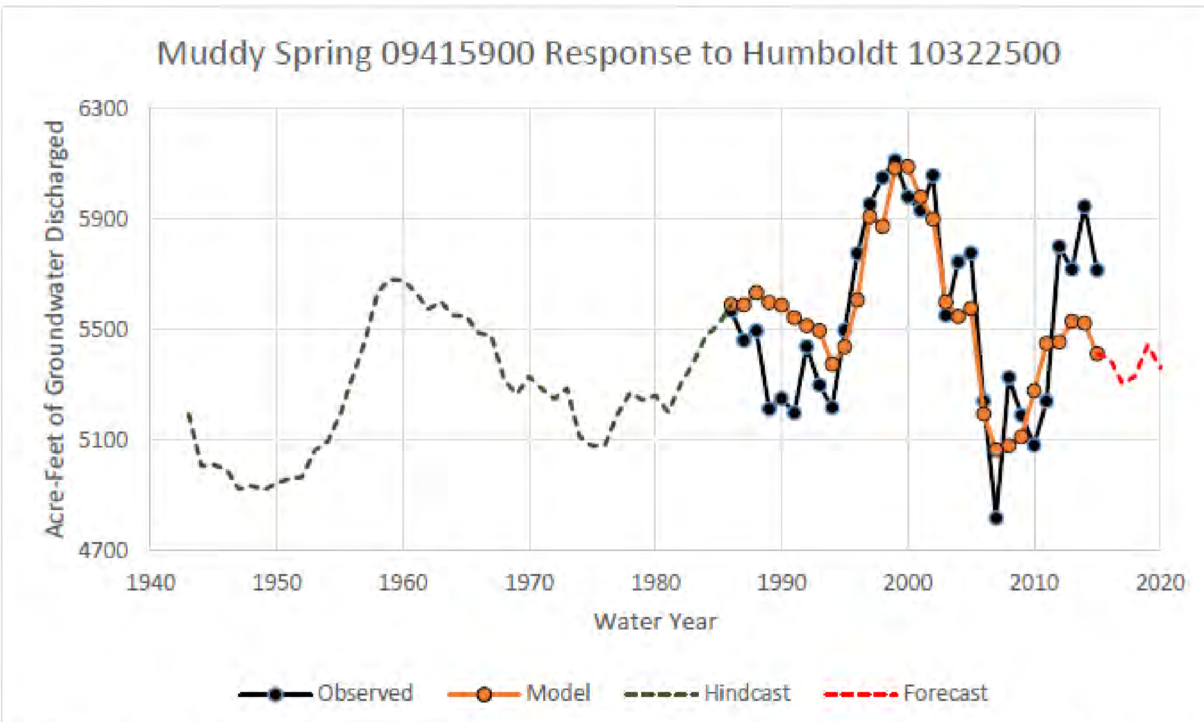


Figure 2. The annual total base flow of the Humboldt River at Palisade provides a climate index time-series dating to 1912, which contains the explanatory variable set that determines discharge at Big Muddy Spring. [file HumboldtBFI.xlsx, sheet 'Hindcast1222']

*Figure 4: Snapshot of Johnson and Mifflin (2019) Appendix II Figure 2.*

Their Appendix II Figure 3 shows a similar relationship for the water levels at EH-4 and flows at North Fork Virgin River gage 09405500, copied here as Figure 5. Apparently, Virgin River flows are used as the surrogate for climate, even though the watershed contributing to the gage is significantly east of the LWRFS and being largely on the Colorado Plateau, has a significantly different climate and precipitation regime. Johnson/Mifflin do not explain why they chose this flow gage as a surrogate over the various measures of climate that could be available, such as Myers (2019) Figure 5. There is also no explanation of lag as was done for the Humboldt River surrogate.

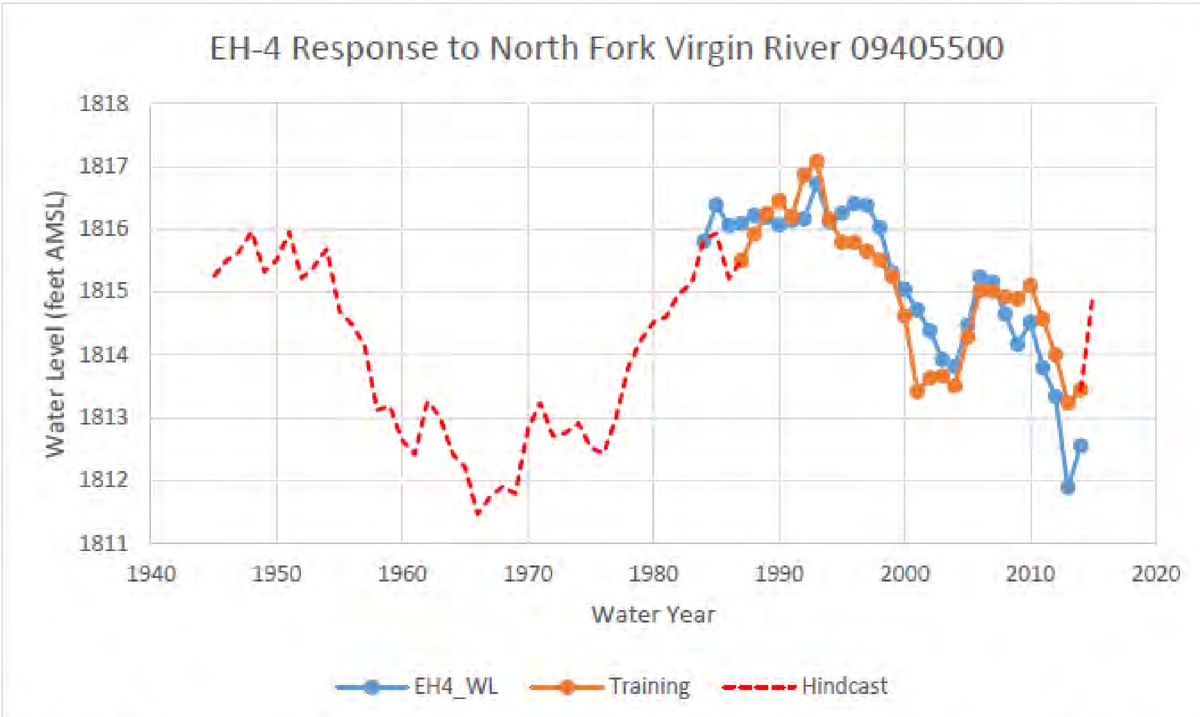


Figure 3. The annual total base flow of the Virgin River (North Fork) at Springdale provides a climate index dating to 1928, which contains the explanatory variable set that determines groundwater elevations in the Reservation area. [file NFvirginBFI2.xlsx, sheet 'Hindcast_0116']

*Figure 5: Snapshot of Figure 3 from Johnson and Mifflin (2019) Appendix II.*

Johnson/Mifflin also apparently use these correlations to justify their arguments that climate controls EH-4, WSW, and Big Muddy Springs with very little impact from pumping. There is no discussion as to how they included pumping variables in the regression in a way they can argue they controlled for pumping in their analysis. They simply dismiss the obvious causation of decreasing spring flow and EH-4 water levels found by Myers (2019) and the authors of other Order 1169 reports.

Finally, Johnson/Mifflin develop a graph of reconstituted discharge, which apparently includes "all known diversions and evapotranspiration effects" to estimate the natural discharge to the Muddy River headwaters (Johnson and Mifflin 2019, Appendix II Figure 6). They do not describe the known diversions and evapotranspiration effects or provide their method for adding these effects to the flow making this graph unsupported.

Johnson/Mifflin (2019) Appendix III describes a FEFLOW groundwater flow model completed to "evaluate interbasin groundwater flow within a region sufficiently large to encompass the 'Eureka Low' of Sass and Lachenbruch (1982) by using head a hydrologic tracer to constrain the physics" (p 50). They consider it a scoping model to "establish if regional flow from northern recharge areas in the highest mountains to discharge at the southern warm springs is physically possible and more importantly, plausible within the decadal time scales suggested by climate response in the MRSA" (p 51). More specifically, they claim to study whether "rapid signal propagation indicated by modern climate response of spring in the MRSA is corroborated by plausible groundwater velocities needed to deliver the 'missing' heat lost from the Eureka Low to the regional springs in a steady-state process" (Id.). The concept is that heat is lost based loosely on flow rate and the Eureka Low is an area of different heat loss that can be used to calibrate the flow model.

Johnson/Mifflin chose to use the FEFLOW finite-element modeling environment (p 51), which is proprietary software so details of the model can only be reviewed by those who have the software. In fact, they imply they used just a demonstration version of the software (Id.).

The report does not document how they constructed the model. Their Appendix III, Figure 2 shows the finite element mesh and a couple of essential properties but no explanation. The figure on the left shows "anisotropy angles", which presumably means the direction of the axis of the highest transmissivity in the horizontal directions. Without expressing the actual anisotropy, this information is not very useful. On the right, the figure characterizes the Eureka Low in terms of the rate of heat input to the aquifer; there is no information about how this is calibrated or even any discussion as to how the heat flow presumably affects the groundwater flow.

Johnson/Mifflin essentially argue that the terminal end of much of the WRFS is in Las Vegas Valley rather than MRSA (p 61). Their Appendix III is most of their technical evidence in support of this idea, but the evidence is little more than a poorly documented modeling study that cannot be reviewed and a random collection of statements regarding heat transport with little discussion of groundwater flow. Evidence based on this model should not be considered in this proceeding because the model is not reviewable.

Appendix IV attempts to establish a relationship between Arrow Canyon pumping and drawdowns at EH-4 with the intent of developing a pristine (no pumping) water level series at EH-4. The multiple regression, presented in Johnson/Mifflin Appendix IV Table 1, claims to establish a relationship that explains EH-4 water levels based on weekly pumping at Arrow Canyon for the previous 13 weeks. Their Figure 1 shows there is a reasonable fit. However, this effectively assumes that water levels at EH-4 are controlled by Arrow Canyon pumping and nothing else. Johnson/Mifflin do not provide evidence supporting this.

Their Appendix IV, Figures 2 and 3 are not referenced in the report, but provide some graphical evidence regarding the regression. They analyzed the original pump test of the Arrow Canyon well on EH-4 based on pristine water levels, after the effects of pumping are removed from the data (Johnson and Mifflin, Appendix IV, Figure 4). Figure 4 suggests that without the pumping (from a pump test) the water level would have been several tenths of feet higher. Figure 5 then shows drawdown based on the difference between the observed water level and the reconstructed pristine water level. Figure 6 plots the new drawdown with log 10 time to allege the pump test encountered a recharge boundary, which they identify as the Muddy River. Using this methodology Johnson/Mifflin could be missing all of the relevant effects. The slope in Figures 5 and 6 changes several times which could be due to the fact that other factors control the water level at EH-4 than just pumping Arrow Canyon. The evidence in Appendix IV does not prove that the primary control on water levels at EH-4 is pumping at Arrow Canyon.

Next, Figure 7 shows EH-4 water levels "cleaned of Arrow Canyon pumping effects". Because they have not eliminated any other effects, this is not a pristine, without pumping, water level. Johnson/Mifflin then suggest that less than 8% of the discharge from Arrow Canyon pumping is drawn from the Warm Springs Refuge, based on 6.5 cfs pumping and a 0.5 cfs springflow reduction (p 68). They acknowledge that other unmonitored springs could be affected, but do not mention that if not captured from spring discharge, the water is withdrawn from storage. Because of the high transmissivity documented in the Order 1169 pump test, that withdrawal at Arrow Canyon may be drawn over up to 1100 square miles. It adds to a cumulative loss of storage that will eventually capture much more discharge. There is no evidence, other than the biased regression analysis in Appendix IV, that allows the statement that recovery at EH-4 is complete 3 months after the cessation of pumping (p 68).

Johnson/Mifflin claim that 40,000 af/y flows from the LWRFS into the Las Vegas Valley, although it refers to this flow as occurring within the Las Vegas Valley capture zone which they describe using model-generated flow lines that emanate within LWRFS and cross basin boundaries to enter Las Vegas Valley. Even if the concept of cross-basin flow from the LWRFS is correct, a Darcy's law calculation would not be the way to estimate it. Darcy's law depends on transmissivity and gradient which means they would have to assume a conductivity value and cross-sectional area. The proper way would be to use Darcy's law to verify the interbasin flow estimated in other ways.

Arguing that Appendix V Figure 12 shows a 2% per year pumping increase based on pumping shown in that figure is fallacious. With the exception of two periods over which pumping increased substantially, year to year pumping decreased. The "trend" is based solely on an almost 1000 af/y increase between 2017 and 2018.

Johnson/Mifflin discuss a regional hydraulic-head gradient and flow between a Steptoe MX well and Tule Springs Pond (p 20), but do not provide evidence of a connection or discuss the flow path. This claim begins a paragraph that seems to be a series of unconnected sentences that together are almost impossible to review. The second sentence references an unpublished report (Mifflin and Johnson 2013) to claim there is a 2832 $m^2$/day transmissivity across the width of California Wash. Without a figure showing the cross-section, this cannot be considered. They determine the width of California Wash that would be necessary, based on the assumed transmissivity, to pass 33,771 $m^3$/day, a hypothetical flow (equal to 10,000 af/y) (p 19).

In sum, the Johnson/Mifflin report is riddled with unsupported claims and its conclusions should not be relied on.

**Rebuttal to Vidler/Lincoln County Report**

The report submitted by Lincoln County and Vidler Water Company in response to interim order #1303 primarily argues that the northern portion of CSV should not be administered as part of the LWRFS and that KSV should not be added to the LWRFS for administration. However, the data and analysis presented by Lincoln County et al (2019) actually supports adding KSV to the LWRFS and certainly does not support removing the northern portion of CSV from the LWRFS.

Lincoln County et al (2019) cited the NSE Ruling #6254 in support of allowing appropriation of groundwater that is hundreds of years upgradient (p 2-3). However, there was no evidence presented in the hearing or the order #6254 that KSV is hundreds of years upgradient from LWRFS. The hearing concerned Delamar, Dry Lake and Cave Valley which some argued is that far upgradient from CSV and Las Vegas Valley and therefore water could be appropriated, although that aspect of Order #6254 has been reversed by the Judge Esty order[1]. The Lincoln County et al assertion that KSV is hundreds of years upgradient from CSV and LWRFS is not supported.

Lincoln County et al invoke NSE Ruling # 5712 as claiming that there is "not substantial evidence" that pumping in KSV will affect the flow at Muddy River Springs, Rogers Spring or Blue Point Springs. That ruling predates the Order 1169 pump and that conclusion has been challenged by Myers (2019). Lincoln County et al also reference Ruling #5712 as suggesting the difference in groundwater levels (1875 ft amsl near KSV and less than 1825 ft amsl near MX-5 and the MRSA) as being due to low transmissivity between the areas. Myers (2019) and FWS (2019) acknowledged the transmissivity is lower than in the larger very high transmissivity zone affected by the Order #1169 pump test, but also noted that the gradient through the lower

[1]White Pine County and Consolidate Cases, Et al, v Jason King, P.E., Nevada State Engineer, State of Nevada Division of Water Resources. In the Seventh Judicial District Court of the State of Nevada in and for the County of White Pine. Case No. CV1204049.

transmissivity is still low as discussed in the following paragraphs and does not represent a barrier or even a substantial impedance to flow. Myers (2019) documented aquifer test effects on the CSV wells near KSV.

Lincoln County et al present a north-south transect of carbonate water level data through CSV and MRSA in Figure 3-4 through 3-7. These figures illustrate well the very flat gradient through a large portion of the transect within the carbonate aquifer. They also illustrate the aquifer becomes steeper in northern CSV, as was also documented by Myers (2019). The steeper gradient indicates the transmissivity in the north of CSV is lower for most of the inflow to the system than from Pahranagat Valley through to MRSA. It is not evidence the northern portion of the valley is separate from the southern portion.

Lincoln County et al also presents data from well KMW-1 that they argue shows how KSV is not part of CSV. The geologic section presented as Figure 3-3 does not show a separation between KSV and CSV; in fact, the cross-section shows that carbonate rock spans the downstream end of KSV so that there would be a connection between KSV and CSV.

Lincoln County et al allege differences between KMW-1 and well CSVM-4 in CSV are evidence that the valleys are different. Their location map, Figure 3-1, shows that KMW-1 lies at the mouth of KSV and CSVM-2 lies about 2.5 miles southwest in CSV. There is 5.5 feet of vertical difference in their water levels which is a 0.00042 gradient. That is very flat and certainly not evidence that a fault they postulate (p 3-4) has any effect on flow between the wells. With the carbonate rock that separates the wells they would be expected to have water level trends that are very similar to trends further south in CSV.

Figure 6 shows a figure from the Lincoln County et al report that compares water level at the two wells. The lines added to their figure show up to four different periods that trend similar to each other and to wells south in CSV. Monitoring at CSVM-4 began just before the wet 2005 period began, so it shows an increase due to the recharge from that wet year. A similar increase probably occurred in KMW-1. After the recharge, a long-term decline began. This decline was not due to “years to dissipate in the aquifer” the effects of a high recharge event (p 3-4) but the response to pumping that began in CSV in 2006. Both wells had a long-term decline from 2006 through about the beginning of the aquifer test period during which the decline became much steeper, as shown on Figure 5. FWS estimated the decline at these wells during the aquifer test to be 0.5 feet (FWS 2019, Figure 5), but their analysis did not account for the lag in the response as discussed here. There is no evidence that the aquifer test occurred during an abnormally dry period, so these wells responded similar to wells further south in CSV. A brief recovery occurred at each well a few months after the aquifer test. The recovery lasted a few months longer in the north than further south because of the lower transmissivity in northern CSV. Since the brief recovery, the water levels have trended downward but at a slower rate than before the aquifer test. The slower rate reflects slightly less pumping in CSV than prior to the test and slightly above average moisture conditions.

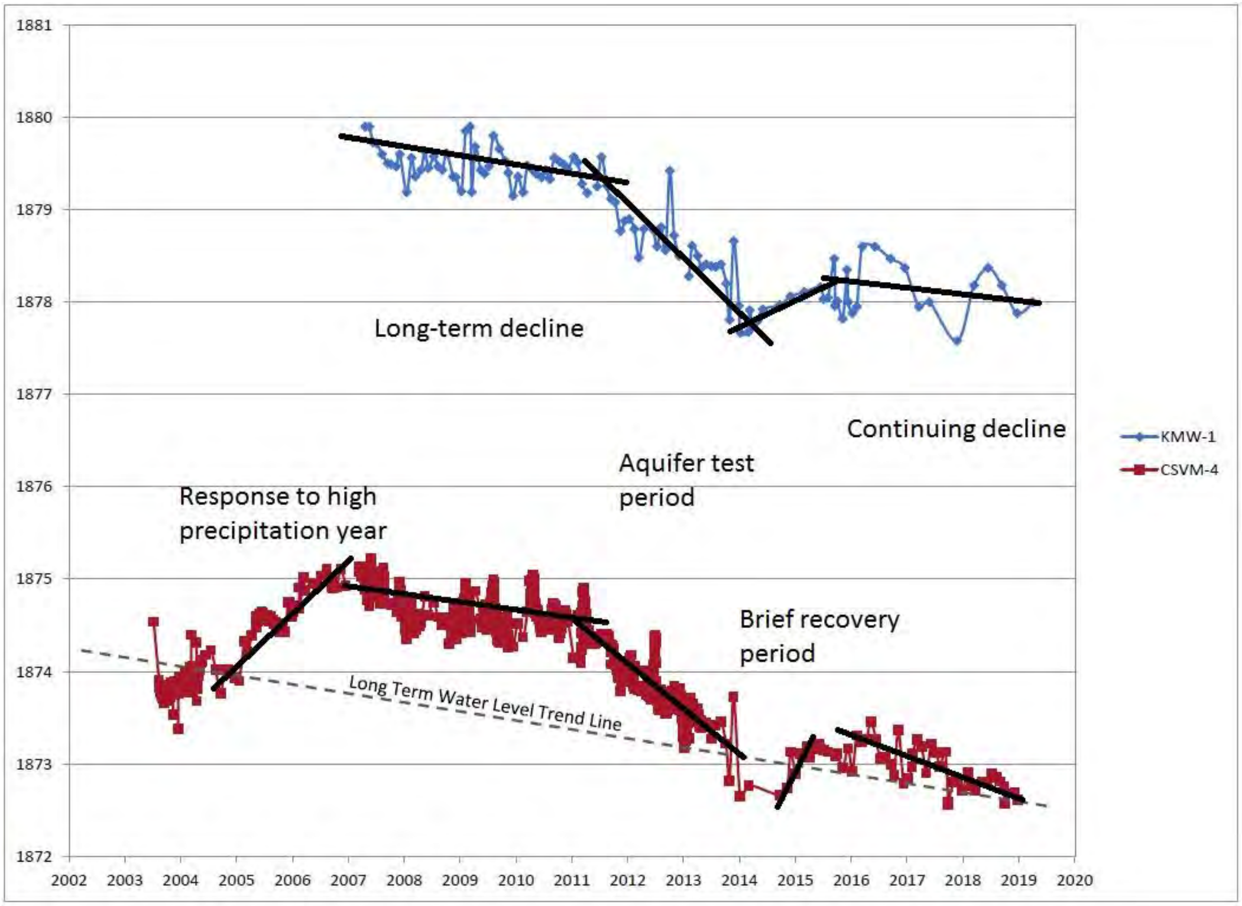


**FIGURE 3-9. COMBINED HYDROGRAPHS OF WELLS KMW-1 AND CSVM-4**

*Figure 6: Trends at hydrographs of wells KMW-1 and CSVM-4. Adapted from Lincoln/Vidler et al (2019) Figure 3-9*

Lincoln County et al (2019) document well the huge precipitation event that occurred during 2005, but its claim of estimating in-basin recharge for KSV to be from approximately 4700 to 7500 af/y (p 3-5), based on data they presented in their Appendix B is inaccurate. The appendix contains precipitation, runoff, and chloride data for precipitation and runoff, but no analysis to estimate the recharge. Assuming the precipitation data is representative of the basin and the runoff data accurately captures the runoff from the basin, two variables remain, evapotranspiration and recharge. They do not present enough data with which to estimate recharge. The estimate presented is not useful evidence of the amount of water available in KSV.

Lincoln County et al (2019) Section 3.3 attempts to use simple chemistry, age, and thermal data as evidence that KSW water differs from the other water in LWRFS that will be managed as one.

As will be described in the following paragraphs, nothing in their analysis prescribes that KSV water does not mix into CSV water and eventually discharge at MRSA or that pumping throughout CSV or KSV will not affect water levels and spring flows throughout the LWRFS.

Groundwater from KPW-1 has total dissolved solids (TDS) at 774 mg/l, a little higher than the groundwater at CSVM-4 which is 682 mg/l (p 3-8). The authors do not describe the basis for these observations, meaning they do not describe whether it is an average or how many samples were taken to obtain that average. It is common for TDS to vary more than 20% between measurements, so the difference between the wells could be random fluctuation in the data. None of the wells in their Table 3-2 stand out as substantially different than the others.

Assuming the observations are accurate, the groundwater at KPW-1 is almost the oldest (29,000 years) and hottest (136° F) of the wells in the area (p 3-9, -10). If the water in KPW-1 originated in KSV as recharge, it circulated deeply over a long time period to exhibit these characteristics. Once it joins water in CSV, the average age of the mixed water is younger and the temperature is cooler due to mixing. Its circulation depth is not relevant to whether KSW mixes with water in CSV and is affected by pumping in CSV or further downgradient. The supposed pathways in Lincoln County et al Figure 3-12 do not account for mixing along the pathways.

Lincoln et al Section 4.0 presents substantial geophysical data and analysis for KSV and northern CSV and attempts an interpretation of the hydrogeologic effects of the interpreted geology. This review does not rebut the geophysical sections and interpretations of the sections, but it does question and rebut the interpreted effects on groundwater flow. As the next paragraphs discuss, the data presented by Lincoln County et al does not support the interpretations, and the geophysics are not evidence that KSV should not be considered part of the LWRFS.

Lincoln County et al claim that "faulting that occurs in northern CSV … explains why the water levels in KMW-1 and CSVM-4 are distinctly higher than those found in the rest of the basin" (p 4-9). They cite their figures 3-4 through 3-9 as demonstrating the change in water level. The correct interpretation of those figures is that the steadily increasing water level going north of CSVM-6 is due to decreasing transmissivity. Their Figure 3-5 shows there is a much more substantial increase in water level north of KSMW-1. Even so, the increase in water levels to CSVM-3 of about 330 feet (Figure 3-6) occurs over about 4 miles, so the gradient is only about 0.0156. This is not evidence of a step increase over a fault.

The claim that "faults significantly impede the flow of groundwater from KSV and northern CSV … into the southern portion of CSV" (p 4-9) ignores the fact that most flow reaching MRSA passes through CSV from Pahranagat Valley and Delamar Valley. The gradient calculated above between KSV and CSV is not a significant impedance.

There is also no evidence to suggest the faulting is substantial enough to "cause the water levels to build up on the upthrown side of the fault … until there is enough head built up (a few tens of feet) for groundwater to push through into northern CSV". If that were the case, there would be evidence of water flowing parallel to the fault through the higher conductivity zone along the fault (p 4-8). Lincoln County et al are simply wrong to say "there were no effects ascribable to the start and subsequent stop of a major pumping stress in monitoring wells KMW-1 or CSVM-4, as shown above in Figure 5 and associated text" (p 4-10). The aquifer test effects simply lasted longer at those wells than at others closer to MX-5 because of the lower transmissivity in northern CSV, and the increasing distance from the point of diversion.

Lincoln County el al claims that these wells are too far from the pumping well for the cone of depression to reach that far (p 4-10). They disprove their own claim by noting the "very large sequence of carbonate rocks between the location of the Order No. 1169 pumping and KSV and northern CSV and that thick sequence likely has a very large transmissivity, which is indicated by the nearly flat-water level elevation in much of the LWRFS" (Id.). This nearly flat-water table declined everywhere due to the pumping, as documented by almost all reports filed on Order 1169. It was more like the lowering of a lake than the spread of a cone of depression. The lowering water table beyond the end of the flat-water table surface more resembles a cone of depression. Myers (2019) Figure 12 shows the expansion of the drawdown with distance from the pumping, similar to a cone of depression.

Finally, they seem to argue there is no connection because "groundwater from KSV has to flow through the Northern LWRFS Boundary Fault where the geologic structure changes" (p 4-10). If it does not flow through the boundary, it has to go somewhere, but Lincoln County et al does not explain where else it would go. FWS noted that "Kane Springs Wash Fault must be permeable over much of central Coyote Spring Valley" (FWS 2019, p 22) based on the observation that water flowing into CSV at the Pahranagat Shear Zone must flow through the carbonate aquifer to the MRSA.

Lincoln County et al (2019) does not present a compelling argument for not managing KSV as part of the LWRFS.

Lincoln County et al also argues that pumpage from the MRSA completely explains reductions in flows of the Muddy River and associated springs and that pumping in CSV has no effect (p 5-3). They support this argument by comparing normalized flows of the Muddy River, which means adjusting recorded flows by removing flood flows and adding back in the diversions, plotting this with the annualized pumping in the MRSA (broken out by carbonate and alluvial pumping) and CSV carbonate pumping. Figure 6 is Figure 5-1 from Lincoln County et al (2019).

The deficit peaks at just less than 8000 af/y in 2003 and 2004 and began to decrease afterwards (Figure 7). MRSA pumping had peaked in 2000 at almost 8000 af/y before dropping to just over 6000 af/y from 2001 through 2006. The most significant decrease in Muddy River deficits occurred from 2005 through 2009 when they had dropped to almost 4000 af/y. Through this period the deficits almost equaled MRSA pumping without including any CSV pumping (Figure 7). Beginning in 2010, the deficit increased about 1500 af/y and remained above 5000 af/y while MRSA pumping increased about 500 af/y for one year before decreasing during 2012. This is the period of the aquifer test as may be seen by the much higher pumping in CSV. For five years, the deficits are higher than pumping in MRSA. This would seem to be a direct reaction to the higher pumping in CSV. The aquifer test pumping caused a broad drawdown which means that it mostly drew water from storage. It slowly captured groundwater discharge, as documented by the hydrograph at Warm Springs West (Myers 2019, Figure 14) and other springs, and as documented for the Muddy River in Figure 7. Overall pumping rates from 2015 through 2018 are similar to 1995 through 1997, although the sources are different, and Muddy River depletions are similar.

Contrary to their claims, Lincoln Co et al's analysis of Muddy River depletions and groundwater pumping is not evidence that pumping in CSV has no effect on discharge from MRSA.

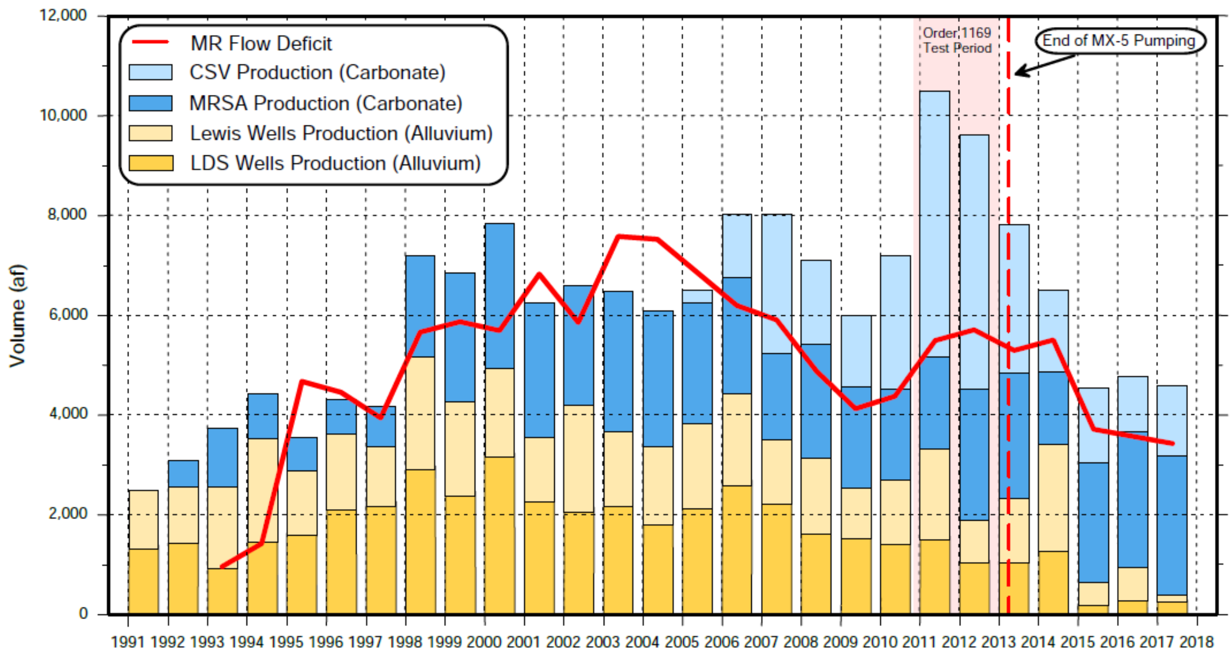


*Figure 7: Muddy River (MR) flow deficit and CSV and MRSA groundwater production. Source: Lincoln County et al (2019) Figure 5-1.*

**Rebuttal to US Fish and Wildlife Service Report**

Most US Fish and Wildlife Service (FWS) data and analysis is accurate but their report argues for a too-high allowable pumpage from LWRFS. FWS claims that full recovery from the aquifer test occurred by late summer 2015 based on measured water levels in carbonate well EH-4 and spring flows. Graphs of EH-4 and WSW flow do not allow that conclusion of full recovery. The water levels at EH-4, EH-5b and UMVM-1 show a distinct downward trend through the aquifer test and continued pumping of MX-5, which ended about April 2013 (Figure 8). Water levels continued a small decline for several months before they began to recover, as reported by FWS. However, water levels at those three wells never reached within a foot of levels seen near the beginning of the aquifer test (Figure 8). The levels remain steady with just a seasonal fluctuation until early 2016 when they again began a downward trend. The same occurred at Warm Springs West. Near the beginning of the aquifer test, flows were near 3.8 cfs but they decreased to less than 3.3 cfs by several months after the test (Figure 9). Although they briefly recovered to almost 3.6 cfs, flows have been decreasing since.

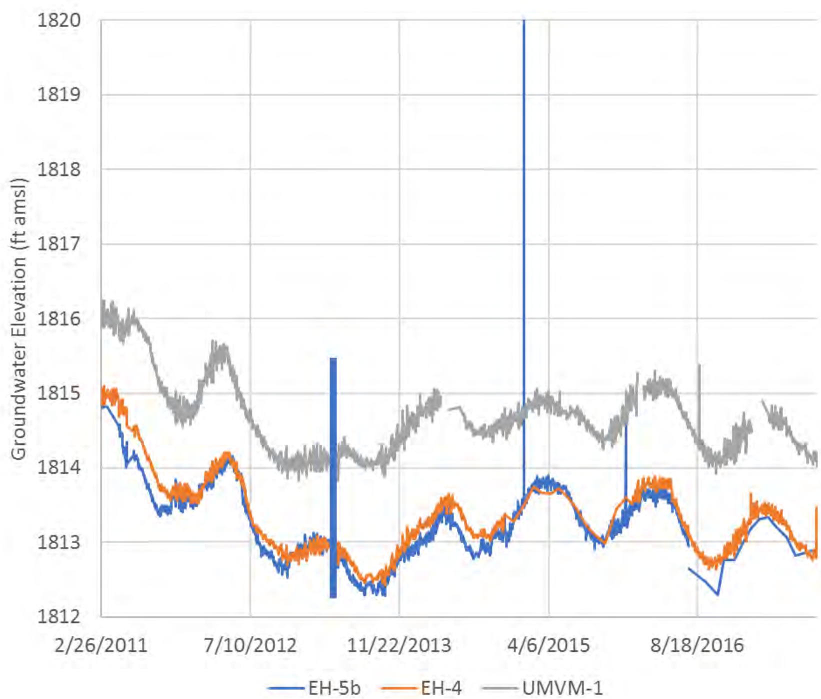


*Figure 8: Plot of monitoring wells EH-5b, EH-4, UMVM-1 for the period during and after the aquifer test. Source: Myers (2019) Figure 8.*

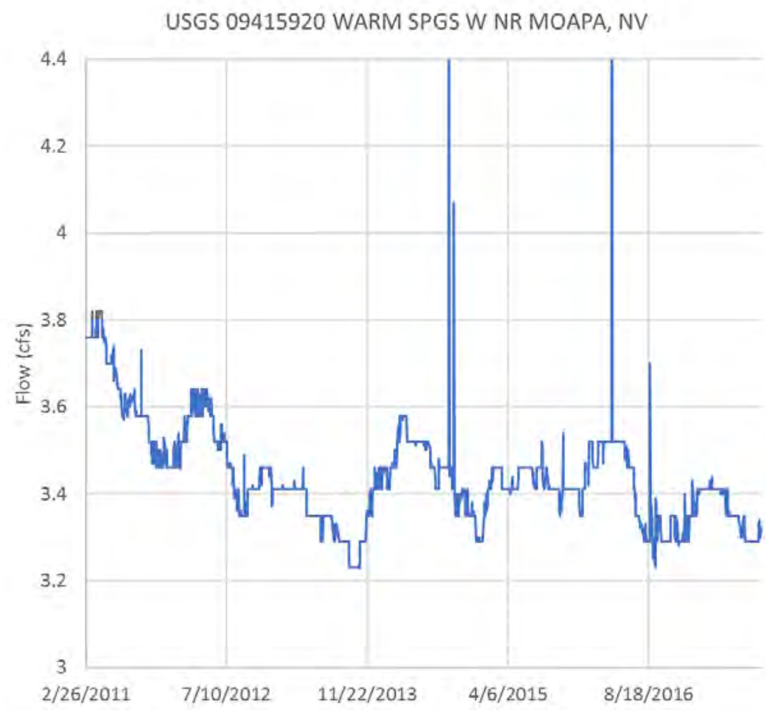


*Figure 9: Hydrograph of Warm Springs West for the period during and after the aquifer test. Source: Myers (2019) Figure 14.*

FWS states that the average pumping of years 2015 through 2017 should be the long-term allowed total pumping rate from carbonate and alluvial aquifers because it claims the discharge of Muddy River Springs and Muddy River at Moapa gage was relatively constant (p 37, 38). This is incorrect, Muddy River flows were steady but flows at Big Muddy Springs (gage #09415900) dropped over 200 cfs from 2015 to 2017 (5799 to 5546 cfs). FWS also incorrectly claims that flow rates at the Refuge springs were reasonably stable in 2015 to 2017 (p 37). Myers (2019) Figures 14 and 15 show a continuing slight decrease in flow rates at Warm Springs West and the Pederson Springs. Myers (2019) concluded that any pumping from the carbonate aquifer would decrease spring flow over the long term because discharge equals the long-term recharge and that infrequent short-term recharge events provide minimal recovery. NPS' groundwater modeling discussed below also predicts long-term spring flow decline due to pumping. Experiencing a long-term decrease does not mean there will be no temporary upticks in flow, as seen at the end of MX-5 pumping, as groundwater storage throughout the carbonate aquifer is depleted. Myers (2019) suggests that the total pumpage from the LWRFS should occur only from alluvium after the flow has discharged from springs and become secondary recharge into the alluvium. This objection to FWS' recommended pumping is not so much to the amount but to the location from which it would be drawn.

FWS argues that total carbonate pumping can continue but not be increased from 2015-2017 levels even if it would replace alluvial pumping. This FWS recommendation will not protect the high-elevation springs. Most carbonate pumping is removed from storage and only a small percent is currently being removed from discharge (the spring flow). As pumping continues and storage removed, which also lowers the head at the carbonate monitoring wells (see the continued lowering at EH-4 and EH-5b in Figure 8). Eventually, more carbonate pumping will be captured from discharge and the spring flow will decease until it reaches critical levels.

FWS section 1.6 develops relationships between the water level at EH-4 and discharges from various springs. All have significant coefficients demonstrating that decreases in water level decreases the discharge at all springs (except Muddy Springs at the LDS). The highest elevation springs have the most significant relationship and proportionally lose the most water as EH-4 water levels decrease. The higher elevation springs will be the first to go dry as carbonate pumping continues. This evidence suggests that FWS should not recommend a continuation of the existing carbonate pumping rates.

**Rebuttal to US National Park Service Report**

The National Park Service (NPS) submitted a report prepared by Tetra Tech which was based on the model Tetra Tech had previously prepared of the LWRFS. Tetra Tech (2019) used their LWRFS groundwater model to analyze various pumping scenarios. Regardless of the simulation, the model results indicate that the long-term trend will be for drawdown to expand and spring discharge to decrease. Unfortunately, none of the simulations pumped as little as was being pumped during 2017 (Tetra Tech, Table 4-1, reproduced here as Figure 10).

| Water Right Holder Pumping Basin | 2017 Withdrawals (ac-ft) | Simulation #1 Withdrawals (afy) | Simulation #2 Withdrawals (afy) | Simulation #3 Withdrawals (afy) |
|---|---|---|---|---|
| | | | | |
| Coyote Springs Investment | | | | |
| Coyote Spring Valley | 1,399 | 4,140 | 1,650 | 1,477 |
| | | | | |
| SNWA | | | | |
| Coyote Spring Valley | | 1,957 | | |
| Garnet Valley | 1,048 | | 1,433 | 1,709 |
| | | | | |
| Moapa Valley Water District | | | | |
| California Wash | | 90 | | |
| Muddy River Springs Area | 2,823 | 1,000 | 5,079 | 2,823 |
| | | | | |
| Moapa Band of Paiutes | | | | |
| California Wash | 43 | | 2,063 | 2,960 |
| Muddy River Springs Area | | 500 | | |
| | | | | |
| NV Energy | | | | |
| California Wash | 29 | | 299 | 356 |
| Garnet Valley | 75 | 75 | 62 | 1,800 |
| Muddy River Springs Area | 296 | 3,160 | 795 | |
| | | | | |
| LDS Church | | | | |
| Muddy River Springs Area | 240 | 2,329 | 655 | 586 |
| | | | | |
| Nevada Cogeneration Associates | | | | |
| Black Mountains Area | 1,507 | | 1,374 | 1,638 |

Table 4-1. Summary of the largest simulated annual withdrawals for selected water-right holders in the LWRFS basins and aquifers.

*Figure 10: Tetra Tech (2019) Table 4-1 showing 2017 pumping withdrawals by water rights hold and basin and the amount pumped for three simulations.*

Each simulation pumped the same amount, but the difference was the location from which it was withdrawn (Tetra Tech 2019, p 20). Simulation #1 included substantially more pumping in CSV than observed in 2017 (Figure 10). Simulations #2 and #3 have much less pumping in CSV but still more than observed in 2017. The simulations also have much more pumping in MRSA than observed, but the location of the pumping, both by aquifer and water right holder, varies.

The biggest difference in the results shows in the drawdown maps (Tetra Tech Figures 4-4 through 4-12). They present drawdown for 10-, 100-, and 200-year simulations for each simulation. After 10 years in the high CSV-pumping simulation #1, drawdown exceeds 2 feet and ranges from 1 to 2 feet over larger portions of CSV and approaches 10 feet for portions of MRSA. Simulation #2 shifts pumping south into Garnet and Hidden Valley with a large area experiencing 1 to 2-foot drawdown. The shift south is greater for Simulation #3 with a large area experiencing 2 to 5-foot drawdown. Going forward 100 years, the differences are much less because drawdown up to 10 feet covers most of the area west of Meadow Valley Wash. There is a large area near Garnet and Hidden Valleys over which drawdown approaches 20 feet.

After 200 years, drawdown approaches 20 feet over large areas. Tetra Tech acknowledges these differences at Tetra Tech (p 20, 21).

Spring discharge decreases with the simulations as well, but the difference among simulations is much less. Over the 500-year period simulated, spring flows would decrease by about 20% with just small variation among simulations. This reflects the long period required to reestablish hydrologic equilibrium (Tetra Tech, p 20). Equilibrium is reestablished when the reduction in spring flow equals the amount being pumped; when this happens, the pumping will have completely captured the discharge. This would violate the trigger points in Warm Springs West and surface water rights on the Muddy River. The lack of difference among outcomes in these simulations is evidence that there is not some perfect scenario that would allow pumping to continue at a much higher rate (that is not to say other scenarios should not be tested, especially those with even less pumpage than simulated by Tetra Tech). The simulations basically confirm Myers (2019) results regarding continued pumping in the carbonate aquifer – drawdown will increase and spring flow decrease regardless of pumping rate; the only difference is the rate of decrease. Eventually the reduction in spring flow will equal the amount of water being pumped.

Tetra Tech' model simulations lead NPS to conclude that all of the Black Mountains Area (BMA) and KSV should be included in the LWRFS management area. Myers (2019) argued the same for inclusion of KSV (and this is discussed further above in rebuttal to Lincoln County et al). The Tetra Tech model showed drawdown in KSV coalescing with that in CSV, although it must be recognized that there was no monitoring well data with which to calibrate the connection between valleys.

Myers (2019) did not address the BMA. Model-simulated drawdown, such as was simulated through the BMA, rarely is accurate near structural boundaries so the accuracy of the predicted drawdown in BMA is questionable. Although there is little doubt that pumping in LWRFS would affect Rogers and Blue Point Spring, the model does not provide evidence that pumping within BMA would spread into LWRFS. Without more evidence it appears that the connection may be distant enough that including the remainder of BMA is not necessary and that flow at the springs should be considered as a long-term impact, tantamount to the way pumping in Delamar, Dry Lake and Cave Valley is considered at MRSA.

The Tetra Tech model raises a quandary that should be addressed. Its simulated drawdown reached the model boundary with Las Vegas Valley. This could have caused the model to overestimate drawdown in the southern reaches of LWRFS. It also suggests that the connection with Las Vegas Valley be better examined. Is there flow from LWRFS to LVV, as suggested by Johnson/Mifflin? Tetra Tech (p 22) suggests any flow would be minimal, although they present no evidence other than unreferenced estimates from the USGS.

**Rebuttal to Southern Nevada Water Authority Report**

SNWA in its abstract claims that "[i]f the conflicts with senior water-right holders are adequately addressed, the annual groundwater production from the carbonate aquifer should be managed between 4,000 – 6,000 afy over the long-term" (SNWA 2019, p ix). This conclusion however violates all of the findings SNWA makes throughout its report. The most important finding that does not support the conclusion is "(c) the data indicated that groundwater production from the MRSA alluvial reservoir or the carbonate aquifer simply cannot occur over the long-term without depleting spring and streamflows and conflicting with senior surface-water rights" (Id.). This rebuttal reviews SNWA (2019) and discusses additional points as to why the ultimate conclusion is faulty.

SNWA shows there have not been any significant climatic trends or shifts in the area since 1895 (SNWA, p 5-1). SNWA Figure 4-2 shows a slight, non-significant upward trend which is likely due to the very high precipitation in 2005.

SNWA notes that since 2016, heads in the carbonate aquifer and discharge measured at Pederson Spring and WSW have declined (SNWA, p 6-2). It notes that a significant increase in pumping as occurred during the aquifer test would increase the rate of decline. The only way to recover groundwater levels to pre-test levels would be for a pulse recharge event like in 2004-2005 (Id.). Stopping pumping is not sufficient. It further elaborates:

> In the long-term, it is expected that **any groundwater production from the carbonate system with in the LWRFS will ultimately capture discharge** to the MRSA (e.g., spring discharge, subsurface inflow the o the alluvial reservoir and, consequently, Muddy River streamflow) because of the high aquifer diffusivity and hydraulic connectivity throughout the flow system and because the MRSA constitutes the majority, if not all, of the discharge from the flow system" (Id., emphasis added).

Moving the pumping center will not help in the long term either, but may just take longer (Id.). SNWA presents four important conclusions:

- groundwater production from the carbonate aquifer in the LWRFS has impacted discharge to the MRSA and, consequently, senior surface-water rights associated with the 1920 Muddy River Decree
- impacts due to groundwater production within areas directly upgradient of the MRSA occur relatively quickly, and the magnitude of the impacts depends upon the pumping rates and durations
- **additional appropriations** that increase groundwater production from the carbonate aquifer within the LWRFS will **accelerate the timing and magnitude** of impacts

- **changing the spatial distribution of pumping within the LWRFS will change the distribution of drawdown and the timing of impacts, but not the long-term outcome**. (SNWA, p 6-4, emphases added)

SNWA's conclusions quoted here are accurate and are supported by the evidence they have analyzed. However, SNWA's attempt to quantify these analyses with ratios of spring flow to total MRSA flow may be incorrect. If high elevation spring discharge drops more rapidly than overall discharge, the ratio would change. Higher elevation springs will be dry before the flow reduction of lower elevation springs are substantively affected. This is based on the fact that a given change in groundwater level causes a larger change in the gradient controlling the discharge than it does for the lower elevation springs. The change in flow is proportional to the change in gradient, and therefore the claim that each "spring contributes to MRSA discharge in the same proportion under any stress conditions" (p 6-11) is incorrect. This does not obviate the overall conclusion that in the long term, capture of aquifer storage will decrease MRSA discharge on a nearly 1:1 ratio (Id.).

SNWA's analysis supports the concept that any carbonate pumping anywhere in the LWRFS will lead to a decrease in critical spring flow. SNWA's analysis does not support the recommendation that 4000 to 6000 af/y can continue to be developed from the carbonate aquifer.

**Endorsement of Great Basin Water Network Letter**

Great Basin Water Network (GBWN) addresses one issue directly pertinent to the subject of Order 1303, that of the boundary of the LWRFS. GBWN argues that the entire White River Flow System (WRFS) should be managed as one. This is a well-founded idea because most of the water that reaches MRSA originates in the northern portions of the WRFS. Myers (2019, p 19) explained how pumping in the northern portion of the WRS will diminish inflow to the LWRFS and eventually decrease water levels and discharges from the springs. It is completely reasonable to manage the entire WRFS as one unit.

**References**

DeMeo, G.A., Smith, J.L., Damar, N.A., Darnell, J., 2008. Quantifying groundwater and surface water discharge from evapotranspiration processes in 12 hydrographic areas of the Colorado Regional Groundwater Flow System, Nevada, Utah, and Arizona. U.S. Geol. Surv. Sci. Invest. Rep. 2008-5116, 22 p.

FWS (U.S. Fish and Wildlife Service) (2019) Issues Related to Conjunctive Management of the Lower White River Flow System. Presentation to the Office of the Nevada State Engineer in Response to Order 1303. July 3, 2019

Lincoln County et al (Lincoln County Water District, Vidler Water Company, Zonge International, Inc.) (2019). Lower White River Flow System Interim Order #1303 Report Focused on the Northern Boundary of the Proposed Administrative Unit. July 3, 2019.

Myers T (2019) Technical Memorandum: Groundwater Management and the Muddy River Springs, Report in Response to Nevada State Engineer Order 1303. Prepared for Center for Biological Diversity.

Myers T (2013) Technical Memorandum, Comments on Carbonate Order 1169 Pump Test Data and the Groundwater Flow System in Coyote Springs and Muddy River Springs Valley, Nevada. Prepared for Great Basin Water Network.

SNWA (Southern Nevada Water Authority) (2019) Assessment of Lower White River Flow System Water Resource Conditions and Aquifer Response, Presentation to the Office of the Nevada State Engineer. Las Vegas NV.

Tetra Tech (2019) Prediction of the Effects of Changing the Spatial Distribution of Pumping in the Lower White River Flow System. Present to US National Park Service. Superior, CO

US DOI (US Fish and Wildlife Service, Bureau of Land Management, National Park Service) (2013) Test Impacts and Availability of Water Pursuant to applications Pending Under Order 1169.

USFWS (US Fish and Wildlife Service, Region 1) (1996) Recovery Plan for the Rare Aquatic Species of the Muddy River Ecosystem, First Revision. Portland OR

**IN THE OFFICE OF THE STATE ENGINEER**
**OF THE STATE OF NEVADA**

| | | |
|---|---|---|
| IN THE MATTER OF THE ADMINISTRATION AND MANAGEMENT OF THE LOV/ER WHITE RIVER FLOW SYSTEM WITHIN COYOTE SPRING VALLEY HYDROGRAPHIC BASIN (210), A PORTION OF BLACK MOUNTAINS AREA HYDROGRAPHIC BASIN (215), GARNET VALLEY HYDROGRAPHIC BASIN (216), HIDDEN VALLEY HYDROGRAPHIC BASIN (217), CALIFORNIA WASH HYDROGRAPHIC BASIN (218), AND MUDDY RIVER SPRINGS AREA (AKA UPPER MOAPA VALLEY) HYDROGRAPHIC BASIN (2t9), LINCOLN AND CLARK COUNTIES, NEVADA | ) ) ) ) ) ) ) ) ) ) ) ) ) ) ) ) | Regarding Nevada State Engineer Interim Order 1303<br><br>**WITNESS LIST, SUMMARY OF WITNESS TESTIMONY, AND EXHIBIT LIST** |

**Witness List, Summary of Witness Testimony, and Exhibit List**

In accordance with the rules set forth in the Lower White River Flow System Order 1303 Notice of Hearing dated August 23, 2019, Patrick Donnelly, an agent of the Center for Biological Diversity, enters this list of witnesses, summary of witness testimony, and exhibit list for use at the evidentiary hearing in the above referenced matter to the Nevada State Engineer.

**List of Witnesses and Summary of Witness Testimony**

The Center for Biological Diversity's sole witness will be Tom Myers, Ph.D. Dr. Myers is a hydrogeologist with advanced degrees from the University of Nevada, Reno. Dr. Myers has previously been admitted by the State Engineer as a hydrogeologist in numerous previous unrelated proceedings. His curriculum vitae is included as an exhibit.

At the evidentiary hearing, Dr. Myers will present a power point, included as an exhibit, outlining his principal conclusions and their rationales as described in his technical report prepared for the Center for Biological Diversity and submitted to the Nevada State Engineer on July 3, 2019 and in his rebuttal report prepared for the Center for Biological Diversity and submitted to the Nevada State Engineer on August 16, 2019.

Dr. Myers' report has three principal conclusions: the Nevada State Engineer should not allow any pumping of the carbonate aquifer within the Lower White River Flow System (LWRFS); the Nevada State Engineer should include Kane Springs Valley within the LWRFS; and that future pumping should be limited to the basin-fill aquifer only, at a limit of no more than 4,000 acre feet per annum.

Dr. Myers' argument for these conclusions is based on an analysis of the results of the Order 1169 pump test, which he asserts demonstrates the interconnectedness of the LWRFS aquifer ("During pumping, water levels throughout this highly transmissive aquifer responded as if the aquifer water is a pond with water level changes transmitted quickly throughout.”). As a result of this interconnectedness, pumping within the carbonate aquifer anywhere in the system is likely to cause drawdown at the Muddy River Springs Area springs.

Analysis of the same data is used to justify the need for Kane Springs Valley to be included in the LWRFS. Monitoring wells in Kane Springs Valley showed a clear drawdown signal in response to the Order 1169 pump tests, and appear to be as interconnected with the rest of the LWRFS as areas in Coyote Springs Valley and elsewhere, albeit with a slower response time due to greater distance from Order 1169 pumping.

Dr. Myers demonstrates with monitoring well and spring discharge data that while the catastrophic discharge declines seen during the Order 1169 pump test ceased upon cessation of pumping, there has still been a decline in discharge since then. He attributes this to carbonate pumping. Therefore, he recommends against any carbonate pumping, and recommends limiting basin-fill pumping to existing levels – about 4,000 acre feet per annum.

Dr. Myers will also present his rebuttals to other parties’ reports, specifically Coyote Springs Investment, Moapa Band of Paiutes, Vidler/Lincoln County, US Fish and Wildlife Service, US National Park Service, and Southern Nevada Water Authority. His rebuttals will not be summarized in detail here, but they primarily trace the lines of evidence summarized above.

**Exhibit list**

CBD Exhibit 1 – Curriculum Vitae for Dr. Tom Myers; 11 pp.

CBD Exhibit 2 – Power Point from Dr. Tom Myers for presentation at the evidentiary hearing for the above referenced matter; 45 pp.

CBD Exhibit 3 – CBD Order 1303 Report by Dr. Tom Myers; 27 pp.

CBD Exhibit 4 – CBD Order 1303 Rebuttal in Response to Stakeholder Reports by Dr. Tom Myers; 30 pp.

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*Attorneys for The City of North Las Vegas*

Affirmation: This document does not contain the social security number of any person.

**IN THE OFFICE OF THE STATE ENGINEER**

**OF THE STATE OF NEVADA**

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| IN THE MATTER OF THE ADMINISTRATION AND MANAGEMENT OF THE LOWER WHITE RIVER FLOW SYSTEM WITHIN THE COYOTE SPRING VALLEY HYDROGRAPHIC BASIN (210), A PORTION OF BLACK MOUNTAINS AREA HYDROGRAPHIC BASIN (215), GARNET VALLEY HYDROGRAPHIC BASIN (216), HIDDEN VALLEY HYDROGRAPHIC BASIN (217), CALIFORNIA WASH HYDROGRAPHIC BASIN (218), AND MUDDY RIVER SPRINGS AREA (AKA UPPER MOAPA VALLEY) HYDROGRAPHIC BASIN (219), LINCOLN AND CLARK COUNTIES, NEVADA | **CITY OF NORTH LAS VEGAS' WITNESS LIST, SUMMARY OF TESTIMONY, AND EXHIBIT LIST** |

City of North Las Vegas, by and through its counsel, Therese A. Ure and Laura A. Schroeder of Schroeder Law Offices, P.C., pursuant to the State Engineer's August 23, 2019 Notice of Hearing, submit: 1) the following list of potential witnesses with a brief summary of their testimony; 2) exhibit list; and 3) copies of documentary evidence attached hereto.

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This submission does not waive any objections to exhibits submitted by any other party in this proceeding.

**Witness List and Summary:**

The City of North Las Vegas may call any or all of the following witnesses and utilize any or all of the following exhibits in this proceeding:

1) Dwight Smith, PE, PG
   Interflow Hydrology, Inc.
   11045 Donner Pass Road, Ste. 2A
   Truckee, CA 96161

Mr. Smith has previously been qualified before the State Engineer as an expert in the area of hydrogeology. Mr. Smith will testify as to the items in the joint reports titled 1) Concept Review of Artificial Recharge in Garnet Valley for the APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada; 2) Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada; 3) Addendum No. 1 - Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada, dated July 2, 2019; and 4) Rebuttal Document submitted on behalf of the City of North Las Vegas, to Interim Order 1303 Report Submittals of July 3, 2019. Mr. Smith will provide testimony regarding 1) the APEX Industrial Complex project located in the City of North Las Vegas, 2) temporary and/or long term Artificial Recharge management strategies, 3) the conceptual Artificial Recharge well location in Garnet Valley, 4) conceptual review of Artificial Recharge hydraulic effectiveness, 5) Artificial Recharge project permitting requirements from Nevada Division of Water Resources and Nevada Division of Environmental Protection , 6) the hydrogeologic setting of Garnet Valley hydrographic basin and/or other regional hydrogeologic settings in the Lower White River Flow System ("LWRFS"), 7) Garnet Valley hydrographic basin hydrogeology, 8) groundwater chemistry and aquifer compatibility, 9) Garnet Valley hydrographic basin boundary conditions, 10) conceptual review of groundwater yield in Garnet Valley hydrographic basin, 11) review of senior water right transfers to APEX,



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and 12) rebuttal testimony concerning inclusion of areas extending to Lake Mead, the use of regional groundwater flow models, transfer pumping from the MRSA alluvium, groundwater flow within the LWRFS, and LWRFS perennial yield. Mr. Smith may also give testimony concerning historic and current groundwater pumping in and around Garnet Valley hydrographic basin. This testimony will include those opinions, conclusions and recommendations as cited in the reports.

**Exhibit List and Copies:** (Exhibit Numbers CNLV Ex. No 1 – CNLV Ex. No. 27)

The City of North Las Vegas' Exhibits are listed in Attachment A hereto. Two original sets as well as a copy on a USB drive of all exhibits listed in Attachment A are being provided to the State Engineer in conjunction with this filing. The exhibit list is also provided to the State Engineer in Excel format on the attached USB drive.

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The City of North Las Vegas reserves the right to introduce records from the State Engineer's files and records. The City of North Las Vegas reserves the right to introduce additional exhibits that may be identified as a result of the testimony or exhibits disclosed by other parties to the proceeding. The City of North Las Vegas further reserves the right to introduce exhibits as may be necessary for rebuttal or impeachment purposes.

DATED this 6th day of September, 2019.

SCHROEDER LAW OFFICES, P.C.

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*Attorneys for The City of North Las Vegas*

# ATTACHMENT A

The City of North Las Vegas
**Exhibit List**
**(CNLV Ex. No 1 – CNLV Ex. No. 27)**

| Exhibit Number | Description |
|---|---|
| CNLV Ex. No. 1 | Dwight Smith – Curriculum Vitae and Qualification List |
| CNLV Ex. No. 2 | Concept Review of Artificial Recharge in Garnet Valley for the APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada – Prepared by Interflow Hydrology, Inc. – July 2019 |
| CNLV Ex. No. 3 | Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada – Prepared by Interflow Hydrology, Inc. – July 2019 |
| CNLV Ex. No. 4 | Addendum No. 1 - Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada, dated July 2, 2019 |
| CNLV Ex. No. 5 | City of North Las Vegas Utilities Department: Interim Order 1303 Report Submittal from the City of North Las Vegas – July 2, 2019 |
| CNLV Ex. No. 6 | Rebuttal Document submitted on behalf of the City of North Las Vegas, to Interim Order 1303 Report Submittals of July 3, 2019 – Prepared by Interflow Hydrology – August 2019 |
| CNLV Ex. No. 7 | Page, W.R., Dixon, G.L., Rowley, P.D., and Brickey, D.W., 2005, Geologic Map of Parts of the Colorado, White River, and Death Valley Groundwater Flow Systems, Nevada, Utah, and Arizona; Nevada Bureau of Mines and Geology, Map 150, 1:250,000 and accompanying Text and References |
| CNLV Ex. No. 8 | Smith, D.L., Johnson, J., Donovan, D., Kistinger, G., and Burns, A., 2004, Climate and Barometric Pressure Influences on Pederson Spring Discharge and the Carbonate Aquifer near the Muddy Springs, Southern Nevada; Journal of the Nevada Water Resources Association, Fall 2004, p76-103. |
| CNLV Ex. No. 9 | Page, W.R., Scheirer, D.S., Langenheim, V.E., Berger, M.A., 2011, Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona; USGS Open File Report 2006-1040 and accompanying Plate |
| CNLV Ex. No. 10 | Poggemeyer Design Group, 2012, Water and Wastewater Master Plan, Apex Industrial Park, City of North Las Vegas, Nevada, prepared for Kapex, LLC, December 28, 2012 |



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| Exhibit Number | Description |
|---|---|
| CNLV Ex. No. 11 | Wilson, Jon W., Drilling, Construction, Water Chemistry, Water Levels, and Regional Potentiometric Surface of the Upper Carbonate-Rock Aquifer in Clark County, Nevada, 2009-2015 |
| CNLV Ex. No. 12 | Southern Nevada Water Authority, 2013, Submittal of Nevada State Engineer Orders 1169 and 1169A Study Report, June 2013. |
| CNLV Ex. No. 13 | Southern Nevada Water Authority, 2016, Garnet Valley Groundwater Production Simulated Effects of Pumping the Southern Nevada Water Authority's Temporary Applications; memorandum submitted to NDWR on January 14, 2016. |
| CNLV Ex. No. 14 | Southern Nevada Water Authority 2018 Water Resource Plan & Water Budget |
| CNLV Ex. No. 15 | 2006 Memorandum of Agreement Hydrologic Review Team: 2018 Annual Determination Report – April 2018, Appended August 7, 2018 |
| CNLV Ex. No. 16 | Southern Nevada Water Authority Transmittal of SNWA Comments on the Numerical Groundwater Flow Model |
| CNLV Ex. No. 17 | Southern Nevada Water Authority, 2013, Technical Review of Numerical Groundwater Flow Model of Selected Basins with the Colorado Regional Groundwater Flow System, Southeastern Nevada, Version 1.0- A Model Prepared by Tetra Tech for the National Park Service, US Fish and Wildlife Service and Bureau of Land Management; submitted to Mr. Bill Van Liew, June 13, 2013, copied to Rick Felling, NDWR; SNWA Doc No. WRD-ED-0020 |
| CNLV Ex. No. 18 | Water Service Agreement between Southern Nevada Water Authority and City of North Las Vegas |
| CNLV Ex. No. 19 | NDWR Permit 77745/ Certificate 19642 |
| CNLV Ex. No. 20 | NDWR Permit 83490 |
| CNLV Ex. No. 21 | NDWR Application 88821 |
| CNLV Ex. No. 22 | NDWR Application 88822 |
| CNLV Ex. No. 23 | NDWR Application 88823 |
| CNLV Ex. No. 24 | NDWR Application 88824 |
| CNLV Ex. No. 25 | NDWR Application 88825 |
| CNLV Ex. No. 26 | LWRFS water rights by priority with 2017 pumpage |
| CNLV Ex. No. 27 | Garnet Valley Pre-2000 Water Rights in Use Summary |

## CERTIFICATE OF SERVICE

I hereby certify that on September 6, 2019, I caused a copy of the foregoing ***CITY OF NORTH LAS VEGAS' WITNESS LIST, SUMMARY OF TESTIMONY, AND EXHIBIT LIST*** to be served on the following parties as outlined below:

***VIA HAND DELIVERY:***

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Nevada Division of Water Resources
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Carson City, NV 89701

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Dated this 6th day of September, 2019.

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InterFlow Hydrology, Inc.
Hydrogeology and Water Resources Consulting

# Technical
# MEMORANDUM

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To: Mr. Randall E. DeVaul, PE, City of North Las Vegas, Director of Utilities
Mr. Robert A. McLaughlin, PE, City of North Las Vegas, Manager, Development & Flood Control

Date: July 2, 2019

RE: **Concept Review of Artificial Recharge in Garnet Valley for the APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada**

From: Dwight L. Smith, PE, PG, Principal Hydrogeologist
Alexa Terrell, MSc., Hydrogeologist

PROFESSIONAL ENGINEER - STATE OF NEVADA
DWIGHT L. SMITH
GEOLOGICAL
No. 11906

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## Executive Summary

The concept of artificial recharge (AR) in southern Garnet Valley appears to be possible for use as an interim method to accommodate greater pumping in northern APEX while infrastructure is completed for the delivery of Colorado River water throughout APEX. The results of this review also suggest AR could be favorable for use as part of a long-term Lower White River Flow System (LWRFS) water management strategy for Garnet Valley by limiting carbonate aquifer drawdown. Under the concept, treated Colorado River water would be conveyed to southern Garnet Valley in Phase 2 of APEX pipeline construction. Pipeline water could then be recharged into the carbonate aquifer using one or more injection wells.

Existing water supply wells in APEX range in depth from approximately 1000 to 2000 feet. Depth to groundwater at a conceptual location for an AR well near the end of the Phase 2 pipeline is estimated to be approximately 750 feet. An AR well of 1250-1500 feet depth may be sufficient, although the AR well depth will depend on the depths where high-permeability aquifer zones are encountered. The top of limestone rock (Bird Spring Formation) is estimated to be approximately 300 feet, or shallower, at the conceptual AR well location. A 1250 foot deep well drilled by Georgia Pacific Corporation approximately 1 mile east of the conceptual AR well location appears to have encountered highly permeable carbonate rocks, although the information reported on the well drillers log is uncertain and has not been verified. If similar conditions are encountered for an AR well, then an injection capacity of up to several thousand gallons per minute (gpm) may be possible. However, based on average transmissivities elsewhere in the carbonate aquifer in APEX, a more modest injection well capacity of approximately 400-600 gpm is estimated.

The effectiveness of AR in southern APEX to support additional pumping from northern APEX wells operated by the City has been tested using a preliminary flow model. The modeling suggests that southern AR can be effective in managing predicted drawdown in the aquifer. Because the conceptual AR is taking place near the Las Vegas Valley basin boundary, some recharged water may be lost as outflow to Las Vegas Valley, or may

result in a reduced gradient of subsurface flow into Garnet Valley, thus lowering the natural quantity of inflow. A preliminary interpretation is that groundwater is flowing from Las Vegas Valley into Garnet Valley, and the inflow may be reduced as a result of AR operation. The conceptual AR effectiveness when considering the reduced inflow is about 75% for Garnet Valley. There is notable uncertainty however regarding the groundwater gradients between Las Vegas Valley and Garnet Valley, due to a lack of accurate water level data. Should gradients be found to differ over what has been assumed, then the AR effectiveness in Garnet Valley could be reduced due to outflow to Las Vegas Valley. However, to the degree that outflow occurs, the water might be captured by a recovery well operated in the southern-most part of the APEX industrial park, which is within Las Vegas Valley.

As next steps in review for AR feasibility, the groundwater gradient between Las Vegas Valley and Garnet Valley will need to be accurately defined by water level measurements. This may necessitate drilling of water level monitoring wells. The aquifer characteristics and water quality need to be defined at the conceptual AR well location. This will require drilling of a test well. Testing of the nearby Georgia Pacific Corporation well, if access and use for testing is possible, could provide additional useful data. The data collected will enable a more thorough feasibility review and will provide necessary data for NDWR and NDEP permitting, and AR system design.

**Introduction**

This memorandum has been prepared to review artificial recharge (AR) as a water management strategy for the APEX Industrial Complex (APEX) located in the City of North Las Vegas, Clark County, Nevada. APEX is located along the Interstate 15 corridor northeast of Las Vegas. The southern-most portion resides in Las Vegas Valley, while the majority of APEX is within Garnet Valley. APEX is bound by public lands on most sides, and by US Hwy 93 on the northeast (Figure 1). BLM utility corridors bisect portions of APEX.

APEX was established following the PEPCON chemical plant explosion in Henderson in 1988, through the efforts of Nevada leaders and US Congress to designate a new heavy industrial area for Southern Nevada. Roughly 18,000 acres were released from the BLM through land auctions to private investors and developers. The APEX area was subsequently annexed into the City in 2008, and the City took over operation of a private water system in APEX in 2010.

APEX currently hosts a variety of industrial and commercial development, including power generating facilities (both natural gas and solar), landfill facilities, gypsum mining, and a high speed transportation testing facility (Hyperloop). However, a large portion of APEX remains undeveloped, in part due to a lack of water supply infrastructure. APEX was the proposed site of the Faraday Future electric car manufacturing facility. In 2016 and 2017, I-15 interchange facilities, widening of Hwy 93, and a 700-acre super-pad were completed prior to Faraday Future announcing withdrawal from the proposed project.

The City of North Las Vegas is planning for future APEX development along the path of manufacturing and technology industries. Water service to APEX is currently by wells, both public and privately owned. The City operates two wells in the northern part of APEX which are equipped for municipal water supply. The Playa Well was drilled in 2016 to 2000 ft in depth and has a tested yield up to 600 gallons per minute (gpm) (West Yost, 2016). The Kapex Well was drilled to 1145 ft in depth in 1990 by the Kerr-McGee Chemical Company, and has a reported well yield of 200 gpm.

The City of North Las Vegas currently owns 10 acre-feet per year (AF/yr) of water rights under permit 77745, with a point of diversion at the Kapex Well. The Southern Nevada Water Authority (SNWA) owns 2,274.57 AF/yr of groundwater rights in the APEX area, under multiple water right permits, which have been available for permanent and temporary transfers to wells to serve APEX facilities. The City has an agreement with SNWA to lease up to 900 AF/yr. SNWA permit 83490 has been issued for 300 AF/yr for use by the City for municipal purposes in APEX, with a point of diversion at the Kapex Well. Similarly, a temporary transfer of SNWA water rights is currently active for 350 AF/yr at the Playa Well (permit 88011T).

The City of North Las Vegas infrastructure plans are to have municipal water service available throughout APEX. In July 2018, construction began on Phase 1 of a water pipeline, extending 12 miles parallel to the I-15 corridor to the southern-most part of APEX (Las Vegas Valley portion). The Phase 1 pipeline will terminate approximately 1 mile from the Garnet Valley hydrographic basin boundary. Phase 2 of the pipeline will extend another 3.3 miles into southern Garnet Valley and south-central APEX (see Figure 1). The water conveyed in the new pipeline to APEX will be treated Colorado River water from Lake Mead, and secondarily, comingled groundwater from Las Vegas Valley (estimated 10%). Applications 88821-88825 have been filed by the City to expand the place of use of groundwater rights in Las Vegas Valley to include the APEX service area in Garnet Valley. The pipeline will allow the City to expand water service along the I-15 corridor and to southern APEX. Subsequent phases 3 to 6 of the water pipeline construction will loop around APEX, enabling water services to all parts. Municipal wells in APEX will ultimately be connected to the system. The build-out water demand for APEX is estimated to be 3761 AF/yr (Poggemeyer, 2012), and is based on a predicted water use of 0.5 AF/yr/acre of developable land, but could vary significantly depending on types of industry. The City's master plan is for water service to be provided from both groundwater pumping and the Colorado River source.

Wastewater is currently handled by each facility within APEX. The City of North Las Vegas master plans include a wastewater collection and tertiary treatment plant within Garnet Valley (Poggemeyer, 2012). Unlike the greater metropolitan Las Vegas area, treated effluent is not proposed to be returned to Lake Mead for return flow credits. Alternatively, industrial re-use or artificial recharge to the groundwater aquifer are envisioned to sustain and augment water resources in the basin.

Groundwater resources management in Garnet Valley is complicated by the regional hydrogeologic connection with other hydrographic basins comprising the Lower White River Flow System (LWRFS). The State Engineer issued Order 1303 in January 2019, which combines the individual hydrographic basins of the LWRFS into one joint administrative unit. Basins incorporated include Coyote Spring Valley (210), Hidden Valley (217), California Wash (218), Muddy River Springs Area (219), Garnet Valley (216) and a portion of the Black Mountains Area (215). Within the LWRFS, the Muddy River Springs Area (aka Upper Moapa Valley Basin) is notably sensitive to drawdown, due to the potential impacts to spring flow and habitat of the Moapa Dace, and interference with decreed surface water rights of the Muddy River. Additional information on the LWRFS and the regional disposition of Garnet Valley is presented in Interflow (2019).

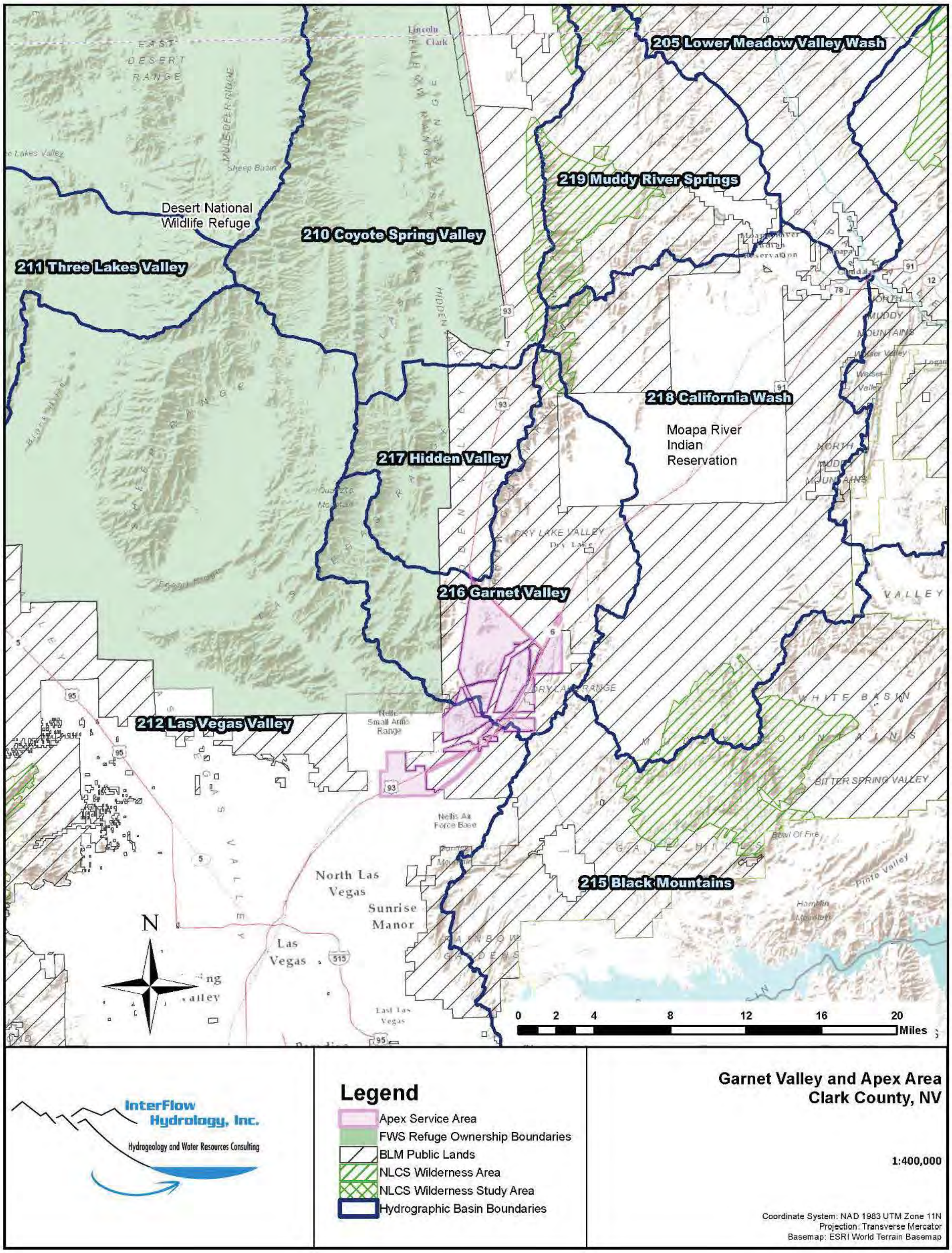



**Figure 1 – Location map of APEX**

**Artificial Recharge Water Management Objectives**

Two water management concepts for AR in Garnet Valley are of interest. One concept is use of AR for a limited duration use to bridge the gap in time between completion of the municipal water infrastructure and on-going industrial development. A portion of Colorado River water brought into the southern part of Garnet Valley upon completion of the Phase 2 pipeline could be used to support pumping from wells in the northern part of APEX, in the interim until the entire water supply infrastructure is completed (perhaps over a 10-year timeframe). Pumping from northern wells could be increased to meet water demands in northern APEX, with AR curtailing drawdown effects. Once the water infrastructure is completed, then AR and pumping from the northern wells could be reviewed and adjusted to achieve long-term aquifer management objectives. It may be found that there are some regional water management and/or infrastructure advantages to continuing long-term AR in APEX in order to support groundwater pumping in APEX. Many variables will need to be carefully considered for long-term AR, including the cost versus benefit and LWRFS aquifer management objectives.

AR is also envisioned as a potential long-term water management component for handling of wastewater in Garnet Valley. Absent of planned return of wastewater to Las Vegas Valley for treatment and subsequent return to Lake Mead, secondary uses of wastewater will be pursued to conserve water resources. To the degree that treated effluent can be returned to the aquifer, AR can help replenish aquifer storage. Use of AR in this manner will be considered a type of indirect potable reuse, and will necessitate a high level of wastewater treatment (A+ level), especially if the wastewater has a sewage component. It is also possible that some types of industrial uses of water (non-sewage) could be returned to the aquifer under lower levels of treatment. This will need to be reviewed and determined on a facility basis, and subject to regulatory compliances.

In summary, the City of North Las Vegas is interested in employing AR for Garnet Valley to support sustainable pumping in northern APEX during the time-period over which water supply infrastructure in APEX is being completed. AR is also a potential option for long-term groundwater management to support sustainable pumping in the APEX area, including potential return of treated wastewater to a reusable water resource in the basin.

**Hydrogeologic Setting**

APEX is located in south-central Garnet Valley, which comprises one of six hydrographic basins in the LWRFS. The general hydrogeologic settling of the basin is summarized in Interflow (2019). Some hydrogeologic details relevant to proposed AR in APEX are discussed below.

Groundwater in Garnet Valley primarily occurs in the Paleozoic age sedimentary rocks, which are comprised of significant amounts of limestone and dolomite (carbonate) rock types. There are little known water resources in the overlying alluvial sediments, which mostly occur above the water table and are unsaturated. The thickness of alluvium in the APEX area ranges from zero (bedrock at surface) to approximately 1000 ft. Alluvial sediments that overlie the carbonate rocks are interbedded deposits of gravel, sands, cemented sediments, fresh-water limestones, and silts and clays.

There have been approximately 30 wells drilled in and near APEX (Figure 2). Depths to the top of limestone bedrock are reported between 0.5 to 1600 feet (Figure 3). Well depths in Garnet Valley range between 500 to 2000 ft, with depths to groundwater reported between 230 to 888 ft (NDWR well log database, 2019). Groundwater level monitoring occurs at several wells in the APEX area, with reported depths from 465 to 883 feet (Figure 4). Groundwater being pumped by wells in APEX is from the upper-most ~1,000 feet of saturated thickness of the carbonate aquifer. The thickness of Paleozoic sedimentary rocks is however much greater, interpreted to be about 20,000 to 25,000 feet beneath Garnet Valley (Page et al, 2011). The Grace Petroleum Arrow Canyon #1 exploration well that was drilled in 1982 on the east side of APEX (Figure 2) and encountered 17,110 ft of Paleozoic sedimentary rocks (Garside et al, 1988). This exploration hole drilled through older

Devonian to Cambrian sedimentary rocks, before encountering younger Permian and Mississippian sedimentary rocks at approximately 9,000 ft in depth. The older rocks overlie the younger due to the Dry Lake Thrust Fault.

The Permian-Mississippian Bird Spring Formation comprises the bedrock outcrops over much of the APEX area (PMb unit, Figure 4). This formation is comprised of limestones, dolostone, siltstones, sandstones and shales (Page et al, 2005). The limestones and dolostones are carbonate rock types. On the far eastern side of APEX, older Mississippian-Devonian rocks outcrop (MDu unit, Figure 4), which are also mostly carbonate rocks, but contains some non-carbonate (clastic) rocks, such as shale and quartzite. The proposed AR project at APEX would provide groundwater recharge to the upper portion of the carbonate aquifer, which over most of the APEX area is Bird Spring Formation.

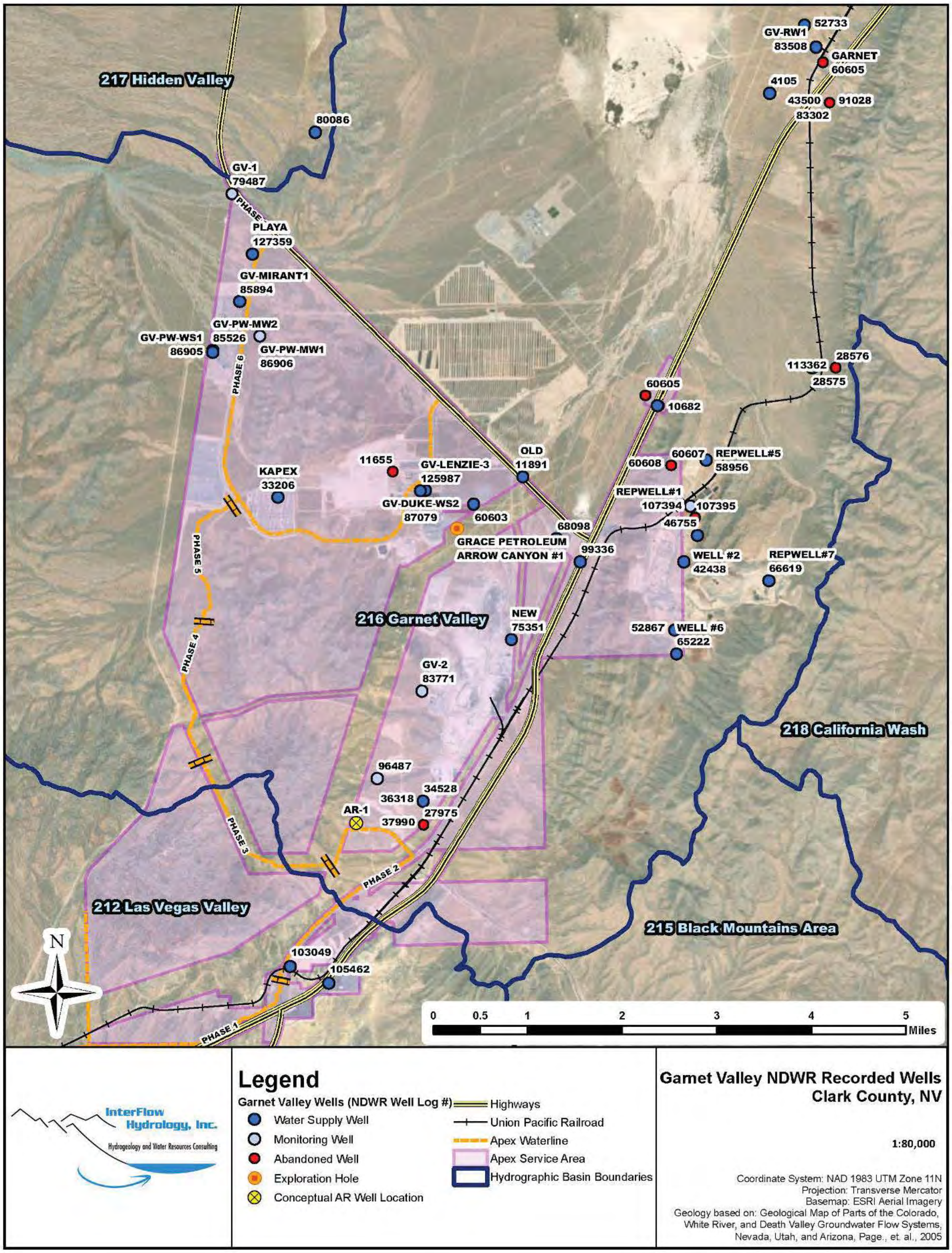



**Figure 2 – Wells Reported in the NDWR Well Log Database**

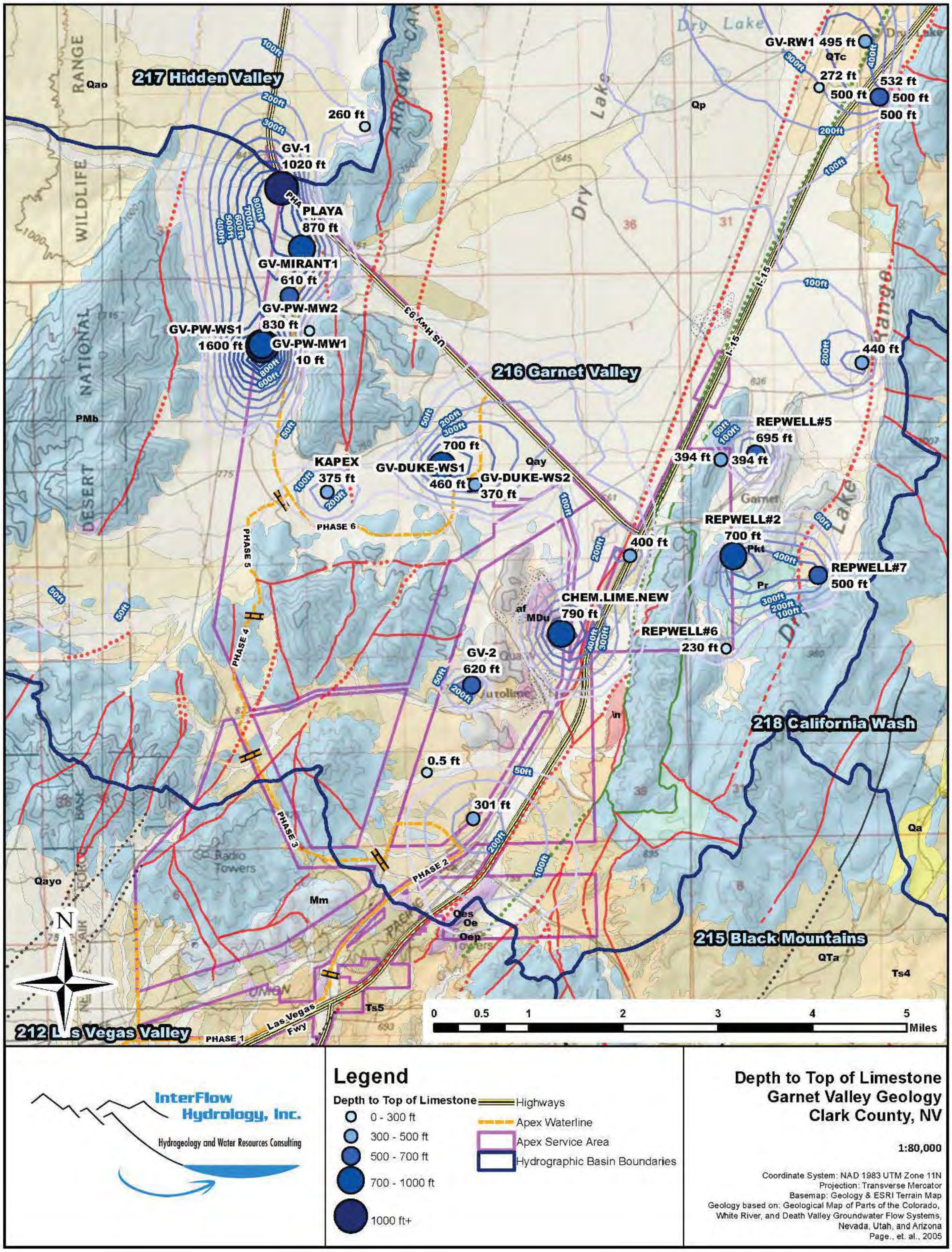



**Figure 3 –Depths to Top of Limestone Bedrock Reported in Driller's Well Logs**

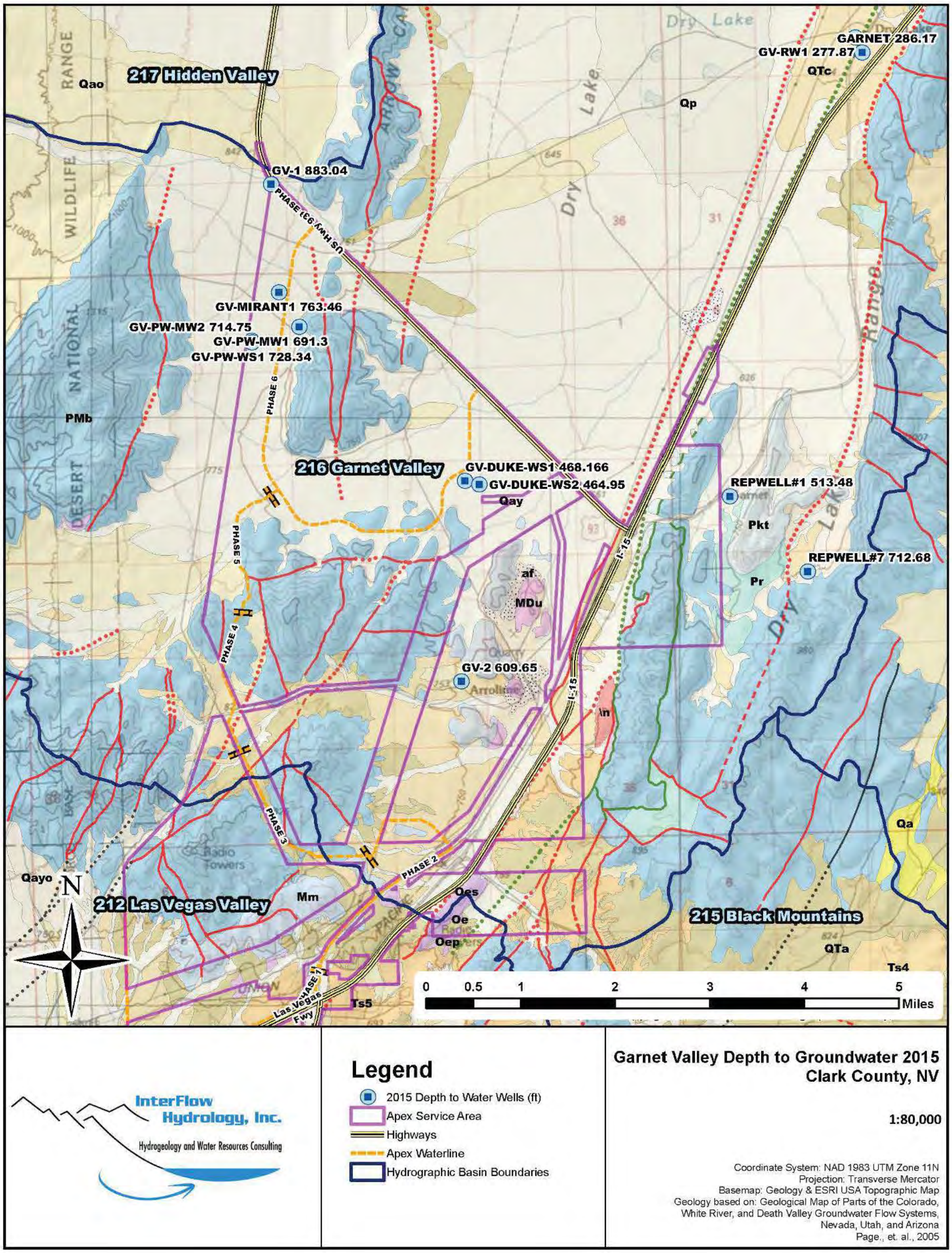



**Figure 4 – Depths to Groundwater Measured as part of Order 1169 Monitoring**

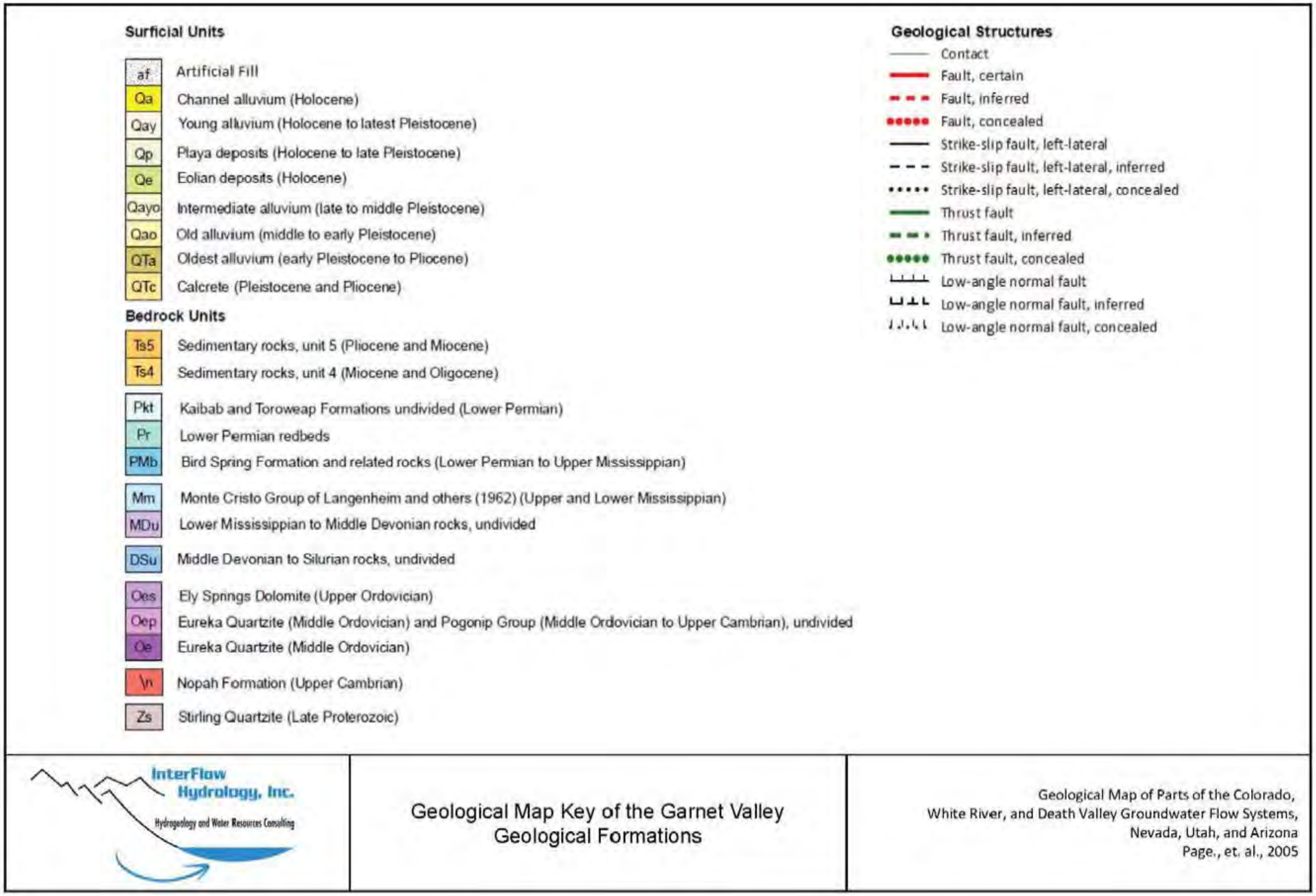



**Figure 5 – Geologic Base Map Key**

**Unsaturated Zone and Aquifer Characteristics**

Alluvium

Due to the composition of alluvial sediments, AR by surface spreading basins appears low in feasibility in the APEX area. Near surface soils mapped by the NRCS (2019) are primarily Bard-Tonopah association and Colorock-Tonopah association on the valley floor. Both of these soil types are reported to have very low water transmission capacity. Alluvium logged in Well Driller's Reports (NDWR, 2019) indicates a significant presence of cemented gravels and clay strata. The hydraulic conductivity of these strata is interpreted to be low, thus limiting the potential for recharge to the deeper carbonate aquifer.

Based on the available information, water impounded in surface basins would have limited ability to infiltrate and would be subject to significant loses to evaporation. Water which did infiltrate would also be subject to perching on low-permeability strata above the primary carbonate aquifer. The spreading basin approach for AR is not evaluated further in this concept review report. It is possible, however, depending on site-specific conditions, that some locations might have more acceptable conditions for infiltration. For example, locations where the alluvium is thin, or has been removed by mining activities, or where impermeable layers are fractured or breached, could conceivably provide locations that could provide rapid infiltration. This type of site, if found to be present, could be useful for AR of treated wastewater.

Carbonate Aquifer

AR by means of injection wells will provide a more direct and immediate means to recharge the carbonate aquifer. The transmissivity of the upper-most carbonate aquifer is estimated using reported pumping and drawdown data in Well Driller's Reports available from the NDWR (2019) database. Figure 6 is a map showing the locations of wells with pumping and drawdown data in the APEX area.

Aquifer transmissivity (T) is the rate of flow through a unit width of the aquifer under a unit hydraulic gradient (Todd, 1980). The specific capacity (SC) is the production rate of a well per unit drawdown. Transmissivity was estimated using the well specific capacity information and two methods, as summarized in Interflow (2019). Results of the two T calculations were averaged to get the estimated T at each well location in Garnet Valley. The average T for fifteen wells is 5275 $ft^2$/day, based on an average SC of 17.25 gpm/ft. The median is lower at 1334 $ft^2$/day based on an SC of 2.5 gpm/ft, and the geometric mean is 1366 $ft^2$/day. The average T is significantly increased by one notably high value (50,300 $ft^2$/day) in southern Garnet Valley at the Georgia Pacific Corporation facility (Figure 6). Well log #34528 reports a production rate of 140 gpm, with only 10 inches of drawdown resulting in a SC value of 168 gpm/ft. The accuracy of this information in uncertain. This well is located near the conceptual AR well near the end of Phase 2 pipeline. High transmissivity would be favorable for AR at rates of up to several thousand gpm.

The more modest apparent transmissivity of upper carbonate aquifer elsewhere in the APEX area would also accommodate AR, but well injection capacities are expected to be lower. The rate of potential injection is dependent on the injection head above the potentiometric water level in the aquifer, along with the transmissivity of the aquifer, and injection well efficiency. An average AR well at APEX, assuming the median SC of 2.5 gpm/ft, under an injection head of 200-300 ft above the aquifer potentiometric water level, and operating under an efficiency of 80% is estimated to have an injection capacity of 400-600 gpm. Under these assumed average conditions, three to four injection wells may be required to accomplish 1000 AF/yr of aquifer recharge. If higher transmissivity is encountered by the AR, similar to reported for the Georgia Pacific Corporation well, AR of this magnitude could be accomplished using one well.

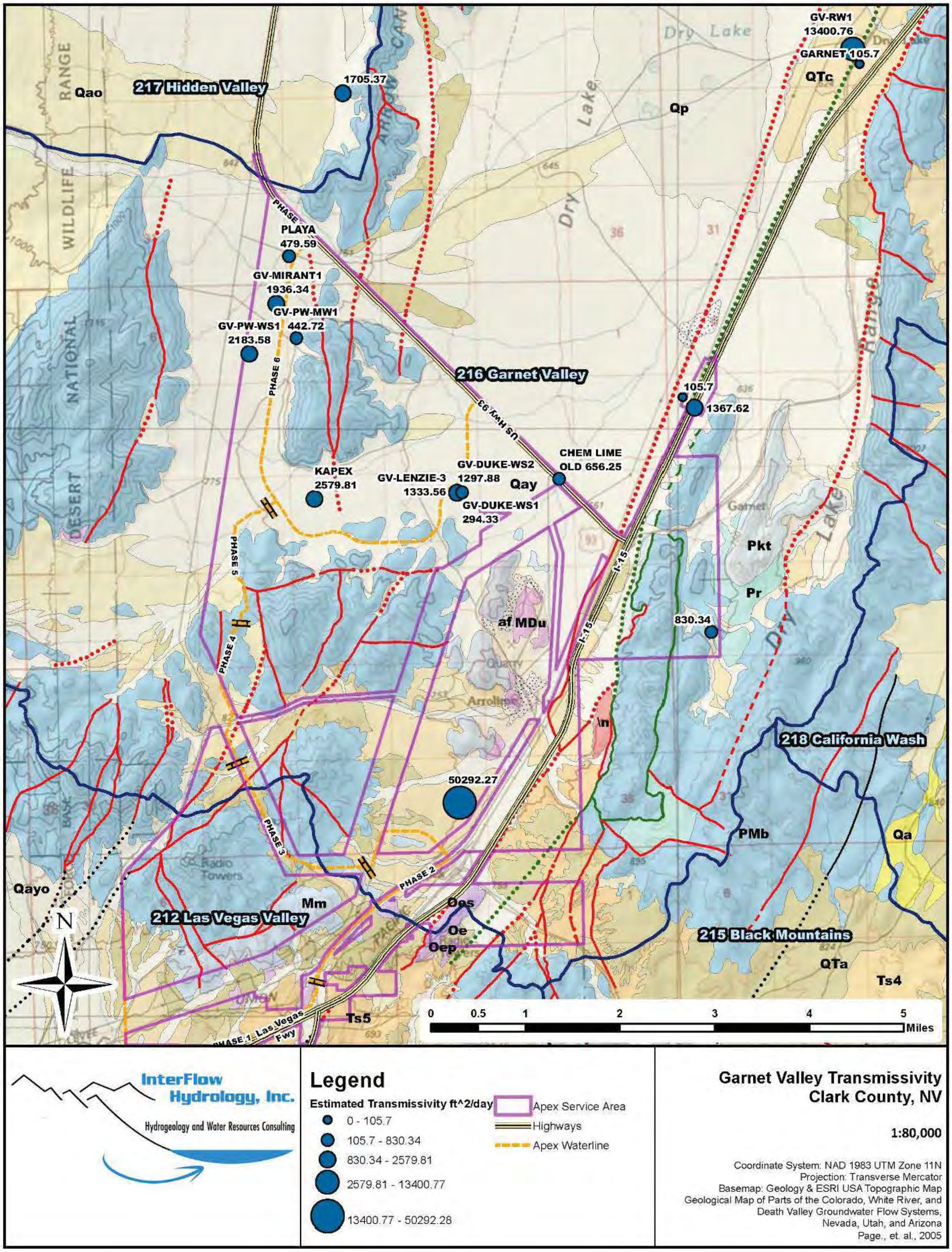



**Figure 6 – Estimated Carbonate Aquifer Transmissivity**

**Conceptual AR Well Location – Southern Garnet Valley**

Phase 2 of the City of North Las Vegas water pipeline will extend into southern Garnet Valley. An AR well is conceptually proposed near the pipeline, perhaps adjacent to, or within, the BLM utility corridor which bisects APEX (see Figure 2). A portion of delivered water into Garnet Valley would be injected into the carbonate aquifer to support increased yield from, and sustainable use of, wells within APEX, including the City's Playa and Kapex wells. The nearest wells to the area of AR well interest are summarized below, and locations are shown in Figure 2.

Approximately one mile east of the conceptual AR well location, NDWR well log #27975 is for a Georgia Pacific Corporation well drilled in 1986 to 1205 feet in depth. Limestone bedrock was encountered at approximately 300 feet in depth, and the reported depth to groundwater is 660 feet. The 6-inch diameter cased well is reported to be screened from 754-1205 feet, and produced a flow rate of 72 gpm for a 24 hour period. Drawdown during pumping is not reported. Well log #37990 indicates that this well was plugged in 1991. The well casing had a break at 580 feet, and the pump was stuck in the well.

Well log #34528 is a replacement well for the above well described for Georgia Pacific Corporation, drilled in August 1992 at a location approximately 2000 ft northeast. The well is completed with 8-inch dimeter casing to 1200 feet in depth. The geology and static water level are not reported. The well is reported to have been pumped at 140 gpm for 4 hours, producing 10 inches of drawdown. Well log #36318 is for a temporary cased test well (6 inch casing in an 8-inch test borehole) drilled to 960 ft in August 1990 (log filed was not filed with NDWR until February 1992). The static water level is reported at 608 feet, and the production is reported at 130 gpm for 72 hours of pumping. No drawdown level is reported. This well log is believed to be a test well at the location of the completed well under log #34528. No geology information is reported.

Well log #96487 is a shallow 50 ft monitoring well which did not encounter groundwater, and reports drilling through limestone.

Based on the nearby well log information, the anticipated top of limestone bedrock at the conceptual AR location is within 300 ft of land surface. Anticipated depth to groundwater is approximately 750 feet, because the land surface elevation at the conceptual AR well location is approximately 140 ft higher than at the Georgia Pacific Corporation well locations.

The apparent transmissivity at the Georgia Pacific Corporation well at approximately 50,300 $ft^2$/day is much higher than the basin average. As noted previously, the accuracy of the reported information on the well log is uncertain. None-the-less, the conceptual AR location appears to be a reasonably favorable location for at least moderate to high transmissivity in the carbonate aquifer (Bird Spring Formation), and there is a sufficient thickness of unsaturated carbonate rock above the potentiometric water level to accommodate injection and localized mounding of groundwater levels.

**Conceptual Review of AR Hydraulic Effectiveness**

A preliminary basin-scale review of AR effectiveness is conducted using the test numerical flow model of Garnet Valley developed to examine the potential boundary conditions in Garnet Valley (Interflow, 2019). This model provides a simplistic representation of the upper portion of the carbonate aquifer in Garnet Valley. As part of the test modeling, a steady-state and 20-year transient model were developed. The 20-yr transient model assumes 2015 pumping amounts remain the same throughout the 20-year simulation period, totaling 1520 AF/yr. An additional 1000 AF/yr of pumping is simulated as occurring from the City's Playa and Kapex wells, distributed 80% to the Playa Well and 20% to the Kapex Well. An AR well is added to the 20-year simulation at the conceptual location in southern Garnet Valley, with an injection rate of 1000 AF/yr. AR injection is simulated as beginning 4 years into the 20-year period, assuming a lag in time between increased pumping at the Playa and Kapex wells, and completion of the Phase 2 pipeline and AR injection well.

Running the model in transient mode requires input of the aquifer storage coefficient. MODFLOW uses the specific storage (Ss) value which is the storage coefficient divided by the aquifer thickness. A Ss value of 8 x $10^{-6}$ is used for the model, based on the reported regional value of 0.008 from SNWA (2016) divided by the simulated aquifer saturated thickness of 1000 ft.

Predicted water level drawdown and mounding in the carbonate aquifer at year 20 is presented in Figure 7. Mounding of water levels in the carbonate aquifer near the injection well are predicted at approximately 20 ft. The model simulates inflow from Las Vegas Valley to Garnet Valley of 698 AF/yr under current conditions, and is simulated to be reduced to 444 AF/yr at year 20 in the simulation (Table 1). Simulated outflow from Garnet Valley to the northern CA Wash basin is partially captured. Simulated inflows from Hidden Valley and/or southern Coyote Spring Valley are predicted to increase by 176 AF/yr (Table 1).

The flow of groundwater from Las Vegas Valley to Garnet Valley is uncertain and needs to be verified by accurate groundwater elevation measurements (Interflow, 2019). The nature of the boundary condition will dictate whether a portion of the AR water in southern Garnet Valley will flow to Las Vegas Valley, or remain within Garnet Valley. The simulated reduction in groundwater inflow to Garnet Valley from Las Vegas Valley is 254 AF/yr and will offset the effectiveness of AR. The lowered AR effectiveness means that the increased simulated pumping is not fully satisfied by an equal magnitude of AR, producing a simulated increase in capture from the LWRFS of 235 AF/yr. In summary, the conceptual test suggests that the AR effectiveness in producing available water in Garnet Valley is about 75%.

However, if the gradients between Las Vegas Valley and Garnet Valley are different than assumed, then the analysis changes. If the groundwater gradient is from Garnet Valley to Las Vegas Valley, then a larger portion of the AR would be lost to outflow to Las Vegas Valley, lowering the AR effectiveness for Garnet Valley. Should it be determined that the southern boundary is an outflow condition from Garnet Valley to Las Vegas Valley, then recovery of the AR water might be achieved by a well located in the southern-most portion of APEX in Las Vegas Valley.

**Table 1 – Summary of Model Simulated Groundwater Flows at Garnet Valley Boundaries**

| Flow From | Flow To | Model Reach No. | Current (2015) Simulated under Steady-State Assumption (AF/yr) | Predicted in 20 Years with Current Pumping plus 1000 AF/yr Increased Pumping and AR (AF/yr) | Difference in Simulated Flow (AF/yr) |
|---|---|---|---|---|---|
| Las Vegas Valley | Garnet Valley | 2 | 698 | 444 | -254 |
| Hidden Valley – South | Garnet Valley | 1 | 1.4 | 23 | +22 |
| Hidden Valley – Central | Garnet Valley | 0 | 61 | 124 | +62 |
| Hidden Valley – North and/or Coyote Spring Valley - South | Garnet Valley | 7 | 456 | 548 | +92 |
| Black Mountains | Garnet Valley | 3 | 7.5 | -1.0 | -9 |
| Garnet Valley | Black Mountains and CA Wash - South | 6 | 0 | 0 | 0 |
| Garnet Valley | CA Wash - Central | 4 | 0 | 0 | 0 |
| Garnet Valley | CA Wash - North | 5 | 103 | 44 | -59 |

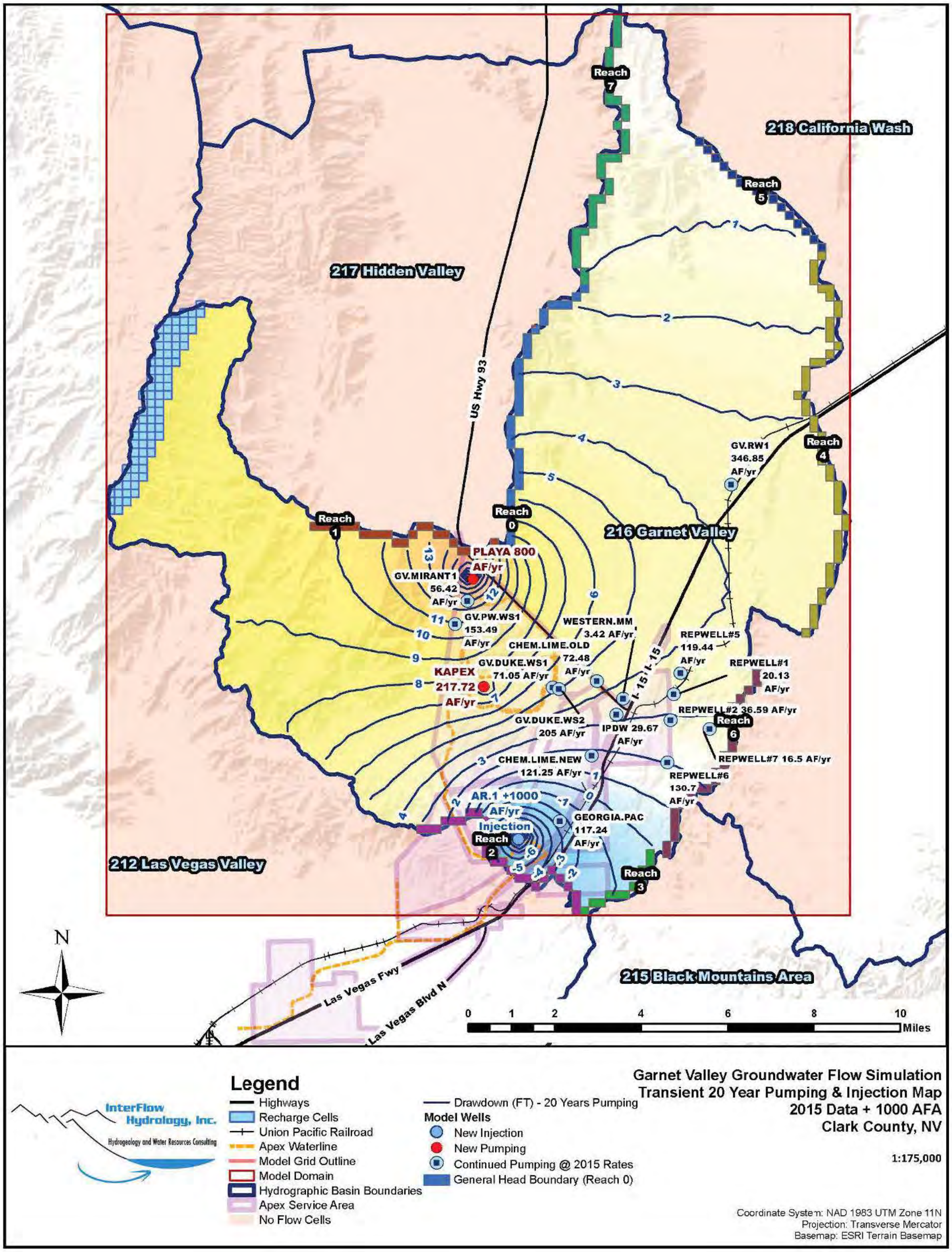



**Figure 7 – Simulated Change in Water Levels at Year 20 in the Pumping and AR Scenario**

**Groundwater Chemistry and Aquifer Compatibility Considerations**

Groundwater chemistry data are available for six wells in the APEX area of Garnet Valley, as published by the USGS (USGS NWIS, 2019) and for the recently drilled Playa Well (West Yost, 2016). The results are summarized in Table 2. The general groundwater chemistry from wells in APEX is similar to that of Las Vegas Valley. Figure 8 is a tri-linear plot that shows the relative percentages of major ionic compounds for groundwater in Las Vegas Valley as compared with the APEX portion of Garnet Valley. Las Vegas Valley groundwater is a chloride-type and mixed-type water, with total dissolved solids (TDS) contents ranging from about 200-400 mg/L in the northern part of the valley, to 700-1500 mg/L in the southern part, for intermediate to deep aquifers that are primarily used for municipal water supply (Dettinger, 1987). Garnet Valley groundwater in the APEX area is a similar chloride and mixed-type water, with an average TDS of about 975 mg/L. Colorado River water at the Hoover Dam outlet also has a similar ionic compound composition to the Las Vegas Valley and Garnet Valley groundwater. However, the TDS is about 36% lower (620 mg/L) in the Colorado River water as compared with the groundwater in APEX.

A pilot and demonstration AR project was implemented by Las Vegas Valley Water District (LVVWD) to examine several issues including Colorado River water and Las Vegas Valley groundwater compatibility (Brothers and Katzer, 1990). Geochemical mineral precipitation as a result of AR injection was observed to be minimal. The compatibilities have been further demonstrated through the last three decades of successful AR operation in Las Vegas Valley. Chemical compatibility is also presumed to be acceptable for injection of Colorado River water into the aquifer at APEX, but should be examined in more detail as the AR project evolves beyond the conceptual level.

The fate of disinfection byproducts has been an issue of study in Las Vegas Valley and is a component of monitoring in the LVVWD aquifer storage and recovery (ASR) system. Organochlorine compounds such as trihalomethanes (THMs) are regulated in drinking water, and can be produced by chlorinated municipal water reacting with organic matter and dissolved organic carbon in the aquifer. The fate of organochlorine compounds was studied in the pilot and demonstration project. Mille et al (1993) and Thomas et al (2005) also examined the fate and transport of organochlorine compounds including trihalomethanes (THMs). LLVWD (2013) has conducted follow-up studies to further evaluate the occurrence, fate and transport of THMs in the program area, and Grunloh (2015) modeled chemical reactions and THMs attenuation from dual use AR and pumping wells. Sorption of THMs is understood to be low. A low level of reaction, dilution of THMs, and to a lesser degree, biotransformation processes have been found to result in acceptable THMs concentrations in Las Vegas Valley. LVVWD year 2018 monitoring found THMs levels well below the maximum contaminant level (MCL) of 0.08 mg/L (LVVWD, 2019).

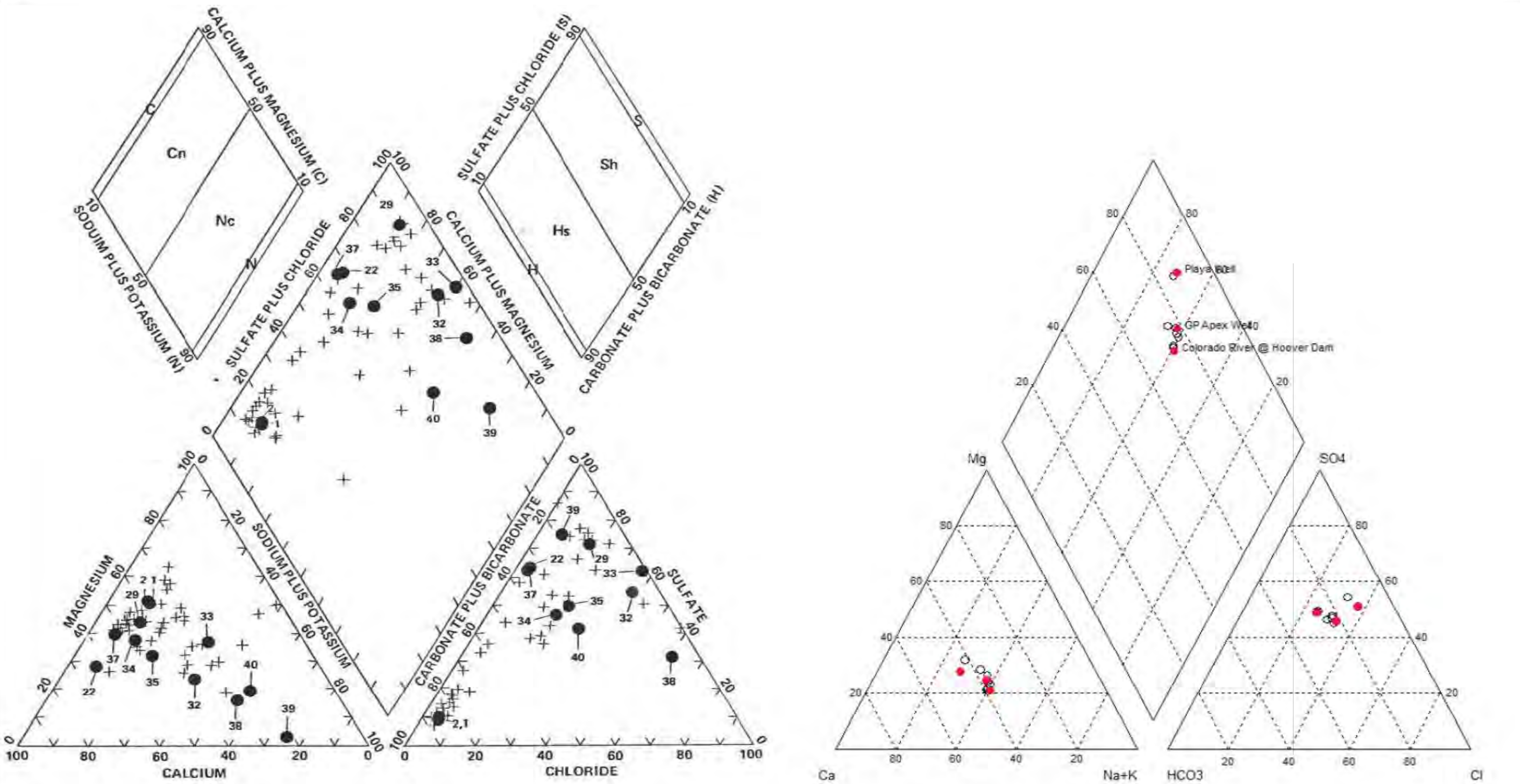
Because the fractured bedrock aquifer of Garnet Valley differs from the basin-fill environment in Las Vegas Valley, THM monitoring, and fate and transport analyses are anticipated to be necessary over the operation of the AR system. However, similar acceptable results are anticipated for the Garnet Valley AR system.

Mobilization of arsenic has occurred at some locations where AR occurs in limestone aquifers (Bloetscher,et al, 2014). Concentrations of arsenic are low in the groundwater at APEX, averaging 0.0035 mg/L, and ranging from 0.0015 to 0.008 mg/L (Table 2). The MCL for arsenic in drinking water is 0.010 mg/L. The source rocks for much of the basin-fill sediments in Las Vegas Valley are from the same limestone formations, and mobilization of arsenic is not a reported problem for the LVVWD ASR program. But the sediments comprising the basin-fill aquifers have undergone physical erosion, chemical weathering, and transport processes that have not occurred in the limestone bedrock aquifer in Garnet Valley. Further testing and monitoring during AR operations will be necessary to understand if mobilization of arsenic from the limestone rocks is of potential concern in Garnet Valley.

Related to AR water quality are the potential issues of biological fouling and particle rearrangement clogging of AR wells, the latter of which is believed to be a problem for some AR wells in Las Vegas Valley (Johnson et al, 1997). Well completions in the carbonate aquifer (fractured bedrock) will differ from those completed in Las Vegas Valley basin-fill, and should not be subject to particle rearrangement issues. Disinfection of municipal water that is proposed for AR should limit biological fouling. However, if other sources of water are used for long-term AR, such as treated industrial wastewater or treated effluent, minimization of biological fouling will need consideration in facility design. Periodic well maintenance / rehabilitation is standard procedure for AR wells, and will undoubtedly be required for the AR well(s) in Garnet Valley to remove mineral scaling and sediment build up, and maintain desired well efficiencies and infiltration capacities.

**Table 2 - Summary of Groundwater Chemistry in the APEX Portion of Garnet Valley and Vicinity**

| Name | UTM X ft | UTM Y ft | Date | pH | pH | Ca | Mg | Na | K | Cl | $SO_4$ | F | Si | $HCO_3$ | TDS | As | Fe | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *field* | *lab* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* | *mg/L* |
| Well 05AADB1 | 2241189 | 13229401 | 6/4/2003 | 7.2 | 7.3 | 111 | 50.1 | 106 | 12.9 | 154 | 329 | 1.55 | 18.8 | 219 | 984 | 0.0031 | 0.0599 | 0.00608 |
| Well 14AAA 1 | 2256407 | 13219566 | 3/31/1986 | 7.4 | 7.8 | 120 | 47 | 140 | 1.3 | 180 | 370 | 1.6 | 23 | 226 | 1000 | -- | 0.005 | -- |
| Grace Water | 2253311 | 13216899 | 4/26/1982 | 7.3 | 7.4 | 123 | 46 | 140 | 16 | 190 | 360 | 1.6 | 21 | 230 | 1010 | -- | 0.85 | 0.09 |
| GP Apex Well | 2250882 | 13201376 | 9/30/1986 | 7 | 7.7 | 120 | 47 | 130 | 13 | 200 | 380 | 1.4 | 23 | 226 | 1030 | 0.008 | 0.004 | 0.014 |
| Playa Well | 2241897 | 13232052 | 10/6/2016 | -- | 7.29 | 97.3 | 36.2 | 59.9 | 14.9 | 315 | 583 | 1.21 | 14.8 | 170 | 975 | 0.00153 | -- | 0.00897 |
| | | | 10/31/2016 | -- | 7.4 | 125 | 58.6 | 84.8 | 15.6 | 242 | 555 | 1 | -- | 175 | 854 | 0.00463 | -- | 0.00583 |
| Colo. River @ Hoover Dam | 2309271 | 13084023 | 2/11/2016 | 7.7 | 8.2 | 80 | 26.6 | 91.1 | 4.63 | 88.5 | 240 | 0.32 | 7.89 | 163 | 624 | 0.0025 | -- | 0.00045 |
| | | | 5/12/2016 | 7.5 | 8.2 | 81.3 | 26.6 | 95.9 | 4.9 | 88.9 | 237 | 0.32 | 7.73 | 164 | 630 | 0.0023 | -- | -- |
| | | | 8/24/2016 | 7.5 | 8.2 | 77.9 | 25.2 | 86.4 | 4.45 | 87.5 | 235 | 0.32 | 7.94 | 157 | 606 | 0.0024 | -- | 0.00059 |
| Muddy River Springs | 2309921 | 13336967 | 1/12/2004 | 7.3 | | 65.3 | 28.4 | 99.2 | 11 | 67.7 | 189 | | 28.4 | 260 | 617 | -- | -- | -- |




1. Las Vegas Water Chemistry (Dettinger, 1987)

2. Garnet Valley & Colorado River Water Chemistry

InterFlow Hydrology, Inc.
Hydrogeology and Water Resources Consulting

Las Vegas Valley Groundwater, Garnet Valley Groundwater and Colorado River Water Chemistry in Trilinear Plots

**Figure 8 – Trilinear (Piper) Plots of Major Ion Chemistry in Las Vegas Valley and Garnet Valley**

**Permitting**

An operational AR project will require two primary permits from State of Nevada agencies. A permit from the Nevada Division of Water Resources (NDWR) to Establish and Operate a Project to Recharge, Store, and Recover Underground Water; and a permit from the Nevada Division of Environmental Protection (NDEP) for Underground Injection Control (UIC). Applications for these permits will require demonstration of technical feasibility of AR-ASR operations and a monitoring plan to address aquifer effects including groundwater quality.

The ASR application to NDWR needs to meet the specific requirements set forth in NRS 534.250 – 534.340, along with other applicable statues for water right applications and drilling and operation of wells. The ASR application requires the following technical items.

- A description of the proposed project including its capacity, plan of operation, and duration.
- A study that demonstrates the area of hydrologic effect of the project.
- Designation of wells for recovery of water within the hydrologic area.
- A study that demonstrates that the project is hydrologically feasible.
- A study that demonstrates that the project will not cause harm to users of land and water within the area of hydrologic effect.
- Means to determine the percentage of recoverable water.
- If the project is within an area of active management, evidence and data to determine that the project is consistent with the program of augmentation for that area.
- A proposed monitoring plan, inclusive of water quality monitoring.
- Evidence for determination that the applicant has the technical and financial capability to operate the project.
- Evidence for determination that the applicant has the right to use the proposed source of water for recharge.

The UIC application to NDEP needs to meet the requirements of NAC 445A.810-925, along with other applicable statutes in NRS 445A.300-730. AR wells are expected to operate as Class V wells. The following information is anticipated to be needed for the UIC application, which is more specifically addressed in a pre-application meeting with NDEP.

- Operating plans, including average and maximum daily rates and injection pressures, procedures for injection, storage and pretreatment, if any, plans and scheduling for well maintenance.
- Injection well design, including seal depths and materials to be used.
- A report presenting the geology and hydrology of the area including water quality of each formation and zone for injection, hydraulic conductivity of the receiving formation, and descriptions of confining zones.
- Injection fluid physical, chemical and biological characteristics.
- Chemical analysis of compatibility of formation water with injectate.
- Proposed monitoring plan.

Applications for injection of reclaimed water for indirect potable reuse must additionally comply with NAC 445A.274-280, which set forth minimum levels of water quality treatment.

The annual monitoring report prepared by LVVWD for operation of the Las Vegas Valley ASR system (LVVWD, 2019) provides an example of the type of monitoring to anticipate for an AR system in Garnet Valley. Monitoring reporting may include summaries of ASR operations, net recoverable recharge, groundwater levels, injection flow rates, chemistry of water used for injection, chemistry of recovered water (trace elements, arsenic, trihalomethanes, major ions, and TDS), well maintenance, and forthcoming year program plans.

**Summary and Recommendations**

In summary, the concept of AR for interim and long-term aquifer management in the APEX portion of Garnet Valley appears viable. A conceptual AR well located in southern Garnet Valley near the terminus of the Phase 2 pipeline appears to be capable of supporting increased pumping from northern APEX from the City's Playa and Kapex wells. Due to the proximity of proposed AR to the boundary of Las Vegas Valley, the recharge quantity may only be about 75% effective in increasing the available water resources in the basin. The effectiveness could be lower, if it is found that the gradient of natural groundwater flow is from Garnet Valley to Las Vegas Valley, rather than visa-versa as assumed in this concept review.

An AR well at the conceptual location near the end of the Phase 2 pipeline is anticipated to encounter Bird Spring Formation limestone within 300 feet of land surface. The static water level is expected at 750 feet. A well completed to 1250 – 1500 feet may be sufficient for AR, but the depth will depend on where permeable zones are encountered in the well. Estimated injection rates of 400-600 gpm can be anticipated based on average carbonate aquifer transmissivity in the APEX area, but could be greater (perhaps several thousand gpm) if the transmissivity of the aquifer at the AR well location is found to be similar to the apparent transmissivity at the Georgia Pacific Corporation well located approximately 1 mile to the east. If transmissivities are lower, then multiple AR wells may be necessary to achieve the magnitude of recharge desired.

Further evaluations are needed for the next step of a review of feasibility and to generate data needed for AR project permitting. Recommendations for follow-up steps to pursue the conceptual Garnet Valley AR are as follows:

- Begin discussions with NDWR and the LWRFS stakeholders regarding the concepts presented, including the short-term and long-term potential uses of AR.

- Obtain accurate water level measurements near the basin boundary of Las Vegas Valley and Garnet Valley. This will necessitate water level data on both sides of the basin boundary, and possibly drilling of dedicated water level monitoring wells, unless existing suitable and accessible wells are identified.

- Obtain aquifer and groundwater chemistry data at the proposed AR well location by drilling of a test well.

- If owner permission and technical ability to conduct testing on the Georgia Pacific Corporation well (log #34528, point of diversion for water right permit 56855) is available, a pumping test at the well will provide useful data on aquifer properties and groundwater quality. Well cleaning, instrumentation, temporary equipping, and discharge retrofitting may be necessary to conduct testing.

- Update the feasibility evaluations and modeling, after additional data are collected.

- Prepare an application to NDWR to operate an AR project, inclusive of a proposed monitoring plan.

- Subsequent to or in tandem with NDWR permitting, prepare an application for UIC permitting, inclusive of necessary AR well and system design, and a proposed monitoring plan.

**References**

Dettinger, 1987, Ground-Water Quality and Geochemistry of Las Vegas Valley, Clark County, Nevada, 1981-83: Implementation of a Monitoring Network. U.S. Geological Survey. Water-Resources Investigations Report 87-4007.

Driscoll, F. G., 1986, Groundwater and wells, 2d ed.: St. Paul, Minnesota, U.S. Filter/Johnson Screens, 1089 p.

Bloetscher, F, Sham, C.H., Danko, J.J., and Ratick, S., 2014, Lessons Learned from Aquifer Storage and Recovery (ASR) Systems in the United States; published in the Journal of Water Resource and Protection, Vol. 6, p. 1603-1629.

Brothers, K., and Katzer, T., 1990, Water Banking Through Artificial Recharge, Las Vegas Valley, Clark County, Nevada; Journal of Hydrology, Vol 115, p. 770-803.

Garside, L.J., Hess, R.H., Fleming, K.L., and Weimer, B.S., 1988, Oil and Gas Development in Nevada, Nevada Bureau of Mines and Geology, Bulletin 104.

Grunloh, S., 2015, Process Modeling of Trihalomethanes during Aquifer Storage and Recovery, a thesis submitted for partial fulfillment of requirements for the degree of Master of Science in Hydrogeology, University of Nevada – Reno.

Interflow Hydrology, 2019, Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada; technical memorandum prepared for the City of North Las Vegas dated July 2, 2019.

Johnson, M., Cole, E., and Brothers, K., 1997, Artificial Recharge in the Las Vegas Valley: An Operational History; University of Nevada – Las Vegas, Water Resources Publication 6-1997.

Las Vegas Valley Water District, 2019, 2018 Groundwater Production and Aquifer Storage and Recovery Program Monitoring Report, prepared for NDWR Permit Nos. R-001, R-003, and R-012 and NDEP UIC Permit No. UNEV87054, prepared February 2019, Doc No. LVVWD-ED-0031.

Mace 1997, Determination of transmissivity from specific capacity tests in a karst aquifer: Ground Water, v. 35, no.4, p. 738-742

Miller, C., Wilson, L., Amy, G., Brothers, K. 1993. Fate of Organochlorine Compounds During Aquifer Storage and Recovery: The Las Vegas Experience. Groundwater 31 (3): 410-416

Nevada Division of Water Resources (NDWR), 2019, water rights, well, water level, and pumping data, accessed via website: March 2019 - May 2019, http://water.nv.gov/.

Page, W.R., Scheirer, D.S., Langenheim, V.E., Berger, M.A., 2011, Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona; USGS Open File Report 2006-1040.

Poggemeyer Design Group, 2012, Water and Wastewater Master Plan, Apex Industrial Park, City of North Las Vegas, Nevada, prepared for Kapex, LLC, December 28, 2012.

Southern Nevada Water Authority, 2016, Garnet Valley Groundwater Production Simulated Effects of Pumping the Southern Nevada Water Authority's Temporary Applications; memorandum submitted to NDWR on January 14, 2016.

Thomas, J., McKay, A., Cole, E., Landmeyer, J., Bradley, P., 2005, The Fate of Haloacetic Acids and Trihalomethanes in an Aquifer Storage and Recovery Program, Las Vegas, Nevada; Groundwater Journal, Vo.. 38 (4), p. 605-614.

Todd, D.K., 1980, Groundwater Hydrology, second edition, John Wiley & Sons, New York.

USDA Natural Resources and Conservation Service (NRCS), 2019, Soil Survey Mapping and Descriptions accessed via website https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

US Geological Survey, National Water Information System, 2019, website accessed May 2019 for water chemistry data.

West Yost Associates, Consulting Engineers, 2016, Playa Well Construction Report, prepared for First Solar, December 2016.

# Technical MEMORANDUM

To: Mr. Randall E. DeVaul, PE, City of North Las Vegas, Director of Utilities
Mr. Robert A. McLaughlin, PE, City of North Las Vegas, Manager, Development & Flood Control

Date: July 2, 2019

RE: **Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada**

From: Dwight L. Smith, PE, PG, Principal Hydrogeologist
Alexa Terrell, MSc., Hydrogeologist
A.T.
PROFESSIONAL ENGINEER STATE OF NEVADA DWIGHT L. SMITH GEOLOGICAL EXP. 6/30/20 No. 11906

**Executive Summary**

Garnet Valley is situated in the southern end of the Lower White River Flow System, which is a collection of 6 hydrographic basins that have groundwater connection through the regional carbonate aquifer. The Lower White River Flow System (LWRFS) encompasses Coyote Spring Valley (210), Muddy River Springs Area (219), Hidden Valley (217), California Wash (218), Garnet Valley (216), and a smaller northwestern portion of the Black Mountains Area (215). State Engineer Interim Order 1303 was issued on January 11, 2019 designating the basins as one collective administrative area. This is the first designation of this type in the State of Nevada.

Most groundwater flow in the LWRFS basins discharges at the Muddy River Springs. Some groundwater appears to travel south to Garnet Valley based on water level elevations. As presently understood, the quantity of flow to Garnet Valley is small. Data are not sufficient to quantify an exact amount. Test modeling conducted in this study estimates groundwater inflow to northern Garnet Valley from southern Coyote Spring Valley and/or northern Hidden Valley at approximately 450 AF/yr. A unique finding of this study is that there appears to be groundwater flow from Las Vegas Valley (212) into southern Garnet Valley. Modeling suggests the magnitude may be about 700 AF/yr, but there is considerable uncertainty, and the gradient from Las Vegas Valley to Garnet Valley has not been clearly defined. This potential inflow needs to be investigated further by measuring water level elevations near the boundary between the basins, which will likely necessitate drilling and installation of two or more water level monitoring wells.

Along with the estimated in-basin recharge by precipitation falling in the Las Vegas Range, the groundwater inflows support existing pumping in Garnet Valley, which has historically been around 1500 AF/yr. There is little evidence of a significant magnitude of groundwater outflow from Garnet Valley to California Wash. It is interpreted in this study that the basin is in a state near to equilibrium with the magnitude of current groundwater pumping. There is a long-term declining water trend in Garnet Valley of approximately 0.3 ft per year, but this trend is observed throughout the LWRFS at similar magnitudes, and is interpreted to be a regional background condition. The declining trend began in the late 1990s. A wet year in 2005 interrupted the declining trend, as did the 2-year Order 1169 pumping test in Coyote Spring Valley in 2011-2012. Increases in pumping in Garnet Valley in 2016-2017 do not appear to have caused observable changes in the water level trends.

Ultimately, there is a pumping threshold in Garnet Valley that could cause undesirable levels of drawdown to propagate northward in the LWRFS, but this threshold has not been characterized by current pumping rates. Manageable levels of drawdown in Garnet Valley need to be achieved to avoid interference with decreed water rights of the Muddy River and Muddy River Springs, and spring discharges that support the endangered species Moapa Dace. Concurrent with the City's construction of the pipeline to deliver Colorado River water to APEX, there should be ample opportunity to test the groundwater pumping component of the water supply and adjust long-term management of water resources as needed to address LWRFS issues while maintaining municipal service.

Pumping groundwater at a higher rate of approximately 2000 AF/yr occurred from APEX in 2016 and 2017, under use of Southern Nevada Water Authority water rights, without noticeable impacts. Additional pumping may be sustainable, but should be tested in increments and supported by adequate monitoring. Water level monitoring in Hidden Valley to the north of APEX is sparse, and occurring at only one well (SHV-1) which is believed to be completed in alluvium rather than the carbonate aquifer. Two additional monitoring well installations are recommended in Hidden Valley, both completed in the carbonate aquifer, and one in the southern part of the basin.

There are existing water rights in Garnet Valley to pump up to 3715 AF/yr, with SNWA holding 2275 AF/yr of these rights (adjusted for combined duties). The SNWA water rights are however some of the most junior water rights in the LWRFS. Transferring senior groundwater rights from the Muddy River Springs Area to the APEX portion of Garnet Valley appears to have merit in two regards: 1.) removing senior pumping from within the Muddy River Springs Area that appears to have historically impacted flows of the Muddy River, and 2.) securing more senior water rights for the APEX municipal system, in the event that groundwater rights become regulated by priority date in the LWRFS. The latter is a concern because the total permitted duty of groundwater rights granted in the LWRFS is approximately 39,700 AF/yr, but the non-committed groundwater resources after considering commitments of spring discharges is probably no greater than 10,000 AF/yr.

A LWRFS Groundwater Management Plan is expected in the future, the specific details of which have not been determined. It is likely that the development of a Groundwater Management Plan will require several years of work between the LWRFS stakeholders and the State Engineer, and potentially more time in the courts, if the plan is appealed. In summary, transferring of senior water rights to the APEX facilities should not be viewed as enabling greater pumping from the basin, but rather, as adding some degree of assurance to the ability to maintain pumping in APEX should future actions require management of groundwater rights by priority date, under current Nevada water law. Transferring of senior water rights to APEX is also not guaranteed to be approved, because applications will need to go through the water right transfer process and could be protested, and will be subject to a State Engineer determination.

**Introduction**

This memorandum has been prepared as a review of groundwater pumping in Garnet Valley and at the APEX Industrial Park (APEX). APEX is located along the Interstate 15 corridor northeast of Las Vegas, and is incorporated into the City of North Las Vegas. The southern-most portion of APEX resides in Las Vegas Valley, while the majority of APEX is within Garnet Valley. APEX is bound by public lands on most sides, and by US Route 93 on the northeast (Figure 1). Bureau of Land Management utility corridors bisect portions of APEX.

Following the explosion at the Pacific Engineering and Production Company of Nevada (PEPCON) on May 4, 1988, Nevada leaders working with the United States Congress designated roughly 18,000 acres of land as a new heavy industrial area for Southern Nevada's future. Through a series of subsequent BLM auctions the land was acquired by private investors and developers. This large industrial area became known generally as APEX Industrial Park and although its vast land provides a unique opportunity for industrial development, because it lacked the utilities necessary for businesses to locate it remains largely vacant tracts of land almost 20 years later.

Today, APEX Industrial Park is a 20 square mile area annexed into the City in 2008 with approximately 7,500 developable acres. It is located along I-15 and US Route 93, has access to Union Pacific Railroad and dry utilities including electric transmission and distribution service and natural gas pipelines. The area is currently zoned M2 throughout the industrial park under the APEX Overlay allowing most industrial and ancillary uses. APEX is the home of the Hyperloop One's Propulsion Open Air Test Track to develop a new high speed, intercity transportation system which uses passenger and cargo capsules inside a reduced-pressure tube system that would reach a top speed of 760 miles per hour. Other businesses committing to the APEX include medical marijuana grow facilities and UNEV Pipeline, LLC's North Las Vegas terminal for their $300,000,000 petroleum pipeline with an initial capacity of 62,000 barrels of product per day and maximum capacity of 118,000 barrels of product per day.

In 2010, the City took over operation of a private water system serving the existing customers located in the APEX Industrial Park. This system remains in operation and will continue to remain in operation until the final water system improvements are completed.

APEX Industrial Park is currently underserved by an inadequate water system. The APEX Master Water and Sewer Plan was approved by City Council in 2012. The goal of the plan was to map out needed water and sewer facilities to make APEX Industrial Park the premier industrial park in Nevada. The master plan indicates a need for an average day water demand of 3.36 million gallons per day (MGD), maximum day demand of 4.57 MGD and peak hour demand of 7.02 MGD. The master plan for water calls for a 14-mile water pipeline and series of water reservoirs and pump stations connecting an existing 24-inch water line in Hollywood Boulevard to the existing groundwater system operated by the City of North Las Vegas Utilities Department.

In September 2014, North Las Vegas engaged Brookings Mountain West to identify the economic and regional significance of APEX Industrial Park. Their economic impact analysis indicated that APEX, when built out, could create 116,000 direct, indirect and induced jobs, generate $193 billion dollars in regional economic impact, and generate $670 million in new annual tax revenue for state and local government. However, the challenge of providing infrastructure to the promising park remained.

In April 2018, the City entered into an oversizing agreement with a private developer to construct the first 10.4 miles of a proposed 25 mile water pipeline to bring water from the City's primary water system to APEX and create a backbone water system to serve all of APEX Industrial Park. The first 7,700 LF of pipe is in the ground and the next 19,000 LF of pipe is scheduled for construction beginning in mid-August 2019. While a funding plan for the final 15 miles of pipeline is not complete, an artificial recharge well is proposed after phase 2 construction is complete that could permit recharging of the Garnet Valley Aquifer to support increased pumping from wells in northern APEX and as a long-term aquifer management tool.

APEX Industrial Park was the proposed site of the Faraday Future electric car manufacturing facility. In 2016 and 2017, I-15 interchange facilities, widening of US Route 93, and a 700-acre super-pad were completed prior to Faraday Future announcing withdrawal from the proposed project.

While the City of North Las Vegas provides water service to APEX, most facilities currently use individual water supply wells. The City of North Las Vegas operates two wells in the northern part of APEX which are equipped for municipal water supply. The Playa well was drilled in 2016 to 2000 ft in depth and has a yield up to 600 gallons per minute (gpm) (West Yost, 2016). The Kapex well was drilled to 1145 ft in depth in 1990 by the Kerr-McGee Chemical Company, and has a yield of approximately 200 gpm.

The City of North Las Vegas currently owns 10.02 acre-feet per year (AF/yr) of water rights under permit 77745, with a point of diversion at the Kapex well. The Southern Nevada Water Authority (SNWA) owns 2,274.57 AF/yr of groundwater rights in the APEX area, under multiple water right permits, which have been available for permanent and temporary transfers to wells in APEX, primarily for power generating facilities. The City has an agreement with SNWA to lease up to 900 AF/yr. SNWA permit 83490 has been issued for 300 AF/yr for use by the City of North Las Vegas for municipal purposes in APEX, with a point of diversion at the Kapex well. A temporary transfer of water rights is currently active for 350 AF/yr at the Playa well (permit 88011T).

Phase 1 of the water pipeline project extends into the southern end of APEX, and will terminate approximately 1 mile from the Garnet Valley hydrographic basin boundary. Phase 2 of the pipeline will extend another 3.3 miles into southern Garnet Valley and south-central APEX. Phases 3-6 will complete the water distribution system to the northern portion of APEX (Figure 2).

The water conveyed in the new pipeline to APEX has a primary source from Lake Mead (~90%), and secondarily, comingled groundwater pumped from Las Vegas Valley (~10%). Applications 88821-88825 have been filed by the City to expand the place of use of groundwater rights in Las Vegas Valley to include the APEX service area in Garnet Valley. The total combined duty of these applications is approximately 847 AF/yr. The build-out water demand for APEX is estimated to be 3,761 AF/yr (Poggemeyer, 2012) and is based on a predicted water use of 0.5 AF/yr/acre of developable land. The actual water demand could vary significantly depending on type of industrial facilities built. The City's master plan is for water service to be provided from both groundwater pumping within Garnet Valley combined with the piped water being ~90% Colorado River source and ~10% Las Vegas Valley groundwater source.

A complicating water management issue for the Garnet Valley groundwater source is connection with other hydrographic basins to the north, including the Muddy River Springs Area, via the regional carbonate aquifer. The State Engineer issued Interim Order 1303 in January 2019 combining six hydrographic basins into one management area, being called the Lower White River Flow System (LWRFS). Groundwater pumped from basins in the LWRFS has the potential to create drawdown in neighboring basins, as was observed in the Order 1169 aquifer pumping test of wells in Coyote Spring Valley conducted by SNWA in 2011 and 2012 (SNWA, 2013). The Muddy River Springs Area (aka Upper Moapa Valley Basin) is notably sensitive to drawdown, due to the potential impacts to spring flow and the associated habitat of the Moapa Dace, and interference with decreed water rights of the Muddy River. Interim Order 1303 also places a temporary moratorium on State Engineer approvals of new development, unless the applicant can show an adequate and sustainable supply of water to meet water demands over the anticipated life of the development. Permanent change applications for existing groundwater rights are also being held in abeyance, pending further determinations for administration of water rights in the LWRFS, although temporary transfers may be granted.

This technical memorandum examines historical, current, and potential future pumping within the APEX portion of Garnet Valley. An examination of the potential water budget and sustainable pumping yield from Garnet Valley is presented, using currently available data. The City of North Las Vegas is negotiations for an agreement to lease senior groundwater rights from the Muddy River Springs Area to transfer to the APEX facilities. Advantages and issues associated with a transfer of these senior water rights will be reviewed.

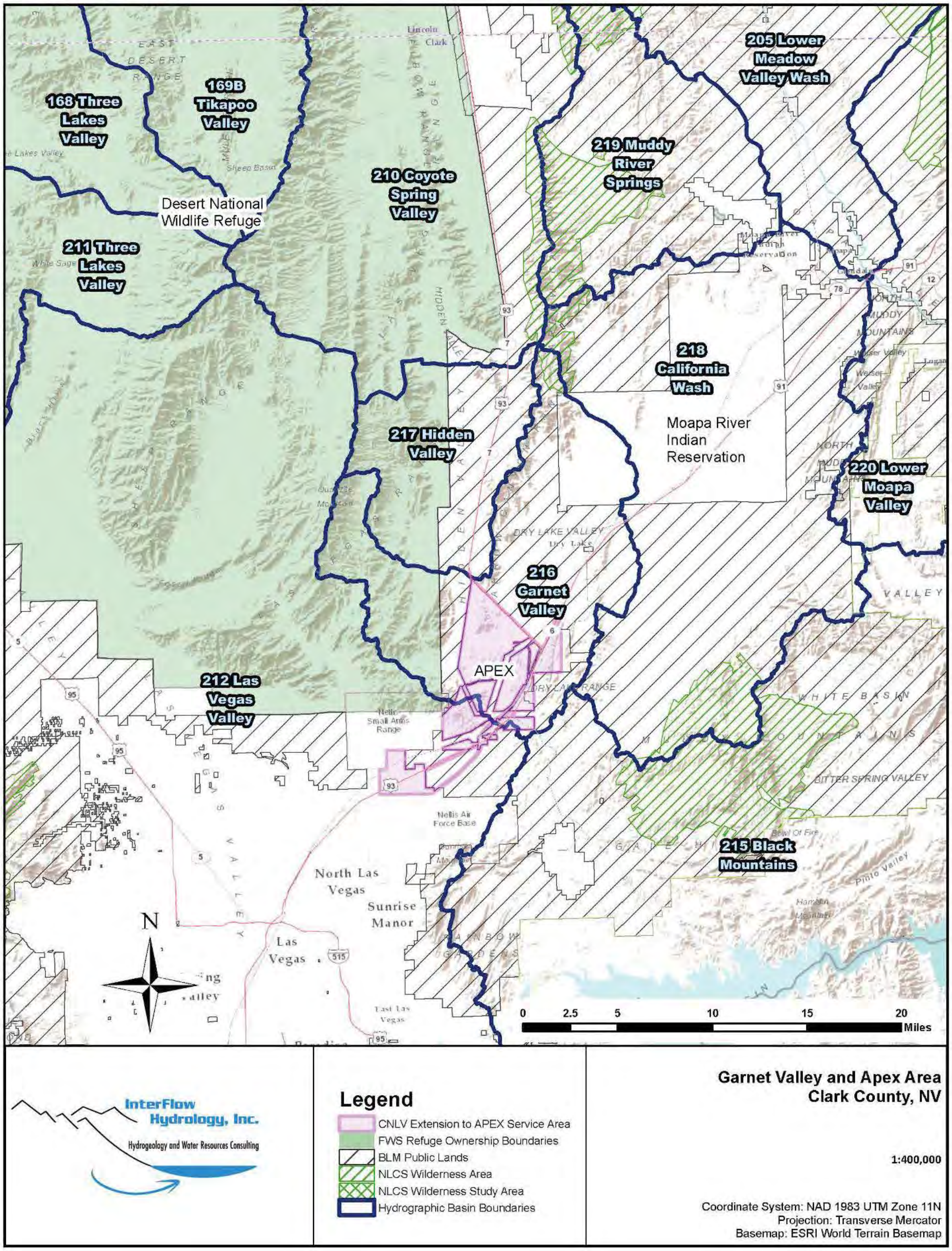



**Figure 1 – Location Map**

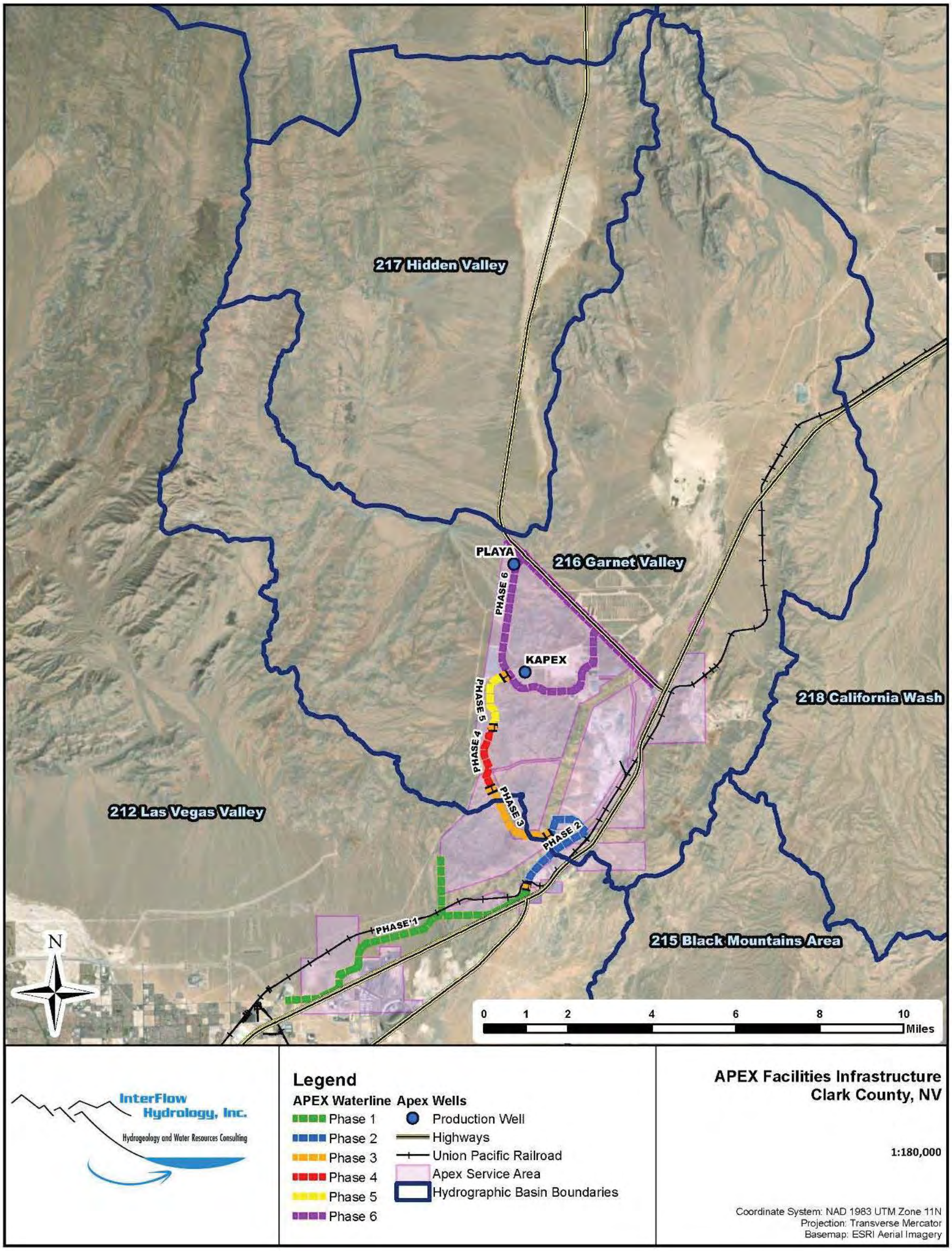



**Figure 2 – APEX Planned Water Supply Infrastructure**

**Regional Hydrogeologic Setting**

APEX is located in south-central Garnet Valley, which comprises one of six hydrographic basins in the LWRFS. Hydrographic basins included in the LWRFS are Coyote Spring Valley (210), Muddy River Springs Area (219), Hidden Valley (217), Garnet Valley (216), California Wash (218), and a small portion of the Black Mountains Area (215), as shown in Figure 3. These basins are hydrologically connected by a thick, but complexly folded and faulted, sequence of Paleozoic sedimentary rocks. The Paleozoic rocks are comprised of both carbonate (limestone and dolomite) rock types and clastic (sandstone, siltstone, quartzite and shale) rocks. The units of carbonate rock can be hundreds to thousands of feet thick and can exhibit high permeability due to faulting and dissolution of the limestone.

Figure 4 shows the regional geology for the LWRFS basins published by Page et al (2005), and Figure 5 is a geologic cross-section trending east-west through Garnet Valley (Page et al, 2011). Figure 6 is a legend for the geologic map units. The thickness of Paleozoic sedimentary rocks is interpreted to be about 20,000 to 25,000 feet beneath Garnet Valley. The Grace Petroleum Arrow Canyon #1 exploration well that was drilled in 1982 on the east side of APEX and encountered 17,110 ft of Paleozoic sedimentary rocks (Garside et al, 1988). This petroleum exploration hole encountered older Devonian to Cambrian age sedimentary rocks overlying younger Permian and Mississippian sedimentary rocks to approximately 9,000 ft in depth. The older rocks were displaced over the younger by the Dry Lake Thrust Fault.

Potentiometric water levels in the carbonate aquifer are monitored by the Southern Nevada Water Authority (SNWA), with contributions from other stakeholders in the LWRFS. Water level and pumping data are recorded on the NDWR website. Water levels reported for the LWRFS in November 2018 are shown in Figure 7. Directions of groundwater flow can be generally described, however, data in some portions of the LWRFS are sparse and interpretations of groundwater flow directions uncertain. Figure 7 shows interpreted directions of groundwater flow from this study.

Groundwater inflow to the LWRFS is understood to originate from hydrographic basins to the north along the White River Flow System. Many investigators have studied the flow system. This study shall build upon their work and not reiterate prior findings. In summary, groundwater flow enters Coyote Spring Valley from the north, and from Kane Spring Valley to the northeast, comingles with recharge from the Sheep Range bounding the west side of the basin, and flows out through the eastern side of the basin to discharge at the Muddy River Springs.

Groundwater in southern Coyote Spring Valley appears to flow northerly to the MX-5 area, and also southerly to Hidden Valley. But data are too sparse in Hidden Valley to clearly understand flow directions through that basin. Subsurface outflow through the Arrow Canyon Range to northern Garnet Valley is possible, as is southerly outflow to the APEX area. The single active monitoring well in Hidden Valley (SHV-1) is suspected to be completed in alluvium rather than the carbonate aquifer, due to unique water level variability as contrasted with other carbonate wells in the LWRFS, complicating the regional flow interpretations. Replacement of this well with a known completion in the carbonate aquifer would be helpful in making regional flow interpretations.

Groundwater flow from Hidden Valley to the APEX area and southern Garnet Valley is postulated, but there is a lack of water level in Hidden Valley to confirm. Well HV-1 is located in southern-most Hidden Valley, but has not been actively monitored since 2000, and the well may no longer be in an adequate condition for monitoring, as it has been “used” for target practice (personal communication, SNWA, 2019). Future groundwater monitoring, potentially associated with managed pumping from northern APEX, should consider installing a monitoring well in southern Hidden Valley, or refurbishing HV-1 if possible.

Regardless of groundwater flow directions, the gradients over much of the regional carbonate aquifer in the LWRFS are shallow, reflecting the high transmissivity of the carbonate aquifer. There are a few known barriers to groundwater flow within the LWRFS basins, including the Kane Springs Fault Zone in northern Coyote Spring Valley, and an unnamed fault on the west side of Coyote Spring Valley. These barriers are not however impermeable, but rather features with lower transmissivity than the adjacent portions of the regional carbonate aquifer.

The Order 1169 pumping test in central Coyote Spring Valley had pumping centered at the MX-5 well and Coyote Springs Golf Club wells, and enabled interpretations of hydrologic connections through the regional carbonate aquifer (SNWA, 2013; USFWS et al, 2013; Mifflin & Associates, 2013). Interpreted drawdown responses were observed in several Garnet Valley monitoring wells. The geologic environment and continuity along with the water level monitoring observations support Garnet Valley being included within the LWRFS groundwater management area.

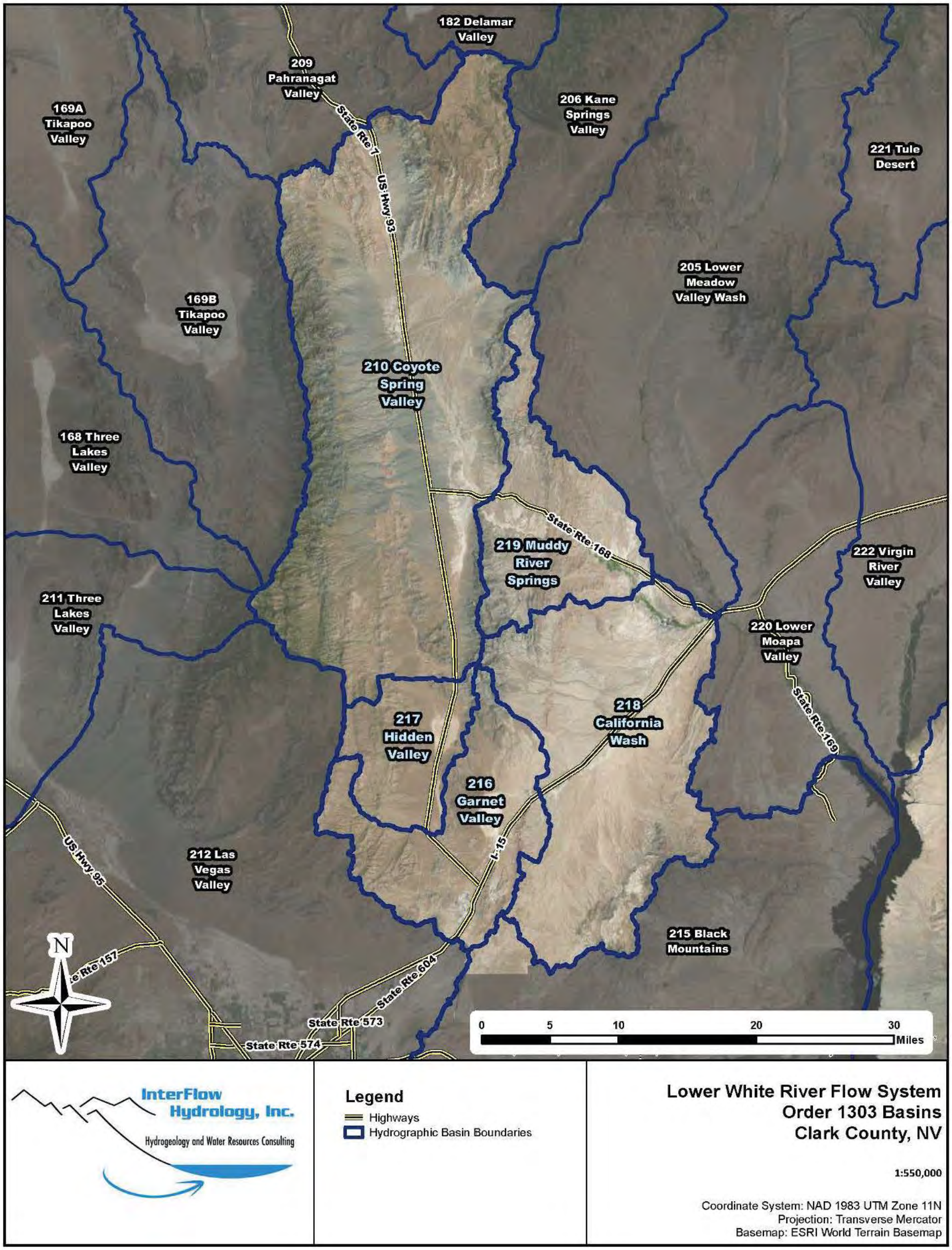



**Figure 3 – LRWFS Basins Map**

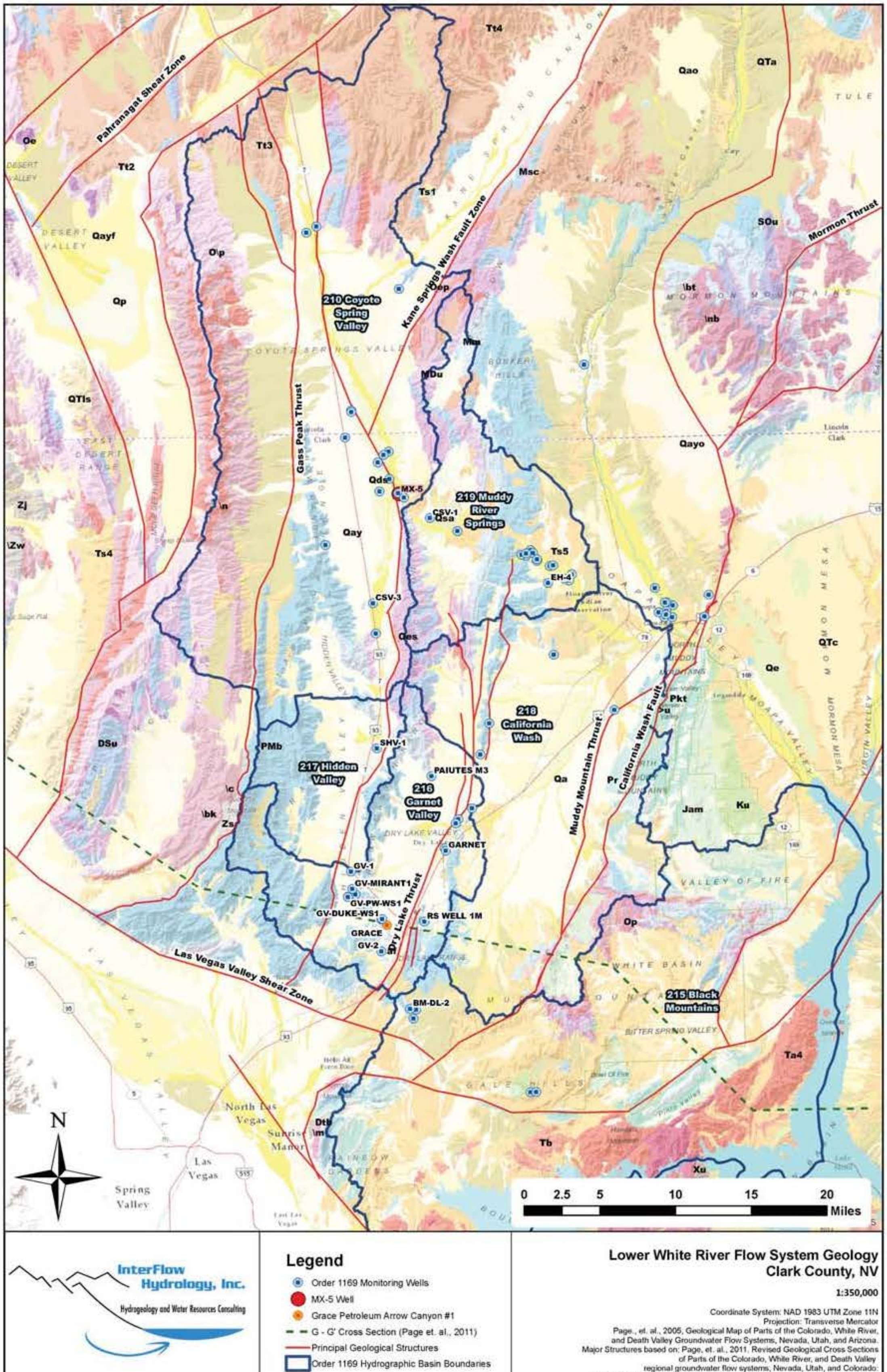
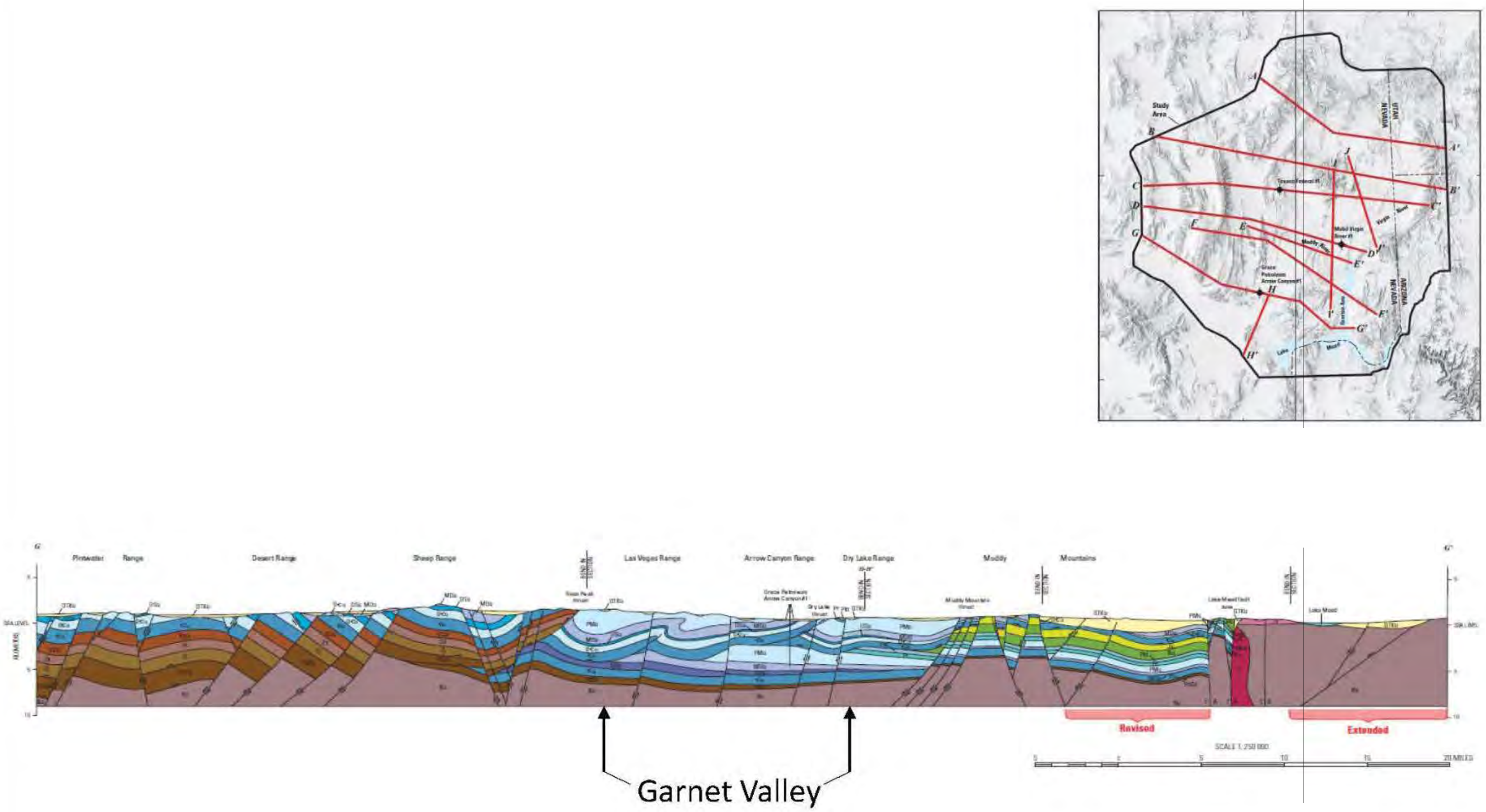



**Figure 4 – Regional Geology of the LWRFS Basins (Page, et al, 2005)**

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Hydrogeology and Water Resources Consulting

Geological Cross Section G-G' through the Garnet Valley and Surroundings Geological Formations

Page, et. al., 2011. Revised Geological Cross Sections of Parts of the Colorado, White River, and Death Valley regional groundwater flow systems, Nevada, Utah, and Colorado: U.S. Geological Survey Open-File Report 2006-1040, 1 sheet, 25 p. pamphlet.

**Figure 5 – Geologic Cross-Section (E-W) through Garnet Valley (Page, et al, 2001)**

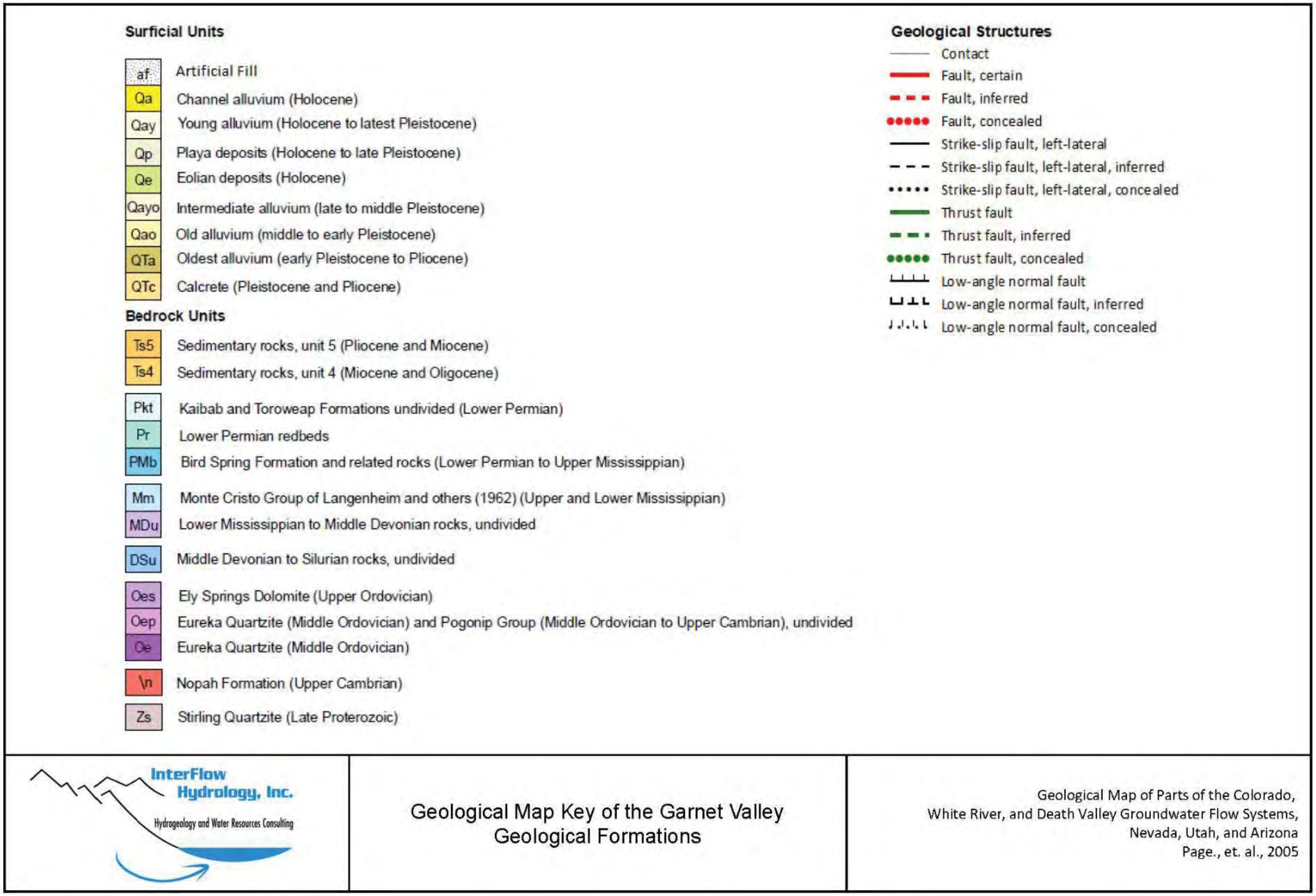


**Figure 6 – Geologic Map Explanation**

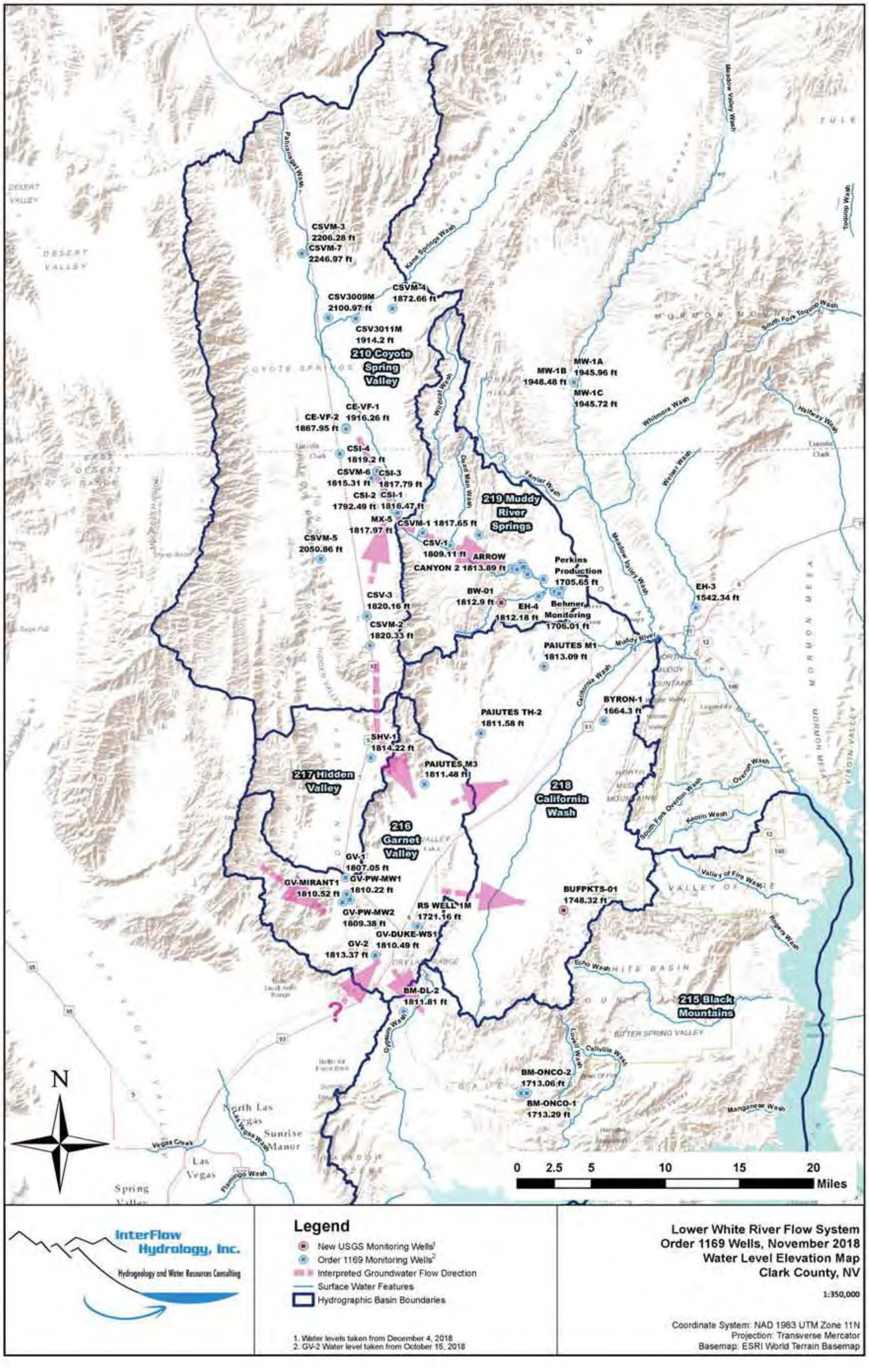


**Figure 7 – Groundwater Potentiometric Levels and Potential Regional Flow Directions**

## Garnet Valley Hydrogeology

### Geologic Setting

Groundwater in Garnet Valley primarily occurs in the Paleozoic age sedimentary rocks, which are comprised of significant amounts of carbonate rocks. Groundwater also occurs in some locations in Garnet Valley in the alluvium that overlies the Paleozoic sedimentary rocks, but much of the alluvium is unsaturated. The thickness of alluvium and depths to the top of the carbonate rock (limestone) in Garnet Valley range from zero (bedrock at surface) to approximately 1600 ft, based on available Well Driller's Reports, also called well logs, on file with NDWR (Figure 8). Alluvial sediments that overlie the carbonate rocks are interbedded deposits of gravel, sands, cemented sediments, fresh-water limestones, and silts and clays. Saturated alluvium is tapped by a few wells in Garnet Valley, including an NDOT well along I-15 and wells used by US Lime (drilled in the 1960-70s). The majority of wells in Garnet Valley tap the upper Paleozoic sedimentary rocks for water supply.

The Permian-Mississippian Bird Spring Formation (PMb) comprises the bedrock outcropping over much of APEX and the mountains bounding the west side of Garnet Valley, including the Arrow Canyon Range and Las Vegas Range (Figure 8). The Bird Spring Formation also comprises portions of the Dry Lake Range bounding the southeastern side of Garnet Valley. This formation consists of limestones, dolostone, siltstones, sandstones and shales (Page et al, 2005), with a considerable portion being carbonate rocks. On the eastern side of APEX and the far northern part of Garnet Valley, older Mississippian-Devonian rocks outcrop (MDu unit, Figure 8), which are carbonate rocks, with non-carbonate (clastic) rocks, such as shale and quartzite.

The Dry Lake Thrust Fault daylights in a N-S direction along the east side of Garnet Valley (Figure 8). This thrust fault may be a hydraulic barrier to easterly groundwater outflow from Garnet Valley to California Wash, and may also define an eastern boundary to the LRWRS. The Las Vegas Shear Zone may form a southern boundary to the LWRFS. In this case, the shear zone incorporates a small portion of the Black Mountains Area within the LWRFS.

### Wells and Groundwater Pumping

There are approximately 50 well logs on file with NDWR for Garnet Valley as summarized in Table 1, with locations shown in Figure 9. Seventeen logs are for abandonment of a well. Wells in Garnet Valley are primarily used for industrial and commercial water supply, and nine wells are for monitoring wells. Well depths range between 423 to 2480 ft (excluding one well drilled to 50 ft which did not encounter groundwater). The average well depth is 988 ft and the median is 736 ft. Well yields are reported for 20 well logs, ranging from 28 to 1500 gpm, with an average of 350 gpm, and a median rate of 135 gpm.

Groundwater being pumped by wells in APEX is primarily from the upper-most 1,000 feet of saturated thickness in the carbonate aquifer. NDWR pumping inventories have been conducted in Garnet Valley since 2001. Annual water use from 2001 to 2005 was approximately 850 AF/yr (Figure 10). In 2006, water use increased due to new power generating facilities and remained relatively constant at an annual volume of approximately 1470 AF/yr through 2015. In 2016 and 2017, groundwater pumping increased to 2081 AF/yr and 1981 AF/yr, respectively, as a result of highway and Faraday Future construction actives. As of the date of this report, the pumping inventory report for 2018 had not yet been published by NDWR for Garnet Valley, but annual pumping is anticipated to be similar to 2006-2015 volumes.

In forthcoming evaluations in this report, year 2015 pumping and associated water levels were chosen to represent current conditions, rather than 2016 or 2017, which experienced temporary increases in pumping, and 2018 which followed that increase. In the representative year 2015, 16 wells pumped a total of 1520 acre-feet, as summarized in Table 2. Of the 1520 AF pumped in Garnet Valley in 2015, 1277.43 AF were from wells reporting as part of the Order 1169 monitoring network. Mining and industrial usage was 710.03 AF, and municipal and commercial uses made up 810.06 AF. No irrigation or domestic use was reported for the 2015 pumpage inventory in Garnet Valley. The majority of the pumped wells are located in the south-central part of Garnet Valley, with the exception of RW-1 which is approximately 5 miles to the northeast. The pumping distribution for 2015 is shown in Figure 11.

Potentiometric Water Levels and Gradients

Wells which were monitored for water levels during 2015 are summarized in Table 2. Water level data were collected from the Order 1169 monitoring network. The average water level elevations were differentiated between static or pumping times, as determined by review of the period of recorded water level hydrographs. There are fifteen wells with water level elevation data for 2015, seven of which contain both pumping and non-pumping water level data, or are next to a pumping well and likely affected by pumping.

The potentiometric water levels in Garnet Valley are shown in Figure 12. Directions of flow are complicated to interpret due to pumping that occurs in the basin. In general, water level elevations are relatively flat through Garnet Valley, except during times of pumping. The water elevations during non-pumping times range from 1797.16 (Rep well #7) to 1814.35 (GV-2) ft above mean sea level (amsl). Rep Well #7 is near to Rep Well #1 which appeared to be pumping during the monitoring periods, and static water levels at Rep Well #7 are probably influenced by pumping. Much of the basin exhibits a static water level around 1811 ft amsl, plus or minus ~3 feet. An anomalously high water level reported at GV-PW-WS-1(~1840 ft) was removed from the dataset as it is suspected to be in error. The well is in poor condition and confident water level measurements cannot be made (personal communications, Andrew Burns, SNWA,2019).

The water level data in the southern-most part of the basin suggests a gradient from the Las Vegas Valley boundary northeasterly toward south-central Garnet Valley (from GV-2 toward central and northern APEX wells). The water level in GV-1 (1808.1 ft amsl) is lower than most static water levels in central-northern APEX, which seems counter to the hypothesis of groundwater inflow from southern Hidden Valley. An apparent potentiometric gradient exists between Hidden Valley and northern Garnet Valley, supporting possible groundwater flow through the Arrow Canyon Range.

Hydrographs for the period of recorded water level measurements in several wells in Garnet Valley are shown in Figures 13 and 14. A long-term declining water level trend is observed from 2007 to 2018. This trend is similarly observed in monitoring wells throughout the LWRFS. The long-term declining trend appears to be potentially associated with changes in long-term climate, due to the consistency of the trend over the LWRFS and over periods of varying magnitudes of regional pumping.

Seasonal variations in water levels may be due to annual pumping cycles, with increases in summer water use causing short-term declines. The stronger than normal seasonal decline in water levels in 2011-2012, followed by rebounding water levels in 2013-2014 (Figure 14) are interpreted to be the influence of increased pumping under Order 1169 in Coyote Spring Valley. This pumping influence, while subtle in magnitude, was observed in many other wells in the LWRFS, and clearly observed in spring discharge at Pederson Spring in the Muddy River Springs complex (see graph in Interim Order 1303).

Carbonate Aquifer Transmissivity

Aquifer transmissivity (T) is the rate of flow through a unit width of the aquifer under a unit hydraulic gradient (Todd, 1980). The transmissivity of the upper-most carbonate aquifer is estimated using reported pumping and drawdown data (specific capacity) in Well Driller's Reports available from the NDWR (2019) database. The specific capacity (SC) is the production rate of a well per unit drawdown. Two equations for approximating transmissivity were used, as published by Mace (1997) and Driscoll (1986). The approximation equations are presented below.

Mace (1997) for fractured karstic carbonate aquifers in the range of 1-1x10$^5$ m$^2$/day:

$$\text{Transmissivity}_{Mace}\ {ft^2}\big/_{day} = 0.76 \times (\text{Specific Capacity } (m^2/\text{day}))^{1.08} \times\ 10.7639\ (\frac{ft^2}{m^2})$$

Driscoll (1986) equation:

$$\text{Transmissivity}_{Driscoll}\ {ft^2}\big/_{day} = \text{Specific capacity } \left({gpm}/_{ft}\right) \times\ 2000\ \times 0.160544(\frac{ft^3}{gal} \times \frac{min}{day})$$

Results from the two calculations were averaged to get an estimated transmissivity at each well location in Garnet Valley, as summarized in Table 3 and presented in Figure 15.

The average T for fifteen wells is 5275 ft$^2$/day, based on an average SC of 17.25 gpm/ft. The median is lower at 1334 ft$^2$/day based on a median SC of 2.53 gpm/ft, and the geometric mean is similar to the median at 1366 ft$^2$/day. The average estimated T is significantly increased by one notably high value (50,300 ft$^2$/day) in southern Garnet Valley at the Georgia Pacific Corporation facility (Figure 15). Well log #34528 reports a production rate of 140 gpm, with only 10 inches of drawdown at this well, resulting in a SC value of 168 gpm/ft. The accuracy of this information is uncertain.

The average saturated thickness for the fifteen wells with specific capacity data is 858 ft, with a median of 808 ft. The computed hydraulic conductivity (K) for the aquifer is the transmissivity divided by the aquifer thickness, and averages 8.7 ft/day, with a median of 1.1 ft/day and geometric mean of 2.0 ft/day.

Three wells with specific capacity data are completed in saturated alluvium rather than the carbonate aquifer. The average T for these three wells is 710 ft$^2$/day. The average T for the twelve wells completed in the carbonate aquifer is 6416 ft$^2$/day, with a median of 1520 ft$^2$/day and geometric mean of 1797 ft$^2$/day. K values for the carbonate aquifer average 10.0 ft/day, with a median of 1.1 ft/day and a geometric mean of 2.0 ft/day.

Groundwater Budget

Rush (1968) published a water budget for Garnet Valley, and several other basins in the region, including Hidden Valley, California Wash and the Black Mountains Area. Recharge from precipitation falling on the Garnet Valley hydrographic basin, in the higher altitude Las Vegas Range, is estimated at 400 AF/yr. California Wash and the Black Mountains Area are both estimated to receive <100 AF/yr of recharge by precipitation, and Hidden Valley is estimated to receive 400 AF/yr. Reconnaissance estimates of recharge to Coyote Spring Valley (includes Kane Spring Valley) and the Muddy Springs Area is 2,600 AF/yr (Eakin, 1964). Recharge by direct precipitation to the LWRFS is estimated at 3,400 AF/yr summing the reconnaissance estimates.

Groundwater discharge from Garnet Valley was interpreted by Rush (1968) to occur as subsurface outflow to California Wash. No playa or phreatophyte discharge of groundwater occurs, due the depth of groundwater below land surface. The perennial yield presently acknowledged by NDWR in Garnet Valley is 400 AF/yr.

In Coyote Spring Valley, NDWR presently lists the perennial yield as 1,900 to 18,000 AF/yr; Muddy River Springs Area at 100 to 36,000 AF/yr; Hidden Valley at 200 AF/yr, and California Wash at 2200 AF/yr. The perennial yield values consider regional groundwater flow into and between basins. However, under State Engineer Interim Order 1303, the basins of the LWRFS will be managed as one hydrographic area. The combined recharge and subsurface inflow to the LWRFS basins is stated to be not greater than 50,000 AF/yr and pre-development discharge of groundwater to the Muddy River Springs is estimated at 36,000 AF/yr. By difference, the maximum that could be sustained from the LWRFS is 14,000 AF/yr, but more realistically, is perhaps around 10,000 AF/yr. Pumping of groundwater will also need to occur in a manner that does not diminish existing decreed water rights of the Muddy River and Muddy River Springs, or jeopardize habitat in the springs that support the endangered species Moapa Dace. To date, there have been approximately 39,700

AF/yr of water rights issued in the LWRFS (NDWR, 2017). Pumping since 2015 in the LWRFS has ranged between 9,090 to 9,637 AF/yr (NDWR, 2019; Interim Order 1303).

<u>Existing Water Rights in Garnet Valley</u>

A summary of current water rights in Garnet Valley is presented in Table 4, and locations of points of diversion are shown in Figure 16. Currently there are 3715.55 AF/yr of permitted water rights in the basin (NDWR, 2019, adjusted for combined duties). Municipal rights total 2274.57 AF/yr, industrial totals 615.15 AF/yr, 350 AF/yr are in a construction manner of use, 283.81 AF/yr in mining and milling, 178.00 AF/yr in quasi-municipal, and 14.02 AF/yr are in a commercial manner of use.

Water rights in Garnet Valley are predominantly considered “junior” relative to other water rights that have been issued in the LWRFS. A potential perennial yield for the LWRFS may be approximately 10,000 AF/yr, derived from basin recharge and subsurface inflow that is not allocated to Muddy River and Muddy River Springs (NDWR, 2018). This would place a priority cutoff date at 1983, if regulation of groundwater rights under the prior appropriation statutes were to occur.

Potential “senior” water rights (pre-1983) in Garnet Valley include Chemical Lime rights for 233.81 AF/yr with 1967 and 1981 priority dates, Republic Environmental Technologies rights for 194 AF/yr with 1981 priority, Nevada Power Company rights for 74.57 AF/yr with a 1981 priority date, the City of North Las Vegas rights for 10.02 AF/yr with a 1981 priority date, and Western Mining & Minerals rights for 4 AF/yr with a 1981 priority date. These totals have been adjusted to account for total combined duties of permits (NDWR, 2017). Total “senior” priority water rights in Garnet Valley are estimated to be 516.4 AF/yr.

SNWA holds the greatest duty of water rights in Garnet Valley (Table 4). The total combined duty of multiple water right permits is 2274.57 AF/yr. These water rights have a priority date of 1989, and are junior for the LWRFS. There are approximately 28,500 AF/yr of water right issued in the LWRFS that have a more senior priority as compared to SNWA’s 1989 priority rights in Garnet Valley (NDWR, 2017). Some of these water rights are SNWA rights in Coyote Spring Valley, with a priority date of 1985. The Coyote Spring Valley water rights are junior to approximately 13,400 AF/yr of more senior issued rights (NDWR, 2017).

**Table 1 - Summary of Wells in Garnet Valley (NDWR database, 2019)**

| Well Log # | Name | UTM X (ft) | UTM Y (ft) | Date Drilled | Depth Drilled (ft) | Static Water (ft) | Well Type | Aquifer Type | Owner |
|---|---|---|---|---|---|---|---|---|---|
| 4105 | | 2270784 | 13240978 | 4/24/1958 | 550 | 272 | Production | Carbonate | STEWART CONSTRUCTION |
| 4106 | | 2274147 | 13240446 | 6/12/1958 | 575 | 260 | Abandoned | Carbonate | STEWART CONSTRUCTION |
| 10682 | | 2264548 | 13223542 | 9/13/1963 | 600 | 230 | Production | Valley Fill | U S LIME |
| 11655 | | 2249744 | 13219883 | 6/17/1971 | 712 | 408 | Abandoned | Carbonate | U S LIME |
| 11891 | OLD | 2257020 | 13219570 | 7/22/1971 | 500 | 338 | Production | Valley Fill | Chemical Lime Co. |
| 27975 | | 2251475 | 13200195 | 9/30/1986 | 1205 | 660 | Abandoned | Carbonate | GEORGIA PACIFIC CORP |
| 28575 | | 2273169 | 13225655 | 1/24/1987 | 700 | ND | Abandoned | Carbonate | FRU-CON CONSTRUCTION CORP |
| 28576 | | 2274477 | 13225684 | 3/30/1987 | 736 | 485 | Abandoned | Valley Fill | GREAT STAR CEMENT CORP |
| 33206 | KAPEX | 2243314 | 13218430 | 2/7/1990 | 1145 | 578 | Production | Carbonate | LVVWD |
| 34528 | | 2251447 | 13201510 | 10/23/1992 | 1598 | 606 | Abandoned | No Data | GEORGIA PACIFIC CORP |
| 36318 | | 2251447 | 13201513 | 8/19/1990 | 960 | 608 | Production | No Data | GEORGIA PACIFIC CORP |
| 37990 | | 2251475 | 13200195 | 12/30/1991 | 1205 | 660 | Abandoned | No Data | GEORGIA PACIFIC CORP |
| 42438 | WELL #2 | 2265986 | 13214836 | 9/3/1993 | 983 | 596 | Production | Carbonate | Republic Env. Tech. |
| 43500 | | 2274147 | 13240446 | 6/23/1993 | 500 | 360 | Abandoned | No Data | LAS VEGAS PAVING CORP |
| 46755 | | 2266752 | 13216308 | 3/23/1989 | 560 | 453 | Production | Valley Fill | ENVIRONMENTAL TECHNOLOGIES |
| 52733 | | 2272743 | 13244764 | 8/25/1982 | 500 | 244 | Production | Valley Fill | UNION PACIFIC RAILROAD |
| 52867 | | 2265478 | 13211019 | 6/7/1996 | 1500 | 645 | Production | Carbonate | SILVER STATE DISPOSAL |
| 58956 | REPWELL#5 | 2267230 | 13220531 | 12/13/1996 | 720 | 405 | Production | Carbonate | Republic Env. Tech. |
| 60603 | | 2254281 | 13218058 | 5/25/1982 | 687 | 460 | Production | Valley Fill | GRACE PETROLEUM |
| 60605 | GARNET | 2273768 | 13242713 | 9/10/1972 | 500 | 240 | Abandoned | Valley Fill | SNWA |
| 60607 | | 2265275 | 13220220 | 1/6/1975 | 423 | 340 | Abandoned | Carbonate | UNIVERSAL ATLAS CEMENT |
| 60608 | | 2265275 | 13220220 | 9/24/1976 | 625 | 332 | Abandoned | Carbonate | UNIVERSAL ATLAS CEMENT |
| 65222 | WELL #6 | 2265586 | 13209678 | 5/26/1997 | 1150 | 650 | Production | Carbonate | Republic Env. Tech. |
| 66619 | REPWELL#7 | 2270735 | 13213766 | 6/21/1997 | 940 | 610 | Production | Carbonate | Republic Env. Tech. |
| 68098 | | 2258903 | 13216136 | 10/11/1997 | 725 | 377 | Production | Valley Fill | WESTERN GYPSUM INC |
| 72577 | CRYSTAL 2 | 2277377 | 13252218 | 9/30/1998 | 497 | 256 | Monitor | Carbonate | NPC (NV Energy) |

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| Well Log # | Name | UTM X (ft) | UTM Y (ft) | Date Drilled | Depth Drilled (ft) | Static Water (ft) | Well Type | Aquifer Type | Owner |
|---|---|---|---|---|---|---|---|---|---|
| 72578 | CRYSTAL 1 | 2278175 | 13253635 | 9/30/1998 | 565 | 230 | Monitor | Carbonate | NPC (NV Energy) |
| 75351 | NEW | 2256387 | 13210482 | 6/1/1999 | 860 | 471 | Production | Carbonate | Chemical Lime Co. |
| 79487 | GV-1 | 2240753 | 13235351 | 5/5/2000 | 1400 | 888 | Monitor | Carbonate | SNWA |
| 80086 | | 2245415 | 13238806 | 6/20/2000 | 2480 | 882 | Production | Carbonate | DRY LAKE WATER CO |
| 82303 | | 2284396 | 13256964 | 10/21/2000 | 680 | 500 | Production | Carbonate | MARTY MIFFLIN & ASSOCIATES |
| 82443 | PAIUTES-M3 | 2268814 | 13268681 | 10/20/2000 | 670 | 580 | Monitor | Carbonate | MBPI |
| 83301 | | 2274147 | 13240446 | 5/17/2001 | 903 | No Data | Abandoned | Carbonate | NEVADA POWER COMPANY |
| 83302 | | 2274147 | 13240446 | 5/18/2001 | 903 | No Data | Abandoned | Carbonate | NEVADA POWER COMPANY |
| 83508 | GV-RW1 | 2273381 | 13243559 | 7/3/2001 | 870 | 260 | Production | Carbonate | NPC (NV Energy) |
| 83771 | GV-2 | 2251393 | 13207618 | 7/19/2001 | 1232 | 620 | Monitor | Carbonate | SNWA |
| 85526 | GV-PW-MW2 | 2239667 | 13226640 | 12/14/2001 | 1500 | 716 | Monitor | Carbonate | SNWA |
| 85610 | GV-DUKE-WS1 | 2251591 | 13218820 | 12/7/2001 | 685 | 426 | Production | Carbonate | SNWA |
| 85894 | GV-MIRANT1 | 2241186 | 13229363 | 3/1/2002 | 2007 | 754.95 | Production | Carbonate | SNWA |
| 86905 | GV-PW-WS1 | 2239674 | 13226548 | 7/25/2002 | 2020 | 684 | Production | Carbonate | SNWA |
| 86906 | GV-PW-MW1 | 2242318 | 13227434 | 1/22/2002 | 1500 | 692 | Monitor | Carbonate | SNWA |
| 87079 | GV-DUKE-WS2 | 2251305 | 13218795 | 5/23/2002 | 2020 | 431.69 | Abandoned | Carbonate | SNWA/NPC (NVEnergy) |
| 91028 | | 2274147 | 13240446 | 7/7/2003 | 575 | No data | Abandoned | Carbonate | NEVADA POWER CO |
| 96487 | | 2248883 | 13202770 | 4/5/2005 | 50 | No Data | Monitor | Carbonate | G P GYPSUM CORP |
| 99336 | | 2260240 | 13214850 | 4/21/2006 | 650 | 408 | Production | Carbonate | INDUSTRIAL PROPERTIES DEVELOPMENT |
| 107394 | REPWELL#1 | 2266367 | 13217956 | 12/31/2008 | 860 | 487 | Monitor | Clastic Rock | Republic Env. Tech. |
| 107395 | | 2266612 | 13217302 | 1/13/2009 | 560 | 505 | Abandoned | No Data | REPUBLIC DUMPCO |
| 113362 | | 2274477 | 13225684 | 2/9/2011 | 736 | 200 | Abandoned | No Data | U S BUREAU OF LAND MANAGEMENT |
| 125987 | GV-LENZIE-3 | 2251301 | 13218803 | 10/15/2016 | 1960 | 433 | Production | Carbonate | NV Energy |
| 127359 | PLAYA | 2241892 | 13232025 | 10/27/2016 | 2000 | 793 | Production | Carbonate | First Solar/Playa Solar LLC |

**Table 2 - Pumping and Water Level Measurements for Wells in Garnet Valley in Year 2015 (data compiled from NDWR, 2019)**

| Well Name | Pumped Amount in 2015 (AF/yr) | UTM X (ft) | UTM Y (ft) | Average 2015 Water Level Elevation (ft amsl) | Water Level Measurement Frequency | Remark | Average Water Level during Pumping (ft amsl) | Average Water Level during Non-Pumping (ft amsl) |
|---|---|---|---|---|---|---|---|---|
| REPWELL #1 | 20.17 | 2266371 | 13217983 | 1726.52 | monthly | Avg of monthly 2015 recordings | 1720.21 | 1730.13 |
| GV-1 | | 2240759 | 13235378 | 1808.10 | daily | Avg of daily recordings for 2015 | | |
| GV-PW-MW2 | | 2239673 | 13226669 | 1810.04 | monthly | Avg of monthly 2015 recordings | | |
| CRYSTAL 1 | | 2278179 | 13253662 | 1811.38 | yearly | 1 recording - 3/19/2015 | | |
| GV-PW-MW1 | | 2242323 | 13227460 | 1810.97 | daily | Avg of daily recordings for 2015 | | |
| CRYSTAL 2 | | 2277383 | 13252246 | 1811.68 | yearly | 1 recording - 3/19/2015 | | |
| PAIUTES-M3 | | 2268818 | 13268706 | 1812.19 | daily | Avg of daily recordings for 2015 | | |
| GV-2 | | 2251399 | 13207644 | 1814.35 | monthly | Avg of monthly 2015 recordings | | |
| REPWELL #5 | 119.67 | 2267234 | 13220558 | | | First recording 1/17/18 | | |
| GV-PW-WS1 | 153.82 | 2239678 | 13226577 | 1800.48 | monthly | Avg of monthly (Jan, July, Oct, Nov, Dec), Feb, May, June ,Aug, Sept avg. 1738.65 | 1738.65 | 1800.48 |
| GV-DUKE-WS1 | 71.2 | 2251596 | 13218847 | 1811.66 | monthly | Avg of July - Dec 2015 monthly. WLs were 1657-1675 in April-May | 1666.35 | 1811.66 |
| GV-DUKE-WS2 | 205.44 | 2252394 | 13218651 | 1813.24 | monthly | Avg of monthly (April, May, July, Aug, Nov, Dec) June, Sept, Oct were 1711.17-1731.81 ft | 1718.82 | 1813.24 |
| REPWELL #7 | 16.54 | 2270739 | 13213792 | 1797.16* | monthly | Avg of Monthly Jan-July 2015 recorded WL | | |
| GV-MIRANT1 | 56.54 | 2241190 | 13229392 | 1810.41 | monthly | Most common WL Elevation recorded | 1755.04 | 1809.90 |
| GV-RW1 | 346.84 | 2273385 | 13243588 | 1791.33 | yearly | 1 recording - 3/19/2015 | 1791.33 | |
| KERR | 17.72 | 2243202 | 13218909 | | | No Data | | |
| NEW | 121.51 | 2256391 | 13210509 | | | No Data | | |
| OLD | 72.63 | 2257024 | 13219597 | | | No Data | | |
| REPWELL #6 | 130.98 | 2265591 | 13209705 | | | No Data | | |
| REPWELL #2 | 36.67 | 2265991 | 13214863 | | | No Data | | |
| GARNET | | 2273774 | 13242739 | 1810.51 | yearly | 1 recording - 2/9/2015 | | |
| Georgia Pacific | 117.24 | 2252464 | 13202457 | | | No Data | | |
| Western MM | 3.42 | 2260206 | 13217461 | | | No Data | | |
| Dry Lake Water, LLC | 29.67 | 2259367 | 13215503 | | | No Data | | |

* Water level probably effected by nearby pumping from REP Well#1

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**Table 3 – Summary of Estimated T Computations for Garnet Valley using NDWR Well Log Data (2019)**

| Site ID | Name | UTM X (ft) | UTM Y (ft) | Well Log No. | Perfs From (ft) | Perfs To (ft) | Well Drilled Depth (ft) | Depth to Limestone (ft) | Static WL (ft) | Saturated Thickness (ft) | Drawdown (ft) | Pump Rate (gpm) | Pump Duration (hrs) | Specific Capacity (gpm/ft) | Mace T ($ft^2$/day) | Driscoll T ($ft^2$/day) | Average Estimated T ($ft^2$/day) | Estimated K (ft/day) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 216 S18 E64 07BB | NDOT | 690032 | 4030724 | 60605 | 350 | 500 | 500 | N/A | 240 | 260 | 140 | 60 | 24 | 0.43 | 73.8 | 137.6 | 105.7 | 0.41 |
| 216 S18 E63 15AACD1 | GV-DUKE-WS1 | 686286 | 4029104 | 85610 | 537 | 685 | 685 | 460 | 426 | 259 | 194 | 225 | 24 | 1.16 | 216.3 | 372.4 | 294.3 | 1.14 |
| 216 S18 E63 04CBBA1 | GV-PW-MW1 | 683460 | 4031730 | 86906 | 900 | 1500 | 1500 | 10 | 692 | 808 | 29 | 50 | 1 | 1.72 | 331.8 | 553.6 | 442.7 | 0.55 |
| 216 S17 E63 33CBCB1 | PLAYA (FIRST SOLAR) | 683330 | 4033129 | 127359 | 1218 | 1969 | 2000 | 870 | 793 | 1207 | 322 | 600 | 24 | 1.86 | 360.9 | 598.3 | 479.6 | 0.40 |
| 216 S18 E63 14AABD1 | US LIME (1971) | 687941 | 4029333 | 11891 | 350 | 500 | 500 | N/A | 338 | 162 | 38 | 96 | 8 | 2.53 | 501.3 | 811.2 | 656.3 | 4.05 |
| 216 S18 E64 18CA | SILVER STATE DISPOSAL | 690519 | 4026727 | 52867 | 1040 | 1480 | 1500 | 0 | 645 | 855 | 325 | 50 | 8 | 0.15 | 1611.3 | 49.4 | 830.3 | 0.97 |
| 216 S18 E63 15AACC1 | GV-DUKE-WS2 | 686199 | 4029097 | 87079 | 877 | 1944 | 2020 | 370 | 431.69 | 1588 | 204.3 | 1000 | 24 | 4.89 | 1024.1 | 1571.6 | 1297.9 | 0.82 |
| 216 S18 E63 15AA | GV-LENZIE-3 | 686198 | 4029099 | 125987 | 900 | 1900 | 1940 | -- | 433 | 1507 | 199 | 1000 | 24 | 5.03 | 1053.6 | 1613.5 | 1333.6 | 0.88 |
| 216 S18 E64 07B | US LIME (1963) | 690236 | 4030544 | 10682 | 250 | 490 | 600 | N/A | 230 | 260 | 450 | 110 | 0 | 0.24 | 2656.8 | 78.5 | 1367.6 | 5.26 |
| 216 S17 E63 21DC | DRY LAKE WATER CO | 684404 | 4035196 | 80086 | -- | -- | 2480 | 260 | 882 | 1598 | 1000 | 300 | 336 | 0.30 | 3314.4 | 96.3 | 1705.4 | 1.07 |
| 216 S18 E63 05AADB1 | GV-MIRANT1 | 683115 | 4032318 | 85894 | 1197 | 1979 | 2007 | 610 | 754.95 | 1252 | 138.6 | 1000 | 72 | 7.22 | 1557.2 | 2316.7 | 1936.9 | 1.55 |
| 216 S18 E63 05DBCD1 | GV-PW-WS1 | 682654 | 4031460 | 86905 | 1240 | 1980 | 2020 | 1600 | 684 | 1336 | 29 | 235 | 20 | 8.10 | 1765.2 | 2601.9 | 2183.6 | 1.63 |
| 216 S18 E63 16BB | KAPEX (KERR-MCGEE CHEM) | 683763 | 4028986 | 33206 | 700 | 1145 | 1145 | 375 | 578 | 567 | 21 | 200 | 48 | 9.52 | 2101.6 | 3058.0 | 2579.8 | 4.55 |
| 216 S18 E63 34AC | GEORGIA PACIFIC CORP | 686242 | 4023828 | 34528 | 0 | 0 | 1200 | -- | 606 | 594 | 0.83 | 140 | 4 | 168.67 | 46844.1 | 54159.4 | 50501.8 | 85.02 |
| 216 S17 E64 21CBBD1 | GV-RW1 | 692928 | 4036645 | 83508 | 553 | 833 | 870 | 495 | 260 | 610 | 32 | 1500 | 72 | 46.88 | 11750.5 | 15051.0 | 13400.8 | 21.97 |

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JA_7200

**Table 4 – Summary of Active Underground Water Rights in Garnet Valley (NDWR database, 2019, not adjusted for combined duty limits)**

| Application # | Change Of Application | Certificate # | Priority Date | Application Status | Source | Type of Use | Duty (AF/yr) | Owner of Record | Site Name |
|---|---|---|---|---|---|---|---|---|---|
| 83553 | 18140 | | 7/24/1959 | PER | UG | IND | 3 | TECHNICHROME | 216 S19 E63 03ADDD1 |
| 64880 | 26277 | 16864 | 7/24/1967 | CER | UG | MM | 150.38 | CHEMICAL LIME COMPANY | 216 S18 E63 23DCAA1 |
| 74399 | 60022 | 17531 | 7/20/1981 | CER | UG | IND | 74.57 | NEVADA POWER COMPANY | 216 S17 E64 21CBBD1 |
| 63261 | 55674 | 16751 | 10/20/1981 | CER | UG | COM | 100 | CHEMICAL LIME COMPANY OF ARIZONA | 216 S18 E63 14AABD1 |
| 63348 | 55674 | 15682 | 10/20/1981 | CER | UG | COM | 4 | WESTERN MINING & MINERALS, INC. | 216 S18 E63 13CAAA1 |
| 77745 | 55674 | 19642 | 10/20/1981 | CER | UG | COM | 10.02 | NORTH LAS VEGAS-CITY | 216 S18 E63 16BBDA1 |
| 83714 | 67718 | 21127 | 10/20/1981 | CER | UG | IND | 157 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 19CDDD1 |
| 83715 | 67718 | | 10/20/1981 | PER | UG | IND | 37 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 19ABBB1 |
| 56855 | 50316 | 14449 | 10/28/1986 | CER | UG | IND | 144.15 | GEORGIA PACIFIC CORPORATION | 216 S18 E63 34ADAB1 |
| 66784 | 50663 | | 3/6/1987 | PER | UG | QM | 178 | DRY LAKE WATER, LLC | 216 S18 E63 27ACAD1 |
| 83707 | 67711 | 21125 | 10/3/1988 | CER | UG | IND | 0.11 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 18ACDB1 |
| 83708 | 67712 | | 10/3/1988 | PER | UG | IND | 68.5 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 18ACDB1 |
| 83709 | 67713 | | 10/3/1988 | PER | UG | IND | 0.11 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 07DDCB1 |
| 83710 | 67714 | 21126 | 10/3/1988 | CER | UG | IND | 0.11 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 20BABA1 |
| 83711 | 67715 | | 10/3/1988 | PER | UG | IND | 40.78 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 19ABBB1 |
| 83712 | 67716 | | 10/3/1988 | PER | UG | IND | 3.7 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 19ABBB1 |
| 83713 | 67717 | | 10/3/1988 | PER | UG | IND | 23.8 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 19ABBB1 |
| 83716 | 67719 | | 10/3/1988 | PER | UG | IND | 68.5 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 18ACDB1 |
| 83717 | 67720 | 21128 | 10/3/1988 | CER | UG | IND | 68.39 | REPUBLIC ENVIRONMENTAL TECHNOLOGIES INC | 216 S18 E64 07DDCC1 |

| Application # | Change Of Application | Certificate # | Priority Date | Application Status | Source | Type of Use | Duty (AF/yr) | Owner of Record | Site Name |
|---|---|---|---|---|---|---|---|---|---|
| 54073 | | | 10/17/1989 | PER | UG | MUN | 2200 | SOUTHERN NEVADA WATER AUTHORITY | 216 S17 E63 32CCCB1 |
| 79001 | 68822 | | 10/17/1989 | PER | UG | MUN | 350 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 05AADB1 |
| 79002 | 72798 | | 10/17/1989 | PER | UG | MUN | 349.8 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 05DACC1 |
| 79003 | 73149 | | 10/17/1989 | PER | UG | MUN | 233.33 | SOUTHERN NEVADA WATER AUTHORITY | 216 S17 E64 21CBBD1 |
| 79004 | 73150 | | 10/17/1989 | PER | UG | MUN | 233.33 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 15AACD1 |
| 79005 | 73151 | | 10/17/1989 | PER | UG | MUN | 233.33 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 15AACC1 |
| 83490 | 54073 | | 10/17/1989 | PER | UG | MUN | 300 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 16BBDA1 |
| 88011T | 68822 | | 10/17/1989 | PER | UG | CON | 350 | SOUTHERN NEVADA WATER AUTHORITY | 216 S17 E63 33CBCB1 |
| 66785 | | | 8/25/2000 | PER | UG | QM | 178 | DRY LAKE WATER, LLC | 216 S17 E63 32AABA1 |
| 72098 | 66785 | 19102 | 8/25/2000 | CER | UG | QM | 13.17 | DRY LAKE WATER, LLC | 216 S18 E63 13CDBC1 |
| 77389 | 66785 | | 8/25/2000 | PER | UG | QM | 80 | DRY LAKE WATER, LLC | 216 S18 E63 33DBBA1 |
| 79948 | 66785 | | 8/25/2000 | PER | UG | QM | 30 | DRY LAKE WATER LLC | 216 S18 E63 13CDBC1 |
| 81344 | 74064 | | 8/25/2000 | PER | UG | QM | 8 | DRY LAKE WATER LLC | 216 S18 E63 13CDBC1 |
| 76862 | | | 3/27/2008 | PER | EFF | STO | 278.73 | NEVADA COGENERATION ASSOCIATES #1 | 216 S18 E63 34ADAC1 |
| 79010 | | | 11/2/2009 | PER | UG | MUN | 233.33 | SOUTHERN NEVADA WATER AUTHORITY | 216 S18 E63 15AACC1 |

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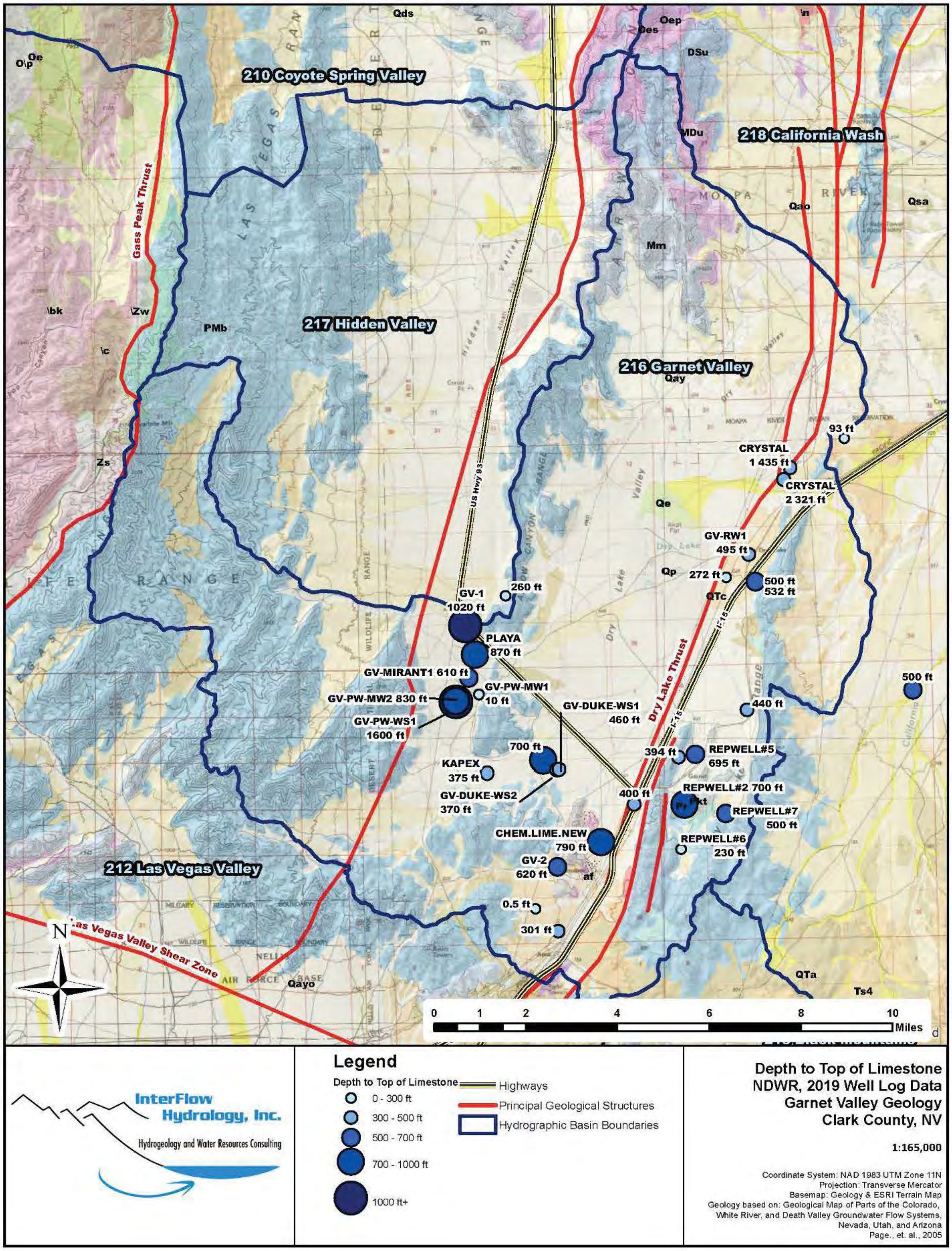


**Figure 8 – Geologic Map of Garnet Valley with Interpreted Depth to Top of Carbonate Rock**

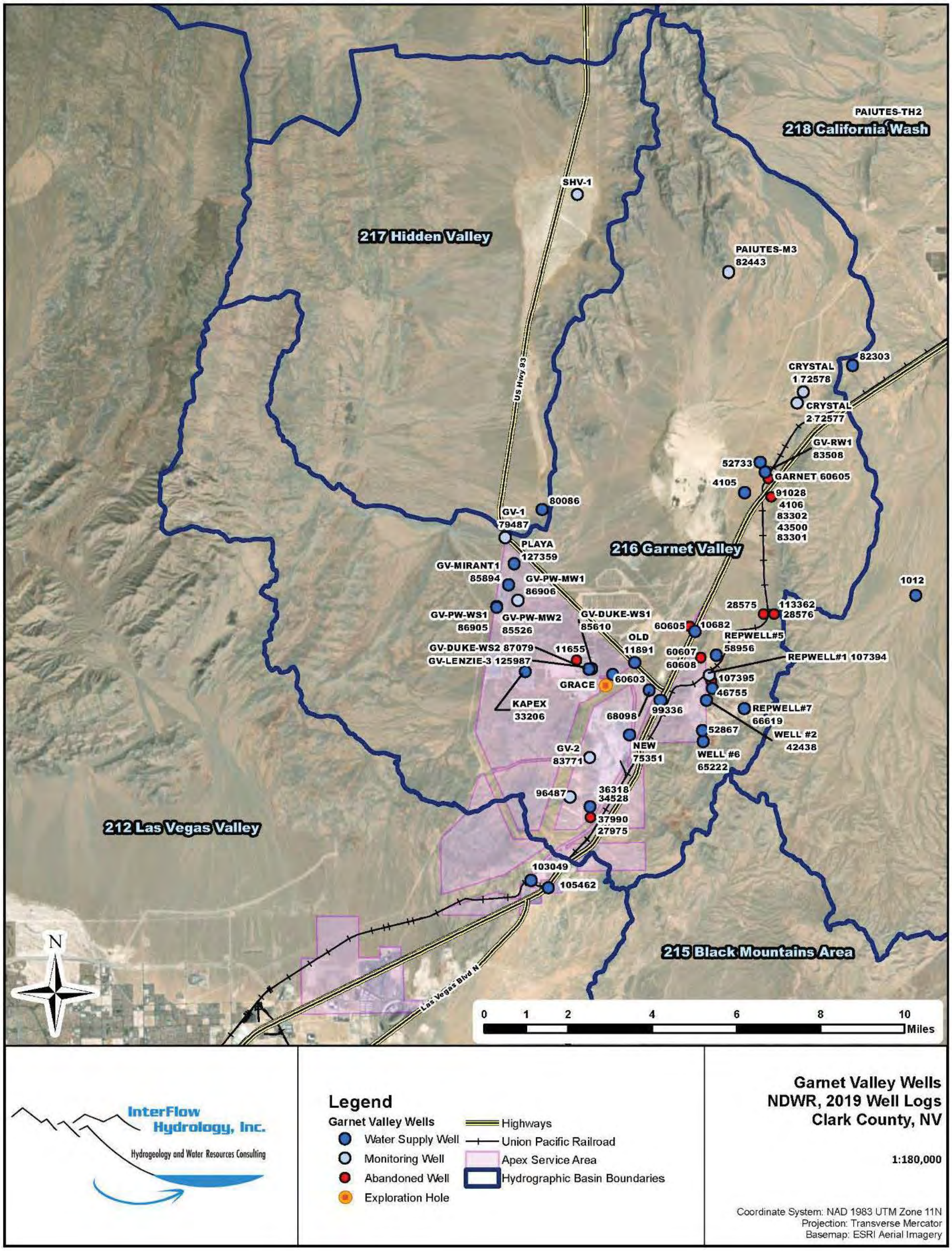


**Figure 9 – Recorded Wells in Garnet Valley**

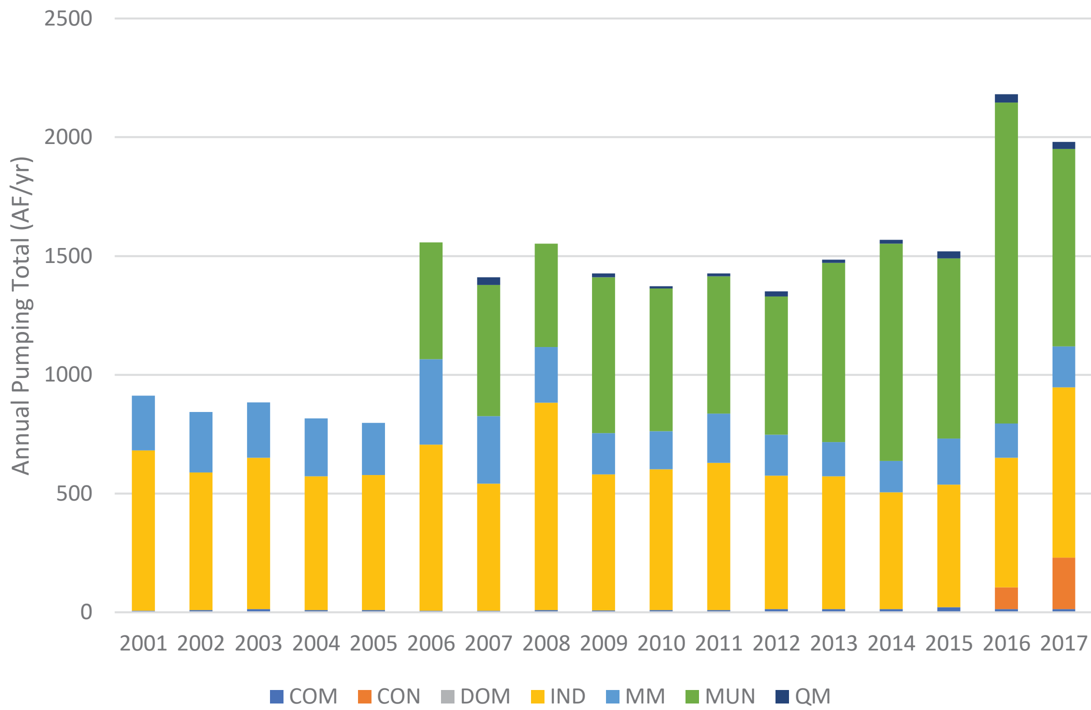


**Figure 10 – Historical Pumping from Wells in Garnet Valley (data from NDWR Pumping Inventories)**

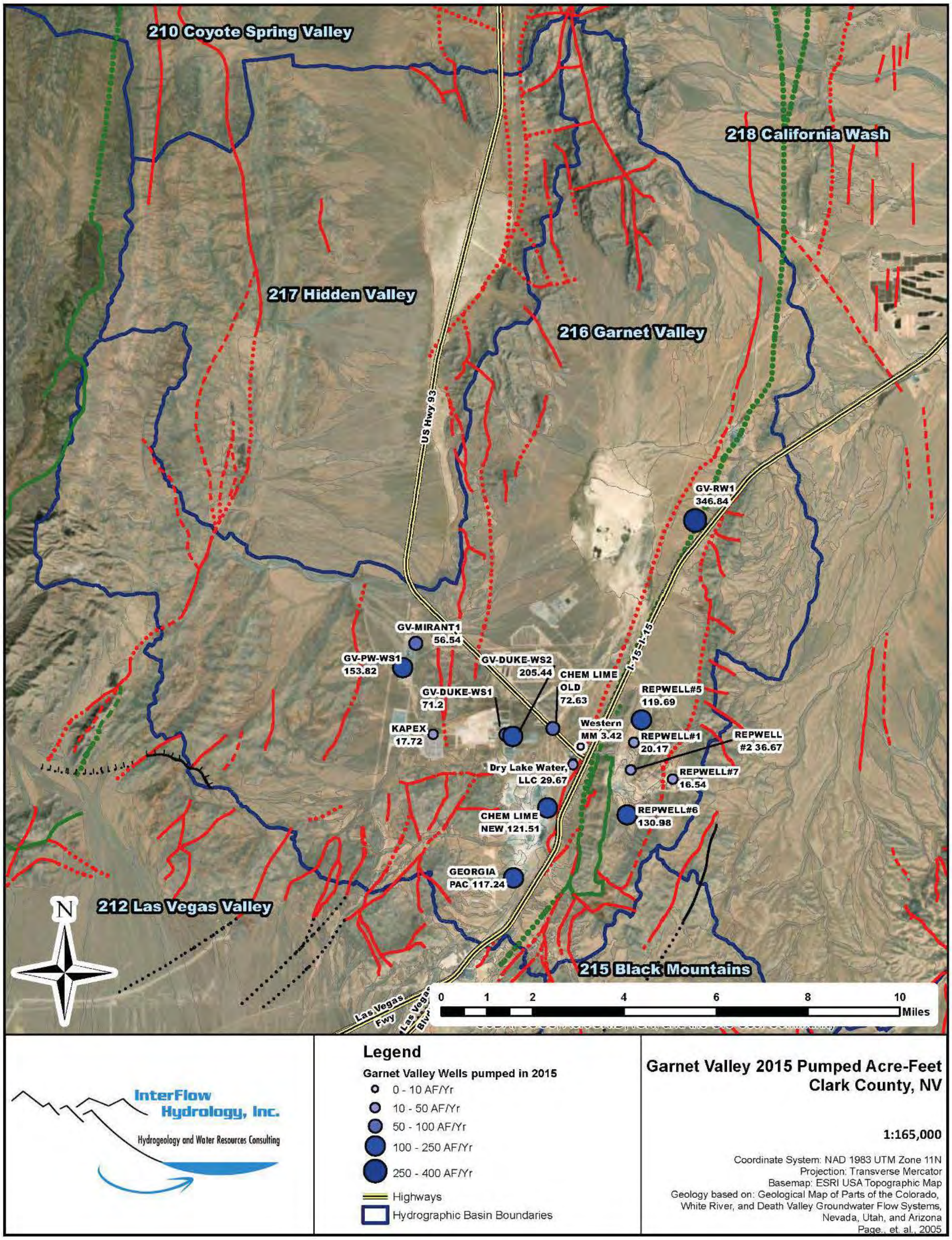


**Figure 11 – Distribution of Pumping in Garnet Valley in Year 2015**

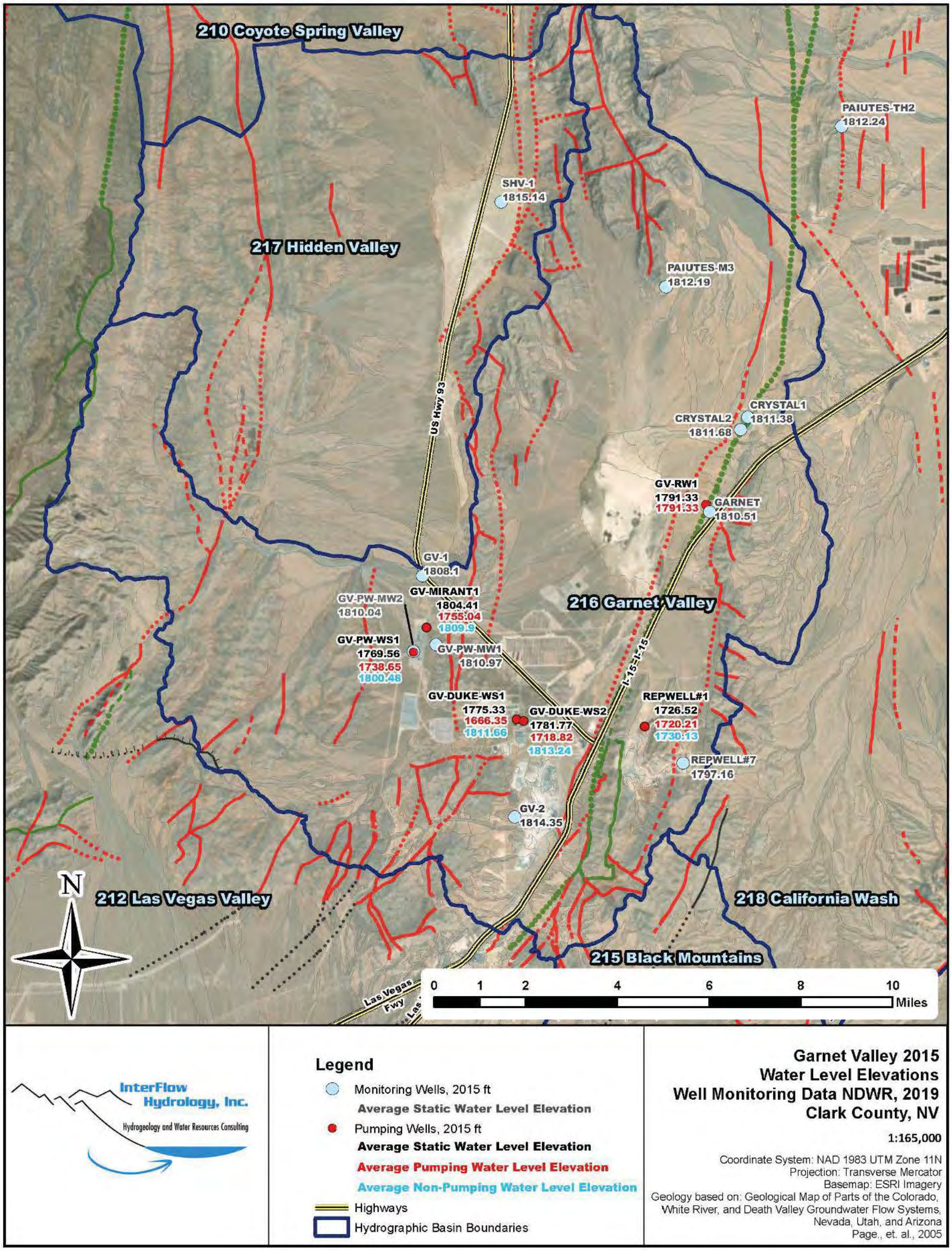


**Figure 12 – Potentiometric Water Levels in Garnet Valley in Year 2015**

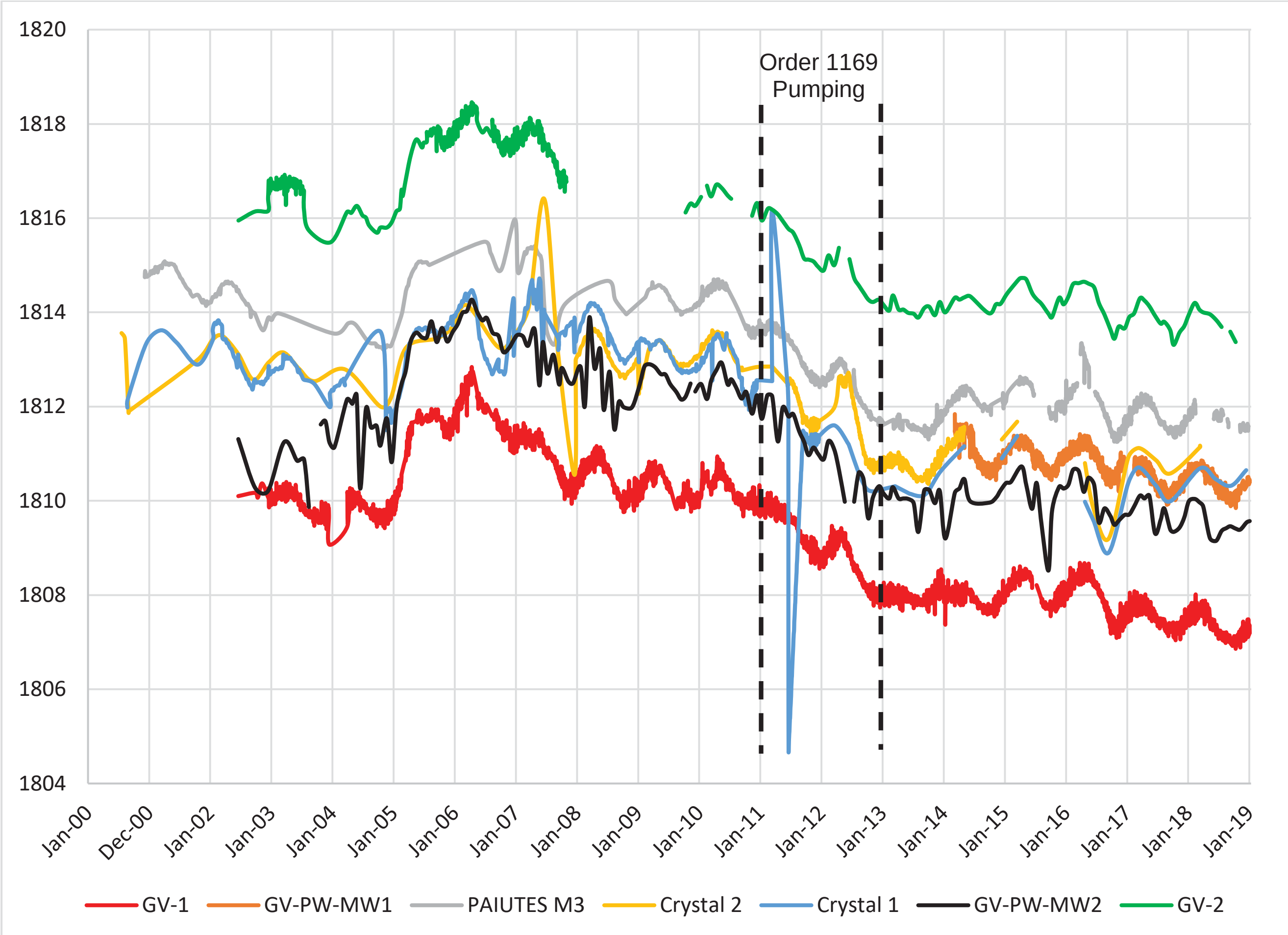


**Figure 13 – Selected Hydrographs in Garnet Valley**

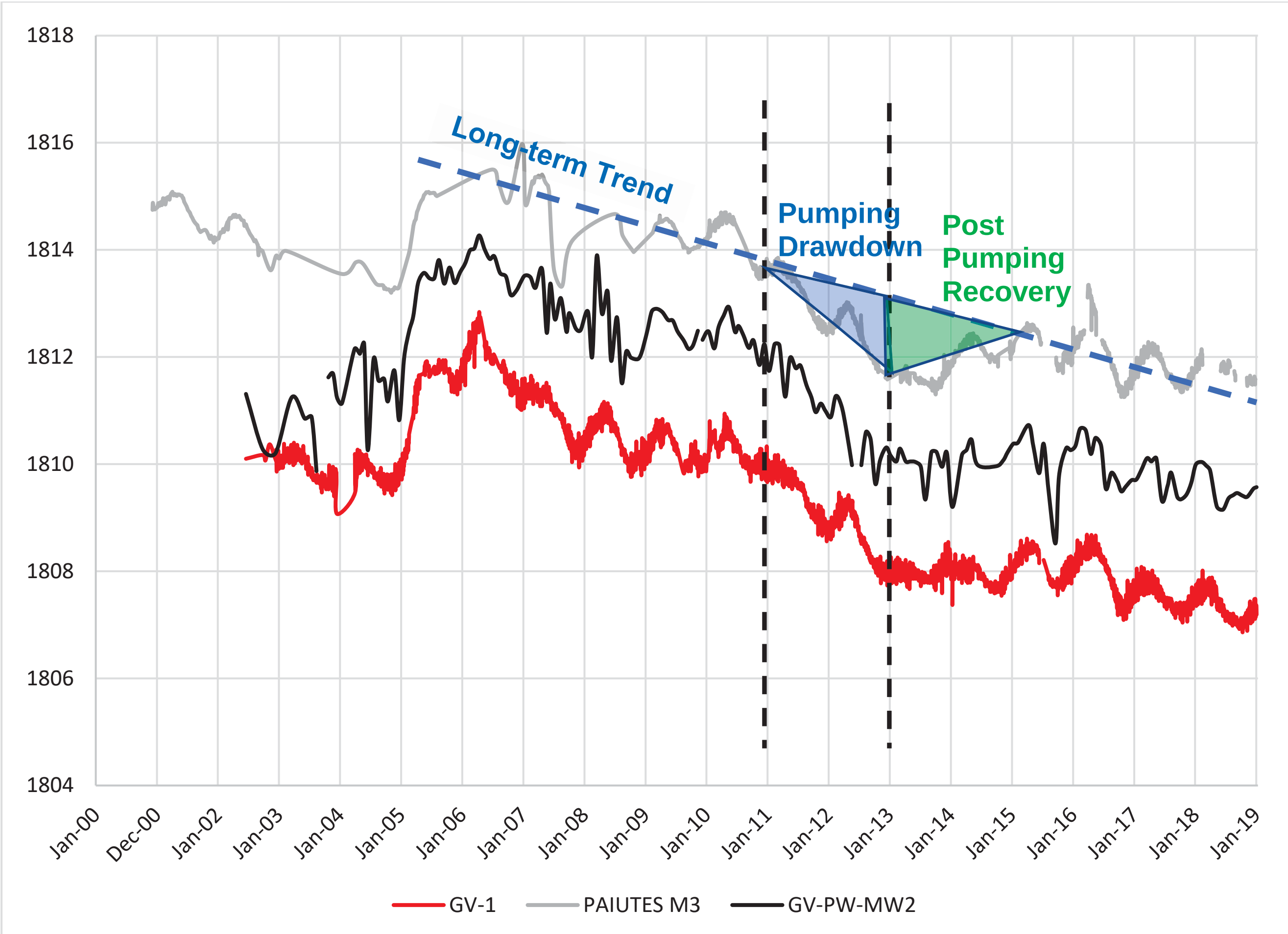


**Figure 14 – Selected Hydrographs in Garnet Valley, Long-Term Trend, and Order 1169 Pumping Influence**

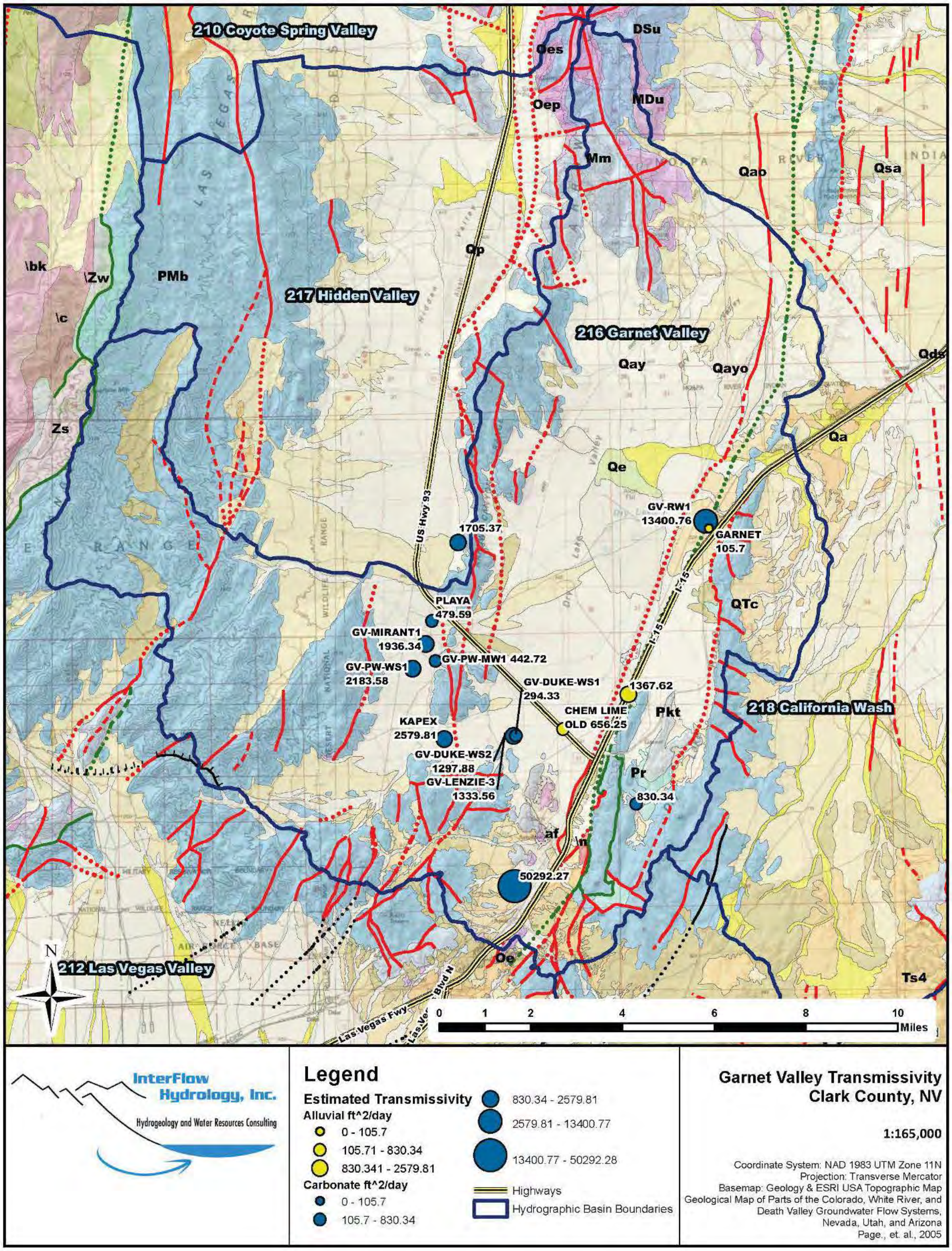


**Figure 15 – Estimated Transmissivity of the Carbonate Aquifer in Garnet Valley**

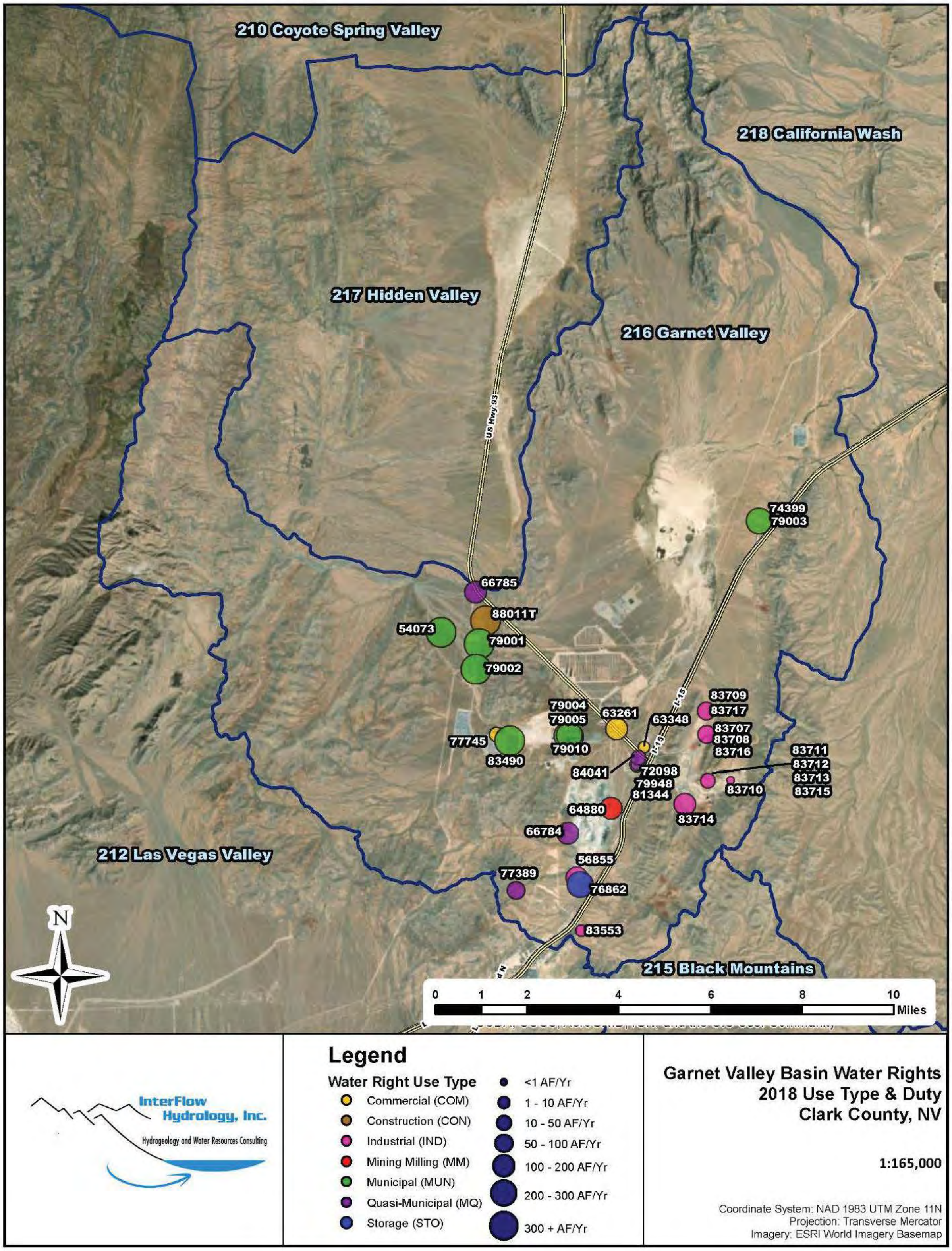


**Figure 16 – Existing Water Rights Points of Diversion and Duties in Garnet Valley**

**Review of Garnet Valley Boundary Conditions**

Las Vegas Valley Boundary

Groundwater flow between Garnet Valley and Las Vegas Valley is not clearly defined. The water level elevation in the southern-most monitoring well in Garnet Valley (GV-2) being the highest observed in the basin (1814 ft amsl) has prompted further examination of the boundary condition.

Dedicated water level monitoring wells are not known to exist at the northeastern-most edge of Las Vegas Valley. In order to gain a preliminary understanding of groundwater elevations and potential groundwater flow direction, well logs on file with NDWR were examined for the general area of Township 19 South, Ranges 62 and 63 East. Well logs selected for evaluation were chosen by their availability of accurate location information, with a preference given to deeper drilled wells, assuming that deeper wells may be more representative of carbonate aquifer water levels. Data analysis using the well logs static water levels needs to consider the date drilled, which spans over several decades from 1962 to 2016. Depth to water can vary seasonally and over the long-term due to climate, pumping, and artificial recharge taking place in Las Vegas Valley, so the date of the well completion and reported static water level reading was noted. Well log data that have been compiled are summarized in Table 5.

The well locations were determined in varyingly accurate ways. Some locations could only be determined to the nearest Quarter-Quarter Section, and are the least accurate. Some well logs contain locations coordinates and with review of map imagery, are assumed to be located more accurately. Some non-domestic wells could also be associated with a water right point of diversion, which provides an accurate location, provided the well was drilled at or near the defined point of diversion. Figure 17 shows the locations of well logs assembled, with color coding for the location plotting method.

Once the well locations were determined as accurately as possible using office methods, the land surface elevation at each well was determined from USGS lidar imagery, if available, or otherwise from ASTER satellite digital elevation model (DEM) at a 30 meter resolution. Groundwater elevations were then calculated based on the depth to water reported in the well log (Table 5).

The resulting map of water level elevations from driller logs (Figure 17) is not definitive. Inaccuracies in groundwater elevations, owing in part to the location and elevation derivation methods, are more likely due to the accuracy of reported static water levels in the well logs, along with the varying time span over which the measurements were made. In order to gain an overview of the compiled data, the average and median groundwater elevations were determined. The average groundwater elevation from the compiled dataset containing 22 groundwater elevation estimates in northeastern-most Las Vegas Valley is 1809.3 ft amsl, and the median is 1821.6 ft amsl. This contrasts with the water level measurements in southern Garnet Valley at GV-2 ranging from 1813.31 to 1818.46 ft amsl (Figure 18), measured between June 2002 to October 2018. The average water level elevation at GV-2 over this time span is 1817.2 ft amsl.

Based on the existing data in northeastern Las Vegas Valley, it is not possible to accurately determine the direction of groundwater flow. The Bird Spring Formation carbonate rocks separate the two basins and provide adequate permeability to facilitate meaningful groundwater flow. The median elevation in northeastern-most Las Vegas Valley is believed to be more reliable than the average, because a few outliers observed in the dataset may unduly bias the average statistic. If the median is representative of groundwater elevations, then the apparent groundwater flow direction is from Las Vegas Valley to Garnet Valley. Monitoring wells with accurate water level measurements and surveyed reference points are needed to confirm this preliminary interpretation.

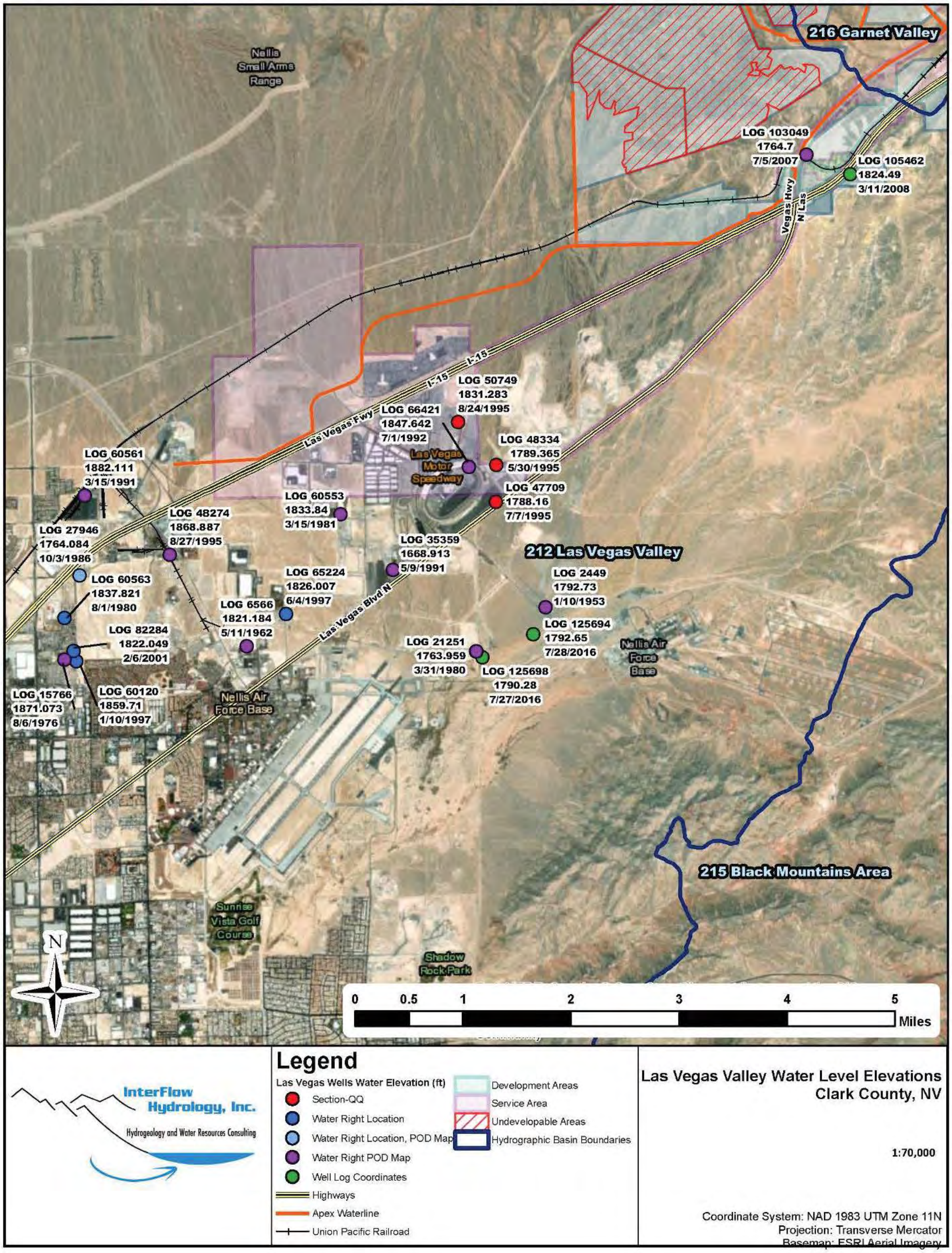


**Figure 17 – Interpreted Water Level Elevations in Northeastern Las Vegas Valley**

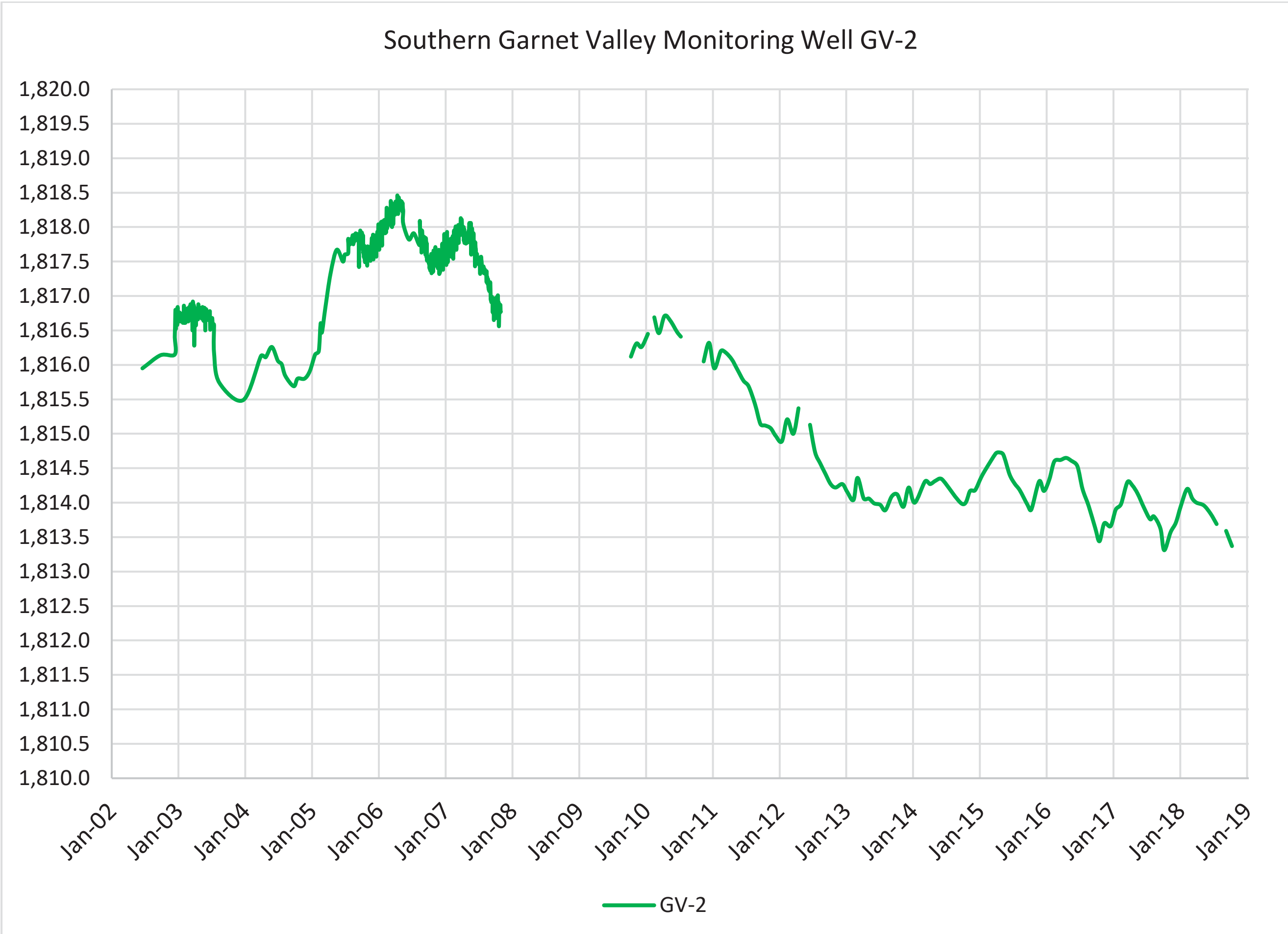


**Figure 18 – Water Level Elevations at Monitoring Well GV-2**

**Table 5 – Summary of Estimated Water Level Elevations in Northeastern Las Vegas Valley using NDWR Well Log Data (2019)**

| Well Log | UTM X (ft) | UTM Y (ft) | Location Basis | Reported Depth to Water (ft) | Date Static Water Level Reported | Land Surface Elevation (ft amsl) | Water Elevation Calculated (ft amsl) |
|---|---|---|---|---|---|---|---|
| 2449 | 2231287.61 | 13170171.60 | Water Right POD | 120 | 1/10/1953 | 1912.73 | 1792.7 |
| 6566 | 2216664.37 | 13168258.29 | Water Right POD | 92 | 5/11/1962 | 1913.18 | 1821.2 |
| 15766 | 2207770.93 | 13167610.59 | Water Right POD | 50 | 8/6/1976 | 1921.07 | 1871.1 |
| 21251 | 2227891.22 | 13168003.19 | Water Right POD | 110 | 3/31/1980 | 1873.70 | 1763.7 |
| 21251 | 2227895.47 | 13168010.27 | Water Right POD | 110 | 3/31/1980 | 1873.96 | 1764.0 |
| 27946 | 2208514.546 | 13171714.86 | Water Right POD | 200 | 10/3/1986 | 1964.08 | 1764.1 |
| 35359 | 2223813.87 | 13171993.69 | Water Right POD | 250 | 5/9/1991 | 1918.91 | 1668.9 |
| 47709 | 2228859.80 | 13175328.46 | Section Quarter-Quarter | 186 | 7/7/1995 | 1974.16 | 1788.2 |
| 48274 | 2212933.04 | 13172731.45 | Water Right POD | 90 | 8/27/1995 | 1958.89 | 1868.9 |
| 48334 | 2228877.98 | 13177137.31 | Section Quarter-Quarter | 220 | 5/30/1995 | 2009.37 | 1789.4 |
| 50749 | 2227015.97 | 13179227.94 | Section Quarter-Quarter | 204 | 8/24/1995 | 2035.28 | 1831.3 |
| 60120 | 2208358.444 | 13167533.05 | Water Right POD | 55 | 1/10/1997 | 1914.71 | 1859.7 |
| 60553 | 2221245.53 | 13174711.79 | Water Right POD | 143 | 3/15/1981 | 1976.84 | 1833.8 |
| 60561 | 2208761.10 | 13175640.13 | Water Right POD | 133 | 3/15/1991 | 2015.11 | 1882.1 |
| 60563 | 2207781.018 | 13169648.86 | Water Right POD | 100 | 8/1/1980 | 1937.82 | 1837.8 |
| 65224 | 2218583.489 | 13169837.18 | Water Right POD | 99 | 6/4/1997 | 1925.01 | 1826.0 |
| 66421 | 2227538.05 | 13177040.82 | Water Right POD | 124 | 7/1/1992 | 1971.64 | 1847.6 |
| 82284 | 2208217.368 | 13168025.83 | Water Right POD | 102 | 2/6/2001 | 1924.05 | 1822.0 |
| 103049 | 2244014.57 | 13192269.94 | Water Right POD | 650 | 7/5/2007 | 2414.70 | 1764.7 |
| 105462 | 2246169.344 | 13191329.032 | Well Log Coordinates, Imagery | 541 | 3/11/2008 | 2365.49 | 1824.5 |
| 125694 | 2230688.87 | 13168841.83 | Well Log Coordinates, Imagery | 116.8 | 7/28/2016 | 1909.45 | 1792.7 |
| 125698 | 2228201.37 | 13167716.06 | Well Log Coordinates, Imagery | 79.8 | 7/27/2016 | 1870.08 | 1790.3 |

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Testing of Boundary Conditions using Numerical Flow Modeling

In order to examine and test potential boundary conditions and surface inflow and outflow from Garnet Valley, a simple 2D numerical flow model was developed using MODFLOW (Langevin, et al, 2017). The model grid is comprised of 1000 ft square cells and incorporates the entire hydrographic basin area (Figure 19). The model has one layer, approximately 1000 ft in thickness, to represent the upper-most saturated thickness of the carbonate aquifer that is tapped by wells in Garnet Valley.

General head boundary (GHB) conditions were established around the periphery of the model at postulated locations of subsurface inflow or outflow (Figure 19). The GHBs derive a flow based on the gradient across the boundary, which is established from a water level elevation at a projected distance beyond the boundary. A conductance term regulates the ease of flow across the boundary, which is derived from the hydraulic conductivity (K) assigned to the boundary. Table 6 summarizes the GHB assumptions, and values assigned for the GHB K, which were determined during model calibration.

Recharge was input into the model on the western-most edge of Garnet Valley (Figure 19), corresponding to the highest altitude portions of the Las Vegas Range. The recharge quantity was set equal to 400 AF/yr, based on the estimate of Rush (1968).

The hydraulic conductivity of the upper carbonate aquifer represented by the model layer was initially set to 2 ft/day (geometric mean of well specific capacity analysis), but adjusted upward to 5.5 ft/day during model calibration to provide a better fit to measured potentiometric heads in the basin. This K value is mid-range between the average carbonate aquifer K (10 ft/day) and median K (1.1 ft/day) as derived from the well log specific capacity analysis.

Pumping was input in the model based on the year 2015 distribution and volumes, as shown in Figure 20. Year 2015 was selected because the yearly pumping amount had been constant for 10-years at approximately 1,500 AF/yr. The pumping is assumed to have reached a state of equilibrium (steady-state) in the groundwater system, for model calibration and boundary testing purposes.

Calibration of the steady-state model was to average 2015 water level elevations at fifteen wells in Garnet Valley, as summarized in Table 2. Potentiometric water level elevation targets are called “head targets” in the modeling. Seven head targets are water levels recorded at pumping wells. In these cases, the average water level over the entire year, including both pumping and non-pumping periods, was input as the head target. The averaged head targets correspond to the average annual pumping simulated in the model. This approach ignores well efficiency and radial flow convergence effects within a model cell. As a result, the model should tend to simulate higher water level elevations than the head targets at the seven pumping wells. But these points are still important to the model calibration, because data are sparse in Garnet Valley. To reflect the greater potential error in pumping well head targets, they are assigned 1/10$^{th}$ weight during calibration as contrasted with head targets from non-pumping monitoring wells (assigned a weight of 1).

Calibration of the model included adjustments to GHB K values to loosen or tighten the hydraulic properties regulating flow across each defined boundary, combined with reviews of GHB sensitivity to model calibration. Automated calibration adjustments to the GHB K values was accomplished in part using PEST (Doherty, 2010), which runs iterations of the parameters to derive a solution providing the statistical best fit to the data. GHB calibrated K values are presented in Table 6. Boundary sensitivity to GHB conductance variations are plotted in Figure 21. The flatter the GHB conductance curve, the lower the sensitivity of the boundary to model calibration. A qualitative description GHB sensitivity observed during calibration is provided in Table 6.

The model calibration results are reviewed by comparing the match between observed and simulated water levels at the calibration head targets. The difference between the observed (measured) and simulated water level is called the residual. Residuals and calibration statistics are reported applying the head target weighting reported above. The residual mean for head targets (average difference) is 0.26 ft. The scaled residual standard deviation and scaled RMS error are 3.6%. Models calibrated to achieve within 10% are generally acceptable for use, and within 5% is generally considered good. For a simplistic 2D model, the calibration statistics are considered good. Model calibration statistics are presented in Table 7, and a plot of simulated versus measured water level elevations is presented as Figure 22. Simulated potentiometric water level elevations and head target residuals are shown in Figure 23.

Test Model Results and Observations

This modeling exercise was undertaken to examine and test potential inflows and outflows that would provide a reasonable match to observed potentiometric water levels in Garnet Valley. The model simulates flows across the boundaries of Garnet Valley as summarized in Table 8. The total subsurface inflow is simulated at 1217 AF/yr. The test model derives 518 AF/yr of inflow to the northern-most part of Garnet Valley from Southern Coyote Spring Valley and/or northern Hidden Valley. The test model derives significant inflow from Las Vegas Valley at 698 AF/yr. Outflows are simulated at 111 AF/yr, primarily from the northern-most part of Garnet Valley to northwestern California Wash. No outflow is simulated across the eastern Garnet Valley boundary to central and southern California Wash.

The test model results should not be interpreted as quantification of a water budget for the Garnet Valley basin, but rather should be viewed as a conceptual test of boundary conditions with the following general observations:

- Significant subsurface inflow likely occurs from Southern Coyote Spring Valley and/or Northern Hidden Valley into Garnet Valley, through the Arrow Canyon Range, and the model boundary condition exhibits moderate sensitivity to achieve calibration to observed water level elevations.

- Significant subsurface inflow to Garnet Valley likely occurs from Las Vegas Valley, and the boundary condition exhibits high sensitivity to achieve satisfactory model calibration.

- Groundwater inflow from southern Hidden Valley to Garnet Valley appears low, however there could be offsetting scenarios with recharge simulated on the western edge in the Las Vegas Range and the magnitude of inflow at this boundary. The sensitivity of this boundary to achieve satisfactory calibration is moderate.

- Groundwater outflow from Garnet Valley to central California Wash appears to be low, and the model boundary exhibits high sensitivity to high conductance values that would allow for significant groundwater outflow.

- Groundwater outflow from Garnet Valley to northern California Wash is supported by the model; however, the model boundary sensitivity is low, and the magnitude of outflow is uncertain.

**Table 6 – General Head Boundary Assumptions and Values**

| Model Reach No. | Flow From | Flow To | GHB Elevation (ft amsl) | GHB Distance (ft) | Explanation for GHB Parameters | Calibrated Boundary K (ft/day) | Relative Sensitivity of Boundary |
|---|---|---|---|---|---|---|---|
| 2 | Las Vegas Valley | Garnet Valley | 1821.6 | 10000 | Median elevation from review of LV well logs | 5.3 | High |
| 1 | Hidden Valley – South | Garnet Valley | 1815 | 42000 | Water level at SHV-1 | 1.0 | Moderate |
| 0 | Hidden Valley – Central | Garnet Valley | 1815 | 19000-42000 | Water level at SHV-1 | 1.9 | Moderate-High |
| 7 | Hidden Valley – North and/or Coyote Spring Valley - South | Garnet Valley | 1820 | 26000 | Water level at CSVM-2 | 38.4 | Moderate |
| 3 | Garnet Valley | Black Mountain | 1813 | 6000 | Water level at BM-DL-2 | 1.0 | Low |
| 6 | Garnet Valley | Black Mountain and CALIFORNIA Wash - South | 1713 | 60000 | Water level at BM-ONCO-1 | 1.5e-05 | Low - Moderate |
| 4 | Garnet Valley | CALIFORNIA Wash - Central | 1664 | 48000 | Water level at BYRON-1 | 8.5e-06 | High to increase in K Only |
| 5 | Garnet Valley | CALIFORNIA Wash - North | 1812 | 13000 | Water level at Paiutes TH-2 | 10.8 | Low |

**Table 7 – Garnet Valley Boundary Test Model Calibration Summary**

| Calibration Statistic | Value |
|---|---|
| Residual Mean | 0.258 ft |
| Absolute Residual Mean | 2.209 ft |
| Residual Std. Deviation | 3.127 ft |
| Sum of Squares | 147.68 ft |
| RMS Error | 3.138 ft |
| Min. Residual | -7.864 ft |
| Max. Residual | 6.195 ft |
| Number of Observations | 15 |
| Range in Observations | 87.83 ft |
| Scaled Residual Std. Deviation | 0.0356 |
| Scaled Absolute Residual Mean | 0.0252 |
| Scaled RMS Error | 0.0357 |
| Scaled Residual Mean | 0.0029 |

**Table 8 – Summary of Model Simulated Groundwater Flows at Garnet Valley Boundaries**

| Flow From | Flow To | Model Reach No. | Simulated Steady-State Flow Across Boundary (AF/yr) |
|---|---|---|---|
| Las Vegas Valley | Garnet Valley | 2 | 698 |
| Hidden Valley – South | Garnet Valley | 1 | 1.4 |
| Hidden Valley – Central | Garnet Valley | 0 | 61 |
| Hidden Valley – North and/or Coyote Spring Valley - South | Garnet Valley | 7 | 456 |
| Garnet Valley | Black Mountain | 3 | 7.5 |
| Garnet Valley | Black Mountain and CALIFORNIA Wash - South | 6 | 0 |
| Garnet Valley | CALIFORNIA Wash - Central | 4 | 0 |
| Garnet Valley | CALIFORNIA Wash - North | 5 | 103 |

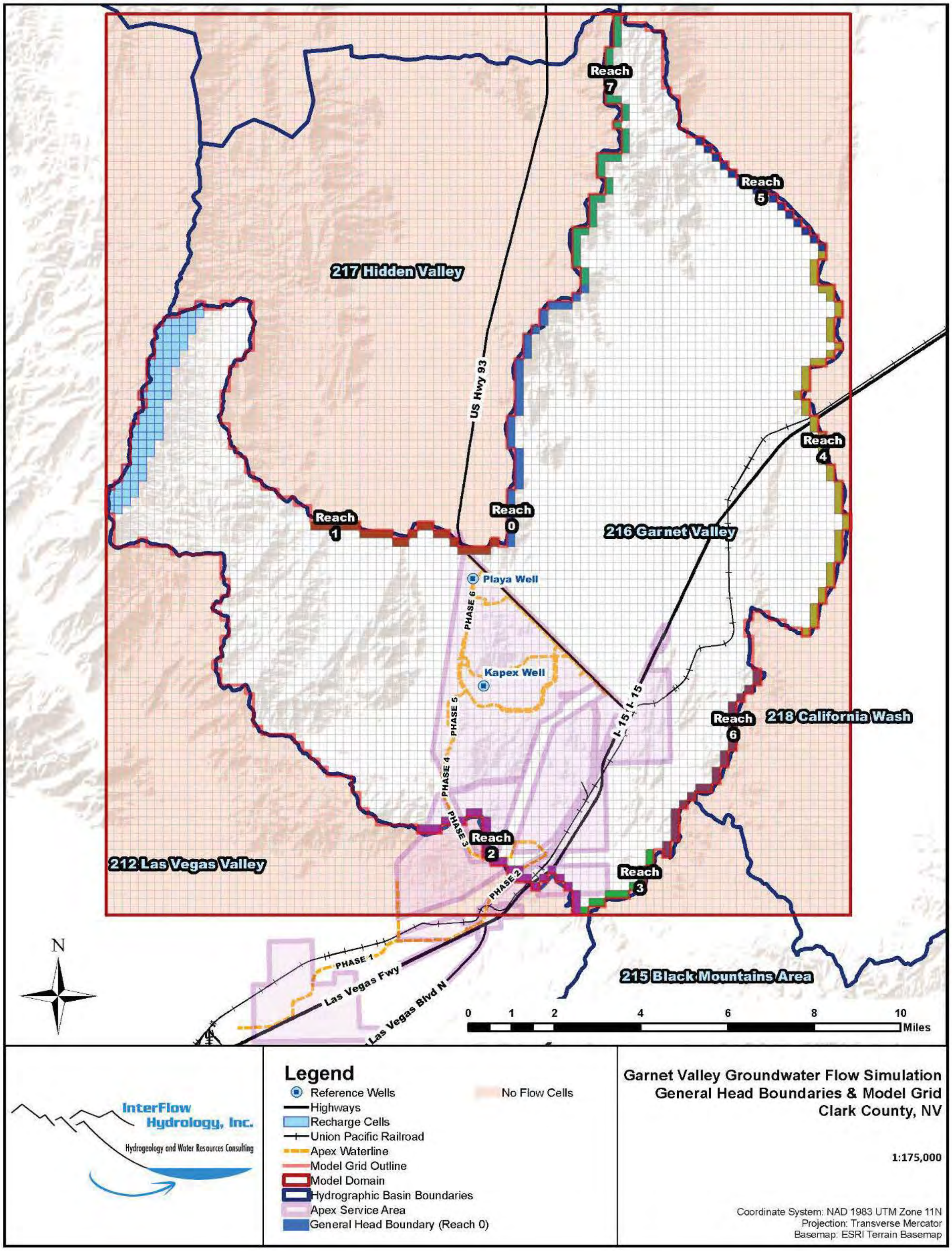


**Figure 19 – Garnet Valley Test Model Grid and Boundary Conditions**

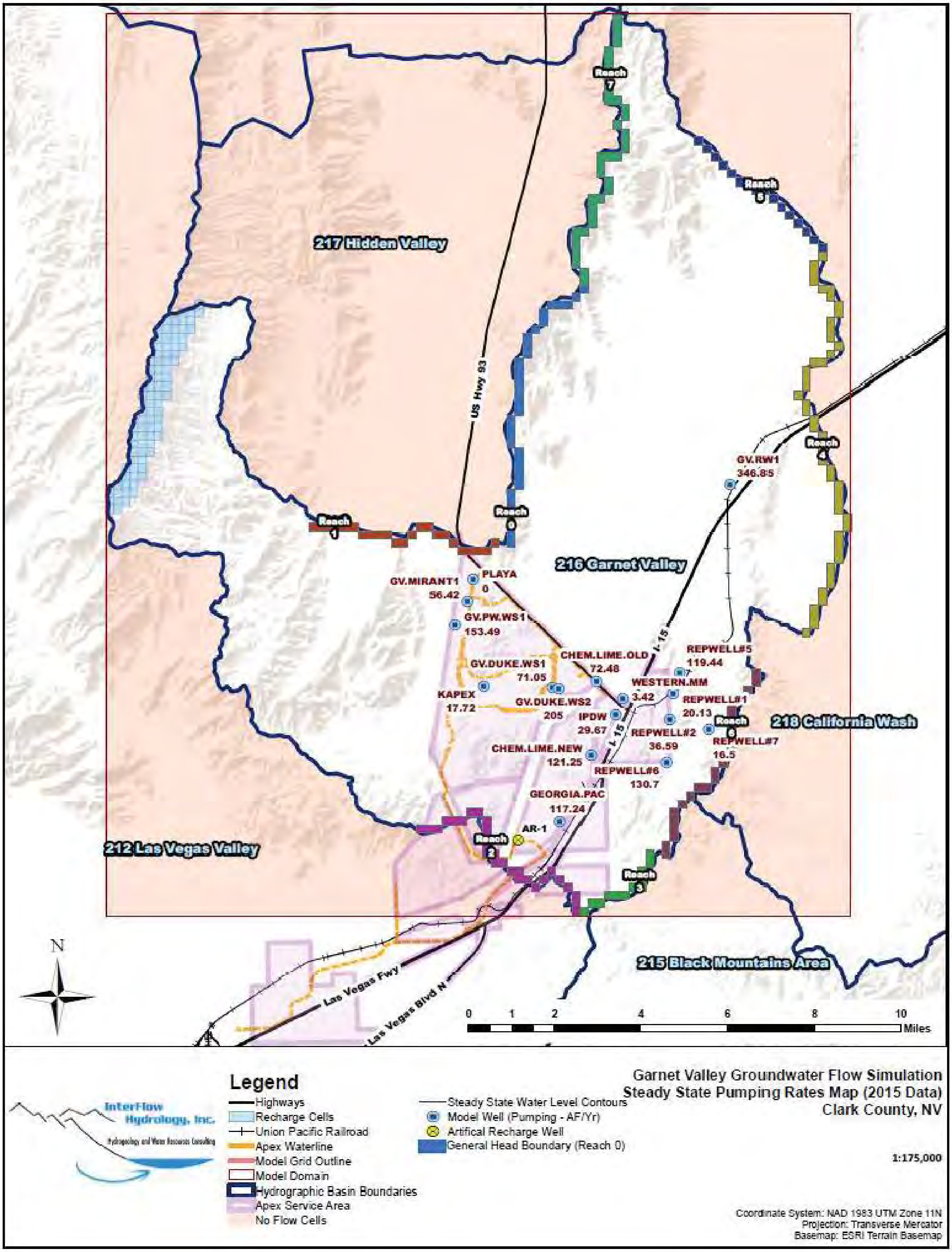


**Figure 20 – Simulated Pumping Distribution**

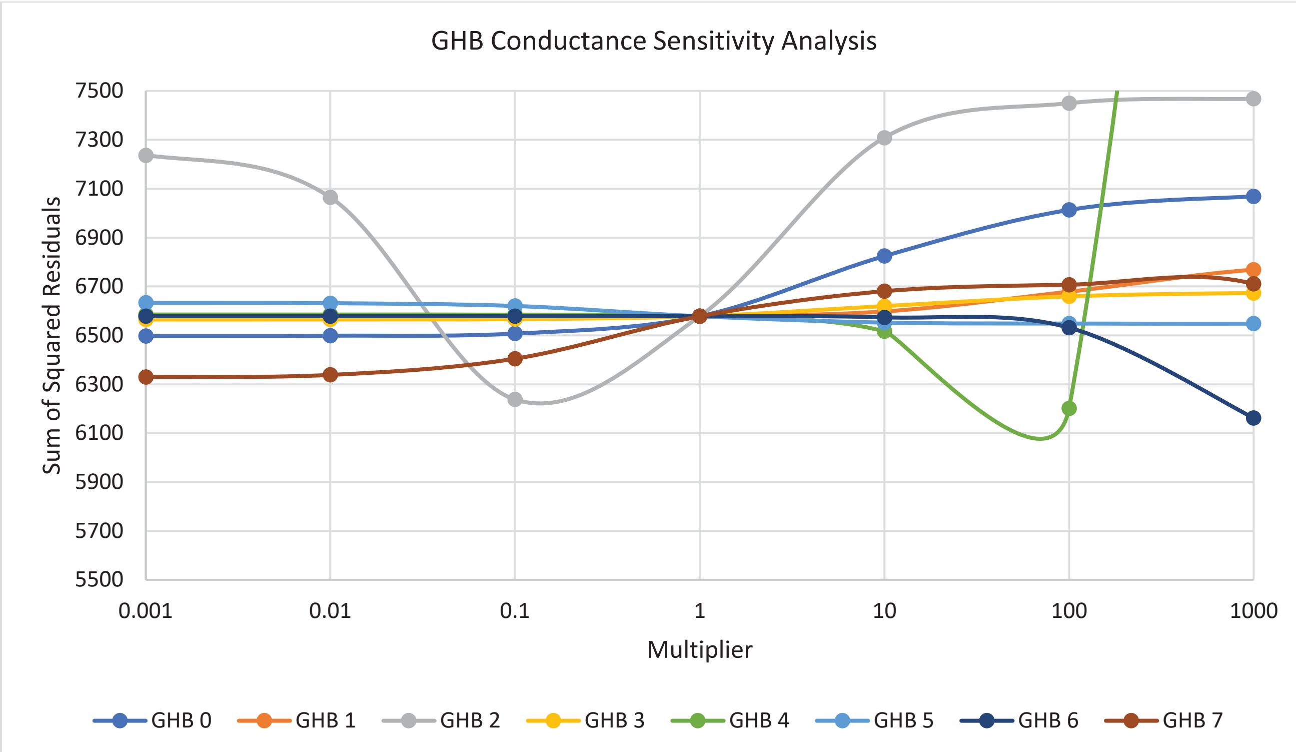


**Figure 21 - GHB Conductance Sensitivity Plot**

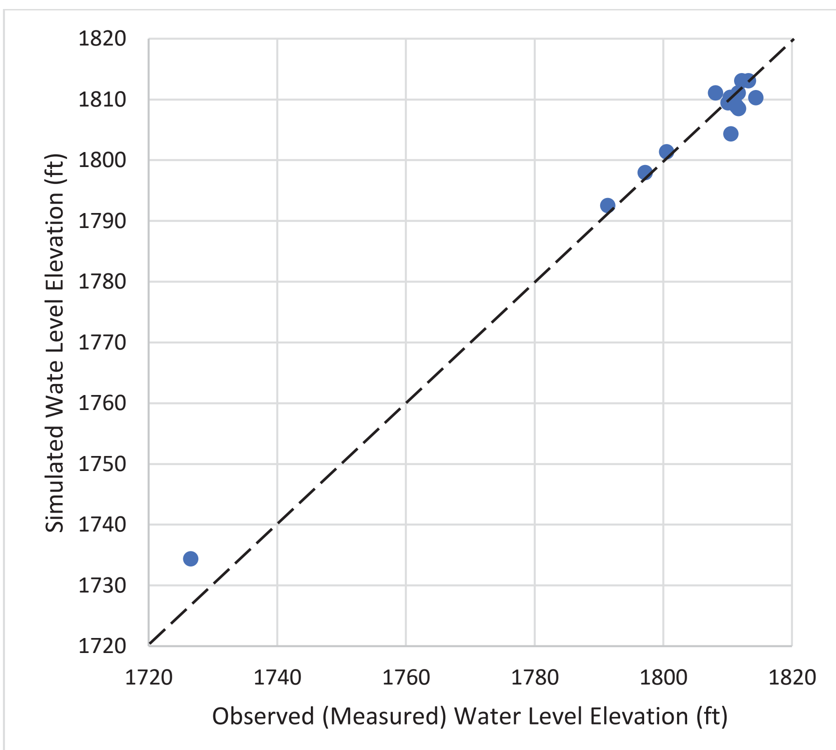


**Figure 22 - Plot of Simulated versus Observed Groundwater Elevations at Model Head Targets**

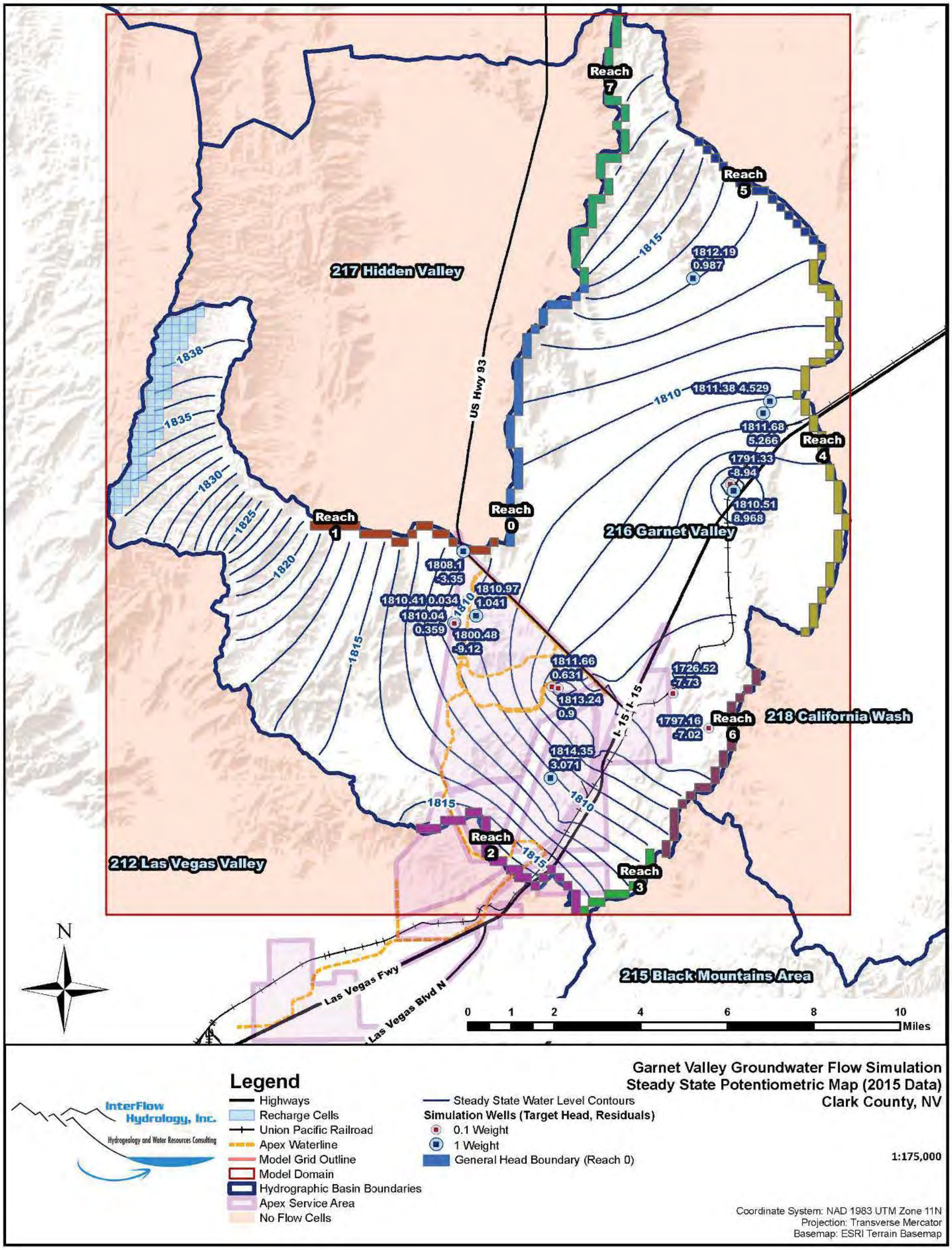


**Figure 23 – Simulated Potentiometric Water Levels**

**Conceptual Review of Groundwater Yield in Garnet Valley**

Sources of groundwater to Garnet Valley include locally derived recharge (~400 AF/yr), and based on the boundary test modeling, subsurface inflow from southern Coyote Spring Valley and/or northern Hidden Valley through the Arrow Canyon Range (~450 AF/yr), and subsurface inflow from northeastern Las Vegas Valley to southern Garnet Valley (~700 AF/yr). These estimates carry notable uncertainty, as data are limited for model calibration.

The model reflects a simple uniform hydraulic conductivity over the entire model area, and only the upper 1000 ft of saturated thickness of the carbonate aquifer. Higher transmissivities and greater thicknesses would accommodate greater flows. However, the ability to capture the deeper groundwater by wells has practical limitations. Data on aquifer transmissivity is sparse in portions of Garnet Valley, particularly the northern portion. The represented transmissivity in the model is however consistent with the available information and produces a reasonable model calibration to observed water level elevations.

In-basin recharge from precipitation is estimated on a reconnaissance level at 400 AF/yr by Rush (1968). This recharge supports a portion of pumping from APEX wells. What appears potentially unaccounted for is precipitation recharge occurring in Hidden Valley, which is estimated by Rush (1968) to also be 400 AF/yr. This recharge would be expected to discharge via subsurface outflow to southern or central Garnet Valley. The boundary testing did not suggest significant inflow from southern Hidden Valley to Garnet Valley is required to produce adequate model calibration. The lack of quantification of outflow could however be due in large part to the lack of the available data in Hidden Valley. Additional monitoring wells in Hidden Valley would aid in understanding gradients and refining interpretations, to possibly account for the Hidden Valley recharge.

There is a long-term declining water level trend in Garnet Valley, but this trend mimics water level trends throughout much of the LWRFS (Figure 24). In Garnet Valley, the declining trend is about 0.3 ft/yr, and has been observed since the beginning of groundwater monitoring in 2000, but was interrupted by a high recharge year in 2005. After the wet period, the declining water level trend resumed. The Order 1169 pumping interrupted the trend in 2011-2014, during the pumping and recovery periods (Figure 25). Otherwise the declining trend has been present throughout the period of record from 2000-2018 in Garnet Valley and from 1998 to present at other LWRFS locations (Figure 24).

The pumping responses in the Order 1169 testing were observed to spread rapidly in the system (SNWA, 2013), being identified within a couple months, including in Garnet Valley, due to high transmissivity and the confined nature of the aquifer. The rapid propagation of drawdown also produced a similarly rapid commencement of spring discharge capture, at Pederson Spring. This observation supports the interpretation that the LWRFS responds rapidly to pumping by reduced spring discharge, and pumping capture of spring discharge is not a highly delayed. This important characteristic of the carbonate aquifer leads to the conclusion that the long-term uniform declining trends in water levels throughout the LWRFS are likely due to other stresses on the system, presumably long-term climate, rather than a delayed response to pumping.

In years 2016 and 2017, pumping from APEX wells increased to ~2,000 AF/yr due to highway and Faraday Future construction activities. A noticeable response to this increase in pumping, however, is not visible in the Garnet Valley water level hydrographs. Conversely, water levels near the Muddy River Springs showed some indication of leveling (note EH-4, Figure 25). It may be that the increase in pumping was not sufficient to have caused a large amount of aquifer storage depletion. A controlled long-term aquifer test, possibly integrated with pumping in APEX to bridge the gap in time for APEX pipeline construction, would be beneficial to understanding the system and potential thresholds for pumping. For example, pumping from the City's Playa and Kapex wells might be increased in increments between 500 AF/yr to 1000 AF/yr, while responses are monitored. Should pumping results indicate unacceptable drawdown, then the proposed artificial recharge (AR) as reviewed in Interflow (2019) can be implemented, and/or a conversion from groundwater use to Colorado

River water supply can take place. Ideally some test pumping would occur prior to implementation of an AR program, to simplify interpretations.

The above observations suggest that partitioning of climate and pumping responses needs to continue to be reviewed and considered when interpreting water level trends in the LWRFS, and in Garnet Valley. Smith et al (2004), and others, have reviewed the importance of differentiating climate versus pumping trends.

In summary, it appears that pumping at 1500 AF/yr and possibly up to 2000 AF/yr in the APEX area has not caused detrimental water level declines. As a water development and management strategy for APEX, a controlled pumping test with increased pumping from the Playa and Kapex wells up to 1000 AF/yr could reveal more information, from which a sustainable pumping volume in the APEX area may be determined. Additional monitoring wells should complement the pumping, especially in Hidden Valley. Under the City's water supply strategy of using both groundwater and imported Colorado River water to provide a conjunctive water supply, along with artificial recharge to help manage groundwater pumping drawdown and potentially return treated wastewater to the beneficial use (Interflow, 2019), there will be ample flexibility and a backstop to manage use of groundwater resources, and to accommodate short-term increased pumping to determine a sustainable groundwater pumping volume in the basin.

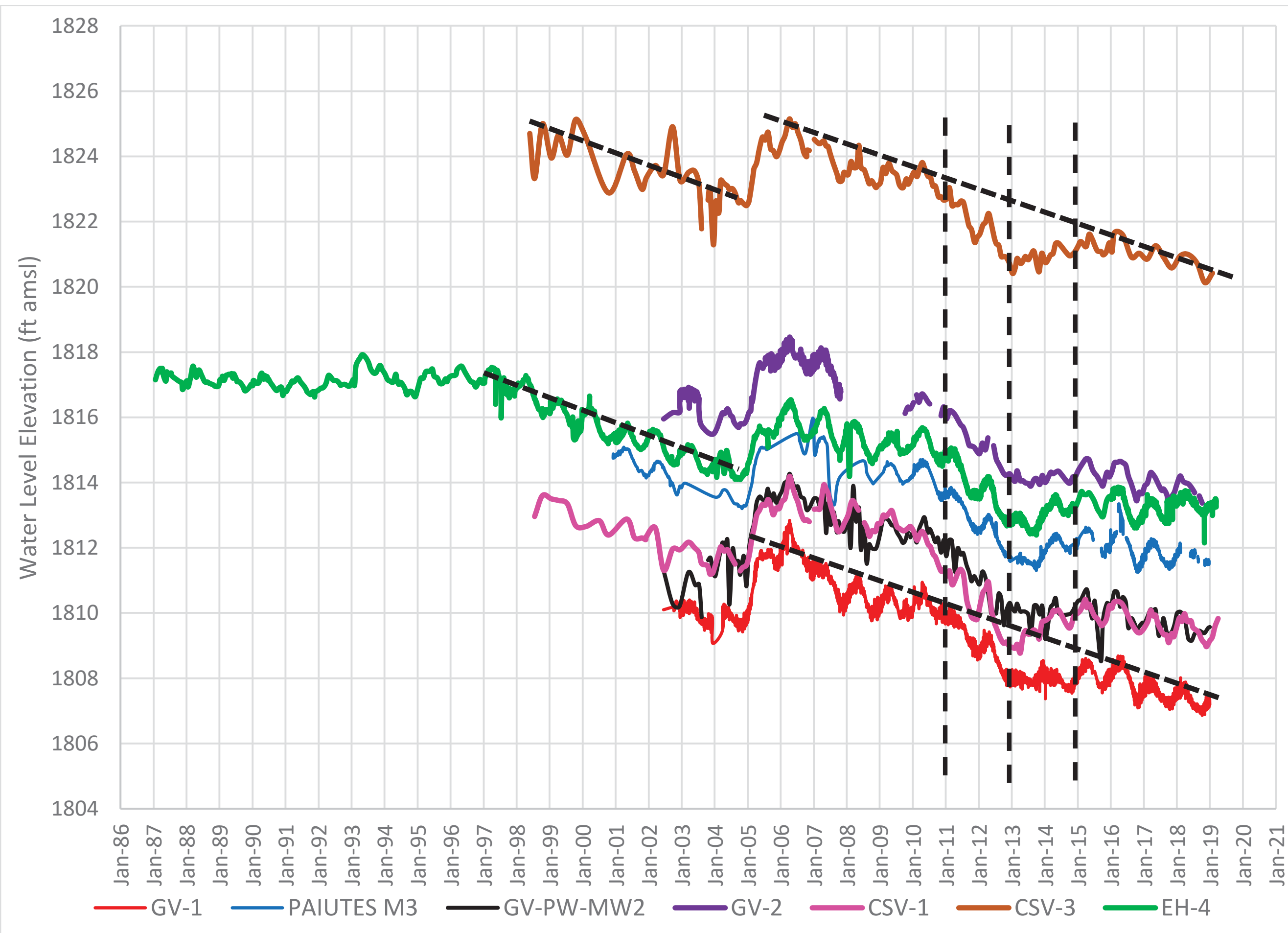


**Figure 24 – Hydrograph Comparison of Garnet Valley Water Level Trends with other LWRFS Locations**

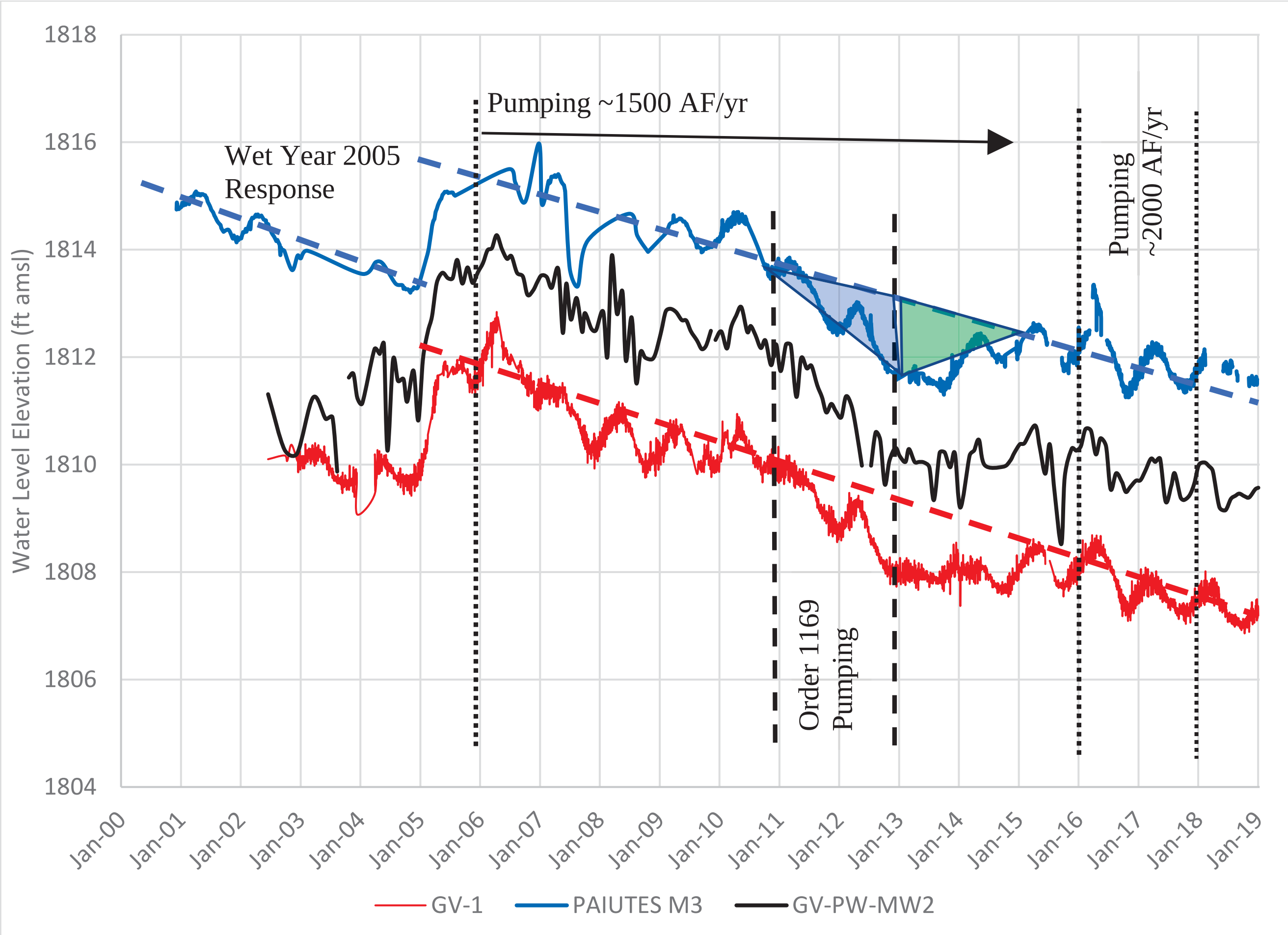


**Figure 25 – Hydrograph Interpretations in Garnet Valley**

**Review of Senior Water Rights Transfers to APEX**

The City of North Las Vegas is in negotiations with the Church of Jesus Christ of Latter Day Saints (Church) to lease senior groundwater water rights from the Muddy River Springs Area, with plans to transfer the rights to the Playa and Kapex wells in Garnet Valley, subject to State Engineer approval.

The Church's groundwater rights in the Muddy River Springs Area have a priority date of 1947 for permits 50723, 50728-29, and 50731-33; a priority date of 1949 for permit 50724; and a priority date of 1965 for permits 50725-27, and 50730. The 1947 year water rights are some of the most senior underground water rights in the LWRFS, with only 343 AF/yr of more senior rights (NDWR, 2017). The 1949 year right has 3507 AF/yr of more senior water rights, but including 1952 AF/yr of the 1947 rights. The 1965 priority water rights have 4531 AF/yr of senior water rights, including the other LDS rights which total approximately 2330 AF/yr. The points of diversion for the active permits currently reside at Church wells: LDS East, LDS West and LDS Central, as shown in Figure 26.

The manner of use of the Church water rights is currently designated as industrial, with change applications granted in 1988 for the water supply to the Reid-Gardner Station power plant. The 1988 permit date does not change the base water right priority date. These groundwater rights were under a lease agreement with NV

Energy until April 2017. Prior to use for power generation, these water rights were used for irrigation in the Muddy River Springs Area.

Under the joint administration the LWRFS basins, transfers of points of diversion between basins may be permitted, however, permanent change applications are currently being held in abeyance under Interim Order 1303. Assuming future administration of groundwater rights by the State Engineer in the LWRFS will accept permanent transfers, the water right change applications will be subject to administrative reviews under NRS 533. Applications to change water rights are filed with the office of the State Engineer (NDWR), publicly advertised, open to protest for a period of time, and then go through a review and determination process by the State Engineer, which may include a water right hearing if the applications are protested. Rulings issued by the State Engineer may also be appealed, furthering the time required to obtain a permit. There is no guarantee that change applications will be approved until the process has been successfully completed. Terms of granted permits may include restrictions and a monitoring plan.

In the case of the Church owned water rights, the applications to change the water rights to serve the City of North Las Vegas' wells in Garnet Valley will require changes to the points of diversion, manner of use, and place of use. Applications for temporary changes of water right permits (1-year duration) may initially be needed. Temporary change applications do not require public advertisement and can commonly be issued within a couple months. Permanent change applications may require 6-12 months to go through the permitting process, but will require the condition of Interim Order 1303 to hold permanent changes application in abeyance to be lifted.

<u>Benefits to Transferring the Church's Underground Water Rights out of the Muddy River Springs Area</u>

The Church's wells tap the shallow alluvium (~200 ft thick) overlying the carbonate rock along the Muddy River Springs corridor. Pumping from the alluvium has been interpreted by SNWA (2013) to create a nearly 1:1 capture of Muddy River flow, as measured at the down-stream Moapa Gage (Figure 26). This interpretation is supported by a relatively straightforward accounting of historical pumped volumes from the Muddy River Springs Area and total flow at the Moapa Gage, beginning at pre-pumping conditions in the 1940s and working forward in time, as presented in Figure 27.

The exact process of stream flow capture by pumping is not clearly known, and could be due to direct lowering of the water table adjacent to the stream bed (classic stream flow capture), or could be by indirect means of capture of flow from springs that discharge through the alluvium on the valley floor, producing discharge to the Muddy River. The springs that discharge through the alluvium have an established conduit of flow through the alluvium that may be hydraulically supported by a high water table and saturated alluvium outside the conduit. When the water table is lowered, leakage from the conduit occurs back into the alluvium, rather than discharging to land surface. This condition has been observed at other springs in Nevada where water table drawdown has affected the discharge of springs occurring through alluvial conduits. For example, springs in Diamond Valley, such as Sulphur, Tule, Bailey, Shipley and Eva once derived flow from an underlying carbonate aquifer, discharging through thin alluvial cover to land surface (Smith, 2013; Smith, 2019). Drawdown in the alluvium in Diamond Valley upset the hydraulic balance between the conduits and alluvium, and depleted spring flows. In summary, pumping of the Church's wells may potentially capture flow of the Muddy River as measured at the down-stream Moapa Gage by both induction of river flow and by indirect means of capture of spring discharge tributary to the river.

In recognition of the effects of pumping from established points of diversion for the Church's water rights in the alluvium along the Muddy River Springs corridor, ceasing to pump these water rights at the existing points of diversion will mitigate potential impacts to existing decreed water rights on the Muddy River, and perhaps provide an advantage to sustaining spring flows on the valley floor. This could in turn benefit the Moapa Dace habitat.

Benefits to Securing Senior Water Rights to Support APEX Pumping

It appears that there are currently sufficient underground water rights in Garnet Valley to support municipal service to APEX in the future. The total permitted water rights are 3715 AF/yr (NDWR, 2019) of which SNWA holds approximately 2275 AF/yr (total combined duty). It is not certain if the SNWA water rights (up to 900 AF/yr) will remain available to pump from the City of North Las Vegas wells.

However, if regulation by priority date occurs in the LWRFS, then the SNWA water rights will be considered junior. It is likely that administrative actions in the LWRFS would first declare the basins a Critical Management Area (CMA), initiating opportunity for stakeholders to craft and submit a Groundwater Management Plan (GMP). The GMP would need to be approved by a majority of water right owners, and be approved by the State Engineer within 10 years of the declaration as a CMA. A GMP could conceivably work around the prior appropriations system of water rights administration, but may initiate challenges in court. The future of GPMs in this regard is unclear and untested to the point of a GMP being fully implemented.

It seems unlikely that curtailment of water rights based on water right priority would occur until the 10-yr timeframe for completion of a GMP has expired, and only in the case that the GMP failed to deliver an acceptable solution. However, if Muddy River Springs discharge diminishes to the point that actions are required, or dictated by the courts, to protect the Moapa Dace, then regulation by priority date is one of the only tools legally available to the State Engineer. While the future of underground water rights and potential regulation by priority date in the LWRFS is uncertain, there might be an advantage to transferring senior water rights to APEX to provide an increased level of certainty in water right holdings in support of municipal water service from the groundwater source in Garnet Valley, particularly over the period of time needed to rely upon wells until the Colorado River water pipeline is completed throughout APEX.

Beyond the bridge period for completion of the pipeline, the City of North Las Vegas could be in a more secure position going into the uncertain future regarding underground water rights. However, the Colorado River water source being brought into Garnet Valley also provides a viable supply of water along with long-term use of groundwater in the LWRFS.

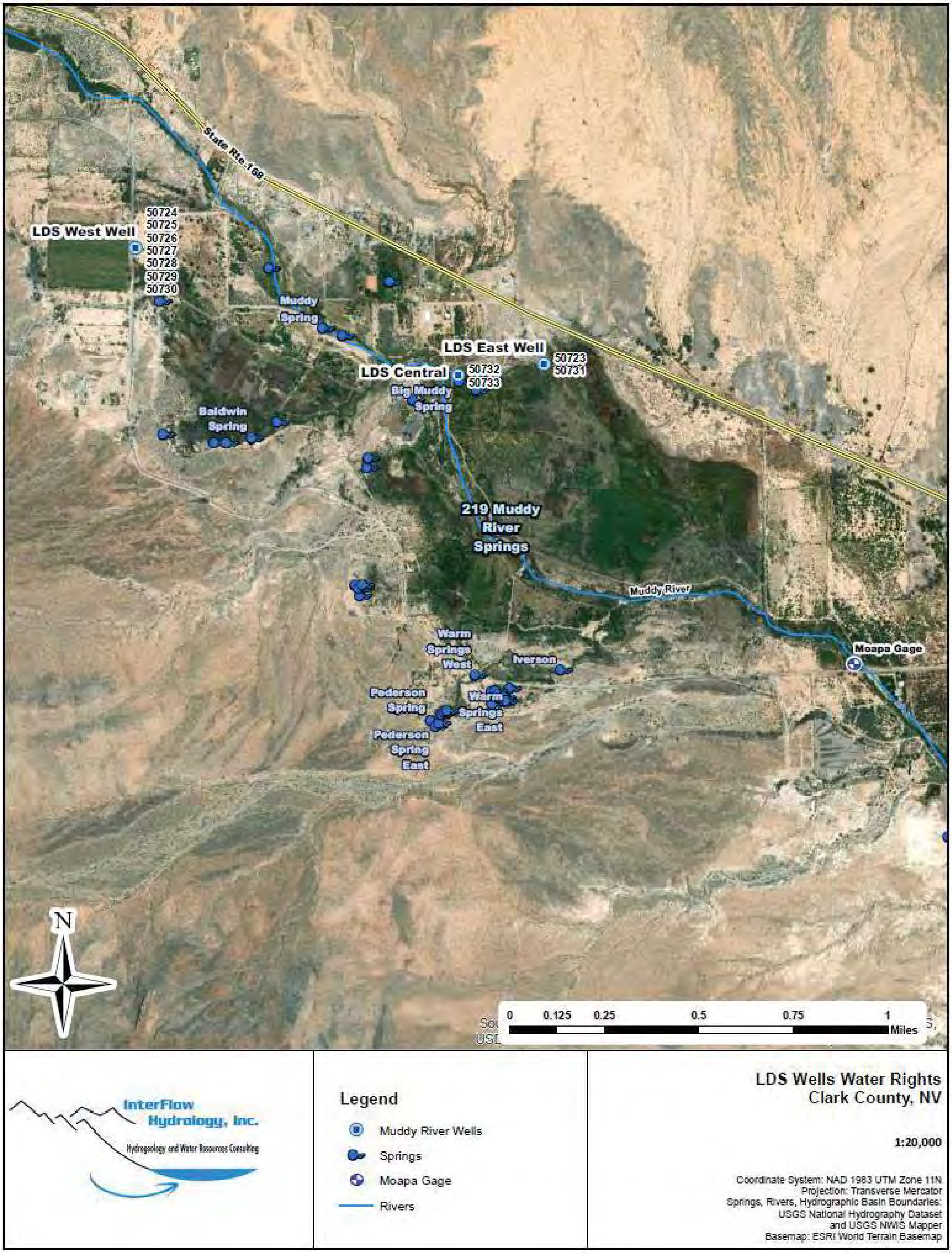


**Figure 26 – Locations of the LDS East, LDS West, and LDS Central Wells**

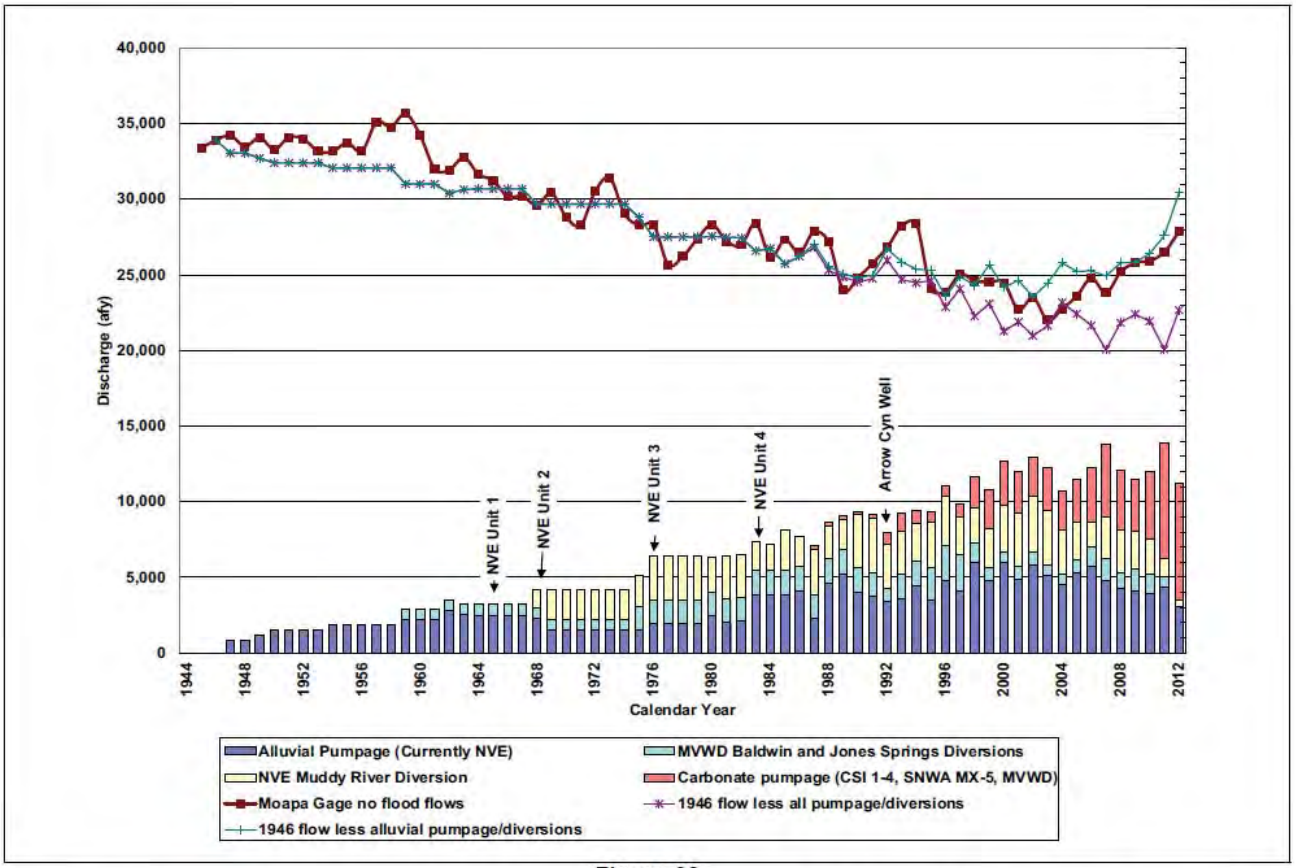


**Figure 28**
**Comparison Between Decline in Flow at the Moapa Gage and Alluvial vs.Carbonate Groundwater Pumpage and Surface-Water Diversions**

**Figure 27 - SNWA (2013) Exhibit Demonstrating Alluvial Pumping Capture of Muddy River Flow**

## Summary and Recommendations

Conceptual review of groundwater flow at the boundaries of Garnet Valley suggest that inflow occurs from southern Coyote Spring Valley and/or northern Hidden Valley, and from Las Vegas Valley. Along with estimated recharge of 400 AF/yr, the current pumping of ~1500 AF/yr may be in near equilibrium with inflow and recharge. A portion of groundwater outflow to northern California Wash is perhaps not captured by existing pumping. Some uncertainty exists however as to the potential upper limit of the quantity of groundwater that can be sustainably pumped from the APEX area. Higher pumping of approximately 2000 AF/yr occurred in 2016 and 2017, without evidence of responses in lowering of regional water levels, although a long-term mild declining trend in regional water levels throughout the LWRFS has been ongoing for approximately 20 years.

Increases in pumping in Garnet Valley should be exercised cautiously, and perhaps in stages or increments. The monitoring network should be expanded to include at least two carbonate aquifer monitoring wells in Hidden Valley, one near SHV-1, which is believed to be completed in alluvium, and one in the southern part of Hidden Valley.

An interesting finding in this hydrogeologic review is the possible subsurface inflow from Las Vegas Valley to southern Garnet Valley. A reconnaissance review of available water level data from wells in northeastern-most Las Vegas Valley and boundary test modeling supports the postulated flow, however no accurate data are available to make a conclusive determination. Two or more monitoring wells are recommended near the boundary of Las Vegas Valley and Garnet Valley from which accurate water level measurements may be made. The wells should be completed in carbonate rocks. To the degree that groundwater inflow from Las Vegas Valley occurs to Garnet Valley, it can likely be developed without impacting the LWRFS. This subsurface inflow may be the primary source of recharge that is supporting existing pumping in the APEX area, along with recharge to that portion of the Las Vegas Range in the basin. Confirmation and more accurate quantification of inflow by establishing gradients and transmissivity is recommended to aid in groundwater resources management in the APEX area.

Leasing senior groundwater rights located in the LWRFS has merit in a couple regards. Senior groundwater rights in Muddy River Springs Area have historically been pumped from alluvium, which appears to capture flows of the Muddy River, thus potentially interfering with senior decreed water rights. Transferring of senior groundwater rights out of this environment and to a distal and down-gradient portion of the LWRFS will help alleviate this potential water right conflict. For the City of North Las Vegas, securing senior groundwater rights will help assure that pumping from the Playa and Kapex wells is not likely to be subject to curtailment, should actions be necessary to regulate groundwater rights of the LWRFS by priority date. A lease of senior water rights and transfer of these water rights to the Playa and Kapex wells can help bridge the time required to complete the Colorado River pipeline throughout APEX. SNWA has ample water rights in Garnet Valley, however, they are junior rights and potentially subject to LWRFS curtailment, should regulation by priority date occur.

## References


Doherty, J., 2010, PEST, Model-Independent Parameter Estimation - User Manual. 5th Edition, with Slight Additions, Watermark Numerical Computing, Brisbane.

Driscoll, F., 1986, Groundwater and Wells, published by Johnson Division, St. Paul, MN.

Eakin, T., 1964, Ground-water Appraisal of Coyote Spring and Kane Spring Valleys and Muddy River Springs Area, Lincoln and Clark Counties, Nevada; Nevada Department of Conservation and Natural Resources, Ground-Water Resources – Reconnaissance Series, Report 25.

Garside, L.J., Hess, R.H., Fleming, K.L., and Weimer, B.S., 1988, Oil and Gas Developments in Nevada; Nevada Bureau of Mines and Geology, Bulletin 104.

Interflow Hydrology, Inc., 2019, Concept Review of Artificial Recharge in Garnet Valley for the APEX Industrial Complex, City of North Las Vegas, Nevada; Technical Memorandum dated June 27, 2019.

Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, Sorab, and Provost, A.M., 2017, Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 p., https://doi.org/10.3133/tm6A55.

Mace 1997, Determination of transmissivity from specific capacity tests in a karst aquifer: Ground Water, v. 35, no.4, p. 738-742

Mifflin & Associates, 2013, Summary of Order 1169 Testing Impacts, per Order 1169A; prepared for the Moapa Band of Paiutes.

Nevada Division of Water Resources, 2017, LWRFS Groundwater Rights by Priority, table of water rights and cumulative duty.

Nevada Division of Water Resources, 2018, Presentation by Jason King on July 24, 2018.

Nevada Division of Water Resources, 2019, Data obtained from the NDWR website, including water rights, water levels, pumping inventories, and Order 1169 archived data.

Page, W.R., Dixon, G.L., Rowley, P.D., and Brickey, D.W., 2005, Geologic Map of Parts of the Colorado, White River, and Death Valley Groundwater Flow Systems, Nevada, Utah, and Arizona; Nevada Bureau of Mines and Geology, Map 150, 1:250,000.

Page, W.R., Scheirer, D.S., Langenheim, V.E., Berger, M.A., 2011, Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona; USGS Open File Report 2006-1040.

Poggemeyer Design Group, 2012, Water and Wastewater Master Plan, Apex Industrial Park, City of North Las Vegas, Nevada, prepared for Kapex, LLC, December 28, 2012.

Rush, E.F, 1968, Water-resources Appraisal of the Lower Moapa-Lake Mead Area, Clark County, Nevada; Nevada Department of Conservation and Natural Resources, Ground-Water Resources – Reconnaissance Series, Report 50.

Smith, D.L., Johnson, J., Donovan, D., Kistinger, G., and Burns, A., 2004, Climate and Barometric Pressure Influences on Pederson Spring Discharge and the Carbonate Aquifer near the Muddy Springs, Southern Nevada; Journal of the Nevada Water Resources Association, Fall 2004, p76-103.

Smith, D.L., 2013, Shipley Hot Spring Historic and Current Discharge, and Evidence for Impact to Flow Due to Groundwater Pumping in Diamond Valley, Eureka County, Nevada; Expert witness report prepared for Sadler Ranch, LLC water right hearing for mitigation rights.

Smith, D.L., 2019, Pre-1905 Discharge of Select Springs, Diamond Valley, Eureka County, Nevada; Expert Witness report submitted for Sadler Ranch LLC vested water filings.

Southern Nevada Water Authority, 2013, Submittal of Nevada State Engineer Orders 1169 and 1169A Study Report, June 2013.

Todd, D.K., 1980, Groundwater Hydrology, Second Addition, published by John Wiley & Sons, New York, NY

US Fish and Wildlife Service, Bureau of Land Management, and National Park Service, 2013, Test Impacts and Availability of Water Pursuant to Applications Pending Under Order 1169.

West Yost Associates, Consulting Engineers, 2016, Playa Well Construction Report, prepared for First Solar, December 2016.

MEMORANDUM

To: Mr. Robert A. McLaughlin, PE, City of North Las Vegas, Manager, Development & Flood Control

Date: August 12, 2019

RE: **Addendum No. 1 - Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada, dated July 2, 2019**

From: Dwight L. Smith, PE, PG, Principal Hydrogeologist

Figure 10 in the above reference report should be replaced with the following amended Figure 10, which has municipal (MUN) water usage added for years 2002-2005. This is a correction made in accordance with the remarks in the NDWR basin inventory published for basin 216 for year 2006, regarding prior absent reported pumping under LVVWD water right permit number 54073 (permit issued on April 13, 2001). This addendum is being made for accuracy of reporting, and does not change any of the analyses or conclusions provided in the above referenced report.

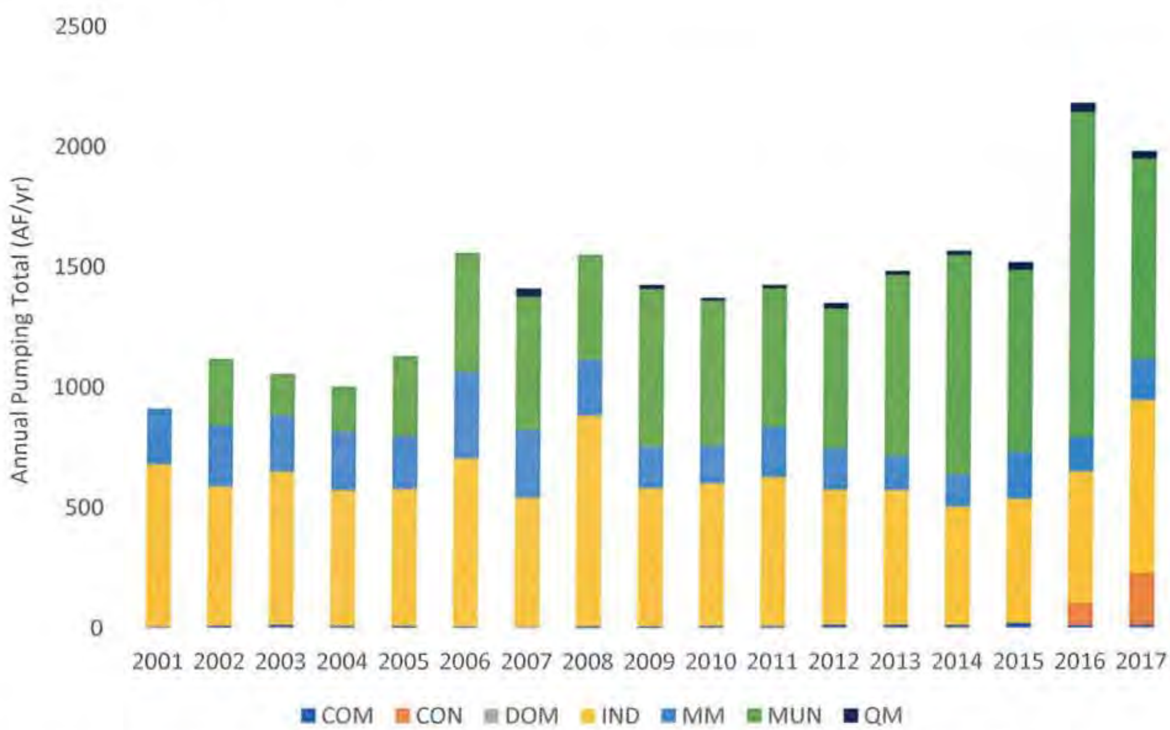


**Figure 10 (Amended) – Historical Pumping from Wells in Garnet Valley (data from NDWR Pumping Inventories)**

SE ROA 34704

Mayor
**John J. Lee**

Council Members
**Isaac E. Barron**
**Pamela A. Goynes-Brown**
**Scott Black**
**Richard J. Cherchio**

City Manager
**Ryann Juden**

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*www.cityofnorthlasvegas.com*

July 2, 2019

Mr. Tim Wilson, P. E.
Nevada Division of Water Resources
901 South Stewart Street, Suite 2002
Carson City, Nevada 89701

RE: Interim Order 1303 Report Submittal from the City of North Las Vegas

Dear Mr. Wilson:

This letter has been prepared pursuant to Interim Order 1303 issued by the State Engineer on January 11, 2019, designating a multi-basin area for joint administrative management of water rights in the Lower White River Flow System (LWRFS). The City of North Las Vegas is the municipal water purveyor for the APEX industrial complex in southern Garnet Valley, which is included in the Order 1303 joint basins administrative area.

The goal of the City of North Las Vegas is to implement a long-term, sustainable, and secure water supply source for APEX. A conjunctive water supply strategy is being implemented using Colorado River water along with locally pumped groundwater. This water supply strategy will provide both flexibility and redundancy, allows for adaptive management, and the ability to integrate into a future groundwater management plan for the LWRFS.

The framework of the City's water supply strategy for APEX is as follows:

1. Build a water supply pipeline from Las Vegas Valley to Garnet Valley to bring Colorado River water supply into APEX, with the pipeline constructed in phases;
2. Pump groundwater from the City's Playa and Kapex municipal wells to provide for increased water demands in northern APEX, until the pipeline infrastructure is completed, and over the long-term in a managed approach utilizing senior water rights to be obtained by the City;
3. Implement artificial recharge (AR) of Colorado River water brought into Garnet Valley in Phase 2 of pipeline construction to support increased pumping from wells in northern APEX, and as a long-term aquifer management tool;
4. Develop a centralized or decentralized approached for wastewater treatment, with reclaimed water being returned to the aquifer via an AR approach, or replacing fresh water uses.

5. Over the long-term, adjust the Colorado River water delivery, pumping, and AR to maintain a sustainable water supply that meets the needs of industries in APEX while conforming with LRWFS water management objectives.

The City has already initiated the first step of this water supply strategy, with Phase 1 of the water supply pipeline under construction. Phase 1 includes construction of 7,700 LF of 24-inch pipe, 19,000 LF of 36-inch pipe, 2 water pumping stations and 2 ground storage reservoirs. The 24-inch pipe is already constructed and construction of the 36-inch pipe is scheduled to begin in mid-August 2019. Phase 1 is scheduled to be complete in April 2021. Phase 2 is currently under design and consists of 3.3 miles of 36-inch pipe, 1 pump station and 1 ground storage reservoir. Phase 2 is estimated to be complete in April 2022. Upon completion of phase 2, the City will be in a position to construct an AR well to support increased pumping from wells in northern APEX, and as a long-term aquifer management tool. The enclosed map of Apex Utilities Infrastructure Projects outlines the master plan for Apex Industrial Park. Phases 1, 2 and 3 are currently funded. A financing plan is being developed for the final phases of the project.

The City has initiated technical studies to support items 2 and 3 of the APEX water supply strategy. Copies of the technical reports prepared by Interflow Hydrology are enclosed for review and reference, and support the observations presented in this letter. The technical review of pumping and potential water yield in Garnet Valley is referenced as Interflow 2019a; and the AR concept review is referenced as Interflow 2019b. Implementation of these components of the water supply strategy will be subject to regulatory approvals. Increases in pumping from northern APEX wells is envisioned to occur in a staged manner, with monitoring to better define the drawdown effects. While substantial water rights exist at these wells, additional water right transfers to the wells may be necessary, and transfers of senior water rights in the LWRFS are being pursued. The AR concept will require additional feasibility review and testing, and will likewise operate under an approved monitoring plan.

As part of Interim Order 1303, stakeholders in the LWRFS have an opportunity to present information for consideration by the State Engineer for future water rights management. Items specifically listed for response to Interim Order 1303 are as follows:

a. The geographic boundary of the hydrologically connected system;
b. Aquifer recovery since the completion of the Order 1169 pumping test in Coyote Spring Valley;
c. Long-term annual quantity of groundwater that may be pumped from the LWRFS, including relationships between location of pumping and discharge to the Muddy River Springs, and capture of Muddy River flow;
d. Effects of movement of water rights between alluvial wells and carbonate wells to senior decreed water rights to the Muddy River.

Responses are provided below, focusing on issues related specifically to the City of North Las Vegas water supply in Garnet Valley and APEX.

**The geographic boundary of the hydrologically connected system**

Interflow (2019a) examined possible boundary conditions for Garnet Valley. It is agreed that a majority of Garnet Valley including the APEX area, appears to be within the geologic environment that connects the LWRFS basins. Data are sparse in some parts of Garnet Valley. It is possible, that boundary conditions exist along the western edge of Garnet Valley, which have yet to be defined. It is also unclear if the eastern-most edge of Garnet Valley, east of the Dry Lake Trust Fault, should be included within the LRFWS. The Dry Lake Trust Fault produces a significant discontinuity in the sedimentary rocks, which appears to cause a barrier to eastward groundwater flow. Likewise, the portion of the California Wash hydrographic basin east the Dry Lake Trust Fault may not have hydrologic connection to the LWRFS.

A small portion of the Black Mountains Area, generally north of the Las Vegas Shear Zone, appears to be hydraulically connected by similar sedimentary rocks to southern Garnet Valley. The boundary condition between southwestern Garnet Valley and northeastern Las Vegas Valley is uncertain, and additional evaluation is needed.

**Aquifer recovery since the completion of the Order 1169 pumping**

In Garnet Valley, there has existed a long-term declining water level trend of approximately 0.3 ft/yr. This declining trend is observed to be similar throughout the LWRFS (Interflow, 2019a). The declining water levels appear to be a background condition, since it has been experienced since the late 1990s, and persisted over two decades. A notably wet year in 2005 caused a regional shift upward in the water levels, but the declining trend resumed. The Order 1169 pumping test caused an inflection of regional water levels downward during pumping and upward during post-pumping recovery.

There will undoubtedly be debate over the cause(s), and there is to date no agreed upon explanation. Some investigators believe it is associated with long-term climate, and others have associated the response with pumping from the carbonate aquifer. What is generally agreed upon is that responses to pumping in the carbonate aquifer, as documented in the Order 1169 test, can propagate rapidly through the LWRFS. Equilibration to historical pumping within the LWRFS by discharge capture would therefore be thought to occur relatively rapidly, being directly dependent on drawdown.

**Long-term annual quantity of groundwater that may be pumped from the LWRFS**

This is undoubtedly a challenging question to address, and we have not examined this question for the entire LWRFS. Garnet Valley is situated at the lowest elevation of the LWRFS. Gradients to the southern portion of the LWRFS suggest that there exists some amount of subsurface discharge from the southeastern part of the LWRFS. This outflow can theoretically be captured by wells for beneficial use, with minimal capture of other LWRFS discharges (Muddy River Springs). Concern has been expressed about down-gradient Blue Point and Roger's springs. But these spring sources are not connected directly to the LRWFS, based on a lack of geologic continuity, intervening structural (geological) barriers, and as evidenced by incongruent groundwater elevations and water chemistry. It is improbable that capture of the modest amount of subsurface outflow from the LWRFS would have any affect to these springs.

Conceptually, if the Garnet Valley basin were being pumped at a rate greater than could be sustained without necessitating capture of discharge from the Muddy River Springs, then rates of water level decline (drawdown) would be greater than the regional trend, and there would be a developing "cone of depression" in the pumping area. This is not observed in the water level monitoring data in Garnet Valley. Rather, the pumping at approximately 1,500 AF/yr appears to have equilibrated in the system, capturing subsurface outflow from the basin and perhaps inducing greater groundwater inflow from Las Vegas Valley (Interflow, 2019a).

Notable is a two-year (2016-2017) increase in pumping in Garnet Valley from 1,500 AF/yr to 2000 AF/yr that does not appear to have caused regional drawdown effects. Water levels in the Muddy River Springs area during this time period did not show a downward inflection as a result of the increased pumping. Preliminary indications are that this level of pumping might be acceptable in the APEX area.

The City's water management strategy is to test increased pumping in a staged approach from the Playa and Kapex wells, complimented with monitoring of regional water levels. In this manner, it is hoped to identify a threshold for management of pumping in the APEX area. Once a threshold for sustainable groundwater pumping is better understood, the conjunctive water supply strategy can be adjusted appropriately, with water supply in part from the groundwater pumping and in part from the piped Colorado River source. Active aquifer management using AR as a drawdown management tool can also be used to establish a sustainable water supply program for APEX (Interflow, 2019b).

**Effects of movement of water rights between alluvial wells and carbonate wells**

The City of North Las Vegas is pursuing a lease/purchase agreement for senior water rights from the Muddy River Springs area for transfer to the City owned Playa and Kapex wells in Garnet Valley, subject to approvals by the State Engineer. Water rights currently exist at both the Playa and Kapex wells, primarily owned by SNWA and under temporary transfer, and there is an agreement with the City for up to 900 AF/yr of SNWA water rights to be available for municipal supply. However, these water rights are junior in the LWRFS. For security in water rights and municipal water supply to APEX, use of senior water rights would be more desirable, offering some buffer to potential regulation by water right priority, should this become necessary in the LWRFS.

We believe the concept of transferring senior water right out of the Muddy River Springs area to Garnet Valley also has merit for the overall LWRFS water management objectives, as it would transfer water rights that have historically been pumped from along the Muddy River corridor, and have been demonstrated to capture flows of the Muddy River, thereby conflicting with decreed water rights. Transferring the senior groundwater rights out of the river corridor will alleviate this direct conflict with Muddy River rights, and in Garnet Valley, will reduce reliance upon junior water rights.

**Closing Note**

These comments and interpretations are respectfully submitted, and the City of North Las Vegas is looking forward to participating as a productive and responsible LWRFS stakeholder, while striving to secure a reliable water supply for APEX. We look forward to further discussions and cooperative actions, as a LWRFS stakeholder, and appreciate the opportunity to submit this report to the State Engineer.

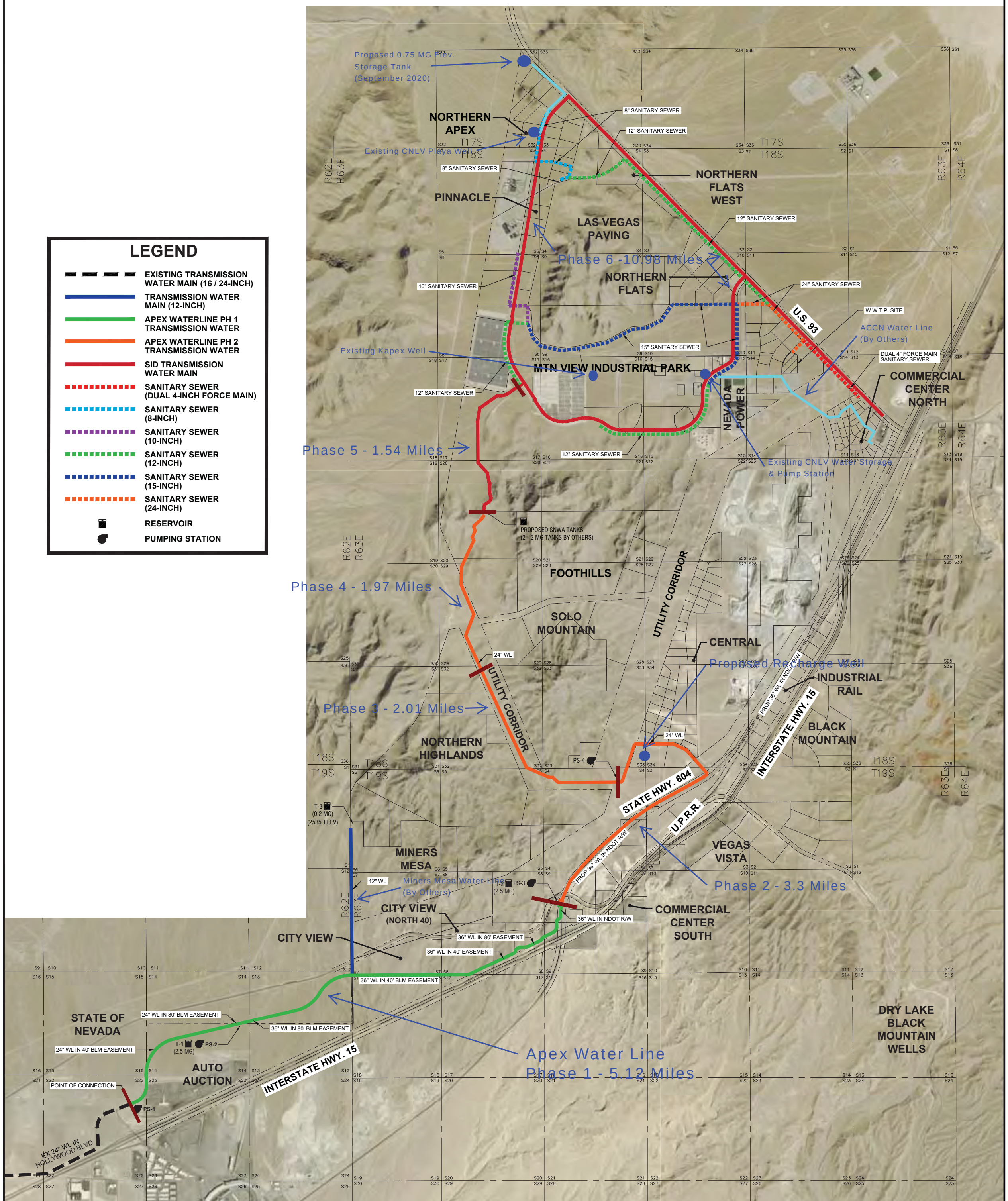
Sincerely,

Randall E. DeVaul, P.E.
Director of Utilities

Cc: Ryann Juden, City Manager
Alfredo Melesio, Assistant City Manager
Micaela Moore, City Attorney
Dwight Smith, Interflow Hydrology, Inc.

# APEX UTILITIES INFRASTRUCTURE PROJECTS

## CITY OF NORTH LAS VEGAS, NEVADA

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SE ROA 34710

InterFlow Hydrology, Inc.
Hydrogeology and Water Resources Consulting

# MEMORANDUM

To: Mr. Robert A. McLaughlin, PE, City of North Las Vegas, Manager, Development & Flood Control

Date: August 14, 2019

RE: **Rebuttal Document submitted on behalf of the City of North Las Vegas, to Interim Order 1303 Report Submittals of July 3, 2019**

From: Dwight L. Smith, PE, PG, Principal Hydrogeologist

### Rebuttal Item No. 1 – NPS (Tetra Tech) – Section 1.1 Setting, and discussion related to inclusion of areas extending to Lake Mead

NPS concerns over LWRFS connection to Rogers Spring, Blue Point Spring and other springs near Lake Mead are acknowledged. But the data do not support additional portions of the Black Mountains Area, extending to Lake Mead, belonging in the LWRFS administrative area. As shown in Interflow (2019) Figure 5, an east-west geologic cross-section through Garnet Valley to Lake Mead prepared by Page, et al (2011), there are significant faults and non-carbonate rocks intervening. Major intervening faults include the Dry Lake Thrust Fault on the east side of Garnet Valley and the Muddy Mountains Fault on the east side of California Wash. Rock types to the east of the Muddy Mountains Fault are primarily clastic sedimentary rocks (not carbonate rocks) which are not conducive to regional groundwater flow. A postulated deep route for groundwater flow (thousands of feet deep) and through the Muddy Mountain Fault is speculative. Significantly lower potentiometric water levels at the springs (land surface at Rogers Spring is 1562 ft amsl, and at Blue Point Spring is 1579 ft amsl; USGS NWIS data) reflect the intervening geology, with potentiometric heads at the springs being ~200 feet lower than potentiometric water levels in the LWRFS.

### Rebuttal Item No. 2 – NPS (Tetra Tech) – Sections 3 and 4, use of the regional groundwater flow model

Model limitations are stated by Tetra Tech in reporting, and I would like to additionally express concerns should the model be significantly relied upon by the State Engineer in the current Order 1303 proceedings, or for future water resources management in the LWRFS. For reference, SNWA provided a Tetra Tech model review, submitted to the NPS with copies to NDWR (SNWA, 2013). In my professional opinion, the model in its present state of calibration does not provide a level of certainty needed in advancing the water resources management objectives for the LWRFS. The modeling reliability would benefit from transient calibration using Order 1169 pumping test stresses and observed water level and spring discharge responses, along with addressing issues raised in SNWA (2013), including excessively high hydraulic conductivities at the Muddy River Springs, and lower discharge accounting at the Moapa gage than is measured.

SE ROA 34711

The model calibration is cause to temper reliance upon predictive simulations in addressing Order 1303 objectives for joint hydrographic basin administration.

**Rebuttal Item No. 3 – SNWA (page ix) "(d) changing the points of diversion to move groundwater production from the MRSA alluvial reservoir to locations sourced by the carbonate aquifer will not mitigate these conflicts, only delay their inevitable occurrence"**

*This rebuttal comment is also applicable to other Interim Order 1303 report submittals that take a similar stance regarding a lack of benefit in transferring pumping from the MRSA alluvium.*

While I understand SNWA's broadly taken position, I believe that delaying negative impacts presented by conflicting pumping is of benefit, at a minimum, in the short-term years while groundwater management plans are being developed and implemented. It may be further determined through managed pumping and expanded monitoring efforts that shifting pumping to more distal or fault isolated portions of the carbonate aquifer may provide long-term groundwater management solutions. There are areas which lack data to make any conclusive interpretations. In summary, I believe there are clear benefits to the transfer of senior priority water rights from the MRSA to locations in APEX where otherwise junior water rights will need to be pumped and relied upon for near-term municipal water supply. In this case, transfers of senior water rights out of the MRSA to southern Garnet Valley should be permitted as a beneficial step in LWRFS water resources management.

To the extent that groundwater pumping might eventually capture flow of the Muddy River, the City of North Las Vegas, as a member agency of SNWA feels this should be reviewed further as an acceptable use of the Muddy River water rights, and a more cost-effective means to provide water to APEX (utilize local groundwater to the extent possible to minimize utilization of Colorado River water).

**Rebuttal Item No. 4 – SNWA Section 3.4.2.2 Occurrence and Movement (beginning on page 3-11), and resultant conclusions.**

*This rebuttal comment is also applicable to other Interim Order 1303 report submittals that have stated positions regarding groundwater flow within the LWRFS.*

There is a component of groundwater flow to Garnet Valley that does not naturally flow to the Muddy River springs or Muddy River. Garnet Valley is at the distal end of the LWRFS, based on groundwater elevation data. Groundwater elevations in Garnet Valley are the lowest in the LWRFS, except as occur in eastern portions of the California Wash basin, which arguably may not be in hydraulic connection. Some of the early water level elevation measurements made in the LWRFS region (1987-2002) are shown in Figure 1. Interflow (2019) Figure 7 shows current potentiometric water levels.

A gradient toward Garnet Valley defines movement of groundwater to southern Garnet Valley. As a non-tributary component of carbonate aquifer flow, it can be available to capture and use without direct impact to the Muddy River. The magnitude of the natural (pre-development) subsurface flow is poorly understood, and difficult to define with existing data, but is likely low in magnitude based on the current understanding. None the less, in response to the interpretations that no groundwater can be pumped without ultimately capturing flows of the Muddy River, this interpretation is inaccurate in the case of southern Garnet Valley because there is a naturally occurring component of groundwater flow that can be captured for beneficial use.

**Rebuttal Item No. 5 – SNWA Section C, page 8-4, regarding LWRFS Perennial Yield**

*This rebuttal comment is also applicable to other Interim Order 1303 report submittals that have stated positions regarding perennial yield within the LWRFS.*

Many stakeholders conclude that some amount (~4,000 to 9,300+ AF/yr) of groundwater pumping can be managed in the LWRFS. Regarding the magnitude of groundwater that can be safely pumped in southern Garnet Valley by the City of North Las Vegas and APEX facilities, the City acknowledges the uncertainty and connectivity concerns and is providing: (i) a means to more thoroughly understand the local carbonate aquifer responses to pumping; (ii) long-term water management options and a backstop for impacts of groundwater pumping should they occur in an unacceptable manner. The APEX water supply strategy provides avenues for long-term adaptive management of the water resources, including:

- Future ability to distribute water supply between groundwater and surface water (Colorado River) sources;
- AR of carbonate aquifer to curtail / manage carbonate aquifer drawdown; and
- Treated wastewater reuse, including potentially potable reuse via treatment and AR to the carbonate aquifer.

Groundwater is currently being relied upon by existing facilities within APEX and is an important component of water supply for the City of North Las Vegas, especially to bridge industrial water supply over the next decade, until municipal facilities are completed to allow for implementation of adaptive management. In the interim, pumping for APEX will reveal more about a sustainable yield for this portion of the LWRFS.

**References**

Interflow Hydrology, Inc., 2019, Garnet Valley Groundwater Pumping Review for APEX Industrial Complex, City of North Las Vegas, Clark County, Nevada.

Page, W.R., Scheirer, D.S., Langenheim, V.E., Berger, M.A., 2011, Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona; USGS Open File Report 2006-1040.

Southern Nevada Water Authority, 2013, Technical Review of Numerical Groundwater Flow Model of Selected Basins with the Colorado Regional Groundwater Flow System, Southeastern Nevada, Version 1.0- A Model Prepared by Tetra Tech for the National Park Service, US Fish and Wildlife Service and Bureau of Land Management; submitted to Mr. Bill Van Liew, June 13, 2013, copied to Rick Felling, NDWR; SNWA Doc No. WRD-ED-0020.

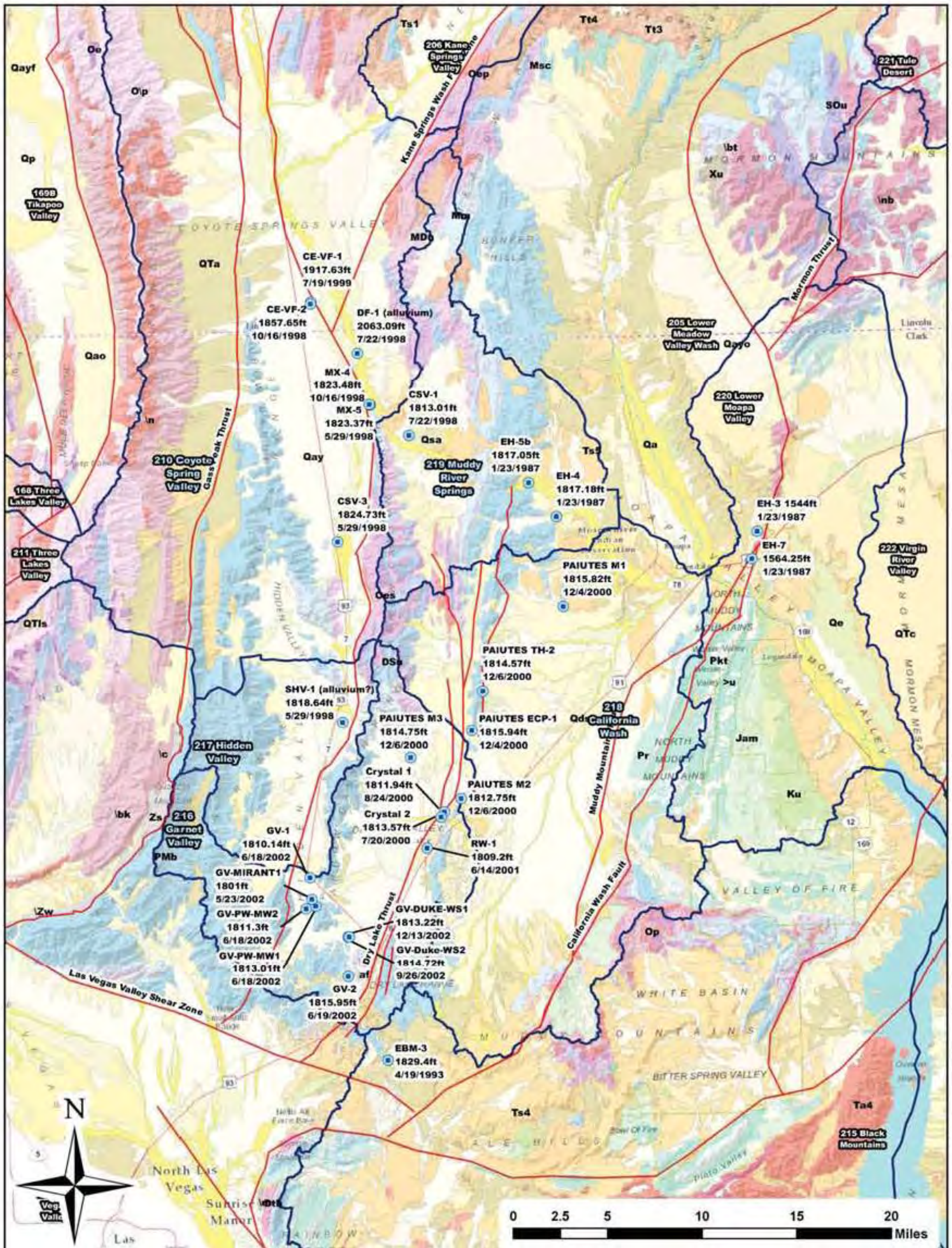



**Figure 1**
**Order 1169 Wells, 1987 - 2002**
**Earliest Recorded Water Level Elevation Map**
**Clark County, NV**

**1:300,000**

Coordinate System: NAD 1983 UTM Zone 11 N
Projection: Transverse Mercator
Page., et. al., 2005, Geological Map of Parts of the Colorado, White River, and Death Valley Groundwater Flow Systems, Nevada, Utah, and Arizona.
Major Structures based on: Page, et. al., 2011. Revised Geological Cross Sections of Parts of the Colorado, White River, and Death Valley regional groundwater flow systems, Nevada, Utah, and Colorado: U.S. Geological Survey Open-File Report 2006-1040, 1 sheet, 25 p. pamphlet.

SE ROA 34714

Prepared in cooperation with the Southern Nevada Water Authority, U.S. Fish and Wildlife Service, National Park Service, and Virgin Valley Water District



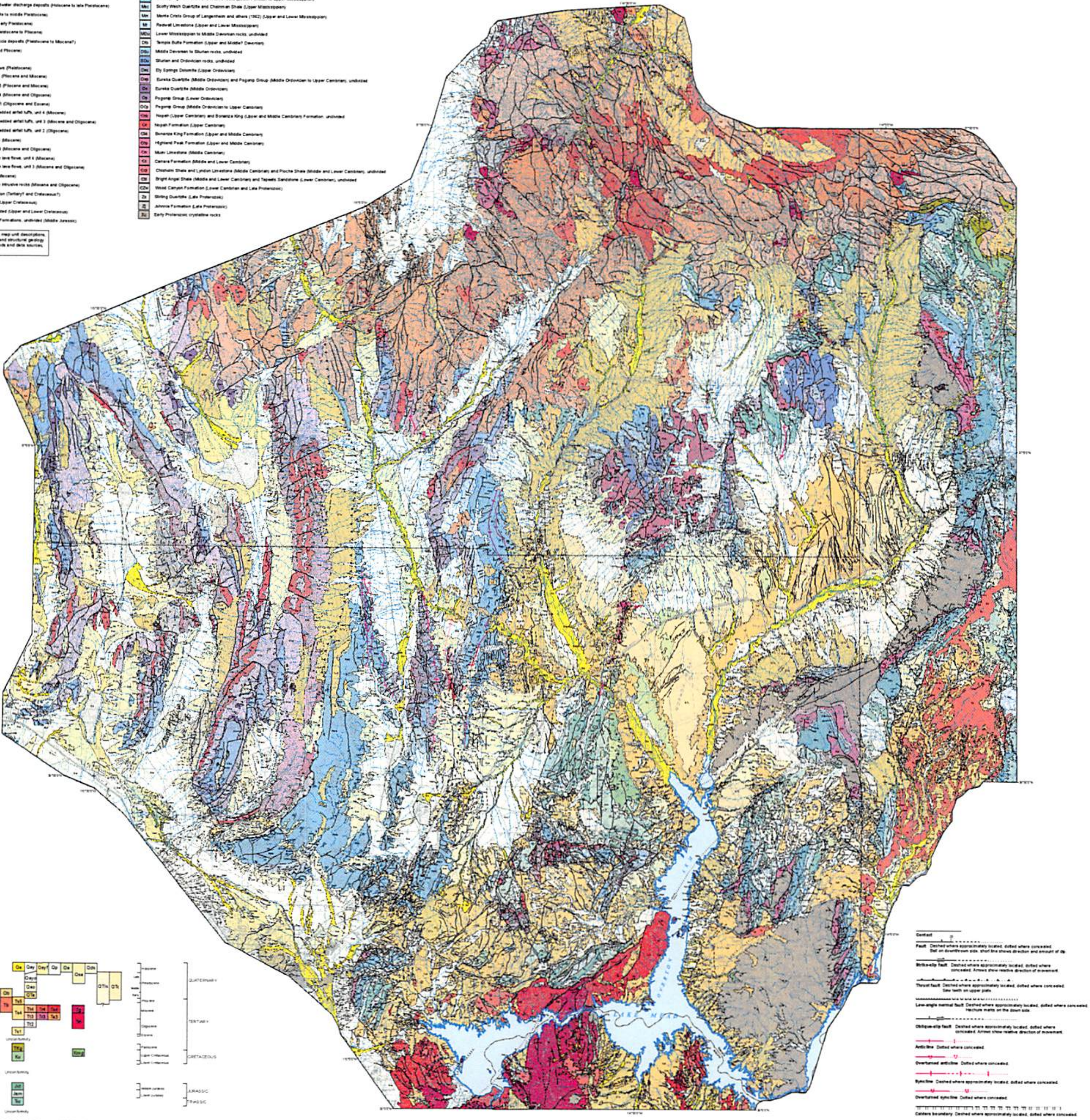
**Surficial Units**

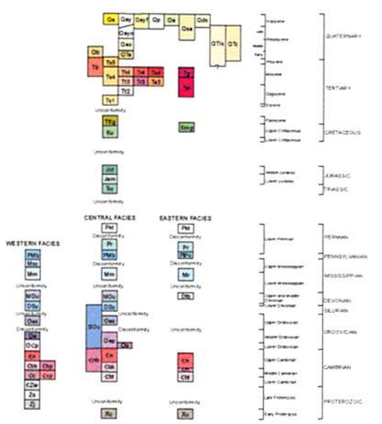
- Qa — Channel alluvium (Holocene)
- Qay — Young alluvium (Holocene to latest Pleistocene)
- Qayf — Young fine-grained alluvium (Holocene to late Pleistocene)
- Qp — Playa deposits (Holocene to late Pleistocene)
- Qe — Eolian deposits (Holocene)
- Qsa — Spring-apron deposits (Holocene to middle Pleistocene)
- Qds — Modern and past groundwater discharge deposits (Holocene to late Pleistocene)
- Qayo — Intermediate alluvium (late to middle Pleistocene)
- Qao — Old alluvium (middle to early Pleistocene)
- QTa — Oldest alluvium (early Pleistocene to Pliocene)
- QTls — Landslide and megabreccia deposits (Pleistocene to Miocene?)
- QTc — Calcrete (Pleistocene and Pliocene)

**Bedrock Units**

- Qb — Younger basaltic lava flows (Pleistocene)
- Tb — Older basaltic lava flows (Pliocene and Miocene)
- Ts5 — Sedimentary rocks, unit 5 (Pliocene and Miocene)
- Ts4 — Sedimentary rocks, unit 4 (Miocene and Oligocene)
- Ts1 — Sedimentary rocks, unit 1 (Oligocene and Eocene)
- Tt4 — Ash-flow tuffs and interbedded airfall tuffs, unit 4 (Miocene)
- Tt3 — Ash-flow tuffs and interbedded airfall tuffs, unit 3 (Miocene and Oligocene)
- Tt2 — Ash-flow tuffs and interbedded airfall tuffs, unit 2 (Oligocene)
- Tr4 — Rhyolite lava flows, unit 4 (Miocene)
- Tr3 — Rhyolite lava flows, unit 3 (Miocene and Oligocene)
- Ta4 — Intermediate-composition lava flows, unit 4 (Miocene)
- Ta3 — Intermediate-composition lava flows, unit 3 (Miocene and Oligocene)
- Tg — Granitic intrusive rocks (Miocene)
- Ti — Intermediate-composition intrusive rocks (Miocene and Oligocene)
- TKg — Grapevine Wash Formation (Tertiary? and Cretaceous?)
- Kwg — Granite of Walker Wash (Upper Cretaceous)
- Ku — Cretaceous rocks, undivided (Upper and Lower Cretaceous)
- Jct — Carmel and Temple Cap Formations, undivided (Middle Jurassic)
- Jan — Aztec Sandstone, Navajo Sandstone, Kayenta Formation, and Moenave Formation, undivided (Lower Jurassic)
- Trr — Triassic rocks, undivided (Triassic)
- Pkt — Kaibab and Toroweap Formations undivided (Lower Permian)
- Pr — Lower Permian redbeds
- PPc — Callville Limestone and related rocks (Lower Permian and Pennsylvanian)
- PMb — Bird Spring Formation and related rocks (Lower Permian to Upper Mississippian)
- Msc — Scotty Wash Quartzite and Chainman Shale (Upper Mississippian)
- Mm — Monte Cristo Group of Langenheim and others (1962) (Upper and Lower Mississippian)
- Mr — Redwall Limestone (Upper and Lower Mississippian)
- MDu — Lower Mississippian to Middle Devonian rocks, undivided
- Dtb — Temple Butte Formation (Upper and Middle? Devonian)
- DSu — Middle Devonian to Silurian rocks, undivided
- SOu — Silurian and Ordovician rocks, undivided
- Oes — Ely Springs Dolomite (Upper Ordovician)
- Oep — Eureka Quartzite (Middle Ordovician) and Pogonip Group (Middle Ordovician to Upper Cambrian), undivided
- Oe — Eureka Quartzite (Middle Ordovician)
- Op — Pogonip Group (Lower Ordovician)
- O€p — Pogonip Group (Middle Ordovician to Upper Cambrian)
- €nb — Nopah (Upper Cambrian) and Bonanza King (Upper and Middle Cambrian) Formation, undivided
- €n — Nopah Formation (Upper Cambrian)
- €bk — Bonanza King Formation (Upper and Middle Cambrian)
- €hp — Highland Peak Formation (Upper and Middle Cambrian)
- €m — Muav Limestone (Middle Cambrian)
- €c — Carrara Formation (Middle and Lower Cambrian)
- €cl — Chisholm Shale and Lyndon Limestone (Middle Cambrian) and Pioche Shale (Middle and Lower Cambrian), undivided
- €bt — Bright Angel Shale (Middle and Lower Cambrian) and Tapeats Sandstone (Lower Cambrian), undivided
- €Zw — Wood Canyon Formation (Lower Cambrian and Late Proterozoic)
- Zs — Stirling Quartzite (Late Proterozoic)
- Zj — Johnnie Formation (Late Proterozoic)
- Xu — Early Proterozoic crystalline rocks

See accompanying text for map unit descriptions, discussion of stratigraphy and structural geology of the mapped area, methods and data sources, and references.






Contact
Fault
Strike-slip fault
Thrust fault
Low-angle normal fault
Oblique-slip fault
Anticline
Overturned anticline
Syncline
Overturned syncline
Caldera boundary
Carbonate veins
Fissure
Strike and dip of beds
Strike and dip of foliation in metamorphic rocks
Strike and dip of joints

# GEOLOGIC MAP OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY GROUNDWATER FLOW SYSTEMS, NEVADA, UTAH, AND ARIZONA

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Scale 1:250,000

CONTOUR INTERVAL 200 FEET
WITH SUPPLEMENTARY CONTOURS AT 100 FOOT INTERVALS

2005

NEVADA BUREAU OF MINES AND GEOLOGY
MACKAY SCHOOL OF EARTH SCIENCES AND ENGINEERING
UNIVERSITY OF NEVADA, RENO

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First edition, 2005
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SE ROA 34715

Text and references to accompany Nevada Bureau of Mines and Geology Map 150

# GEOLOGIC MAP OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY GROUNDWATER FLOW SYSTEMS

## NEVADA, UTAH, AND ARIZONA


by

**William R. Page[1], Gary L. Dixon[2], Peter D. Rowley[3], and David W. Brickey[4]**

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## INTRODUCTION

The mapped area is greater than 20,000 km$^2$, and is largely within the Basin and Range physiographic province and its transition with the Colorado Plateau. The area is a desert, with little precipitation except in the mountains and few perennial streams and rivers besides the Colorado River and two tributaries, the Virgin and Muddy Rivers. The Colorado River is impounded by Hoover Dam, in the southwestern corner of the map area, to create Lake Mead, which volumetrically is the largest reservoir in the country. Lake Mead provides most of the culinary and agricultural water to southern California, southern Nevada, and southern Arizona, all among the fastest growing parts of the United States.

The geologic map provides a basis for understanding the complex geology and groundwater hydrology of a vast area whose population is experiencing increasingly significant water shortages (Page and others, 2003). Specifically, rapid urbanization and commercial development is taking place in the I-15 transportation corridor, from Las Vegas, Nevada, through Mesquite, Nevada, and the Arizona Strip to St. George, Utah. This growth has caused increased demand for water from surface sources and from local and regional aquifers. As a result, the geologic framework in the area needs to be described.

The main purpose of the geologic map is to provide our sponsors (National Park Service, U.S. Fish and Wildlife Service, Southern Nevada Water Authority, and Virgin Valley Water District) with digital geologic framework data used as important parameters in developing numerical groundwater flow models. These data describe the distribution, geometry, thickness, composition, and physical properties of geologic units. This information is required to define hydrogeologic units and potential aquifers and confining units. These data also describe the distribution, geometry, and characteristics of faults. Faults act as both conduits and barriers to groundwater flow depending on a variety of factors. When combined with geologic cross sections, well data, and geophysical subsurface information, these data provide a 3-dimensional geologic model characterizing the configuration of hydrogeologic units and faults in the map area that can be integrated with groundwater models using GIS analyses. The map is a printed version of an ARC/Info GIS data base. Geologic cross sections in the map area are being prepared in a separate report.

The southern half of Nevada and its adjacent states contain several huge groundwater basins, known as regional groundwater flow systems that may encompass a dozen or more of the closed topographic basins because they are interconnected in the subsurface. These regional flow systems are defined by hydrologic and geochemical evidence that indicate their groundwater flow paths pass beneath topographic barriers and continue beneath adjacent basins and ranges, referred to as interbasin flow (Eakin, 1966; Eakin and Winograd, 1965). Thomas and others (1986, 1996), Harrill and others (1988), Prudic and others (1995), and Harrill and Prudic (1998) summarized these flow systems for the Great Basin.

The main regional groundwater flow systems covered by this geologic map include parts of the Colorado flow system (Harrill and Prudic, 1998), the White River groundwater flow system (Eakin, 1964, 1966; Thomas and

Welch, 1984; and Kirk, 1987), and the Death Valley groundwater flow system (e.g., Winograd and Thordarson, 1975; Laczniak and others, 1996; Harrill and Prudic, 1998; D'Agnese and others, 2002; Workman and others, 2002, 2003). The White River flow system is contained within the much larger Colorado flow system; our map covers only the southern part of these flow systems and the eastern part of the Death Valley system (see figure on map sheet).

The primary source (recharge area) of the water in the flow systems is precipitation in the mountains surrounding basins in the map area and the numerous basins farther north and northeast. The principal discharge area for the White River flow system is Muddy River springs (Dettinger and others, 1995) (fig. 1), a series of about eight major springs (Schmidt and Dixon, 1995) that discharge 36,000 ac-ft/yr (44 $hm^3$/yr) to form the Muddy River. Movement of groundwater in the map area is primarily by fracture flow, that is along fractures (mostly joints; the "damage zone" of Caine and others, 1996) formed by faulting (e.g., Haneberg and others, 1999). The flow paths are generally southward, as indicated by potentiometric maps based on water levels in wells (Thomas and others, 1986; Wilson, 2001). They thus follow the general slope of the topography, from high areas in central Nevada to the low canyons of the Colorado River in southern Nevada. The flow is driven by the hydraulic head parallel to the southward topographic gradient.

Aquifers in the flow systems consist of Paleozoic carbonate rocks and subordinate volcanic rocks and basin-fill sediments (e.g., Plume and Carlton, 1988; Dettinger and others, 1995; Prudic and others, 1995; Burbey, 1997; Harrill and Prudic, 1998). In fact, the importance of the Paleozoic carbonate-rock aquifer to the flow systems that cover much of southern Nevada and adjacent states is so significant that many regional hydrologic reports have focused on the distribution and features of this aquifer (e.g., Dettinger and others, 1995; Burbey, 1997; Wilson, 2001).

## METHODS AND DATA SOURCES

The geologic map contains greater detail and more recent compilations than existing regional geologic maps in the study area and provides stratigraphic and structural continuity across county and state boundaries. It was assembled by compiling all available regional and detailed geologic maps in the area. These maps were modified by the authors, as required to apply new information and concepts about the geology. The sources of geologic mapping are shown in figures 2 and 3. Figure 2 lists detailed map sources at 1:24,000-scale and figure 3 includes regional map sources from 1:50,000 to 1:250,000 scale. In a few remote areas not covered by existing geologic maps, we compiled the geology using reconnaissance scale county geologic maps (Longwell and others, 1965; Tschanz and Pampeyan, 1970) in combination with Landsat and aerial photo interpretation.

Geophysical studies have been completed in many of the major basins of the map area in order to understand the subsurface geology. These studies mainly applied gravity and magnetic methods in combination with analyses of seismic reflection data. Subsurface studies are especially significant in locating buried faults that may control groundwater flow and in modeling basins to better understand interbasinal groundwater flow. Bohannon and others (1993) interpreted subsurface faults and stratigraphic units in the Virgin Valley area based mostly on seismic reflection and well data. Jachens and others (1998) interpreted subsurface faults and other geologic features in the Virgin Valley and Tule Springs Hills areas based on high-resolution aeromagnetic studies. Langenheim and others (2000, 2001a, b, c) modeled the Virgin Valley, Las Vegas Valley, and California Wash basins using seismic reflection and gravity data. Phelps and others (2000) interpreted subsurface faults in the Coyote Spring Valley area based on gravity data.

## ACKNOWLEDGMENTS

Funding for this geologic map was provided by the Southern Nevada Water Authority, U.S. Fish and Wildlife Service, National Park Service, and Virgin Valley Water District. We are grateful to Ernie Anderson, Bob Scott, and Van Williams of the USGS for their unpublished map data. Vicky Langenheim, Geoff Phelps, Bob Morin, Bob Jachens, and Tom Hildenbrand conducted geophysical surveys in the map area. We also thank Mel Kuntz of the USGS, Jim Faulds of the Nevada Bureau of Mines and Geology, Grant Willis of the Utah Geological Survey, and an anonymous reviewer for their technical reviews of the manuscript. Terry Katzer and David Donovan of the Southern Nevada Water Authority provided helpful suggestions to improve the manuscript.

## STRATIGRAPHY

### Proterozoic and Paleozoic Rocks

The oldest rocks in the map area are Early Proterozoic metamorphic and intrusive rocks consisting of gneiss, granite, and schist that are about 1.7 Ga (Quigley and others, 2002); their surface distribution is shown in figure 4. These crystalline rocks form both geologic and hydrologic basement and are considered barriers to groundwater flow because of their low permeability. The crystalline rocks may be locally permeable where highly fractured, but fractures in these rocks are generally poorly connected (D'Agnese and others, 1997). Early Proterozoic rocks exposed in the Beaver Dam and Virgin Mountains form the eastern boundary of the flow systems. Early Proterozoic rocks also form the core of the Mormon Mountains in the central part of the map area (fig. 4), where they act as a local barrier to groundwater flow (Burbey, 1997), although through-going, north-striking faults in the eastern Mormon Mountains may provide conduits for some component of southward groundwater flow through the mountain range.

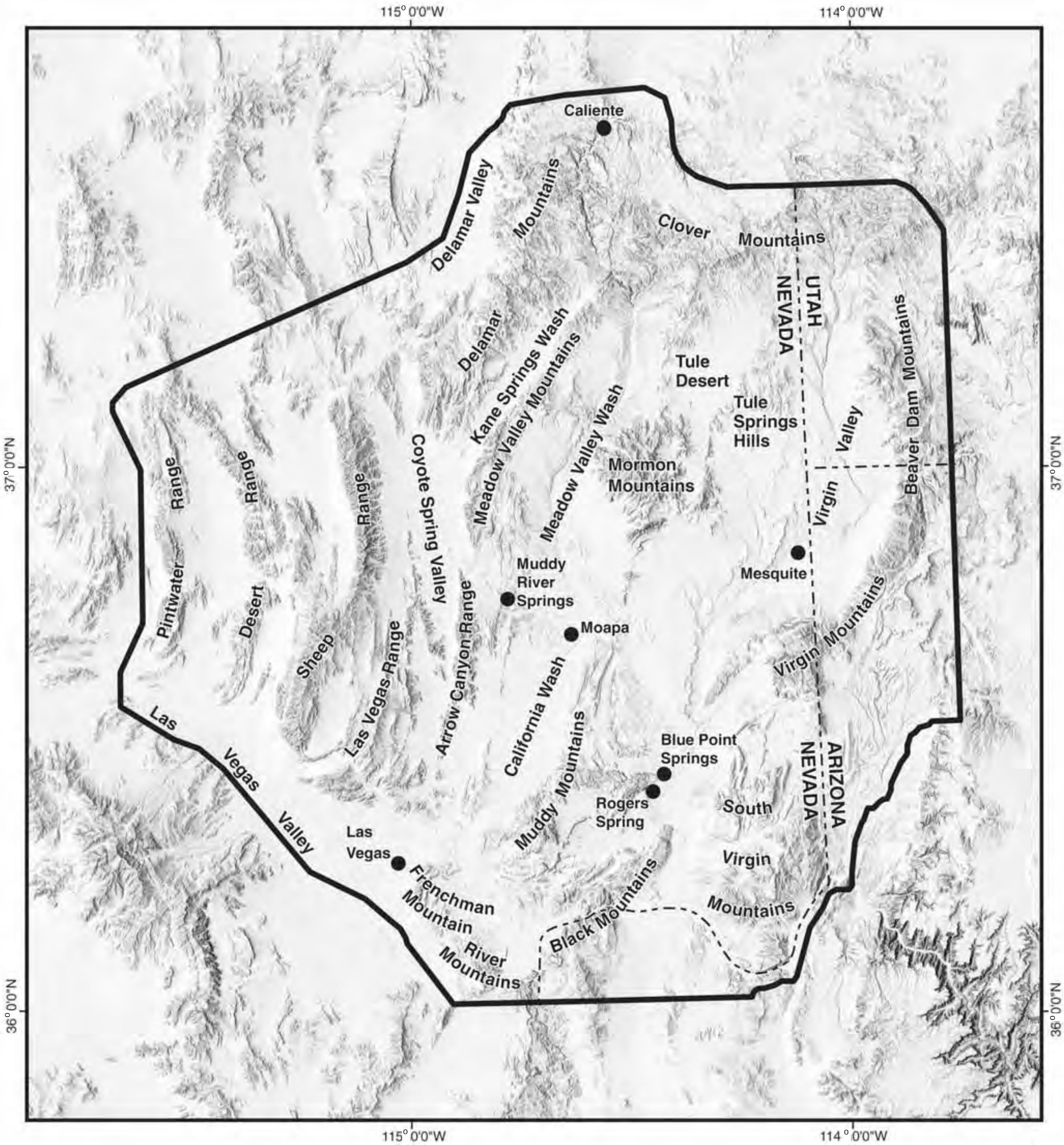


**Figure 1. Index map showing major physiographic features in the map area.**

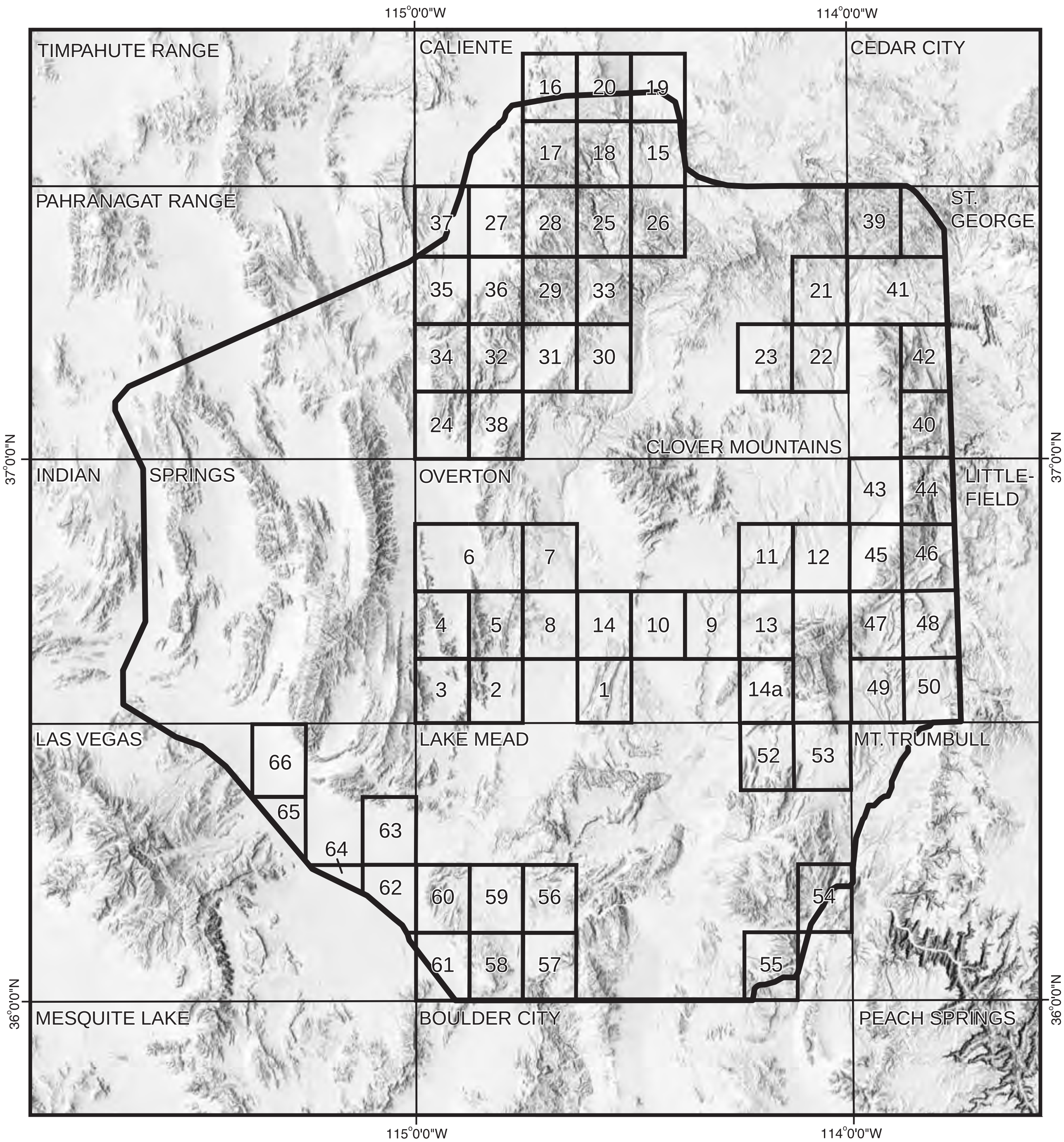


**Figure 2.** Index to 1:24,000-scale geologic mapping sources. See table 1 for quadrangle names and references.



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**Table 1. Geologic mapping sources for the study area. Locations of the 1:24,000-scale geologic maps are shown in figure 3.**

**Overton 30 x 60 Quadrangle**

1. Weiser Ridge (Bohannon, 1992a)
2. Arrow Canyon SE (W.R. Page, unpub. mapping, 1999)
3. Arrow Canyon SW (W.R. Page, unpub. mapping, 1999)
4. Arrow Canyon NW (Page, 1998)
5. Arrow Canyon (Page, 1992)
6. Wildcat Wash SE and Wildcat SW (Page and Pempeyan, 1996)
7. Farrier (Schmidt, 1994)
8. Moapa West (Schmidt and others, 1996)
9. Overton NE (V.S. Williams, unpub. mapping, 1999)
10. Overton NW (V.S. Williams, unpub. mapping, 1999)
11. Flattop Mesa (V.S. Williams, unpub. mapping, 2000)
12. Mesquite (Williams, 1996)
13. Riverside (Williams and others, 1997a)
14. Moapa East (Williams and others, 1997b)

14a. Whitney Pocket (Beard, 1993)

**Caliente 30 x 60 Quadrangle**

15. Eccles (P.D. Rowley, unpub. mapping,1993)
16. Caliente NW (P.D. Rowley, unpub. mapping,1993)
17. Chokecherry Mtn. (P.D. Rowley, unpub. mapping,1993)
18. Caliente (P.D. Rowley and others, unpub. mapping,1993)
19. Indian Cove (Rowley and Shoba, 1991)
20. Chief Mountain (Rowley and others, 1994)

**Clover Mountains 30 x 60 Quadrangle**

21. Dodge Spring (Anderson and Hintze, 1993)
22. Scarecrow Peak (Hintze and Axen, 1995)
23. Lime Mountain (Hintze and Axen, 2001)
24. Delamar 3 SW (Page and others, 1990)
25. Elgin NE (P.D. Rowley, unpub. mapping, 1994)
26. Ella Mountain (P.D. Rowley, unpub. mapping, 1994)
27. Delamar (P.D. Rowley, unpub. mapping, 1995)
28. Slidy Mountain (P.D. Rowley and R.B. Scott, unpub. mapping, 1994)
29. Elgin SW (R.B. Scott, unpub. mapping, 1994)
30. Vigo NE (R.B. Scott and A. Harding, unpub. mapping, 2003)
31. Vigo NW (Scott and others, 1991a)
32. Delamar 3 NE (Scott and others, 1990a)
33. Elgin (R.B. Scott and P.D. Rowley, unpub. mapping, 1993)
34. Delamar 3 NE (Scott and others, 1990b)
35. Delamar Lake (Scott and others, 1993)
36. Gregerson Basin (Scott and others, 1991b)
37. Delamar NW (Swadley and Scott, 1990)
38. Delamar 3 SE (Swadley and others, 1994)

**St. George 30 x 60 Quadrangle**

39. Goldstrike (R.E. Anderson, unpub. mapping, 1993)
40. Jarvis Peak (Hammond, 1991)
41. Motoqua and Gunlock (Hintze and others, 1994)
42. Shivwits (Hintze and Hammond, 1994)

**Littlefield 30 x 60 Quadrangle**

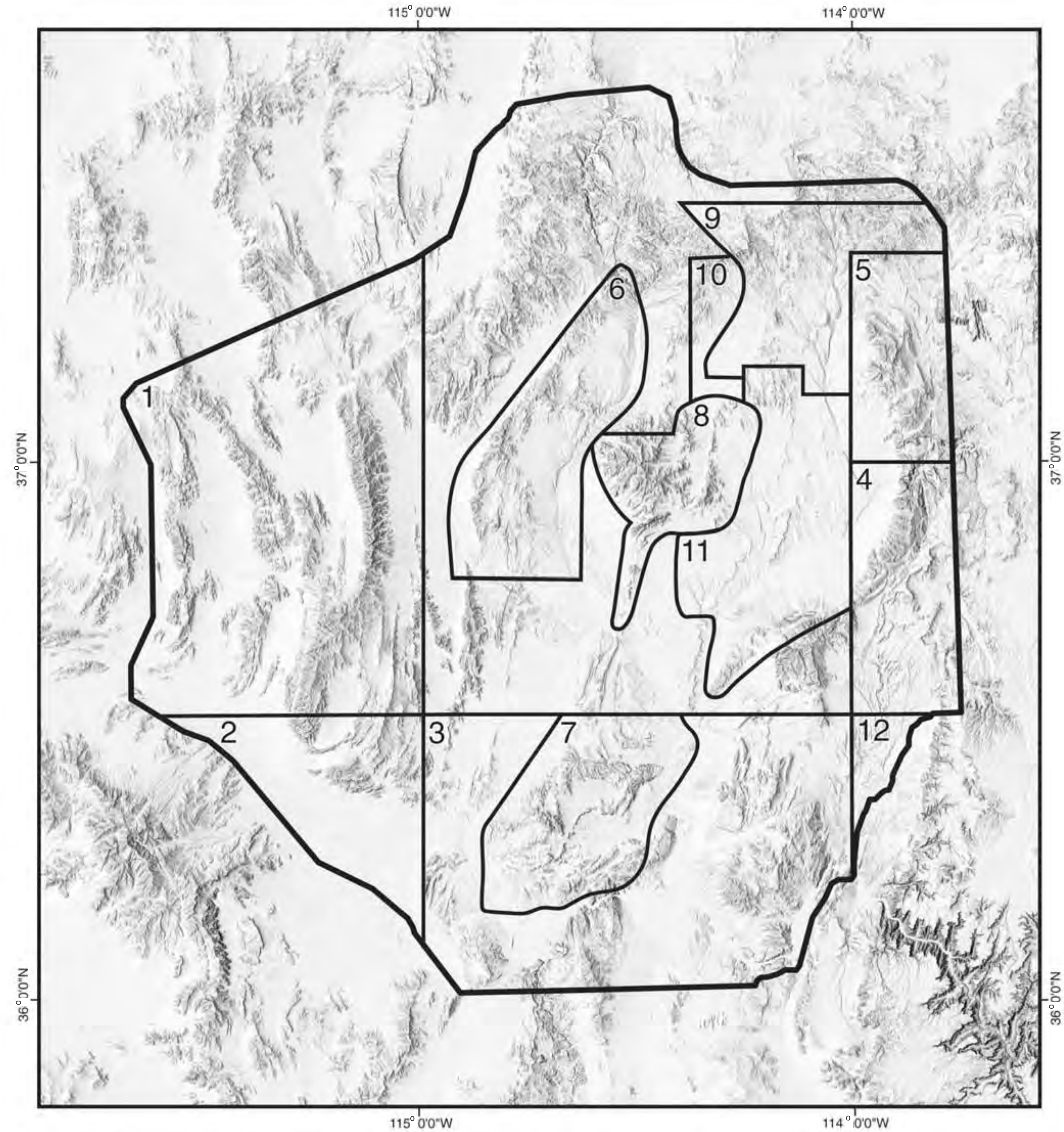
43. Littlefield (Billingsley, 1995)
44. Mountain Sheep Spring (Bohannon and others, 1991)
45. Elbow Canyon (Billingsley and Bohannon, 1995)
46. Mount Bangs (Bohannon and Lucchitta, 1991)
47. Jacobs Well and southern part of the Elbow Canyon (Bohannon, 1991)
48. Cane Springs (Lucchitta and others, 1995a)
49. Red Pockets (Bohannon, 1992b)
50. Cane Springs Southeast (Lucchitta and others, 1995b)

**Lake Mead 30 x 60 Quadrangle**

52. Devils Throat (Beard, 1991)
53. St. Thomas Gap ( Beard, 1992)
54. Iceberg Canyon (Brady and others, 2002)
55. Hiller Mountains (Howard and others, 2003)
56. Callville Bay (Anderson, 2003)
57. Hoover Dam (Mills, 1994)
58. Boulder Beach (Smith, 1984)
59. Government Wash (Duebendorfer, 2003)
60. Frenchman Mountain (Castor and others, 2000)
61. Henderson (Bell and Smith, 1980)

**Las Vegas 30 x 60 Quadrangle**

62. Las Vegas NE (Matti and others, 1993)
63. Valley (Lundstrom and others, 1998)
64. Las Vegas NW (Matti and others, 1987)
65. Tule Springs Park (Bell and others, 1998)
66. Corn Creek Springs (Bell and others, 1999)




1. Workman and others (2003)
2. Page and others (2005)
3. Beard and others (in press)
4. Billingsley and Workman (1998)
5. Hintze (1986)
6. Pampeyan (1993)
7. Bohannon (1983)
8. Axen and others (1990), Skelly (1987), Olmore (1971), and Wernicke and others (1985)
9. R.E. Anderson (unpub. mapping, Clover Mountains and Bull Valley Mountains, 1990)
10. Ekren and others (1977)
11. Dixon and Katzer (2002)
12. Billingsley and Wellmeyer (2003)

**Figure 3. Index to geologic mapping sources, 1:50,000 to 1:250,000-scale maps.**

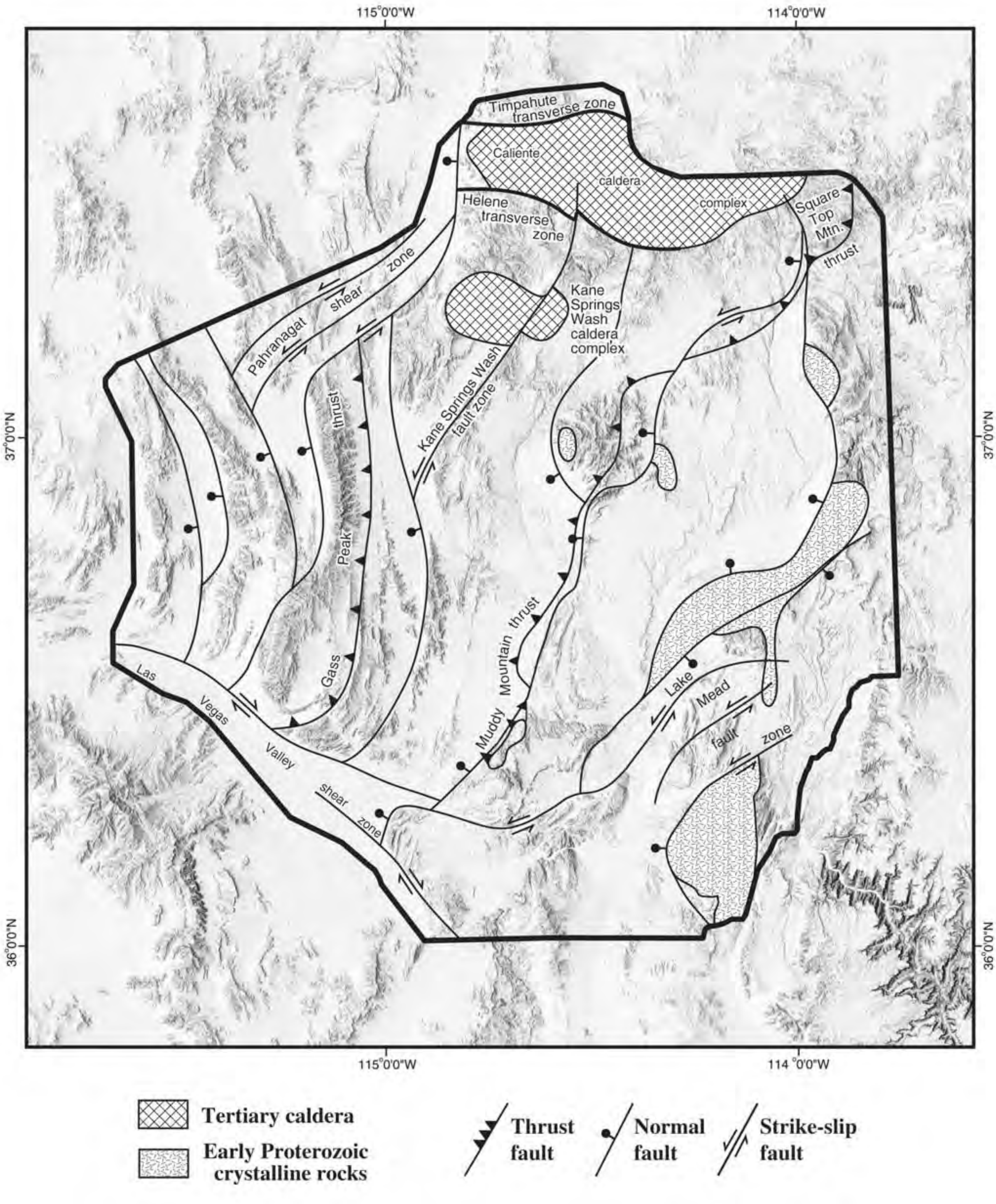



**Figure 4. Generalized map of the principal structural features in the map area.**

Late Proterozoic sedimentary rocks are exposed in the Desert and Sheep Ranges and northern Delamar Mountains. These are mostly clastic rocks and consist of quartzite, conglomerate, sandstone, siltstone, and shale, but they contain subordinate amounts of limestone and dolostone. The Late Proterozoic sedimentary rocks are well-cemented, contain few or no pore spaces, and have low permeability. They were deposited in shallow marine waters along a passive continental margin of what is now western North America (Stewart, 1976; Stewart and Poole, 1972). Late Proterozoic rocks are interpreted to represent initial deposits of the Cordilleran miogeocline (Stewart and Poole, 1972; Stewart, 1972, 1976).

Like the Late Proterozoic sedimentary rocks, Lower Cambrian rocks are also predominantly well-cemented, clastic units containing mainly quartzite, conglomerate, siltstone, and shale. Together, the Lower Cambrian and Late Proterozoic sedimentary rocks in the western part of the map area form a confining unit. In the Desert Range, these rocks attain their maximum thickness in the map area and may form a potential barrier to westward groundwater flow. In the Death Valley groundwater flow system, these same rocks are referred to as the lower clastic aquitard (Winograd and Thordarson, 1975), or the lower clastic confining unit (Belcher and others, 2002). Late Proterozoic clastic units pinch out in the eastern part of the map area and are absent in the Mormon, Virgin, and Beaver Dam Mountains. Here, the lower clastic confining rocks include the Lower Cambrian Tapeats Sandstone and the Lower and Middle Cambrian Bright Angel Shale that have a combined thickness ranging from 125 to 445 m.

Middle Cambrian through Lower Permian rocks are widely distributed in the map area and record a significant shift in deposition to predominantly carbonate sedimentation, from mostly clastic sedimentation in pre-Bonanza King Late Proterozoic and Cambrian units. The carbonate rocks are predominantly limestone and dolostone and form the regional aquifer in the map area (Dettinger and others, 1995). The Middle and Upper Cambrian Bonanza King Formation (and equivalent Highland Peak and Muav Formations) forms the basal part of the regional carbonate aquifer in the White River and Colorado flow systems, and in the Death Valley groundwater flow system (Winograd and Thordarson, 1975; Laczniak and others, 1996; Belcher and others, 2002; D'Agnese and others, 2002). Groundwater flow through the carbonate rocks is mostly through fractures and faults. Because the rocks are soluble in groundwater, dissolution features are also important in the development of secondary porosity and permeability. Zones of high transmissivity in the carbonate rock aquifer are indicated by large spring discharge (36,000 ac-ft/yr [44 $hm^3$/yr] at Muddy River Springs) in areas of low potentiometric gradient, and by water wells exhibiting extremely high hydraulic conductivity (900 $ft^2$/d [84 $m^2$/d] at MX-5 in Coyote Spring Valley) (Dettinger and others, 1995).

Middle Cambrian through Lower Permian rocks are dominantly carbonate rocks with the exception of several units that have greater proportions of clastic material: these units include the Upper Cambrian Dunderberg Shale Member of the Nopah Formation, Middle Ordovician Eureka Quartzite, Upper Mississippian Chainman Shale, Upper Mississippian Indian Springs Formation, and the Lower Permian redbeds. These clastic units are generally not thick enough to form regional confining units in the map area, but they may act as confining units locally within the region, especially the Lower Permian redbeds which have a maximum thickness of 600 m.

The upper part of the carbonate aquifer in the map area includes the Bird Spring Formation and partly equivalent Callville Limestone. Lower Permian redbeds overlie these formations and represent a shift from dominantly carbonate marine to mostly continental and marginal marine sedimentation. Continental sedimentation predominated through the Mesozoic and into the lower Tertiary.

## Late Proterozoic-Paleozoic facies belts

Late Proterozoic-Paleozoic rocks in the map area can be broadly subdivided into western, central, and eastern facies belts (see correlation of map units). Rocks in the western belt include Late Proterozoic through Devonian units deposited as part of the Cordilleran miogeocline in offshore carbonate shelf and intertidal depositional settings, and an overlying Mississippian to Permian sequence deposited mostly in a carbonate platform depositional setting. Units of the western belt are exposed as far east as the Las Vegas Range, Arrow Canyon Range, Meadow Valley Mountains, and Delamar Mountains (fig. 1).

The eastern facies belt includes cratonic platform rocks of the Colorado Plateau region exposed in the Beaver Dam and Virgin Mountains, and in the Lake Mead area including Frenchman Mountain. The rocks are mostly shallow marine sediments deposited in near-shore, intertidal, and continental settings. The facies belt is characterized by a large magnitude unconformity separating Middle Devonian from Upper Cambrian rocks (see correlation of map units). Rock units in the belt also include significant amounts of evaporite deposits, especially in the Permian formations. The central facies belt includes rocks that are transitional between the eastern and western belts; these rocks are exposed in the Muddy Mountains, Mormon Mountains, and Tule Springs Hills (fig. 1).

Thickness of Middle Cambrian to Lower Permian carbonate rocks, which define the regional aquifer, decrease dramatically across the belts from west to east over a distance of about 100 km—from about 4 to 6 km thick in the western belt to less than 2 km thick in the eastern belt. The carbonate rocks average about 2.5 km thick in the central belt. The thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton, but the large thickness variation across the belts is primarily due to southeast-vergent Mesozoic thrusting (see section on Structural Geology below).

## Mesozoic Rocks

Mesozoic rocks are predominantly continental clastic units consisting of conglomerate, sandstone, siltstone, mudstone, shale, gypsum, but they also include minor limestone and dolostone. These rocks were deposited in fluvial, lacustrine, eolian, and marginal marine environments, and include Triassic, Jurassic, and Cretaceous units that are about 3 to 4 km thick (Bohannon, 1983). These rocks have low permeability compared with the Paleozoic carbonate rocks because of their high proportion of clastic material. They are generally considered confining units, but they may be permeable where highly fractured. Units containing large amounts of shale and mudstone, such as in the Triassic formations, generally have low permeability. The Jurassic Navajo Sandstone in the Utah part of the map area is an aquifer (Heilweil and others, 2002), but in other parts of southern Nevada, such as in Las Vegas Valley, the Aztec Sandstone has low permeability. This example illustrates the variability in hydrologic properties of the Mesozoic rocks in the map area. The distribution of Mesozoic rocks is limited to the eastern half of the map area, although some units extend into the Basin and Range province and westward into the Jurassic arc terrane of southeastern California (Marzolf, 1990). East-vergent thrusting related to the Sevier orogeny affected the map area from Early Cretaceous into early Tertiary time (see structure section below).

## Tertiary Rocks

Tertiary rocks in the map area belong to three sequences based on age. The oldest is the basal Tertiary unit of fluvial and lacustrine origin, partly derived from erosion of highlands resulting from Sevier deformation to the west. The best-known unit is the Eocene and Oligocene Claron Formation (Anderson and Rowley, 1975) that makes up the colorful rocks of Bryce Canyon National Park, but these rocks are confined to the northeastern part of the map area.

The second sequence consists of voluminous calc-alkaline volcanic rocks of rhyolite to andesite composition, as well as their source plutons. Most of these igneous rocks were deposited between about 35 to 20 Ma, but in the northern Colorado River extensional corridor near and south of Lake Mead, calc-alkaline magmatism began at about 20 Ma and continued until about 12 Ma (Faulds and others, 2001). Many volcanic rocks are ash-flow tuffs erupted from calderas, but stratovolcanoes were locally present. Ash-flow tuffs are potential aquifers where broken by faults. The largest caldera in the map area is the east-elongated (80 km east-west versus 35 km north-south) Caliente caldera complex (at least 24 Ma to 13.5 Ma, representing eruptions of calc-alkaline rocks, then bimodal rocks) in the northeastern part of the area (fig. 4). The caldera is broken by numerous north-striking fault zones that may provide important conduits for north-south groundwater flow in the region.

The third sequence of Tertiary rocks evolved during the major episode of east-west basin-range extension. North of Lake Mead, this extension took place from about 20 Ma to present (e.g., Rowley and Dixon, 2001). Over most of the map area, volcanic rocks of bimodal composition (high-silica rhyolite and basalt) and of generally low volume intertongue with basin-fill deposits. In the northern Colorado River extensional corridor, however, major extension followed and accompanied later calc-alkaline volcanism, whereas basalts generally accompanied only the waning stages of extension (Faulds and others, 2001). The basin-fill deposits are mostly fluvial sediments deposited in grabens that resulted from the basin-range faults. In some places, as in the Virgin Valley, the basin-fill sediments are at least 8 km thick (Langenheim and others, 2000, 2001a); they constitute the dominant aquifer in the Virgin Valley basin (Dixon and Katzer, 2002; Johnson and others, 2002). Langenheim and others (2001c) reported Tertiary basin-fill deposits in the California Wash basin (fig. 1) to be from 2 to 3 km thick based on seismic reflection and gravity data. The geometry of basins in the map area is generally complex, and geophysical investigations have demonstrated that many of the basins, such as Virgin Valley, Las Vegas Valley, and Meadow Valley Wash, consist of a series of sub basins (Langenheim and others, 2000, 2001a, b).

During basin-range extension, the map area was broken by mostly north-striking normal faults. Northeast-striking left lateral faults, northwest-striking right-lateral faults, and low angle normal (detachment) faults occur locally. In addition, the map area includes a series of east-striking transverse faults, which started to form in the late Mesozoic and early Tertiary (Ekren and others, 1976; Brothers and others, 1996; Rowley, 1998; Rowley and Dixon, 2001) and continued to deform the area.

# Structural Geology

Major thrust faults in the map area include the Muddy Mountain thrust in the Muddy Mountains and its equivalent thrusts that extend northward to the Beaver Dam Mountains (Square Top Mountain thrust), and the Gass Peak thrust in the eastern Sheep Range (fig. 4). The faults strike north to northeast and are part of the Sevier orogenic belt (Armstrong, 1968; Fleck, 1970). The Muddy Mountains thrust is the frontal thrust of the Sevier orogenic belt in southern Nevada. The thrust is reported to be late Albian to Cenomanian(?) in age (Bohannon, 1983; Carpenter and Carpenter, 1994; Fleck and Carr, 1990).

The thrust faults partly control the thickness of the Paleozoic carbonate aquifer from west to east across the map area. The Gass Peak thrust transported thick western facies rocks about 30 km eastward (Guth, 1980, 1981) above thin transitional central facies rocks. The Muddy Mountain thrust juxtaposes transition rocks above even thinner eastern facies cratonic platform rocks. Therefore, a large thickness variation exists in the Paleozoic rocks from west to east (from 6 km to less than 2 km) across the map area, because the rocks were telescoped into a narrower zone by Mesozoic thrusting.

The control of groundwater flow by thrust faults in the map area is poorly understood. Burbey (1997) suggested that Late Proterozoic-Lower Cambrian clastic confining units in the upper plate of the Gass Peak thrust may restrict eastward groundwater flow from the Sheep Range and areas to the west. The Muddy Mountain thrust in the Muddy Mountains juxtaposes Paleozoic carbonate rocks in the upper plate against less permeable Mesozoic rocks in the lower plate; such relationships suggest that the thrust acts as a flow barrier. Although the thrust may act as a barrier in localized zones along strike, we believe that overprinting of the thrust by Tertiary normal faults (California Wash fault zone; Langenheim and others, 2002) provides linkage between rocks in the upper and lower plates allowing for some component of groundwater flow across the thrust. This example may apply to other pre-Tertiary thrust faults in the map area, especially where the thrusts are highly modified by younger Tertiary extensional faults.

During Sevier thrusting and following its termination in the Paleocene, erosion of highlands created by these thrusts contributed clastic material that was shed largely to the east. The early Tertiary was a time of deep dissection of these highlands, with deposition of the resulting detritus in the northeastern part of the area and in areas farther east.

East-striking transverse fault zones began to form in the late Mesozoic and transected the Great Basin (Ekren and others, 1976; Rowley, 1998; Rowley and Dixon, 2001). Like transform zones in the ocean basins, they allowed the bounding crustal blocks to deform in different ways and at different rates. The transverse zones also partly controlled emplacement of plutons and caldera complexes, beginning with the start of calc-alkaline magmatism at about 35 Ma. The most notable of these zones in the map area is the Timpahute transverse zone (fig. 4), which defined the northern side of the Caliente caldera complex. Another zone, the Helene transverse zone (fig. 4), controlled not only the southern side of the Caliente caldera complex but also gold mineralization in Delamar and other mining districts on the southern side of the caldera complex. The Caliente caldera complex is elongated east-west because it was extended in that direction by north-striking normal faults and synchronous intracaldera eruptions were focused by bounding transverse faults.

In the northern part of the map area, east-west extension took place during calc-alkaline magmatism. Extension was accompanied by north-directed lateral compression, resulting in north-northeast- and north-northwest-striking strike-slip and oblique-slip faults (Rowley and Dixon, 2001). The oblique left-lateral, north-northeast-striking Kane Springs Wash fault zone (fig. 4) likely began to form during the time of calc-alkaline magmatism, as did the many unnamed right-lateral, northwest-striking faults in the northeastern part of the mapped area.

At about 20 Ma, with increased east-west extension, bimodal magmatism began in the Great Basin in the northern part of the map area (Rowley and Dixon, 2001). To the south, calc-alkaline intermediate magmatism began about 20 Ma and continued to about 12 Ma (Faulds and others, 2001). Locally before 10 Ma, basin-range faulting blocked out north-trending ranges and intervening basins. These faults, which define the Desert, Sheep, Arrow Canyon, and Delamar Ranges, are especially prominent in the western part of the map area. Locally, during east-west extension, east-northeast-striking faults formed, including the Pahranagat shear zone (fig. 4). The east-northeast-striking fault zones accommodate left-lateral oblique-slip movement and merge laterally with north-striking basin-range faults. The northwest-striking Las Vegas Valley shear zone (fig. 4) is a large magnitude right-lateral strike-slip transverse fault zone (Rowley, 1998) with about 50 km lateral offset. Major movement on the shear zone is constrained between 14 and 8.5 Ma (Duebendorfer and Black, 1992). The shear zone truncates the southern Las Vegas, Sheep, Desert, and Pintwater Ranges in the area and extends for nearly 150 km from the Lake Mead area to Mercury, Nevada.

## DESCRIPTION OF MAP UNITS

### Surficial Units

Relative age assignments for surficial deposits are estimated chiefly on the basis of their height above present streams, degree of post-depositional modification of original surface morphology, and degree of soil development—especially the morphology and thickness of calcium-carbonate-enriched horizons.

**Qa** **Channel alluvium (Holocene)** Unconsolidated silt, sand, and gravel in active channels and flood plains of rivers and streams. As thick as 10 m.

**Qay** **Young alluvium (Holocene to latest Pleistocene)** Unconsolidated fine- to coarse-grained gravel and sand and less common silt and clay deposited in alluvial fans and piedmont slopes. Deposits exhibit minor to no dissection. From 1 to 20 m thick.

**Qayf** **Young fine-grained alluvium (Holocene to late Pleistocene)** Unconsolidated silt, sand, and minor pebble gravel. Deposits form low relief surfaces and exhibit little or no dissection. Exposed in axial parts of valleys in distal portions of alluvial fans and adjacent to playa deposits (Qp). As thick as 10 m.

**Qp** **Playa deposits (Holocene to late Pleistocene)** Clay, silt, sand, and minor secondary carbonate and evaporite minerals. Playa surfaces are smooth and flat. As thick as 10 m.

**Qe** **Eolian deposits (Holocene)** Unconsolidated to slightly consolidated silt and sand deposited as dunes, sand ramps, and sand sheets. Deposits include buried paleosols. As thick as 10 m.

**Qsa** **Spring-apron deposits (Holocene to middle Pleistocene)** Mostly consolidated limestone and travertine deposited near fault-controlled springs. Limestone and travertine deposits contain organic debris (root casts and other plant material) and form spring mounds and aprons. Deposits exposed at southern end of Meadow Valley Mountains and California Wash areas, Nevada, and Virgin Valley area of Utah and Nevada. Generally less than 10 m thick.

**Qds** **Modern and past groundwater discharge deposits (Holocene to late Pleistocene)** Mostly unconsolidated to consolidated mud, silt, and sand, that locally form small bluffs in the axial parts of major basins. These sediments locally contain organic zones (black mats) and fossils such as fresh-water mollusks and late Pleistocene bone fragments of mammoth, horse, camel, and bison (Quade and others, 1995, 1998). Thickness 1 to 10 m.

**Qayo** **Intermediate alluvium (late to middle Pleistocene)** Partially consolidated sand and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes. Deposit surfaces have low to moderate relief and dissection and may stand as high as 10 m above active channels. From 0 to 10 m thick.

**Qao** **Old alluvium (middle to early Pleistocene)** Partly consolidated silt, sand, and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes. Deposits have well-developed calcareous soils and are moderately to highly dissected. From 0 to 30 m thick.

**QTa** **Oldest alluvium (early Pleistocene to Pliocene)** Consolidated sand and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes; includes well developed soil horizons. Deposit surfaces form ballena topography and are highly dissected. Unit mostly exposed in the proximal parts of major drainages flowing into the Colorado River, including Beaver Dam and Meadow Valley Washes. Unit may be 100 m thick or greater.

**QTls** **Landslide and megabreccia deposits (Pleistocene to Miocene?)** Unit includes highly brecciated rock-avalanche deposits and kilometer-size coherent landslide blocks. Base of unit may be bound by shear slip surface. Unit is composed mostly of Paleozoic bedrock units exposed along mountain range margins, as along the west side of the Sheep Range and west flank of the Beaver Dam Mountains. Maximum thickness about 100 m.

**QTc** **Calcrete (Pleistocene and Pliocene)** Well consolidated caliche containing embedded pebbles, cobbles, boulders, sand and silt. Caliche beds contain laminar and thin bedded to massive carbonate nodules and pisolites. Deposit surfaces have low relief and represent soil and/or groundwater deposition. Unit best exposed at Mormon Mesa (Machette, 1985). Unit is 1 to 20 m thick.

## Bedrock Units

Within much of the Tertiary section, we have followed the mapping strategy of Ekren and others (1977), in which sedimentary and volcanic units are subdivided based upon rock type and age range. The age range follows five main stages in the evolution of this part of the Basin and Range province. Unit 1 consists of sedimentary rocks that predate the oldest Tertiary volcanic units in the area. Unit 2 consists of the oldest Tertiary volcanic rocks of calc-alkaline composition, about 32 to 26 Ma; no sedimentary rocks are associated with this age range. Unit 3 consists of younger calc-alkaline volcanic rocks and related sedimentary rocks ranging in age from 26 to 18 Ma. Unit 4 consists of the older bimodal sequence (locally calc-alkaline) of volcanic rocks and related sedimentary rocks, associated in most areas with the early phases of major regional basin-range extension and ranging in age from 17 to 11 Ma. Unit 5 consists of the younger bimodal sequence of volcanic rocks and related sedimentary rocks associated with both the main episode of regional extension and waning extension, and ranges in age from about 11 to 2 Ma; volcanic rocks of this age are included within the older basaltic flows (Tb). Within the pre-Tertiary regional sedimentary section, some regional sedimentary units are separated geographically, into Proterozoic-Paleozoic facies belts, even though they may be partly or entirely correlative (see correlation of map units). This is because facies changes prevent exact correlations between areas and thus different names have been applied to rocks of the same age.

**Qb** **Younger basaltic lava flows (Pleistocene)** Exposed only in the northeastern Beaver Dam Mountains. Resistant, dark-gray and black, mostly crystal-poor olivine basalt lava flows and cinder cones. Maximum thickness of individual flow sequences about 100 m.

**Tb** **Older basaltic lava flows (Pliocene and Miocene)** Resistant, dark-gray and black, mostly crystal-poor olivine basalt lava flows and cinder cones. Includes flows in and near Kane Springs Valley of about 8.0 to 5.6 Ma (Scott and others, 1995b), and in the Lake Mead area of about 11 to 4.4 Ma (Faulds and others, 2001). Maximum thickness of individual flow sequences about 200 m.

**Ts5** **Sedimentary rocks, unit 5 (Pliocene and Miocene)** The primary unit is the Muddy Creek Formation (11 to 5 Ma). Muddy Creek Formation is soft to moderately consolidated, tan, gray, and pink, fluvial and lacustrine, tuffaceous sandstone, mudstone, gypsum, halite, and conglomerate that fills fault-block basins. Other named and unnamed units of the same general age fill many other basins: these include the Panaca Formation in the Panaca basin (Rowley and Shroba, 1991), and several unnamed units in northern Kane Spring Valley. The unit also includes age-equivalent basin-fill deposits in the Lake Mead area consisting of conglomerate, sandstone, siltstone, mudstone, limestone, and gypsum. Maximum thickness at least 1,000 m, but may be 3,000 m or more in deeper basins.

**Ts4** **Sedimentary rocks, unit 4 (Miocene and Oligocene)** Moderately to well consolidated, mostly gray and tan, fluvial and lacustrine, locally tuffaceous sandstone, tuff, conglomerate, limestone, siltstone, mudstone, and gypsum that fill the lower parts of fault-block basins. The primary unit is the Horse Spring Formation (20 to 12 Ma; Bohannon, 1984). Also included is the red sandstone unit (12 to 11 Ma) that unconformably overlies the Horse Spring Formation (Bohannon, 1984). Total maximum thickness of the Horse Spring at least 2,600 m in Muddy Mountains (Bohannon, 1984), but may be 3,000 m or more in deeper basins.

**Ts1** **Sedimentary rocks, unit 1 (Oligocene and Eocene)** Moderately to well consolidated, white, pink, red, and tan, fluvial and lacustrine limestone, sandstone, mudstone, and conglomerate that pinch out westward. Includes the Claron Formation (Oligocene and Eocene) in the northeast part of the map area; roughly correlative rocks extend as far west as the Dodge Spring Quadrangle (Anderson and Hintze, 1993), although they are only 70 m thick at that locality. Unit also includes age-equivalent basin-fill conglomerate and tuff as much as 100 m thick in the Pintwater Range area (Guth, 1980). Maximum thickness about 500 m.

**Tt4** **Ash-flow tuffs and interbedded airfall tuffs, unit 4 (Miocene)** Poorly to densely welded, crystal-poor, bimodal high-silica rhyolite and peralkaline ash-flow tuff and related airfall tuffs; gray, red, tan, and brown. Includes Ox Valley Tuff (13.5 Ma), tuff of Etna (14.0 Ma), tuff of Rainbow Canyon (15.6 Ma), tuff of Acklin Canyon (17.1 Ma), and tuff of Dow Mountain (17.4 Ma), derived from the Caliente caldera complex (Rowley and others, 1995; Snee and Rowley, 2000). Also includes the tuff of Narrow Canyon (15.8 Ma), tuff of Boulder Canyon (15.1 Ma), and Kane Wash Tuff (14.7 to 14.4 Ma), derived from the Kane Springs Wash caldera complex (Scott and others, 1995a, b). Maximum thickness of outflow sheets generally less than 200 m, but intracaldera tuffs at least 500 m thick.

**Tt3** **Ash-flow tuffs and interbedded airfall tuffs, unit 3 (Miocene and Oligocene)** Poorly to densely welded, crystal-poor and crystal-rich, calc-alkaline, low-silica rhyolite and dacite ash-flow tuff and related airfall tuffs; gray, brown, tan, and pink. Includes the tuff of Teepee Rocks (17.8 Ma), Hiko Tuff (18.3 Ma), Racer Canyon Tuff (18.7 Ma), and both Bauers Tuff Member (22.8 Ma) and Swett Tuff Member (23.7 Ma) of the Condor Canyon Formation, all derived from the Caliente caldera complex (Rowley and others, 1995; Snee and Rowley, 2000); the Harmony Hills Tuff (22.0 Ma), probably derived from the eastern Bull Valley Mountains (Williams, 1967; Anderson and Rowley, 1975); the Leach Canyon Formation (23.8 Ma), probably derived from the Caliente caldera complex (Williams, 1967; Anderson and Rowley, 1975); and the Pahranagat Formation (22.6 Ma) and Shingle Pass Tuff (26.4 Ma), derived from the central Nevada caldera complex (Best and others, 1993) 50 km north of the map area. Thickness of individual outflow sheets generally less than 300–450 m, but thickness of intracaldera tuffs at least 1,000 m.

**Tt2** **Ash-flow tuffs and interbedded airfall tuffs, unit 2 (Oligocene)** Moderately to densely welded, crystal-poor and crystal-rich, calc-alkaline, low-silica rhyolite, dacite, and trachydacite ash-flow tuff and related airfall tuffs; gray, brown, reddish-brown, and pink. Includes the Isom Formation (about 27 Ma), probably derived from the Indian Peak caldera complex (Best and others, 1993) 20 km north of the map area; the Monotony Tuff (27.3 Ma), derived from the central Nevada caldera complex (Best and others, 1993); and the Needles Range Group (32 to 28 Ma), derived from the Indian Peak caldera complex (Best and others, 1989). Thickness of individual outflow sheets generally less than 500 m.

**Tr4** **Rhyolite lava flows, unit 4 (Miocene)** High-silica rhyolite. Includes thick sequences in the Caliente caldera complex, some related to emplacement of the Ox Valley Tuff. Maximum thickness about 300 m.

**Tr3** **Rhyolite lava flows, unit 3 (Miocene and Oligocene)** Low-silica rhyolite. Includes an east-striking string of domes and dikes along the south side of the Caliente caldera complex that have the same age as the Hiko Tuff. Maximum thickness about 300 m.

**Ta4** **Intermediate-composition lava flows, unit 4 (Miocene)** Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia; red, reddish-brown, brown, and gray. Andesite of the Hamblin-Cleopatra volcano (14.2 to 11.5 Ma) in the southern Lake Mead area (Anderson, 1973). Maximum thickness about 300 m.

**Ta3** **Intermediate-composition lava flows, unit 3 (Miocene and Oligocene)** Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia; red, reddish-brown, brown, and gray. In the northeast part of the map area, includes the crystal-rich andesite of Maple Ridge underlying the Racer Canyon Tuff, and the andesite of Little Creek that lies between the Harmony Hills Tuff and the Condor Canyon Formation (Blank, 1959, 1993; Rowley and others, in press). Includes thick stratovolcano deposits, derived from an adjacent pluton, between the Caliente and Kane Springs Wash caldera complexes. Maximum thickness about 1,000 m.

**Tg** **Granitic intrusive rocks (Miocene)** Granite or other silicic intrusive rock; gray, tan, and locally pink. On the north side of the Kane Spring Wash caldera complex, includes the trachyte stock of Sawmill Spring (14.4 Ma), which postdates volcanic units from the complex. On the west side of the Kane Springs Wash caldera complex, includes the stock of Jumbo Wash, which predates volcanic units from the complex, but is probably less than 15.6 Ma (Scott and others, 1995b).

**Tai** **Intermediate-composition intrusive rocks (Miocene and Oligocene)** Gray quartz monzonite, granodiorite, diorite, and other intermediate-composition intrusive rocks. In the Lake Mead area, includes diorite and granodiorite source plutons for the Hamblin-Cleopatra volcano and the volcanic rocks of the Black Mountains. In the south Clover Mountains and southwest Bull Valley Mountains, includes 22 to 20 Ma quartz monzonite porphyry plutons of the northeast-striking Iron Axis, such as the Mineral Mountain pluton (Hacker and others, 2002; Rowley and others, in press); includes small dioritic breccia pipes and a nearby large, although fault-fragmented, diorite and granodiorite pluton that was the source of an andesitic stratovolcano complex along the south side of the Caliente caldera complex. Includes the 25-Ma Cobalt Canyon stock of quartz monzonite at the northern edge of the map area (Rowley and others, 1994).

**TKg** **Grapevine Wash Formation (Tertiary? and Cretaceous?)** Mostly tan conglomerate and sandstone derived from erosion of Sevier thrust sheets. Exposed northwest of Gunlock, Utah, where its maximum thickness is about 600 m.

**Kmg** **Granite of Walker Wash (Upper Cretaceous)** Muscovite-biotite granite exposed in Walker Wash of the Lake Mead area; intrudes Early Proterozoic gneiss.

**Ku** **Cretaceous rocks, undivided (Upper and Lower Cretaceous)** Sevier-age synorogenic deposits, including the Baseline Sandstone and Willow Tank Formation, and the Iron Springs Formation and Cedar Mountain Formation. The Baseline Sandstone consists of red, white, and brown sandstone and conglomerate. The Willow Tank Formation consists of conglomerate, sandstone, siltstone, and mudstone; also includes tuff beds with a K-Ar date of about 98 Ma (Fleck, 1970). The Baseline Sandstone and Willow Tank Formation, which overlie Jurassic sandstone along an angular unconformity, are exposed mostly in the Muddy Mountains and are from 1,000 to more than 1,600 m thick. In the northeast part of the map area, unit consists of the Iron Springs Formation, which is tan mudstone, shale, sandstone, and conglomerate about 1,000 m thick. The Iron Springs Formation is underlain by a 7-m-thick bentonite bed which has a fission-track date of 101.7 Ma; beneath the bentonite bed is the Cedar Mountain Formation which is gray conglomerate about 20 m thick (Biek, 2003; Hintze and others, 1994).

**Jct** **Carmel and Temple Cap Formations, undivided (Middle Jurassic)** The Carmel Formation consists of red and gray siltstone, limestone, dolostone, and mudstone about 160 m thick and containing a tuff bed dated at 165 Ma (Hintze and others, 1994). The underlying Temple Cap Formation consists of red mudstone, sandstone, and gypsum as much as 150 m thick.

**Jam** **Aztec Sandstone, Navajo Sandstone, Kayenta Formation, and Moenave Formation, undivided (Lower Jurassic)** Includes the Aztec Sandstone in most of southern Nevada (Basin and Range province), and the correlative Navajo Sandstone in southwest Utah and northwest Arizona (Colorado Plateau province). Unit also includes the Kayenta and Moenave formations which underlie both the Aztec Sandstone and Navajo Sandstone. Aztec, Navajo, and Kayenta Formations are red, yellow, and light gray, fine-grained, cliff-forming, cross-bedded quartzose sandstone; the Moenave Formation consists of resistant red siltstone, shale, and sandstone. Gradational contact between map unit and underlying Triassic rocks. Aztec is from 850 to 1,200 m thick in the Muddy and Virgin Mountains and about 200 m thick at Frenchman Mountain; Navajo is 600–700 m thick; combined thickness of Kayenta and Moenave Formations ranges from 170 to 800 m.

**ŦRu** **Triassic rocks, undivided (Triassic)** Includes Chinle and Moenkopi Formations. The Chinle Formation (Upper Triassic) consists of the Petrified

Forest and Shinarump Members; the Petrified Forest Member is variegated red, purple, gray, and yellow, bentonitic mudstone, siltstone, and sandstone. The underlying Shinarump Member is orange, brown and gray, massive-bedded, trough-crossbedded conglomeratic sandstone and conglomerate; includes some petrified wood fragments. The Chinle Formation unconformably overlies the Moenkopi Formation (Middle? and Lower Triassic) which consists, from top to base, of the upper red member, Shnabkaib Member, Virgin Limestone Member, lower red member, and Timpoweap Member. The upper red member is red sandstone, siltstone, mudstone, conglomerate, and gypsum. The Shnabkaib Member is white, light gray, and pink to red slope-forming dolostone, mudstone, siltstone, sandstone, and gypsum. The Virgin Limestone Member is thin bedded to laminated limestone and dolostone, and gypsiferous siltstone and mudstone. The Timpoweap Member is gray, sandy limestone and gypsiferous siltstone, yellow and red conglomeratic sandstone, and gray to brown conglomerate. Moenkopi Formation unconformably overlies the Kaibab Limestone. Map unit is about 1,000 m thick.

**Pkt** **Kaibab and Toroweap Formations undivided (Lower Permian)** The Kaibab Formation consists of the Harrisburg and Fossil Mountain Members. The Harrisburg Member consists of gray and yellow cherty dolostone and limestone, and red and gray siltstone, sandstone, and gypsum. The Fossil Mountain Member is yellowish-gray sandy and cherty limestone. The Toroweap Formation consists of the Woods Ranch, Brady Canyon, and Seligman Members. The Woods Ranch Member is gray, orange, and red siltstone, sandstone, gypsum, and minor dolostone and limestone. The Brady Canyon Member is gray cherty limestone and dolostone. The Seligman Member is gray and red sandy limestone, dolostone, gypsiferous sandstone, siltstone, and minor shale. The Toroweap Formation unconformably overlies the Lower Permian redbeds unit. Combined, the Kaibab and Toroweap Formations are about 300 to 550 m thick.

**Pr** **Lower Permian redbeds** Red and tan cross-bedded sandstone, siltstone, and sandy shale. Unit defined by Longwell and others (1965) and correlated with parts of the Queantoweap and Esplanade Sandstones and the Hermit Formation. Unit is 400 to 600 m thick.

**PPc** **Callville Limestone and related rocks (Lower Permian and Pennsylvanian)** Mapped in the Virgin and Beaver Dam Mountains. Map unit partly equivalent to the Bird Spring Formation. The Callville Limestone (Pennsylvanian) consists of gray fossiliferous limestone and dolostone. Also includes layers and nodules of brown chert; brown sandstone beds common in upper half. Map unit includes the Pakoon Dolostone (Lower Permian). The Pakoon is light-gray dolostone with minor limestone, sandstone, and gypsum. Unit is from 460 to 880 m thick.

**PMb** **Bird Spring Formation and related rocks (Lower Permian to Upper Mississippian)** Gray and yellowish-gray bioclastic limestone, dolostone, siltstone, silty limestone, brown sandstone, and gray and red shale. Forms stair-step ledges. Contains abundant discontinuous layers and nodules of gray to brown-weathering chert; chert makes up more than 50 percent of rock volume in some beds. Upper part is mostly gray cherty bioclastic limestone and brown sandstone of Leonardian age (Page and others, 2005). Middle part is a distinctive red, silty limestone marker unit (Page, 1992, 1993, and 1998); marker unit contains submarine debris flow conglomerate and turbidite beds and represents a slope to basin sequence in contrast to the carbonate shelf sequence that typifies most of the Bird Spring Formation in the region. The basal 20 to 60 m of the map unit in west and south-central parts of map area consists of the Upper Mississippian Indian Springs Formation of Webster and Lane (1967) and Webster (1969). The Indian Springs Formation is yellowish-gray bioclastic limestone, black to red shale, and tan sandstone. The map unit attains a maximum thickness in the Las Vegas Range area, where it is about 2,500 m thick; top of unit not exposed in most of map area.

**Msc** **Scotty Wash Quartzite and Chainman Shale (Upper Mississippian)** Mapped in northern Meadow Valley Mountains near the margin of Kane Springs Wash. Scotty Wash Quartzite is tan, red and brown crossbedded quartzite. The Chainman Shale is black, olive-gray, and brown, fissile shale, red siltstone, and gray limestone. The siltstone is exposed mostly in the lower part of the unit and is interbedded with thin, crinoidal limestone. Map unit is partly correlative with Indian Springs Formation of Webster and Lane (1967). Unit is 200 to 320 m thick.

**Mm** **Monte Cristo Group of Langenheim and others (1962) (Upper and Lower Mississippian)** Carbonate platform rocks consisting of Yellowpine, Bullion, Anchor, and Dawn Limestones. The Yellowpine Limestone is gray limestone containing sparse nodules of gray to brown chert. The Bullion Limestone is gray encrinitic limestone and some beds of brown chert. The Anchor Limestone is gray limestone and brown chert. The Dawn Limestone is gray bioclastic, oolitic limestone and brown chert. The Monte Cristo Group is about 300 m thick in the Muddy Mountains and Tule Springs Hills, 280 m thick in the Mormon Mountains, 460 m thick in the southern Meadow Valley Mountains, and about 500 m thick in the Arrow Canyon and south Las Vegas Ranges.

**Mr** **Redwall Limestone (Upper and Lower Mississippian)** Consists of the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members. Unit is mostly equivalent to the Monte Cristo Group of Langenheim and others (1962) but is thinner and represents cratonic platform sequence of the Colorado Plateau province. Members of the Redwall are correlative and lithologically similar to the Yellowpine, Bullion, Anchor, and Dawn Limestones of the Monte Cristo Group, respectively. The Horseshoe Mesa Member consists of cliff-forming limestone containing nodules and layers of chert. The Mooney Falls Member is cliff-forming bioclastic limestone. The Thunder Springs Member consists of bioclastic limestone and chert. The Whitmore Wash Member is gray, bioclastic limestone and dolostone. Mapped in the Virgin and Beaver Dam Mountains and Lake Mead area. The Redwall Limestone is about 200 to 260 m thick.

**MDu** **Lower Mississippian to Middle Devonian rocks, undivided** In western part of the map area unit consists of the Upper and Middle Devonian Guilmette Formation and either the overlying Lower Mississippian and Upper Devonian Crystal Pass Limestone (in the Arrow Canyon Range and south Meadow Valley Mountains) or the Lower Mississippian and Upper Devonian Pilot Shale and Lower Mississippian Joana Limestone (in the north Meadow Valley Mountains, Delamar Mountains, and Sheep Range). The Crystal Pass Limestone is micritic limestone containing sparse gastropods and intraclasts and is about 60 to 70 m thick. The Joana Limestone is gray, cherty, bioclastic limestone about 250 m thick. The Pilot Shale is gray and red platy limestone and is about 215 m thick in the Meadow Valley Mountains. The Guilmette Formation is gray burrow-mottled dolostone and limestone and minor dolomitic quartzite. The Guilmette Formation is 440 to 480 m thick. In eastern part of map area (Muddy Mountains, Tule Springs Hills, and Mormon Mountains), map unit includes Sultan Limestone of Hewett (1931). The Sultan Limestone is mostly equivalent to, but thinner than the Guilmette Formation, and includes the Crystal Pass, Valentine, and Ironside Members. The Valentine and Ironside Members consist of dark-gray limestone and light-gray dolostone. The Sultan is 200 to 400 m thick in the map area.

**Dtb** **Temple Butte Formation (Upper and Middle? Devonian)** Gray dolostone with subordinate beds of purple and gray siltstone and sandstone. Unit represents a cratonic platform sequence of the Colorado Plateau province and is partly equivalent to the Sultan Limestone and Guilmette Formation but is restricted to a Devonian age. Also partly equivalent to the Muddy Peak Limestone of Longwell (1921). Unit mapped in the Virgin and Beaver Dam Mountains and the Lake Mead area. Unit is 150 to 220 m thick in the Beaver Dam Mountains and 60 to 120 m thick in the Virgin Mountains.

**DSu** **Middle Devonian to Silurian rocks, undivided** Miogeoclinal sequence exposed in western part of map area, includes rocks equivalent to parts of the Middle Devonian Simonson Dolomite, the Lower Devonian Sevy Dolomite, and the Silurian Laketown Dolomite. The Simonson Dolomite consists of light to dark gray dolostone, 250 m thick in the Sheep Range and southern Delamar Mountains, 170 m thick in the Meadow Valley Mountains, and 100 m thick in the Arrow Canyon Range. The Sevy Dolomite consists of gray, aphanic dolostone to dolomudstone that includes cherty argillaceous unit of Johnson and others (1989) at top. The Sevy Dolomite is 235 m thick in the southern Delamar Mountains, and 100 to 150 m thick in the Meadow Valley Mountains and Arrow Canyon Range. The Laketown Dolomite displays a tri-part character that is widely recognized in the Great Basin: upper dark, middle light, and lower dark dolostone parts; the upper dark dolostone is medium dark gray, fossiliferous dolostone. The middle part is light-gray, fossiliferous dolostone. The lower part is medium-gray, vuggy and burrowed dolostone containing some layers and nodules of brown chert. The Laketown Dolomite is Early Silurian age based on conodonts collected in the Sheep Range (Page and others, 2005). The Laketown Dolomite is about 300 m thick in the Sheep Range and southern Delamar Mountains, 150 m thick in the Meadow Valley Mountains, about 160 m thick in the Lime Mountain area, and about 100 m thick in the Arrow Canyon Range. In the latter two areas, typical tri-part character is absent and the rocks are mostly light-gray dolostone.

**SOu** **Silurian and Ordovician rocks, undivided** Unit mapped only in Mormon Mountains and Tule Springs Hills and includes rocks equivalent to parts of the Silurian Laketown Dolomite, Upper Ordovician Ely Springs Dolomite, Middle Ordovician Eureka Quartzite, and Middle and Lower Ordovician Pogonip Group. Unit is about 260 m thick in the Mormon Mountains and 730 m thick in Tule Springs Hills.

**Oes** **Ely Springs Dolomite (Upper Ordovician)** In the western part of map area, uppermost part of unit is composed of light-olive-gray, burrow-mottled, finely saccharoidal dolostone to dolomudstone. Middle and lower parts of the formation consist of medium-dark-gray dolostone containing planar laminations and some scattered chert. In the Arrow Canyon Range, basal beds include pale-red shale and siltstone. Unit unconformably overlies Eureka Quartzite. Unit is from 120 to 140 m thick in the western part of the map area, and 100 m thick in the Tule Springs Hills and Mormon Mountains, and is absent in the Virgin, Beaver Dam, and Muddy Mountains, as well as at Frenchman Mountain and in the Lake Mead area.

**Oep** **Eureka Quartzite (Middle Ordovician) and Pogonip Group (Middle Ordovician to Upper Cambrian), undivided** Unit mapped in the Meadow Valley Mountains (460 m thick), southern Delamar Mountains (610 m thick), and the Arrow Canyon Range (650 m thick). Rocks are lithologically similar to, but thinner than those described for the Eureka Quartzite (Oe) and Pogonip Group (O€p) below.

**Oe** **Eureka Quartzite (Middle Ordovician)** Light- to moderate-brown and white to light-brown, fine to medium grained quartzite, friable sandstone, and minor sandy carbonate beds. Contains tabular-planar crossbeds and *skolithus* burrows. Map unit is 50 to 120 m thick in the Sheep and Desert Ranges, 40 to 50 m thick in the southern Delamar Mountains and Arrow Canyon Range, 10 m thick in the Dry Lake Range, and 3 to 8 m thick in the Mormon Mountains and Tule Springs Hills. Unit is absent in cratonic platform (Frenchman Mountain, Lake Mead area, and the Muddy, Virgin, and Beaver Dam Mountains).

**Op** **Pogonip Group (Lower Ordovician)** Unit exposed only in the Muddy Mountains and consists of cherty gray dolostone equivalent to Lower Ordovician part of the Pogonip Group; these rocks were called the Monocline Valley Formation by Longwell and Mound (1967) and Bohannon (1983). Map unit is 220 m thick. Ordovician rocks are absent in cratonic platform (Frenchman Mountain, Lake Mead area, and Virgin and Beaver Dam Mountains).

**O€p** **Pogonip Group (Middle Ordovician to Upper Cambrian)** Miogeoclinal section of the Pogonip Group exposed in western part of map area. Consists of the Antelope Valley and Goodwin Limestones. The Antelope Valley Limestone consists of gray to orange and yellowish-gray bioclastic and arenaceous limestone and dolostone. Beds are burrow-mottled and have abundant ooids, oncoids, and intraclasts, and contain scattered brown chert nodules and layers. Lower part of unit is equivalent to the Goodwin Limestone which consists of orange and gray limestone and abundant brown chert layers, intraclasts, and ooids. Samples from the lower beds of the Goodwin Limestone in the Sheep Range and in ranges to the west have produced Late Cambrian conodonts (Page and others, 2005). Pogonip Group is 600 to 900 m thick.

**€nb** **Nopah (Upper Cambrian) and Bonanza King (Upper and Middle Cambrian) Formations, undivided** Mapped only in the Mormon Mountains and Tule Springs Hills.

**€n** **Nopah Formation (Upper Cambrian)** Light- to dark-gray burrow-mottled dolostone, minor gray to orange silty limestone, and scattered chert layers and nodules. Alternating light and dark gray beds form several distinctive color bands. At base of unit, includes the Dunderberg Shale Member, which consists of brown silty limestone and siltstone and olive green shale. Map unit is 300 to 380 m thick in the Sheep Range, 560 m in the southern Delamar Mountains, about 400 m thick in the Meadow Valley Mountains, 115 m thick in the Mormon Mountains, about 200 m thick in the Tule Springs Hills and Muddy Mountains, and 400 m thick in the Beaver Dam Mountains.

**€bk** **Bonanza King Formation (Upper and Middle Cambrian)** Light- to dark-gray and olive-gray dolostone and subordinate light-brown to orange, silty dolostone. Partly equivalent to the Highland Peak Formation as used by Tschanz and Pampeyan (1970) in Lincoln County, and to the Muav Formation of the Colorado Plateau province. Unit is 900 m thick in the Sheep Range, 700 m thick in the Meadow Valley Mountains, 770 m thick in the Mormon Mountains and Tule Springs Hills, and 1,800 m thick in the Desert Range.

**€hp** **Highland Peak Formation (Upper and Middle Cambrian)** Light- and dark-gray limestone and dolostone. Unit is restricted to Delamar Mountains in the northern part of the map; well exposed in the Pioche mining district where it was first named (Westgate and Knopf, 1932) and described (Merriam, 1964). Unit has a maximum thickness of 1,500 m.

**Ꞓm** **Muav Limestone (Middle Cambrian)** Light to dark gray and brown limestone, dolostone, and mudstone. Cratonic platform facies exposed in the eastern part of the map area (Beaver Dam and Virgin Mountains, Lake Mead area, and Frenchman Mountain). Unit as much as 410 m thick in the northern Virgin Mountains.

**Ꞓc** **Carrara Formation (Middle and Lower Cambrian)** Gray, yellow, and red limestone, siltstone, sandstone, and shale. Exposed in the western part of the map area. About 300 m thick in the Desert Range area, and about 265 m thick in the Sheep Range.

**Ꞓcp** **Chisholm Shale and Lyndon Limestone (Middle Cambrian) and Pioche Shale (Middle and Lower Cambrian), undivided** Unit exposed only in the Delamar Mountains in northern part of map area. Chisholm Shale is brown shale (Walcott, 1916; Westgate and Knopf, 1932) about 35 m thick. The Lyndon Limestone is gray limestone and sandstone (Westgate and Knopf, 1932) about 50 m thick. The Pioche Shale is green shale (Walcott, 1908) as much as 275 m thick.

**Ꞓbt** **Bright Angel Shale (Middle and Lower Cambrian) and Tapeats Sandstone (Lower Cambrian), undivided** Cratonic platform facies mapped in the Mormon Mountains, Tule Springs Hills, Frenchman Mountain, Lake Mead area, and Virgin and Beaver Dam Mountains. The Bright Angel Shale is greenish gray and gray micaceous siltstone, sandstone, quartzite, and minor limestone and dolostone. Equivalent to the Pioche Shale, Lyndon Limestone, and Chisolm Shale defined in the Pioche, Nevada area, and to the Carrara Formation in the western part of the map area. The Bright Angel Shale is about 140 m thick in the Mormon Mountains, 80 to 100 m thick in the Beaver Dam and Virgin Mountains, and 180 m thick at Frenchman Mountain. The Tapeats Sandstone is orange quartzite, conglomerate, and sandstone. Equivalent in part to the Prospect Mountain Quartzite as used in parts of Lincoln and Clark County, Nevada (Tschanz and Pampeyan, 1970; Longwell and others, 1965). About 145 m thick in the Mormon Mountains, 365 m thick in the Beaver Dam Mountains, 80 m thick in the Virgin Mountains, and 50 m thick at Frenchman Mountain.

**ꞒZw** **Wood Canyon Formation (Lower Cambrian and Late Proterozoic)** Brown quartzite, sandstone, siltstone, shale, and sandy shale. Lower contact with the Stirling Quartzite is transitional. Unit is about 600 to 700 m thick in the Desert Range, and an incomplete section in the Sheep Range is about 450 m thick. Unit is exposed in the northern part of the map area in Delamar Mountains, and is as much as 480 m thick (Stewart, 1984).

**Zs** **Stirling Quartzite (Late Proterozoic)** Purple, pink, maroon, gray, and white conglomeratic quartzite, quartzite, and sandstone, and minor beds of sandy shale and siltstone. Lower contact with the Johnnie Formation is transitional. Unit is 945 m thick in the Desert Range, but only the uppermost 100 m is exposed in Las Vegas Range (Maldonado and Schmidt, 1991). In the north part of the map area (Delamar Mountains), upper contact is transitional with the Wood Canyon Formation, and formation is as much as 600 m thick, with the base not exposed (Stewart, 1984).

**Zj** **Johnnie Formation (Late Proterozoic)** Brown, gray, and green quartzite, sandstone, siltstone, and dolostone. Upper part contains greater proportion of shale compared to lower part and several brown to tan oolitic dolostone beds. Lower part is predominantly fine-grained quartzite and thin beds of shale. Unit is about 1,580 m thick in the Desert Range.

**Xu** **Early Proterozoic crystalline rocks** Gneiss, schist, and granite exposed at Frenchman Mountain, Lake Mead area, Virgin Mountains, Beaver Dam Mountains, and Mormon Mountains. Rocks are dated at 1.7 Ga (Quigley and others, 2002).

## REFERENCES


Anderson, J.J., and Rowley, P.D., 1975, Cenozoic stratigraphy of the southwestern High Plateaus of Utah, *in* Anderson, J.J., Rowley, P.D., Fleck, R.J., and Nairn, A.E.M., eds., Cenozoic geology of southwestern High Plateaus of Utah: Geological Society of America Special Paper 160, p. 1–52.

Anderson, R.E., 1973, Large magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Anderson, R.E., 2003, Geologic map of the Callville Bay Quadrangle, Clark County, Nevada, and Mohave County, Arizona: Nevada Bureau of Mines and Geology Map 139, 1:24,000.

Anderson, R.E., and Hintze, L.F., 1993, Geologic map of the Dodge Spring Quadrangle, Washington County, Utah, and Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1721, scale 1:24,000.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin v. 79, p. 429–458.

Axen, G.J., Wernicke, B.P., Skelly, M.F., and Taylor, W.J., 1990, Mesozoic and Cenozoic tectonics of the Sevier thrust belt in the Virgin River Valley area, southern Nevada, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 123–154.

Beard, Sue, 1991, Preliminary geologic map of the Devils Throat quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 91-132, scale 1:24,000.

Beard, Sue, 1992, Preliminary geologic map of the St. Thomas Gap quadrangle, Clark County, Nevada, and Mohave County, Arizona: U.S. Geological Survey Open- File Report 92-326, scale 1:24,000.

Beard, Sue, 1993, Preliminary geologic map of the Whitney Pocket quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 93-716, scale 1:24,000.

Beard, Sue, Anderson, R.E., Block, D.L., Bohannon, R.G., Brady, R.J., Castor, S.B., Duebendorfer, E.M., Faulds, J.E., Howard, K.A., Kuntz, M.A., Rowland, S.M., Wallace, M.A., and Williams, V.S., in press, Geologic map of the Lake Mead 30’ x 60’ Quadrangle, Nevada, U.S. Geological Survey Scientific Investigation Map Series, scale 1:100,000.

Belcher, W.R., Faunt, C.C., and D’Agnese, F.A., 2002, Three-dimensional hydrogeologic framework model for use with a steady-state numerical ground-water flow model of the Death Valley regional flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 01-4254.

Bell, J.W., and Smith, E.I., 1980, Geologic map of the Henderson Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 67, scale 1:24,000.

Bell, J.W., Ramelli, A.R., and Caskey, S.J., 1998, Geologic map of the Tule Springs Park Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 113, scale 1:24,000.

Bell, J.W., Ramelli, A.R., dePolo, C.M., Maldonado, F., and Schmidt, D.L., 1999, Geologic map of the Corn Creek Springs Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 121, scale 1:24,000.

Best, M.G., Christiansen, E.H., and Blank, R.H., Jr., 1989, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah: Geological Society of America Bulletin, v. 101, p. 1076–1090.

Best, M.G., Scott, R.B., Rowley, P.D., Swadley, W C, Anderson, R.E., Gromme, C.S., Harding, A.E., Deino, A.L., Christiansen, E.H., Tingey, D.G., and Sullivan, K.R., 1993, Oligocene-Miocene caldera complexes, ash-flow sheets, and tectonism in the central and southeastern Great Basin, *in* Lahren, M.M., Texler, J.H., Jr., and Spinosa, C., eds., Crustal evolution of the Great Basin and Sierra Nevada: Field Trip Guide, Geological Society of America, Cordilleran and Rocky Mountain Sections Meeting, p. 285–311.

Biek, R.F., 2003, Geologic map of the Harrisburg Junction Quadrangle, Washington County, Utah: Utah Geological Survey Map 191, 1:24,000.

Billingsley, G.H., 1995, Geologic map of the Littlefield quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-559, scale 1:24,000, 15 p.

Billingsley, G.H., and Bohannon, R.G., 1995, Geologic map of the Elbow Canyon quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-560, scale 1:24,000, 16 p.

Billingsley, G.H., and Wellmeyer, J.L., 2003, Geologic map of the Mount Trumbull 30' X 60' Quadrangle, Mohave and Coconino Counties, Arizona: U.S. Geological Survey Geological Investigations Series Map I-2766, scale 1:100,000.

Billingsley, G.H., and Workman, J.B., 1998, Geologic map of the Littlefield 30' x 60' Quadrangle, Mohave County, northwestern Arizona: U.S. Geological Survey Miscellaneous Field Investigations Map I-2628, scale 1:100,000.

Blank, H.R., Jr., 1959, Geology of the Bull Valley district, Washington County, Utah [Ph.D. dissertation]: University of Washington, 177 p.

Blank, H.R., 1993, Preliminary geologic map of the Enterprise Quadrangle, Washington and Iron Counties, Utah: U.S. Geological Survey Open-File Report 93-203, scale 1:24,000.

Bohannon, R.G., 1983, Geologic map, tectonic map, and structure sections of the Muddy and northern Black Mountains, Clark County, Nevada: U.S. Geological Survey Miscellaneous Investigations Map I-1406, scale 1:62,500.

Bohannon, R.G., 1984, Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona: U.S. Geological Survey Professional Paper 1259, 72 p.

Bohannon, R.G., 1991, Geologic map of the Jacobs Well and southern part of the Elbow Canyon quadrangles, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2288, scale 1:24,000.

Bohannon, R.G., 1992a, Geologic map of the Weiser Ridge Quadrangle, Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1714, scale 1:24,000.

Bohannon, R.G., 1992b, Geologic map of the Red Pockets quadrangle, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2288, scale 1:24,000.

Bohannon, R.G., Grow, J.A., Miller, J.J., and Blank, R.H., Jr., 1993, Seismic stratigraphy and tectonic development of Virgin River depression and associated basins, southeastern Nevada and northwestern Arizona: Geological Society of America Bulletin, v. 105, p. 501–520.

Bohannon, R.G., and Lucchitta, Ivo, 1991, Geologic map of the Mount Bangs quadrangle, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2166, scale 1:24,000.

Bohannon, R.G., Lucchitta, Ivo, and Anderson, R.E., 1991, Geologic map of the Mountain Sheep Spring quadrangle, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-2265, scale 1:24,000.

Brady, R.J., Fryxell, J.E., and Wernicke, B.P., 2002, Preliminary geologic map of the Iceberg Canyon Quadrangle, Clark County, Nevada and Mohave County, Arizona: Nevada Bureau of Mines and Geology Open-File Report 03-18, 1:24,000.

Brothers, K., Katzer, T., and Johnson, M., 1996, Hydrology and steady state ground-water model of Dry Lake and Delamar Valleys, Lincoln County, Nevada: Las Vegas Valley Water District, Cooperative Water Project, Water for Nevada's Future, Report no. 16, Hydrographic basins 181 & 182, 47 p.

Burbey, T.J., 1997, Hydrogeology and potential for ground-water development, carbonate-rock aquifers, southern Nevada and southeastern California: U.S. Geological Survey Water-Resources Investigations Report 95-4168, 65 p.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025–1028.

Carpenter, J.A., and Carpenter, D.G., 1994, Structural and stratigraphic relations in a critical part of the Mormon Mountains, Nevada, *in* Dobbs, S.W., and Taylor, W.J., eds.: Nevada Petroleum Society 1994 Conference Volume II, (Book 1), p. 95–126.

Castor, S.B., Faulds, J.E., Rowland, S.M., and dePolo, C.M., 2000, Geology of the Frenchman Mountain Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 127, scale 1:24,000.

D'Agnese, F.A., Faunt, C.C., Turner, K., and Hill, M.C., 1997, Hydrogeologic evaluation and numerical simulation of Death Valley regional ground-water flow system, Nevada and California: Water-Resources Investigations Report 96-4300, 124 p.

D'Agnese, F.A., O'Brien, G.M., Faunt, C.C., Belcher, W.R., and San Juan, Carma, 2002, A three-dimensional numerical model of predevelopment conditions in the Death Valley regional ground-water flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 02-4102, 114 p.

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

Dixon, G.L., and Katzer, T.C., 2002, Geology and hydrology of the lower Virgin River Valley in Nevada, Arizona, and Utah: Virgin Valley Water District, Mesquite, Nevada, Report no. VVWD-01, 126 p.

Duebendorfer, E.M., 2003, Geologic map of the Government Wash Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 140, scale 1:24,000.

Duebendorfer, E.M., and Black, R.A., 1992, Kinematic role of transverse structures in continental extension: an example from the Las Vegas Valley shear zone, Nevada: Geology, v. 20, p. 1107–1110.

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

Eakin, T.E., 1966, A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p. 251–271.

Eakin, T.E., and Winograd, I.J., 1965, Interbasin movement of ground water in south central Nevada-Some implications: Geological Society of America Special Paper 82, 52 p.

Ekren, E.B., Bucknam, R.C., Carr, W.J., Dixon, G.L., and Quinlivan, W.D., 1976, East-trending structural lineaments in central Nevada: U.S. Geological Survey Professional Paper 986, 16 p.

Ekren, E.B., Orkild, P.P., Sargent, K.A., and Dixon, G.L., 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1041, scale 1:250,000.

Faulds, J.E., Feuerbach, D.L., Miller, C.F., and Smith, E.I., 2001, Cenozoic evolution of the northern Colorado River extensional corridor, southern Nevada and northwest Arizona, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The geologic transition, High Plateaus to Great Basin-A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 239–272.

Fleck, R.J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: Geological Society of America Bulletin, v. 81, p. 1705–1720.

Fleck, R.J., and Carr, M.D., 1990, The age of the Keystone thrust: Laser-fusion $^{40}Ar/^{39}Ar$ dating of foreland basin deposits, southern Spring Mountains, Nevada: Tectonics, v. 9, p. 467–476.

Guth, P.L., 1980, Geology of the Sheep Range, Clark County, Nevada [Ph.D. thesis]: Massachusetts Institute of Technology, 189 p.

Guth, P.L., 1981, Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada: Geological Society of America Bulletin, v. 92, p. 763–771.

Hacker, D.B., Holm, D.K., Rowley, P.D., and Blank, H.R., 2002, Associated Miocene laccoliths, gravity slides, and volcanic rocks, Pine Valley Mountains and Iron Axis region, southwestern Utah, *in* Lund, W.R., ed., Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada, Field trip guide, Geological Society of America, Rocky Mountain section meeting, Cedar City, Utah: U.S. Geological Survey Open-File Report 02-172, p. 236–283.

Hammond, B.J., 1991, Geologic map of the Jarvis Peak Quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 212, scale 1:24,000.

Haneberg, W.C., Mozley, P.S., Moore, J.C., and Goodwin, L.B., eds., 1999, Faults and subsurface fluid flow in the shallow crust: American Geophysical Union Geophysical Monograph 113, 222 p.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C, scale 1:1,000,000.

Harrill, J.R., and Prudic, D.E., 1998, Aquifer systems in the Great Basin region of Nevada, Utah and adjacent states-Summary report: U.S. Geological Survey Professional Paper 1409A, 61 p.

Heilweil, V.M., Watt, D.E., Solomon, D.K., and Goddard, K.E., 2002, The Navajo aquifer system of southwestern Utah, *in* Lund, W.R., ed., Field Guide to Geologic Excursions in Southwestern Utah and Adjacent areas of Arizona and Nevada, Geological Society of America Rocky Mountain Section Meeting, Cedar City, Utah, May 7th-9th, 2002; U.S. Geological Survey Open-File Report 02-172, p. 105–130.

Hewett, D.G., 1931, Geology and ore deposits of the Goodsprings Quadrangle, Nevada: U.S. Geological Survey Professional Paper 162, 172 p.

Hintze, L.F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, Southwestern Utah, *in* Griffen, D.T., and Phillips, R.J., eds., Thrusting and Extensional Structures and Mineralization in the Beaver Dam Mountains, Southwestern Utah: Utah Geological Association Publication 15, p. 1–36.

Hintze, L.F., Anderson, R.E., and Embree, G.F., 1994, Geologic map of the Motoqua and Gunlock Quadrangles, Washington County, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2427, scale 1:24,000.

Hintze, L.F., and Axen, G.J., 1995, Geologic map of the Scarecrow Peak Quadrangle, Washington County, Utah, and Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1759, scale 1:24,000.

Hintze, L.F., and Axen, G.J., 2001, Geologic map of the Lime Mountain Quadrangle, Lincoln County, Nevada: Nevada Bureau of Mines and Geology Map 129, scale 1:24,000.

Hintze, L.F., and Hammond, B.J., 1994, Geologic map of the Shivwits Quadrangle, Washington County, Utah: Utah Geological Survey Map 153, 21 p., scale 1:24,000.

Howard, K.A., Hook, S.J., Phelps, G.A., and Block, D.L., 2003, Geologic map of the Hiller Mountains Quadrangle, Clark County, Nevada, and Mohave County, Arizona: Nevada Bureau of Mines and Geology Map 137, 1:24,000.

Jachens, R.C., Dixon, G.L., Langenheim, V.E., and Morin, R., 1998, Interpretation of an aeromagnetic survey over part of Virgin Valley, Tule Desert, and the valley surrounding Meadow Valley Wash, southeastern Nevada: U.S. Geological Survey Open-File Report 98-804, 16 p.

Johnson, J.G., Sandberg, C.A., and Poole, F.G., 1989, Early and Middle Devonian paleogeography of western United States, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World: Calgary, Canadian Society of Petroleum Geologists, Memoir 14, v. 1, Regional synthesis, p. 161–182.

Johnson, Michael, Dixon, G.L., Rowley, P.D., Katzer, T.C., and Winters, Michael, 2002, Hydrology and ground-water conditions of the Tertiary Muddy Creek Formation in the lower Virgin River basin of southeastern Nevada and adjacent Arizona and Utah, *in* Lund, W.R., ed., Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada, Field trip guide, Geological Society of America, Rocky Mountain section meeting, Cedar City, Utah: U.S. Geological Survey Open-File Report 02-172, p. 284–315.

Kirk, S.T., 1987, Analysis of the White River groundwater flow system using a deuterium-calibrated discrete-state compartment model [M.S. thesis]: University of Nevada, Reno, 81 p.

Laczniak, R.J., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96-4109, 60 p.

Langenheim, R.L., Jr., Carss, B.W., Kennerly, J.B., McCutcheon, V.A., and Waines, R.H., 1962, Paleozoic section in Arrow Canyon Range, Clark County, Nevada: American Association of Petroleum Geologists Bulletin vol. 46, no. 5, p. 592–609.

Langenheim, V.E., Glen, J.M., Jachens, R.C., Dixon, G.L., Katzer, T.C., and Morin, R.L., 2000, Geophysical constraints on the Virgin River depression, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 00-407, 26 p.

Langenheim, V.E., Bohannon, R.G., Glen, J.M., Jachens, R.C., Grow, J.A., Miller, J.J., Dixon, G.L., and Katzer, T.C., 2001a, Basin configuration of the Virgin River depression, Nevada, Utah, and Arizona-A geophysical view of deformation along the Colorado Plateau-Basin and Range transition, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The geologic transition, High Plateaus to Great Basin-A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 205–226.

Langenheim, V.E., Grow, J.A., Jachens, R.C., Dixon, G.L., and Miller, J.J., 2001b, Geophysical constraints on the location and geometry of the Las Vegas valley shear zone, Nevada: Tectonics, v. 20, no. 2, p. 189–209.

Langenheim, V.E., Miller, J.J., Page, W.R., and Grow, J.A., 2001c, Thickness and geometry of Cenozoic deposits in California Wash area, Nevada, based on gravity and seismic reflection data: U.S. Geological Survey Open-File Report 01-393, 24 p.

Langenheim, V.E., Page, W.R., Miller, J.J., and Grow, J.A., 2002, Geophysical and geological constraints on the hydrogeologic framework of the California Wash region, southern Nevada: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A-16.

Longwell, C.R., 1921, Geology of the Muddy Mountains, Nevada, with a section to the Grand Wash Cliffs in Arizona: American Journal of Science. 5th Series, v. 1, p. 39-62.

Longwell, C.R., and Mound, M.C., 1967, A new Ordovician formation in Nevada dated by conodonts: Geological Society of America Bulletin, v. 78, p. 405-412.

Longwell, C.R., Pampeyan, E.H., Bowyer, B., and Roberts, R.J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology Bulletin 62, 177 p.

Lucchitta, Ivo, Basdekas, P.G., Bohannon, R.G., and Reick, H.J., and Dehler, C.M., 1995a, Geologic map of the Cane Springs quadrangle, Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-86, scale 1:24,000.

Lucchitta, Ivo, Dehler, C.M., and Basdekas, P.G., 1995b, Geologic map of the Cane Springs Southeast quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-48, scale 1:24,000.

Lundstrom, S.C., Page, W.R., Langenheim, V.E., Young, O.D., Mahan, S.A., and Dixon, G.L., 1998, Preliminary geologic map of the Valley quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 98-508, scale 1:24,000.

Machette, M.N., 1985, Calcic soils of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Maldonado, F., and Schmidt, D.L., 1990, Geologic map of the southern Sheep Range, Fossil Ridge, and Castle Rock area, Clark County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2086, scale 1:24,000.

Marzolf, J.E., 1990, Reconstruction of extensionally dismembered early Mesozoic sedimentary basins; southwestern Colorado Plateau to the eastern Mojave Desert, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada, Geological Society of America Memoir 176, p. 477-500.

Matti, J.C., Castor, S.B., Bell, J.W., and Rowland, S.M., 1987, Geologic map of the Las Vegas NW Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 3Dg, scale 1:24,000.

Matti, J.C., Castor, S.B., Bell, J.W., and Rowland, S.M., 1993, Las Vegas NE Quadrangle geologic map: Nevada Bureau of Mines and Geology Map 3Cg, scale 1:24,000.

Merriam, C.W., 1964, Cambrian rocks of the Pioche mining district, Nevada: U.S. Geological Survey Professional Paper 469, 55 p.

Mills, J.G., Jr., 1994, Geologic map of the Hoover Dam Quadrangle, Arizona and Nevada: Nevada Bureau of Mines and Geology Map 102, scale 1:24,000.

Olmore, S.D., 1971, Style and evolution of thrusts in the region of the Mormon Mountains, Nevada [Ph.D. dissertation]: University of Utah, 211 p.

Page, W.R., 1992, Preliminary geologic map of the Arrow Canyon Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 92-681, 1:24,000-scale.

Page, W.R., 1993, A regional marker unit within the Upper Paleozoic Bird Spring Formation, southern Nevada-Evidence for slope facies [abs.]: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 131.

Page, W.R., 1998, Geologic map of the Arrow Canyon NW Quadrangle, Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1776, scale 1:24,000.

Page, W.R., and Pampeyan, E.H., 1996, Preliminary geologic map of the Paleozoic rocks in the Wildcat Wash SE and Wildcat Wash SW Quadrangles, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Open-File Report 96-26, 18 p., scale 1:24,000.

Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Workman, J.B., Mahan, S.A., Paces, J.B., Rowley, P.D., Dixon, G.L., Burchfiel, B.C., Bell, J.W., and Smith, E.I., 2005, Geologic and geophysical maps of the Las Vegas 30' x 60' Quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, 1:100,000-scale.

Page, W.R., Rowley, P.D., Dixon, G.L., and Brickey, D.W., 2003, Geologic map of the lower Colorado regional ground-water flow system, Nevada, Arizona, and Utah [abs.]: Nevada Water Resources Association Annual Conference, Sparks, Nevada, p. 57

Page, W.R., Swadley, W.C., and Scott, R.B., 1990, Preliminary geologic map of the Delamar 3 SW Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90-366, scale 1:24,000.

Pampeyan, E.H., 1993, Geologic map of the Meadow Valley Mountains, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-2173, scale 1:50,000.

Phelps, G.A., Jewel, E.B., Langenheim, V.E., and Jachens, R.C., 2000, Principal facts for gravity stations in the vicinity of Coyote Spring Valley, Nevada, with initial gravity modeling results: U.S. Geological Survey Open-File Report 00-420, 18 p.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-A, scale 1:1,000,000.

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995, Conceptual evaluation of regional ground-water flow in the

carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-D, 102 p.
Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near Yucca Mountain, Nevada, during Quaternary time: Geological Society of America Bulletin, v. 107, p. 213–230.
Quade, J., Forester, R.M., Pratt, W.L., and Carter, C., 1998, Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin: Quaternary Research, v. 49, p. 129–148.
Quigley, M.C., Karlstrom, K., Beard, S., and Bohannon, R.G., 2002, Influence of Proterozoic and Laramide structures on the Miocene extensional strain field, north Virgin Mountains, Nevada/Arizona, *in* Lund, W.R., ed., Field Guide to Geologic Excursions in Southwestern Utah and Adjacent areas of Arizona and Nevada, Geological Society of America Rocky Mountain Section Meeting, Cedar City, Utah, May 7th-9th, 2002; U.S. Geological Survey Open-File Report 02-172, p. 86–104.
Rowley, P.D., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, western United States—their tectonic and economic implications, *in* Faulds, J.E., and Stewart, J.H., eds., Accommodation zones and transfer zones—the regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, p. 195–228.
Rowley, P.D., and Dixon, G.L., 2001, The Cenozoic evolution of the Great Basin area, U.S.A.—New interpretations based on regional geologic mapping, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The geologic transition, High Plateaus to Great Basin-A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 169–188.
Rowley, P.D., and Shroba, R.R., 1991, Geologic map of the Indian Cove Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1701, scale 1:24,000.
Rowley, P.D., Nealey, L.D., Unruh, D.M., Snee, L.W., Mehnert, H.H., Anderson, R.E., and Gromme, C.S., 1995, Stratigraphy of Miocene ash-flow tuffs in and near the Caliente caldera complex, southeastern Nevada and southwestern Utah, *in* Scott, R.B., and Swadley, W C, eds., Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 43–88.
Rowley, P.D., Shroba, R.R., Simonds, F.W., Burke, K.J., Axen, G.J., and Olmore, S.D., 1994, Geologic map of the Chief Mountain Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1731, scale 1:24,000.
Rowley, P.D., Williams, V.S., Vice, G.S., Maxwell, D.J., Hacker, D.B., Snee, L.W., and Mackin, J.H., in press, Geologic map of the Cedar City 30′ x 60′ Quadrangle, Iron and Washington Counties, Utah: Utah Geological Survey Map, scale 1:100,000.
Schmidt, D.L., 1994, Preliminary geologic map of the Farrier Quadrangle, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Open File Report 94-625, scale 1:24,000.
Schmidt, D.L., and Dixon, G.L., 1995, Geology and aquifer system of the Coyote Spring Valley area, southeastern Nevada: U.S. Geological Survey Open-File Report 95-579, 47 p.
Schmidt, D.L., Page, W.R., and Workman, J.B., 1996, Preliminary geologic map of the Moapa West Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 96-521, scale 1:24,000.
Scott, R.B., Grommé, C.S., Best, M.G., Rosenbaum, J.G., and Hudson, M.R., 1995a, Stratigraphic relationships of Tertiary volcanic rocks in central Lincoln County, southeastern Nevada, *in* Scott, R.B., and Swadley, W.C., eds., Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 5–42.
Scott, R.B., Harding, A.E., Swadley, W.C., and Pampeyan, E.H., 1991a, Preliminary geologic map of the Vigo NW Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 91-389, scale 1:24,000.
Scott, R.B., Novak, S.W., and Swadley, W.C., 1990a, Preliminary geologic map of the Delamar 3 NE Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90-33, scale 1:24,000.
Scott, R.B., Page, W.R., and Swadley, W.C., 1990b, Preliminary geologic map of the Delamar 3 NW Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90-405, scale 1:24,000.
Scott, R.B., Swadley, W.C., and Novak, S.W., 1993, Geologic map of the Delamar Lake Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1730, scale 1:24,000.
Scott, R.B., Swadley, W.C., and Page, W.R., 1991b, Preliminary geologic map of the Gregerson Basin Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90-646, scale 1:24,000.
Scott, R.B., Unruh, D.M., Snee, L.W., Harding, A.E., Nealey, L.D., Blank, H.R., Jr., Budahn, J.R., and Mehnert, H.H., 1995b, Relations of peralkaline magmatism to heterogeneous extension during the middle Miocene, southeastern Nevada: Journal of Geophysical Research, v. 100, no. B6, p. 10,381–10,401.
Skelly, M.F., 1987, The geology of the Moapa Peak area, southern Mormon Mountains, Clark and Lincoln Counties, Nevada [M.S. thesis]: University of Northern Arizona, 150 p.

Smith, E.I., 1984, Geologic map of the Boulder Beach Quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 81, scale 1:24,000.

Snee, L.W., and Rowley, P.D., 2000, New 40Ar/39Ar dates from the Caliente caldera complex, Nevada-Utah-at least 10 million years of Tertiary volcanism in one of the World's largest caldera complexes: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A461.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345–1360.

Stewart, J.H., 1976, Late Precambrian evolution of North America: plate tectonics implication: Geology, v. 4, p. 11–15.

Stewart, J.H., 1984, Stratigraphic sections of Lower Cambrian and upper Proterozoic rocks in Nye, Lander, and Lincoln Counties, Nevada, and Sonora, Mexico: U.S. Geological Survey Open-File Report 84-691, 53 p.

Stewart, J.H., and Poole, F.G., 1972, Lower Paleozoic and uppermost Precambrian Cordilleran Miogeocline, Great Basin, western United States, *in* Dickinson, W.R., ed., Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 28–57.

Swadley, W.C., Page, W.R., Scott, R.B., and Pampeyan, E.H., 1994, Geologic map of the Delamar 3 SE Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map-GQ-1754, scale 1:24,000.

Swadley, W.C., and Scott, R.B., 1990, Preliminary geologic map of the Delamar NW Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90-622, scale 1:24,000.

Thomas, J.M., Mason, J.L., and Crabtree, J.D., 1986, Ground-water levels in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-B, scale 1:1,000,000.

Thomas, J.M., and Welch, A.H., 1984, Isotope hydrology and aqueous geochemistry of the White River groundwater basin, a regional carbonate aquifer in eastern Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 689.

Thomas, J.M., Welch, A.H., and Dettinger, M.D., 1996, Geohemistry and isotope hydrology of representative aquifers in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-C, 100 p.

Tschanz, C.M., and Pampeyan, E.H., 1970, Geology and Mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology Bulletin 73, 188 p.

Walcott, C.D., 1908, Nomenclature of some Cambrian Cordilleran formations: Smithsonian Miscellaneous Collections, v. 53, no. 1, p. 1–12.

Walcott, C.D., 1916, Cambrian trilobites: Smithsonian Miscellaneous Collections, v. 64, no. 5, p. 302-456.

Webster, G.D., 1969, Chester through Derry conodonts and stratigraphy of northern Clark and southern Lincoln Counties, Nevada: University of California Publications in Geological Sciences, v. 79, 121 p.

Webster, G.D., and Lane, N.R., 1967, The Mississippian-Pennsylvanian boundary in southern Nevada, *in* Teichert, C., and Yochelson, E.L., eds., Essays in paleontology and stratigraphy, R.C. Moore Commemorative Volume: Lawrence, Kansas, Kansas University Press, Department of Geology Special Publication 2, p. 503–522.

Wernicke, B., Walker, J.D., and Beaufait, M.S., 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, no. 2, p. 213–246.

Westgate, L.G., and Knopf, A., 1932, Geology and ore deposits of the Pioche district, Nevada: U.S. Geological Survey Professional Paper 171, 79 p.

Williams, P.L., 1967, Stratigraphy and petrography of the Quichapa Group, southwestern Utah and southeastern Nevada [Ph.D. dissertation]: University of Washington, 182 p.

Williams, V.S., 1996, Preliminary geologic map of the Mesquite Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 96-676, scale 1:24,000.

Williams, V.S., Bohannon, R.G., and Hoover, D.L., 1997a, Geologic map of the Riverside Quadrangle, Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1770, scale 1:24,000.

Williams, V.S., Schmidt, D.L., and Bohannon, R.G., 1997b, Preliminary geologic map of the Moapa East Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 97-449, scale 1:24,000.

Wilson, J.W., 2001, Potentiometric surface, carbonate-rock province, southern Nevada and southeastern California, 1998-2000: U.S. Geological Survey Open-File Report 01-335, 15 p.

Winograd, I.J., and Thordarson, W., 1975, Hydrologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712C, p. C1–C126.

Workman, J.B., Menges, C.M., Page, W.R., Ekren, E.B., Rowley, P.D., and Dixon, G.L., 2002, Tectonic map of the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2381-B, 58 p.

Workman, J.B., Menges, C.M., Page, W.R., Taylor, E.M., Ekren, E.B., Rowley, P.D., Dixon, G.L., Thompson, R.A., and Wright, L.A., 2003, Geologic map of the Death Valley ground water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies MF-2381-A, 1:250,000 scale.

# Journal of the Nevada Water Resources Association

**Fall 2004**

**A publication of the Nevada Water Resources Association, providing hydrologic information to the people of Nevada**

**Volume 1, Number 1**

SE ROA 34739

JA_7268

# Nevada Water Resources Association



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# Climate and Barometric Pressure Influences on Pederson Spring Discharge and the Carbonate Aquifer near the Muddy Springs, Southern Nevada

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**ABSTRACT**

The Muddy Springs, including Pederson Spring, derive flow from a regional carbonate aquifer in central-southern Nevada. Annual potentiometric water level fluctuations near Muddy Springs range from 0.6 to 1.2 feet, which are attributed predominantly to barometric pressure responses. Computed barometric efficiencies are 0.42 to 0.67 at well MX-4 situated 9 miles west of Muddy Springs, 0.60 at well UMVM-1 situated 5 miles west, 0.50 at well EH-5B located near the southwestern edge of the springs, and decreasing to 0.25 at well EH-4 located 2 miles east of EH-5B and ¼-mile south of Pederson Spring. Pederson Spring barometric efficiency is calculated at 0.065 cfs per foot of barometric pressure change. Since 1998, declining water levels in nearby observation wells and spring discharges are observed, being generally coincident with both a pronounced dry trend in central-southern Nevada and increased production from a nearby municipal well completed in the carbonate aquifer. Declining trends appear to have commenced in 1998, one year prior to the 5-year dry climate trend which began in 1999. These declining trends appear to be more pronounced than preceding climate influences since the mid-1980s, supporting the hypothesis of pumping influences. These observations are less evident in Pederson Spring discharge, as the declining discharge began in 1999, supporting the hypothesis of climate dominated influences on spring discharge, and suggesting a hydraulic discontinuity between the pumping well and spring. Several other lines of evidence suggest that hydraulic discontinuities exist between the up-gradient carbonate wells and Pederson Spring, including: 1.) fault structures cross cutting the region of the springs, 2.) differences in barometric efficiencies up-gradient and down-gradient of fault structures, and 3.) deviations in degrees of interpreted drawdown effects at well EH-5b, and between well EH-4 and Pederson Spring.

## INTRODUCTION

The Southern Nevada Water Authority (SNWA) has implemented a monitoring program to improve the scientific understanding of the regional carbonate aquifer in the vicinity of Coyote Spring Valley and the Muddy Springs. Implemented over the past 4 years are an improved data collection and archiving system, construction of 8 monitoring wells in Coyote Spring Valley and down-gradient towards the Muddy Springs, and commencement of expanded water level and barometric pressure data collection. Ongoing work includes support of reconstruction of the Pederson Spring weir, and construction of a pipeline and pumping facilities to support a 2-year aquifer pumping test at Well MX-5 situated in east-central Coyote Spring, 9 miles up-gradient of the Muddy Springs.

A subtle declining trend in regional water levels and spring discharges over the past 5 to 6 years has caused some concern and debate. Uncertainty presently exists in interpretations of the causes of the observed trends. Some of the complexities and uncertainties of the system have included undefined climatic responses, barometric pressure responses, pumping responses, uncertain hydraulic connections between the springs and the underlying carbonate aquifer, spring flow measurement inaccuracies, a limited period of time of baseline data, and a limited amount of regional hydrogeologic data regarding the carbonate aquifer system. The response of the hydrologic system in the Muddy Springs area is undoubtedly a function of some combination of the above variables; however, data to support conclusive statements on the magnitudes and effects are lacking. The interpretations presented herein have the objective of advancing the understanding of the hydrologic system, but should be considered preliminary, as data collection and evaluations are on going.

## HYDROGEOLOGIC OVERVIEW

The Muddy Springs are comprised of numerous individual springs and spring groups (complexes) spread over a two square mile area located approximately 5 miles west of the town of Moapa in Clark County, Nevada (Figure 1). Approximately 36,000 acre-feet per year (afy) of ground water has historically discharged from the springs (Eakin, 1964; and Eakin, 1966). The source of water for the springs is presently understood to be derived from a regional carbonate rock flow system. This is based on spring water chemistry and the anomalously large magnitude of discharge at Muddy Springs in relation to the small watershed in which the springs reside. Paleozoic carbonate rocks host a complicated flow system that links many hydrographic basins in Central and Southern Nevada. The regional geology is complex with a long geologic history of tectonic activity associated with the formation of the Basin and Range Province. That portion of the flow system contributory to the Muddy Springs is interpreted to be primarily derived from recharge on mountain ranges along the White River Flow System (WRFS), extending approximately 200 to 300 miles to the north (Eakin, 1966), and perhaps from the Meadow Valley Flow System immediately east of the WRFS (Thomas and others, 2001; LVVWD, 2001) (Figure 1).


Figure 1 – Location Map: Muddy River Springs Area, White River Flow System and Meadow Valley Flow System.

The potentiometric gradient in the carbonate aquifer near the Muddy Springs is shallow, with water levels only varying about 20 feet in altitude within a 10-mile distance from the springs (Figure 2). Aquifer transmissivities in the vicinity of Muddy Spring are high, with interpretations in the range of 200,000 gallons per day per foot (gpd/ft) (Eakin, 1966 for the White River Flow System) to 1,870,000 gpd/ft, or greater, at well MX-5 (Ertec Western, 1981), enabling a large flux of ground water even under low hydraulic gradients.

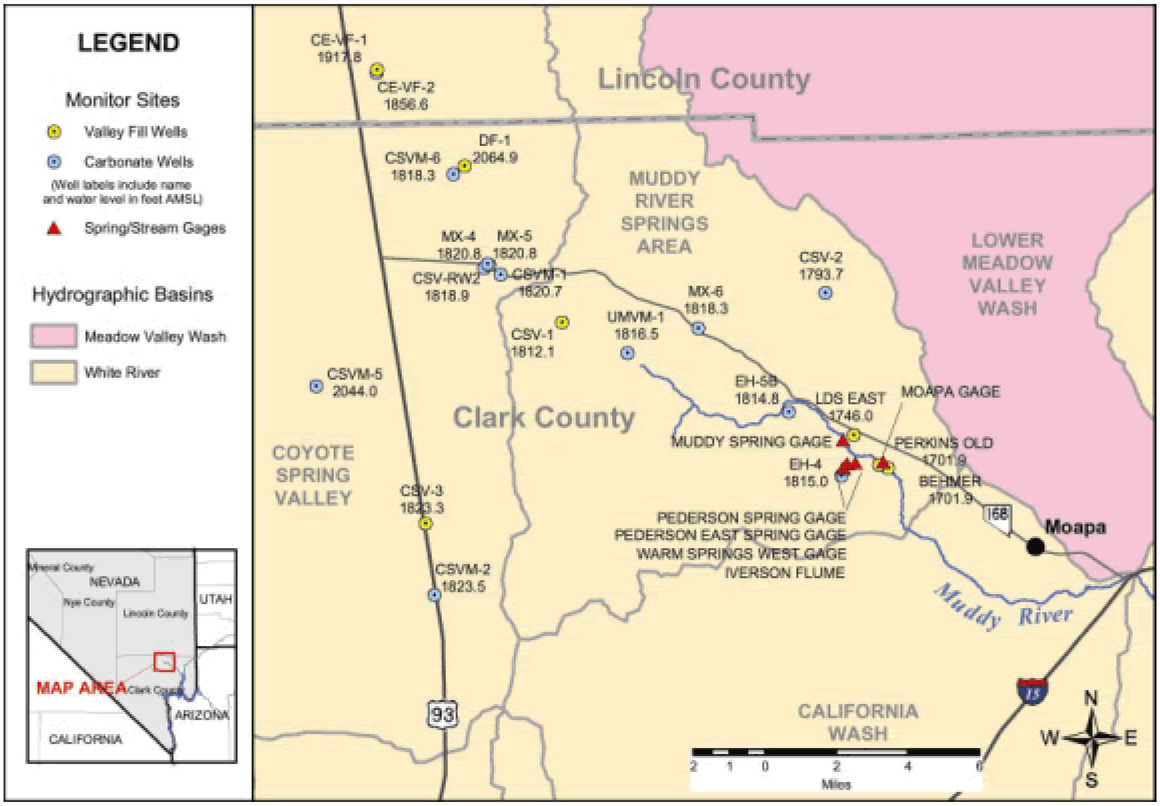


Figure 2 — Wells and springs in Coyote Spring Valley and Muddy Springs Area with potentiometric water surface elevations noted.

**Local Geology**

The Muddy Springs area has been previously mapped by Longwell and others (1965) and further refined by Schmidt and others (1996), and Donovan and others (2004). Figure 3 is a detail of Donovan and others (2004) preliminary geologic map of the Muddy Springs area.

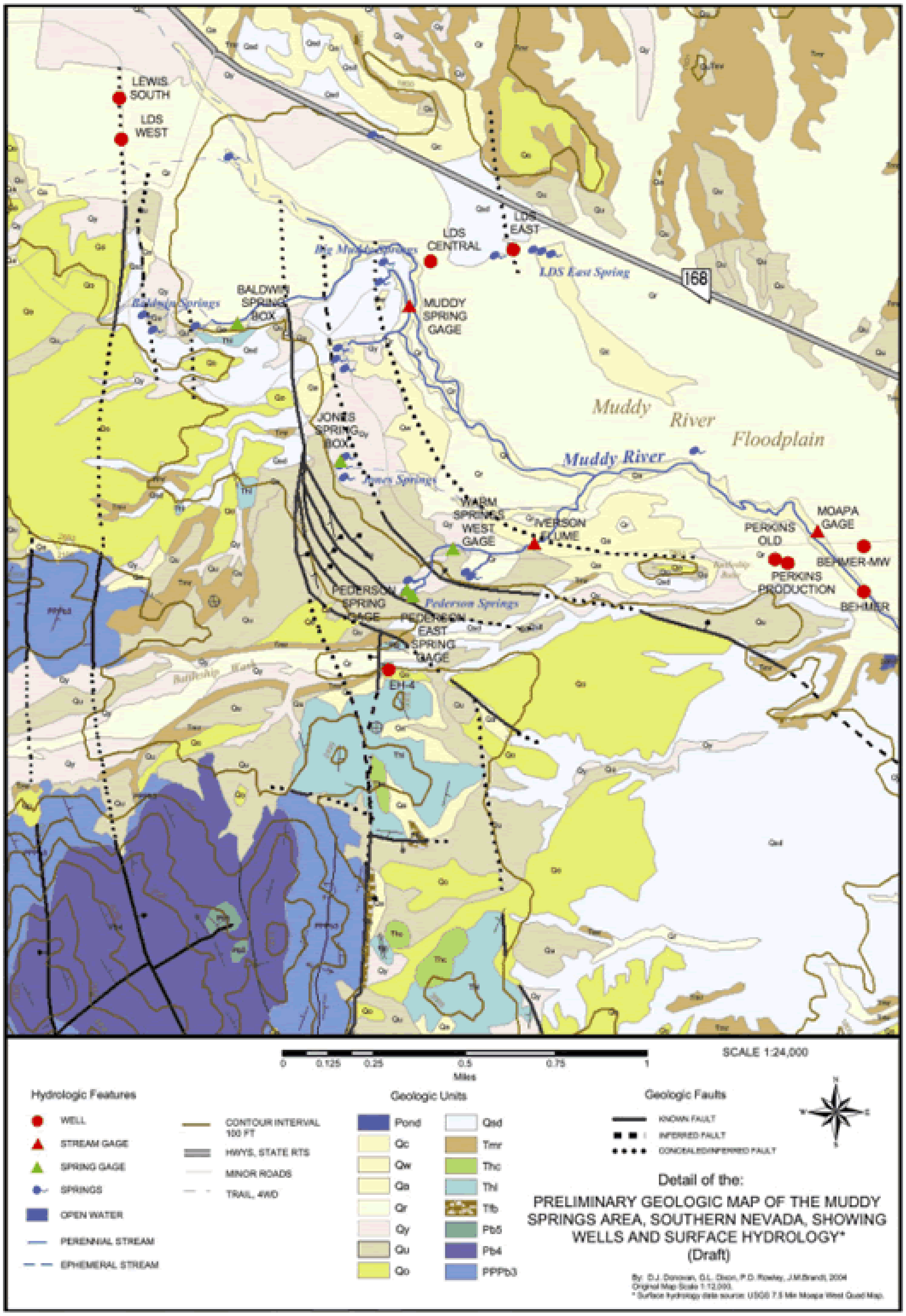


Figure 3 — Geologic Map of the Muddy Springs area.

The Muddy Springs are situated at base of the eastern flank of the Arrow Canyon Range, which is comprised of folded and faulted Paleozoic carbonate rocks. Spring discharge occurs through recent alluvium deposited along the ensized valley floor – flood plain of the Muddy River, and through underlying semi-consolidated alluvial deposits of the Muddy Creek Formation. Mesozoic age compressional features (primarily folds) are common local structural features in the bedrock. Unnamed north-south faults are common in the nearby bedrock. Tertiary and Quaternary normal faults associated with the Basin and Range Province are also common.

Of specific interest to recent mapping was a review of whether the Muddy Springs area was associated with a fault zone, as is common for large springs in the valley lowlands within the Basin and Range Province. The Clark County geologic map (1:250,000 scale, Longwell and others, 1965) does not indicate a major fault structure in this area or in the adjacent part of the Arrow Canyon Range, however, the scale of this regional mapping is such that many faults of significance may not be incorporated. By contrast however, regional correlations by the LVVWD (2001), the detailed bedrock mapping of the Schmidt and others (1996), and adjacent USGS maps, show this area to be structurally deformed with a strong north-south structural orientation caused by Mesozoic compressional features and Tertiary and Quaternary normal faulting.

Geology mapping Donovan and others (2004) has identified an important north-south normal fault, located directly west of the Pederson Spring complex (Figure 3), which is a continuation of the normal faults in adjacent Paleozoic bedrock to the southwest of the springs as previously mapped by Schmidt and others (1996). Several other associated minor subparallel faults have been mapped to the east and within the Pederson Spring complex. Other minor faults have mapped with an orientation of about N60$^{o}$W, which is subparallel with Muddy River. Features such as offset and tilted beds, slickensides, and linear landscape features were used to identify the structures. At various stages in the geologic history of these faults, they have acted as conduits to spring discharge as is indicated by water discharge features such as tufa, mamillary calcite, cementation zones, and dissolution cavities along the trace of and immediately down gradient of the faults.

Also of interest, is the character and distribution of the Quaternary (mid-Pleistocene) paleo-spring deposits (Qsd) shown on Figure 3. The Qsd deposits are similar to the younger (Pleistocene-Holocene) paleo-spring deposits, common in southern Nevada (Quade and others, 1995) but lacks the distinctive organic horizons "black mats" and gastropod shells, and generally have a better developed caliche cap. The older (Miocene) Muddy Creek Formation is more monotonous texturally and is easily differentiated from the Qsd where it is red in color.

The stratigraphic units used on Figure 3 were generalized from previous published mapping and are described in Table 1.

Table 1 – Description of stratigraphic units.

| CODE | UNIT DESCRIPTION |
|---|---|
| **Qc** | Quaternary – Active channel deposits of the Muddy River. |
| **Qw** | Quaternary – (Holocene) Active spring-fed wetlands. |
| **Qa** | Quaternary – alluvium. Unit is similar to Schmidt and others (1996) "slope wash and talus deposits" "Qs". |
| **Qr** | Quaternary – flood plain of Muddy River. Surface is reworked by agricultural development. |
| **Qy** | Quaternary – (Holocene – Pleistocene transition) young paleo-spring deposits Similar to those found near other active spring areas in southern Nevada (Corn Creek, Tule Springs, Mound Spring). |
| **Qu** | Quaternary – undivided Quaternary deposits. Deposits are primarily coarse grained and are either older or contemporary with the younger paleo-spring deposits. |
| **Qo** | Quaternary – Distinctive older coarse-grained terrace deposits that are darker (better developed desert varnish) with a well-developed caliche cap. |
| **Qsd** | Quaternary – (Mid Pleistocene) Older paleo-spring deposits, usually very light in color fine-grained, and strongly calcareous. The bulk of the deposit is located in a north-south trending graben on the east side of map |
| **Tmr** | Tertiary – (late Miocene) Muddy Creek Formation, red and green fine-grained sediment |
| **Thc** | Tertiary – (early to mid Miocene) Horse Spring Formation (conglomerate facies) |
| **Thl** | Tertiary – (early to mid Miocene) Horse Spring Formation (limestone facies) |
| **Tfb** | Fault breccia, assumed to be Tertiary |
| **Pb5** | Permian – Bird Spring Formation, red slope forming member |
| **Pb4** | Permian – Bird Spring Formation, medium gray, fine-grained, massive to thick bedded limestone |
| **PPPb3** | Pennsylvanian and Permian – Bird Spring Formation, medium gray to yellow, fine-grained, dolomitic and silty limestone |

## Regional Water Level Trends

Over the past 5 years, potentiometric water levels in carbonate aquifer wells near the Muddy Springs have declined approximately 1.5 to 2.5 feet (Figure 4). Possible causes of the water level fluctuations and trends in the flow system are: 1.) precipitation and climatic cycles, 2.) pumping from the carbonate aquifer, 3.) pumping from the shallow alluvial aquifer at the Muddy Springs, 4.) alterations to the environment such as spring restoration, 5.) degradation of measurement devices/conditions, and 6.) regional earth crust stress changes associated with earthquakes. Fenelon and Moreo (2002), Bright and others (2001), Harrill and Bedinger (2000), and Avon and Durbin (1994), and many others, have evaluated water level trends and controlling mechanisms in the southern Nevada flow systems, including the regional carbonate aquifer. Buqo (2004) presented a hypothesis of potentiometric water level changes near the terminus of the WRFS being in part due to response to Lake Mead water level fluctuations.

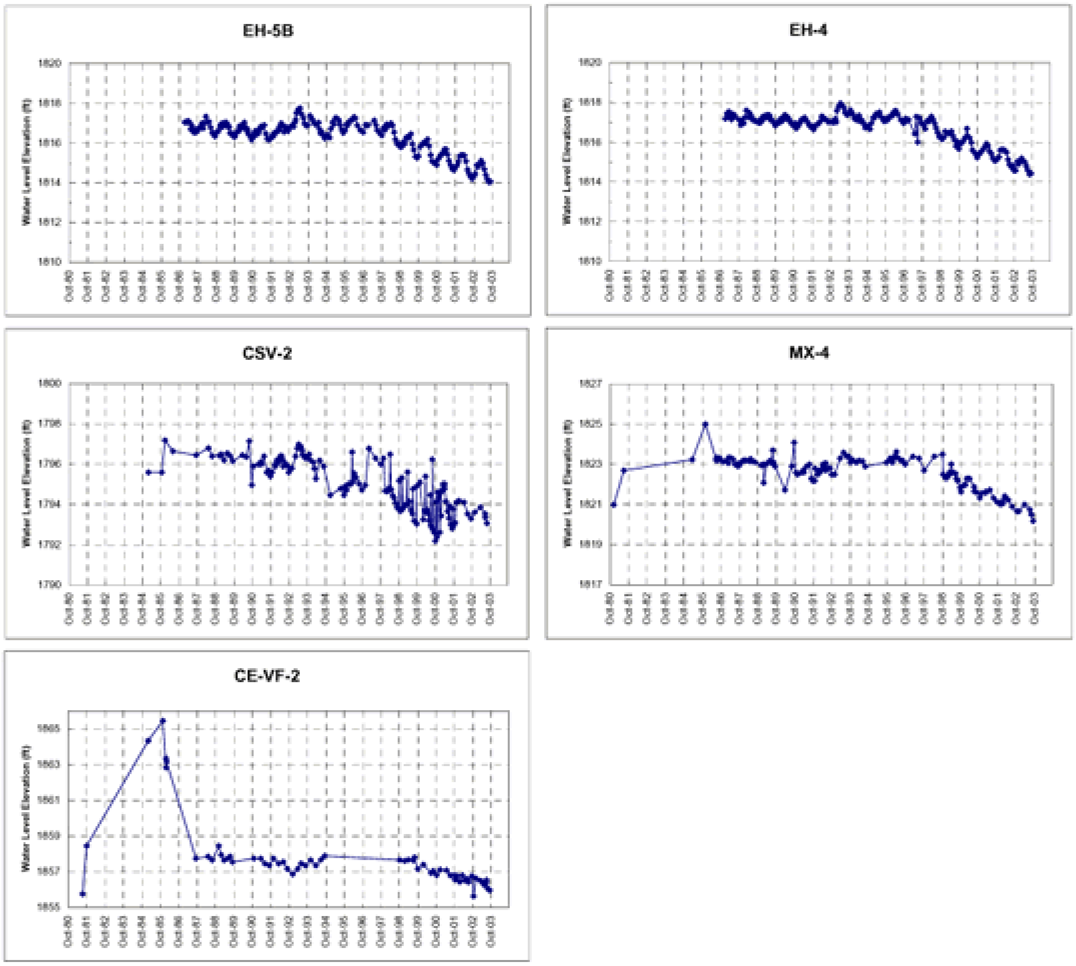


Figure 4 — Carbonate aquifer water level hydrographs, Coyote Spring Valley and Muddy Springs Area. Water level data reported by USGS, SNWA, Nevada Power Company, and MVWD.

**Pederson Spring**

Pederson Spring is one of many springs within the Muddy Springs complex and is situated on the Moapa Valley National Wildlife Refuge. While Pederson Spring discharges a small fraction of spring flow derived from the refuge (approximately 4% of an average 6.2 cubic feet per second (cfs)), it is the highest altitude spring on the refuge and therefore believed to be the most sensitive to potential impacts from pumping from the carbonate aquifer. The Moapa dace, a federally listed endangered species, resides in the spring and streams emanating from the refuge.

Discharge measured at Pederson Spring and the down-gradient Warm Springs West gage have also had a declining trend since 1999 (Figures 5). Discharge measurements have been made at Pederson Spring by the US Geological Survey (USGS) since October 1986, and the monthly average flows typically range from 0.18 to 0.26 cfs.

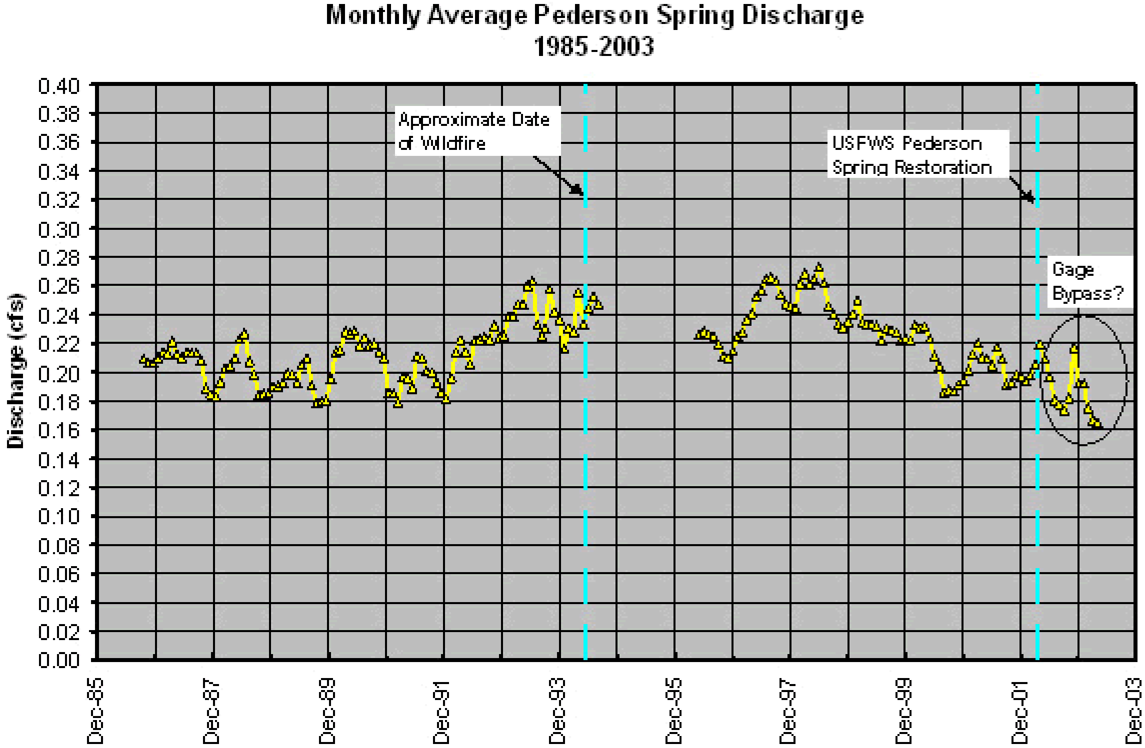


Figure 5 — Pederson Spring Monthly Average Discharge Rates through December 2003. Data source: USGS.

The reliability of Pederson Spring discharge measurements between the time periods of April 2002 to April 2004, as a cumulative measure of spring discharge, is considered by the authors to be low. A progressive leak around the Pederson Spring weir plate is reported by the USGS to have become pronounced in early 2003 (USGS, 2003). Further exasperating the quality of spring discharge measurements have been dramatic changes to the Pederson Spring environment as a result of ongoing restoration work at the refuge, which began in April 2002. While the Pederson Spring pool and weir remained intact during these activities, many palm trees were removed from the vicinity of the spring to within approximately 5 to 10 feet of the pool (Figure 6). Approximately 100 to 150 feet to the east of the pool, five new discharging springs were created at a location where one developed spring formerly existed (Figure 6). The interconnection between springs in the complex is poorly understood, and physical alterations to the spring complex have introduced greater uncertainty as to the accuracy of total spring discharge interpretations. Because of the failing condition of the weir, the USGS in collaboration with SNWA and the U.S. Fish and Wildlife Service (USFWS) replaced the weir structure in late April, 2004 in concert with USFWS spring restoration efforts.

Figure 6 — Upper Pederson Spring Complex (left side), July 2003. Note creation of five new flowing springs (right side) in place of former Playboy Pool site, with removal of palm trees (approximately 60) up to the edge of Peterson Spring Pool.

**Pumping from the Arrow Canyon Well**

Moapa Valley Water District (MVWD) provides water service in the Moapa area, and relies upon both springs and two wells completed in the carbonate aquifer in the vicinity of the Muddy Springs. MVWD's Arrow Canyon well is located approximately ½-mile southwest of the Muddy Springs area, and 2 miles west of the Moapa Valley National Wildlife Refuge (Figure 2). In 1998, MVWD's pumping from the carbonate aquifer increased from around 750 afy (1991 to 1997) to approximately 2,500 afy (1998 to 2003) due to water demands and changes in operational pumping strategies (Figure 7).

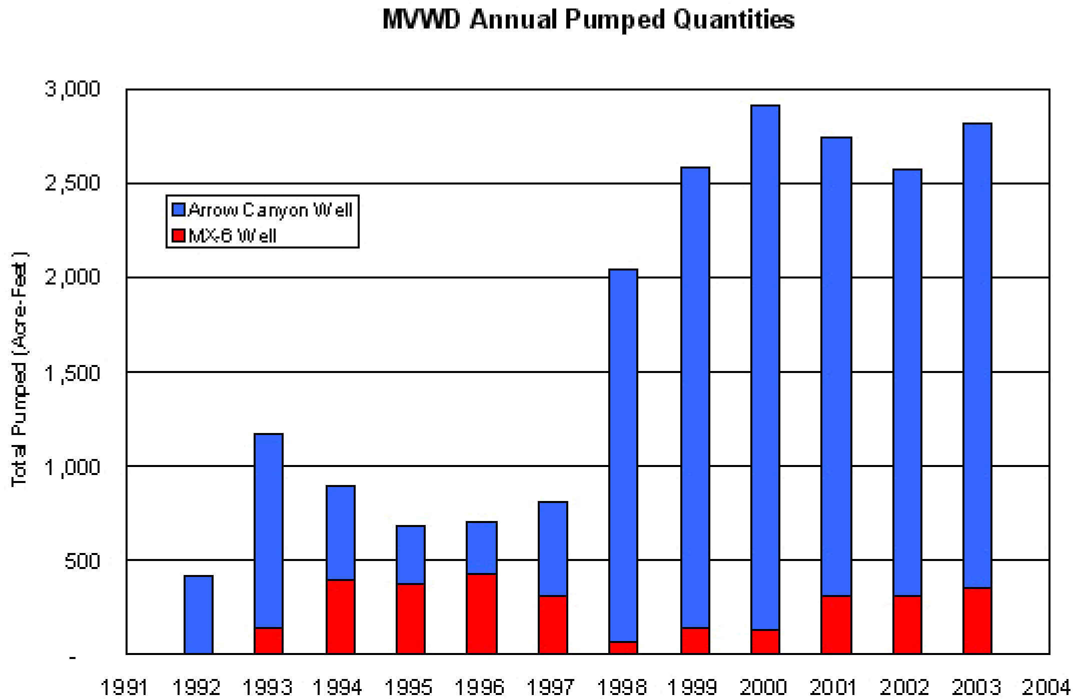


Figure 7 — Annual Total and Seasonal Pumping from MVWD Arrow Canyon and MX-6 Wells. Data source: MVWD.

## REGIONAL CLIMATE

### White River Flow System Climate Trends

Wet and dry climate trends are commonly reflected, although to varying degrees, in natural hydrologic systems. Annual variability in recharge is dependant on climatic variables, particularly high-altitude winter precipitation quantities in the semi-arid mountainous environments found in Central and South Nevada (Winograd and others, 1998). Recharge variation subsequently may produce potentiometric water level fluctuations throughout a flow system, which is a pressure response phenomenon in the confined carbonate aquifer.

Long-term climate trends have been evaluated using cumulative departure from mean precipitation and the Palmer Drought Severity Index as published by the National Climate Data Center (2003). The Palmer Index includes additional variables of temperature and soil moisture deficit. It is interpreted similarly to the cumulative departure from mean precipitation curve, with zero being a normal year, positive numbers being wet climate cycles, and negative numbers being drought cycles with minus 3 representing a "severe" drought condition (Palmer, 1965) (Figure 8).

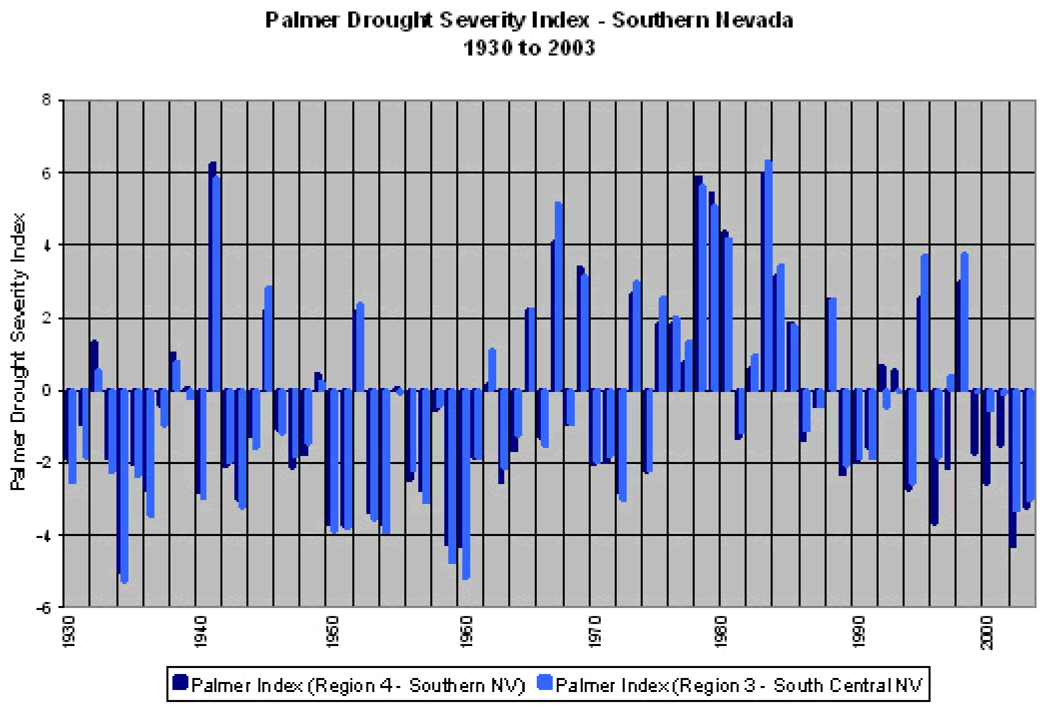


Figure 8 — Palmer Index Bar Plot. Data source: National Climate Data Center, 2003.

An index precipitation dataset has been constructed (1931 through 2003) to represent precipitation falling over the regional flow system contributory to Muddy Springs (Figure 9). An index precipitation dataset has several advantages over use of data from a single station, particularly for interpretations of large regional flow systems. Potential errors related to occurrences of localized precipitation events near a station, climatic variability over distances of tens to several hundred miles, and inherent data collection errors are all reduced over dependence of data from a single station.

Annual precipitation records, as published by the Western Regional Climate Center (WRCC, 2003), for Pahranagat Wildlife Refuge, Sunnyside, Lund, and the Desert Game Range were used for construction of the index precipitation dataset (Table 2), applying weighted averaging based on proportions of recharge to the regional flow system defined by Thomas and others (2001) (Table 3). Additionally, WRCC (2003) precipitation records at Caliente and Las Vegas stations were utilized to reconstruct incomplete Pahranagat records (1998 to 2003) using an averaging technique presented by Dunne and Leopold (1978), and to synthesize records back to a common beginning date of 1931 using relationships defined by linear regression. Cumulative departure from mean index precipitation versus individual station data are presented in Figure 10. Trends observed in the index precipitation data are comparable with individual stations throughout the region, and also compare favorably with limited high altitude and winter only datasets, and are felt to be an adequate representation of the regional climate of the WRFS.

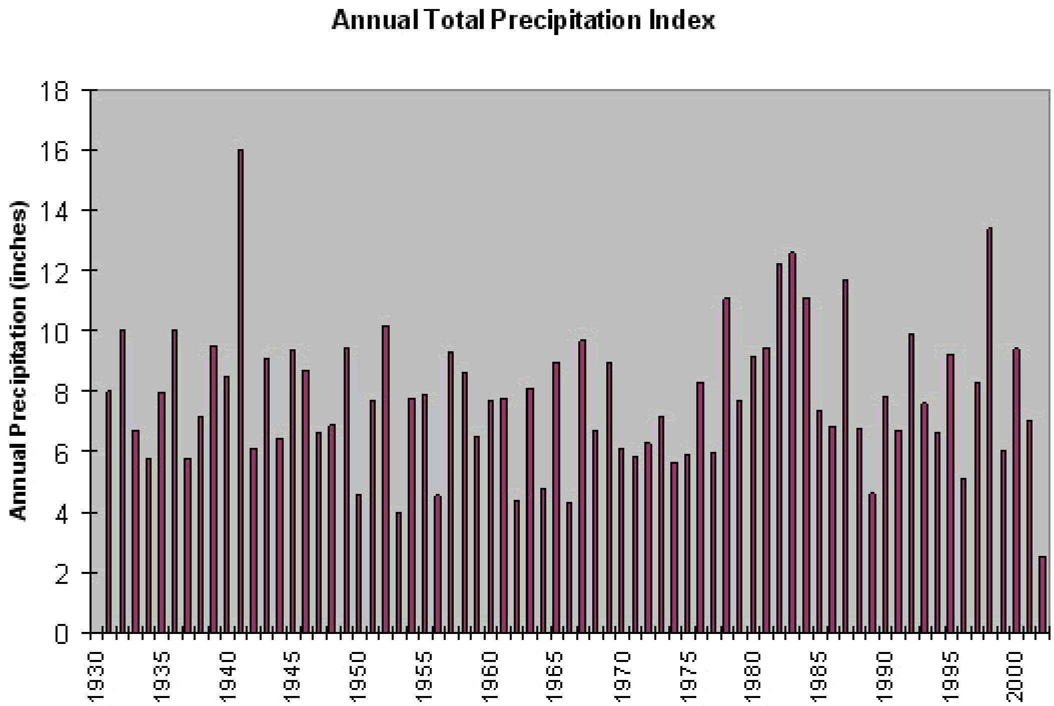


Figure 9 — WRFS Regional Precipitation Index based on records from Las Vegas, Desert Game Range, Pahranagat, Sunnyside, Lund, and Caliente stations. Individual station data source: Western Region Climate Center (WRCC).

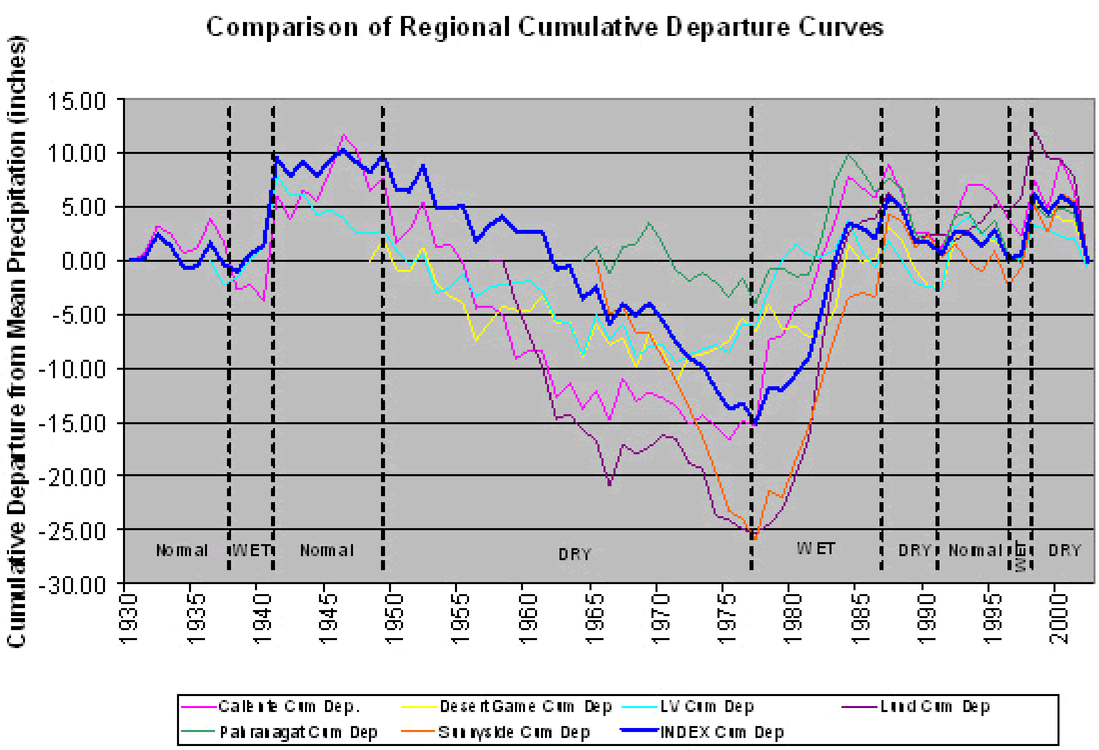


Figure 10 — Cumulative Departure from Mean Precipitation, Comparison for Regional Precipitation Stations. Precipitation data source: WRCC

Table 2 – Summary of regional long-term precipitation records.

| Station Name | NWS* ID Number | Period of Record (continuous annual records) | Long-Term Mean Precipitation (inches) |
|---|---|---|---|
| Lund | 264745 | 1958 - present | 10.44 |
| Sunnyside | 267908 | 1966 - present | 9.50 |
| Caliente | 261358 | 1931 - present | 8.77 |
| Pahranagat | 265880 | 1965 - 1997 | 6.53 |
| Desert Game Range (Corn Creek) | 262243 | 1949 - present | 4.31 |
| Las Vegas Airport | 264436 | 1937 - present | 4.15 |

*NWS – National Weather Service

Table 3 – Summary of development of regional index precipitation from Thomas and others (2001) White River Flow System recharge interpretations.

| Hydrographic Area | Recharge to Regional Flow System (afy) | Percent Total Contribution | Regional Precipitation Trend Represented By Station: |
|---|---|---|---|
| White River Valley, Long and Jakes | 8,000* | 14.8 | Lund |
| Pahroc, Cave, Garden, Coal | 19,000* | 35.2 | Sunnyside |
| Pahranagat, Dry, Delamar, Kane Springs | 23,000** | 42.6 | Pahranagat (Reconstructed Dataset) |
| Coyote Spring Valley | 4,000 | 7.4 | Desert Game Range |
| TOTAL | 54,000 | 100.0 | |

* Assumes approximately 55 percent of regional inflow (LVVWD, 2001) to Pahranagat Valley is consumed by evapotranspiration in Pahranagat Valley, with 45 percent comprising regional outflow reflected in Muddy Springs.

** Assumes approximately 1,000 afy regional recharge derived in Pahranagat Valley, with most local recharge consumed by evapotranspiration within the valley.

**Climate and Potentiometric Water Level Trend Comparisons**

Subtle responses to climate variability appear to be reflected in the potentiometric water levels for wells near the Muddy Springs, as depicted for wells MX-4 and EH-5b (Figures 11 and 12), with a general mimic of climate indices and water levels (wet years producing an upward index trend with corresponding gradual rise in water levels, and visa versa for dry years). However, based on approximately 20-years of water level records, the declining trend in the past 5 to 6 years appears to be more pronounced than past climate responses. The more pronounced declining trend since 1998 could be interpreted as a result of pumping drawdown from the Arrow Canyon well, as a dominate factor superimposed over lesser effects of dry climate. This interpretation, however, is subject to great uncertainty due to the pronounced nature of the current dry climate cycle. A factor that supports the pumping drawdown interpretation is the observation that 1998 was a wetter than average year, however, the declining potentiometric water level trend appeared to have commenced in 1998. Timing of precipitation in 1998 and preceding climatic conditions and resultant soil moisture deficit could easily have dampened the effects of above average moisture for the year. Continued monitoring into the next wet climate cycle will aid in differentiation of the magnitude of these probable pumping versus climate contributory variables.

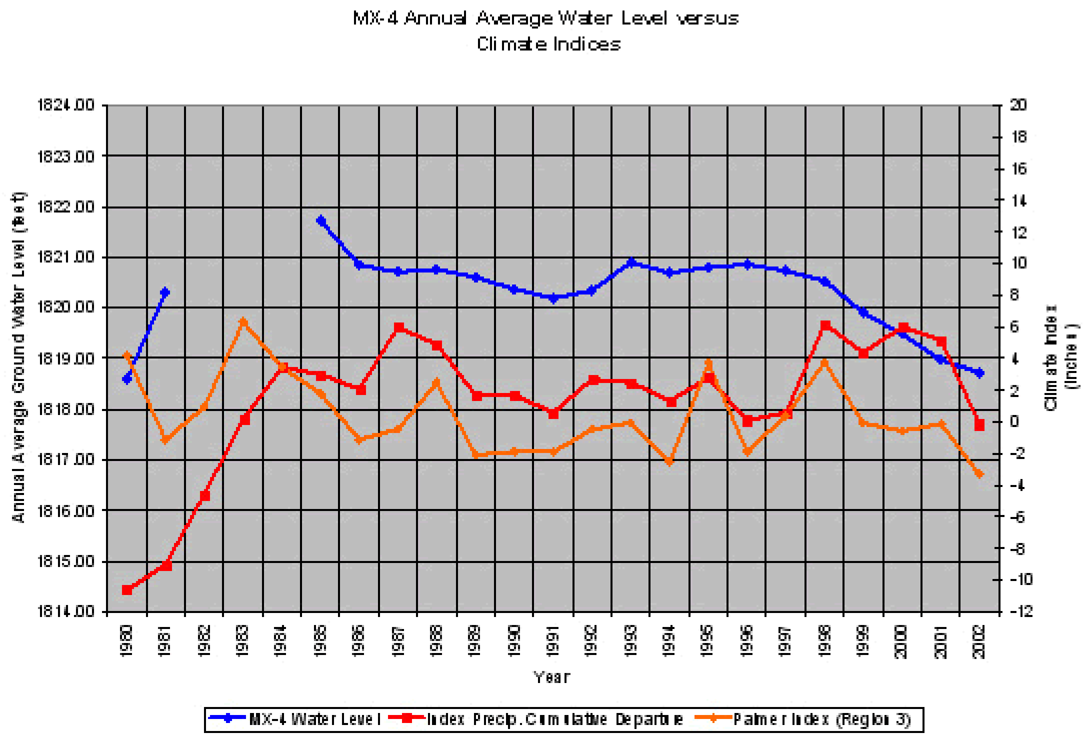


Figure 11 — MX-4 Water Level Elevation versus Regional Climate Trend

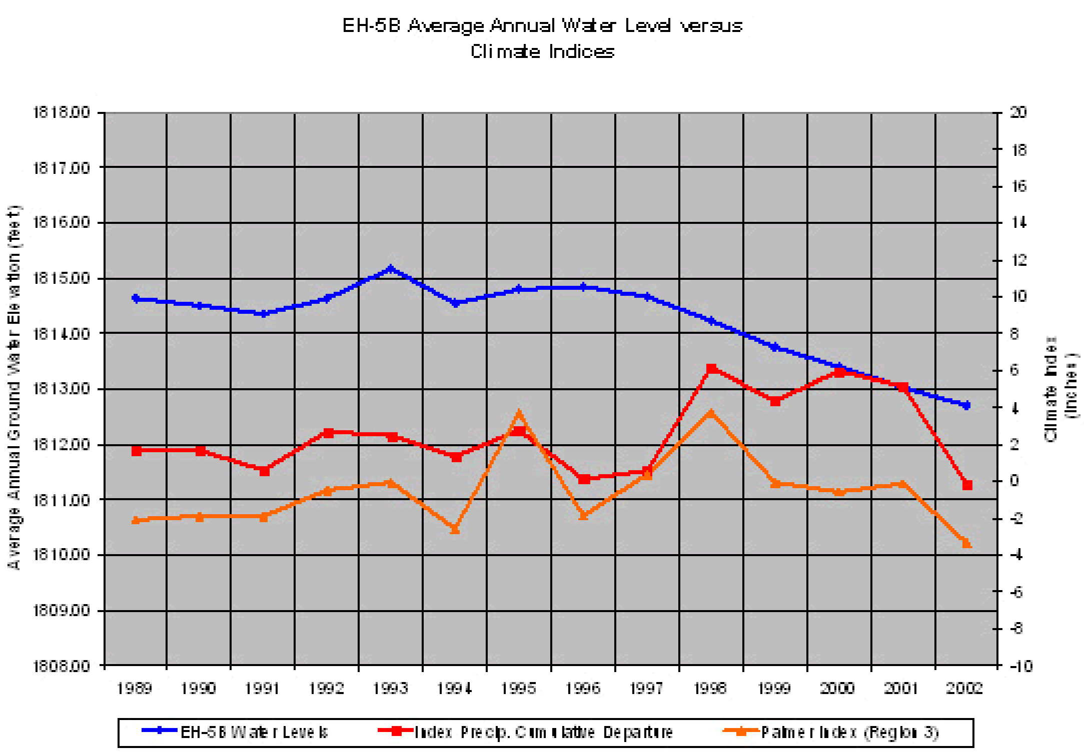


Figure 12 — EH-5B Water Level Elevation versus Regional Climate Trend.



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## INTERPRETED EFFECTS OF REGIONAL PUMPING

Assuming that a majority of the observed water level decline since 1998 is a result of pumping from the Arrow Canyon well (Table 3), a distinct distance-drawdown relationship can be derived (Figure 13). Except for observation well EH-5B, which is the closest well to Arrow Canyon, the interpreted distance-drawdown relationship agrees with Theis drawdown theory (Table 4). A computed carbonate aquifer transmissivity of approximately 630,000 gallons per day per foot (gpd/ft) and a storage coefficient of 0.0007, is derived from the distance-drawdown plot using the Jacob-Cooper straight line method (Driscol, 1986). While this transmissivity is high, it is in general agreement with carbonate aquifer test data from wells in the region (Belcher and others, 2001).

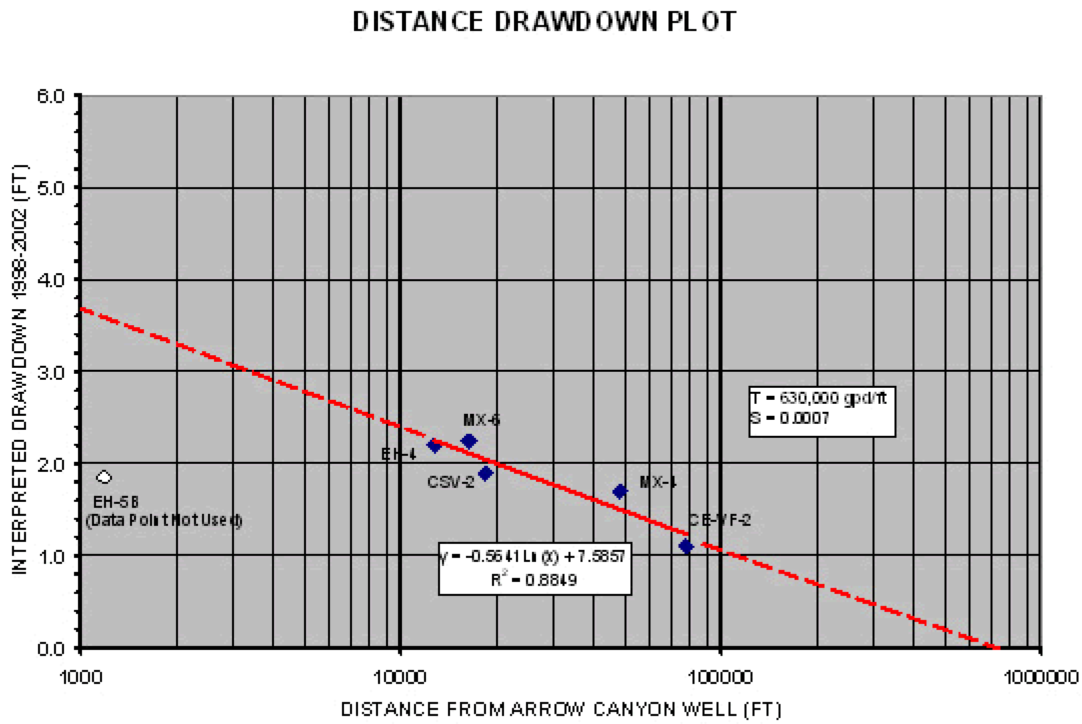


Figure 13 — Distance Drawdown Interpretation for Carbonate Aquifer Wells in the Vicinity of the Arrow Canyon Well.

It is important to note that the distance-drawdown relationship presented in Figure 13 is highly dependent on the interpretation of drawdown in well CE-VF-2, located approximately 14.7 miles from the Arrow Canyon well. Without this single data point, the amount of water level decline amongst the five remaining observation wells is practically uniform (Figure 14), supporting the hypothesis of a regional lowering of potentiometric water levels instead of a distance-drawdown effect.

Table 4 – Comparison of Interpreted Distance-Drawdown from Arrow Canyon Well with Theis.

| Well | Distance from Arrow Canyon (ft) | Drawdown Interpreted from Hydrograph (1998 to 2002) | Theis Predicted Drawdown, (T=630,000 gpd/ft, S=0.0007) | Percent Difference |
|---|---|---|---|---|
| EH-5B | 1,148 | 1.95 | 3.62 | 46.2 |
| EH-4 | 12,714 | 2.2 | 2.27 | 2.9 |
| MX-6 | 16,360 | 2.25 | 2.12 | -6.0 |
| CSV-2 | 18,393 | 1.9 | 2.06 | 7.6 |
| MX-4 | 48,125 | 1.7 | 1.52 | -12.2 |
| CE-VF-2 | 77,572 | 1.1 | 1.25 | 11.7 |

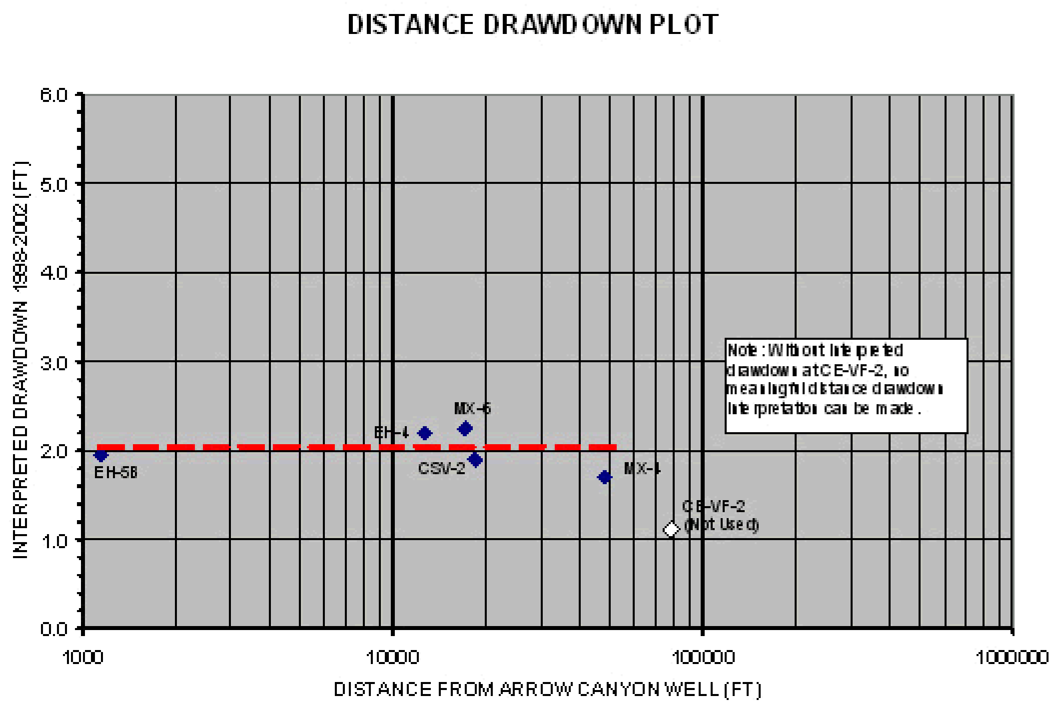


Figure 14 — Alternative Interpretation of Distance Drawdown Data if Well EH-5B is Included andWell CE-VF-2 is Removed from Consideration.

## PEDERSON SPRING DISCHARGE TRENDS

Pederson Spring typically produces a monthly average flow of approximately 0.18 to 0.26 cfs. From one perspective, it can be noted that even after 5 years of a declining trend in discharge, flows are still within historic rates (Figure 5). This observation in itself supports an interpretation that climate is the dominant factor contributing to the presently declining trend. A comparison of climate indices and spring discharge shows spring discharge response that can be visually correlated to climate (Figure 15).

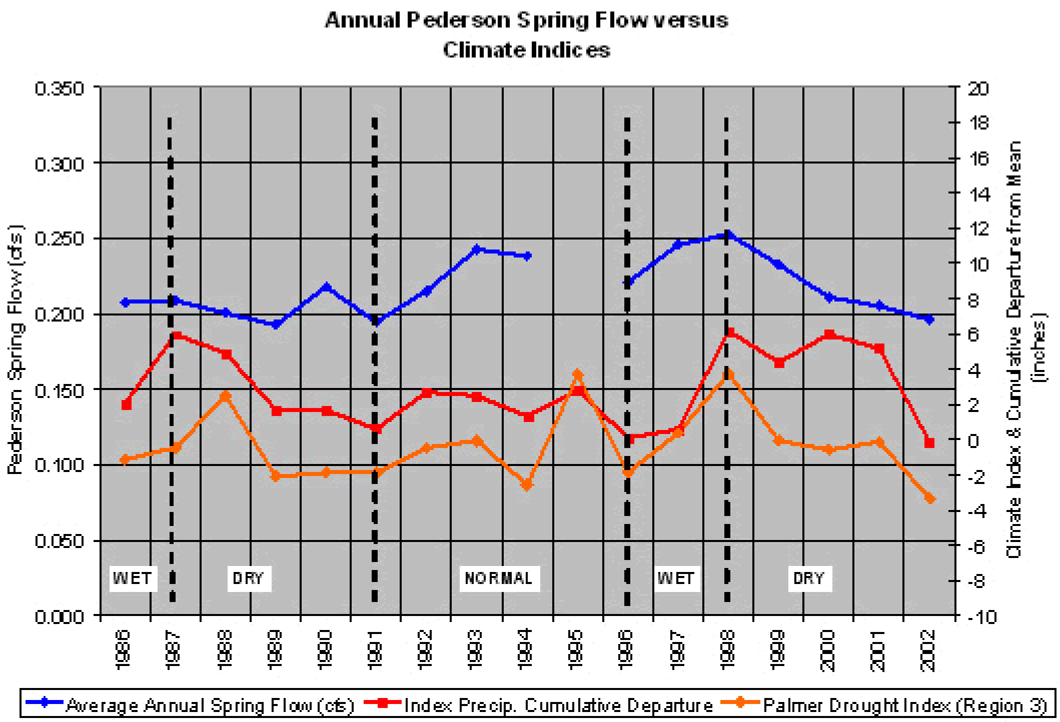


Figure 15 — Comparison of Pederson Spring Flows with Regional Climate Trends. Data source for spring discharge: USGS.

Moapa Valley Water District's pumping of the Arrow Canyon well increased by about 300 percent from 1997 to 1998 (Figure 7) due to changes in operation pumping strategies. During that same time, Pederson Spring and down-gradient Warm Springs West discharges were observed to have remained at the highest mean annual discharge (or annual volume) on record. Given the confined nature of the carbonate aquifer, relatively immediate and clear responses would have been expected but were not observed, suggesting a lack of direct hydraulic connection between the Arrow Canyon well and Pederson Spring. However, interpretations of regional water level trends tend to support pumping drawdown influences to the carbonate aquifer, and time-lagged pumping drawdown effects may still be intertwined in a declining trend that is a combination of climate and pumping affects. Continued monitoring of discharges and water levels into the next wet climate cycle will aid in differentiation of the possible pumping affects versus natural climate affects to the springs.

**Applicability of Darcy's Law in Spring Flow Regimes**

Some interpretations of Pederson Spring discharge and response to aquifer potentiometric water level change have applied the well-known Darcy's Law for fluid flow through porous medium, assuming a direct relationship between head and discharge. This assumption may be overly simplistic to represent the complexities of the spring system. Upward flow from the carbonate aquifer may be visualized as upward flow through a network of calcium carbonate cemented pathways or conduits. Upward velocities through these pathways may be high enough to create a turbulent flow regime, invalidating application of Darcy's Law, which assumes laminar flow and a Reynolds number below a critical range of 1 to 10 (Deming, 2002). Future interpretations of responses of spring discharge to potentiometric water level fluctuations need to take this into consideration.

## BAROMETRIC PRESSURE RESPONSES

### Aquifer Responses of Barometric Pressure Fluctuations

Barometric pressure will fluctuate throughout any given day in response to weather, but also exhibits an annual cycle in southern Nevada (Figure 16). High barometric pressures cause reduced potentiometric water levels in wells, which is a measurable phenomenon in confined aquifer systems, but is less noticeable in unconfined aquifers. Barometric efficiency is a unit-less (ft/ft) coefficient that defines the relationship between atmospheric pressure change and potentiometric water level change, with atmospheric pressure being expressed as equivalent height of water rather than more common units of millibars or inches of mercury. In confined aquifers, barometric efficiencies typically range from 0.2 to 0.7 (Todd, 1980).

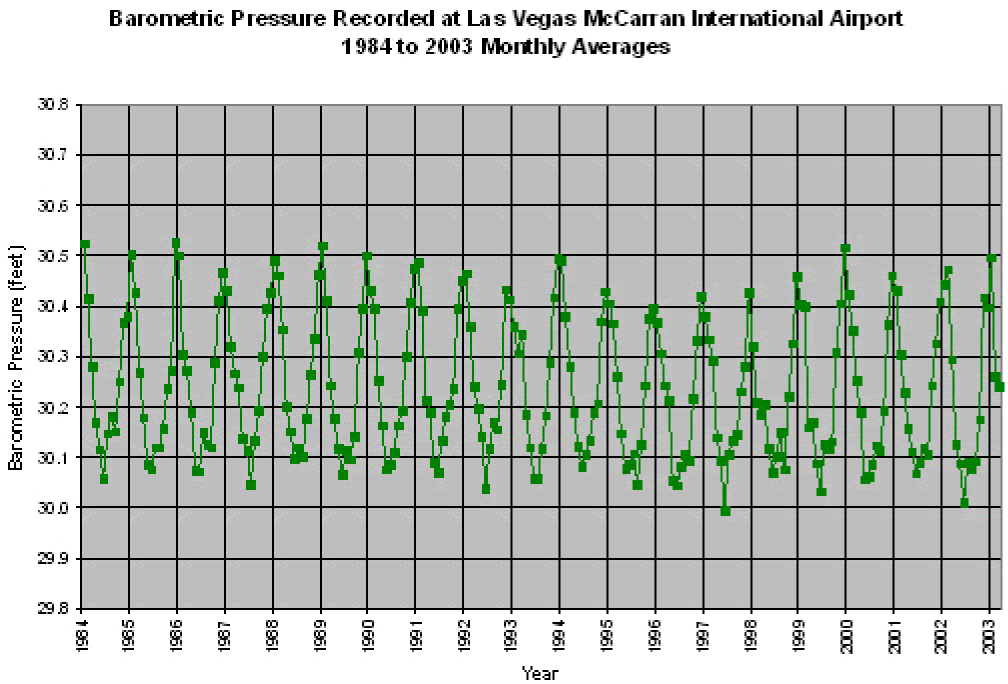


Figure 16 — Monthly Average Barometric Pressure recorded at Las Vegas McCarran Airport. Data Source: National Climate Data Center.

Barometric pressure is documented as measurably affecting potentiometric heads in the carbonate aquifer in southern and central Nevada. Bright and others (2001) documented barometric pressure responses of maximum amplitude of approximately 1.0 feet in well WW-5a at Frenchman Flat. Fenelon and Moreo (2002) calculated barometric efficiencies of 0.48 for Tracer Well 3 in Amargosa Desert, and 1.0 for well JF-3 in Jackass Flats. Kilroy (1992), Harrill and Bedinger (2000), and Fenelon and Moreo (2002) calculated the barometric efficiency of Devils Hole be in the range of 0.31 to 0.40.

Barometric pressure responses in monitoring wells completed in the carbonate aquifer in the vicinity of Muddy Springs appear to range from approximately 0.6 up to 1.2 feet annually (wells MX-4, CSV-4, EH-4, EH-5B, and CE-VF-2, time period mid- to late 1980s to present), without consideration of earth tide influences caused by gravitational attraction of the sun and moon.

Earth tide effects are observed in the vicinity of the Nevada Test Site and Devils Hole to have similar or lesser magnitudes as compared to barometric responses (Harrill and Bedinger, 2000; and Fenelon and Moreo, 2002), creating background noise in the datasets. Effects of earth tides have not been removed from barometric efficiency calculations presented herein. Because the period of frequency of earth tides is in cycles of semi-daily, daily, and cumulative 2-week cycles, and because the length of records evaluated in this study ranged from 1 month to 1 year, earth tide "noise" in the datasets is not expected to significantly affect the barometric efficiency interpretations. However, earth tide fluctuations are believed to account for a large portion of observed data scatter, resulting in lower than optimum correlation coefficients.

Barometric efficiency for well MX-4 was initially defined as approximately 0.67 using daily average data from January 1991 through December 1995 (Figure 17). This computational method utilized barometric pressure data measured in Las Vegas, as no site specific data was being collected at the time, and relies upon the occurrence of annual cycles of barometric pressure and larger scale day to day fluctuations. Annual plots of average daily barometric pressure versus average daily potentiometric water level were analyzed by linear regression, the slope of the regression line defining the barometric efficiency. Correlation coefficients were low and did not exceed 0.58, with apparent shifts in water levels observed in the 1991 and 1993 datasets, accounting for the lowest correlation coefficients. However, the slope of the barometric pressure versus potentiometric water level relationship was visually apparent for all years as best exhibited for 1992 (Figure 18), with annually derived barometric efficiency values falling within plus or minus 37 percent of the 5-year average.

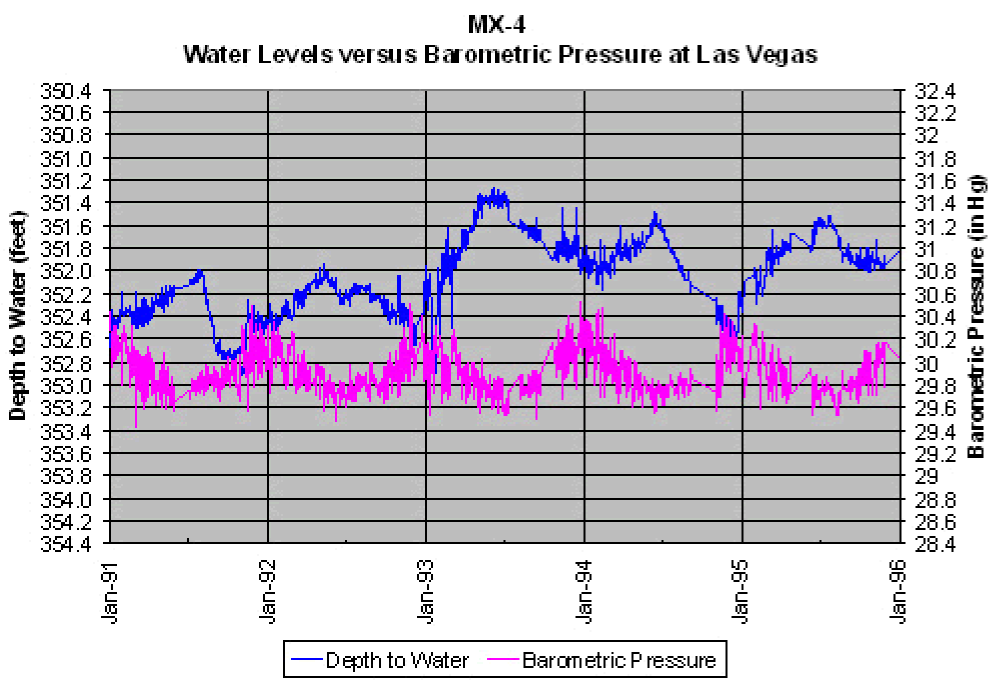


Figure 17 — Depth to water at monitoring well MX-4 versus barometric pressure at Las Vegas. Data sources: Barometric pressure from the National Climate Data Center, MX-4 water levels from USGS.

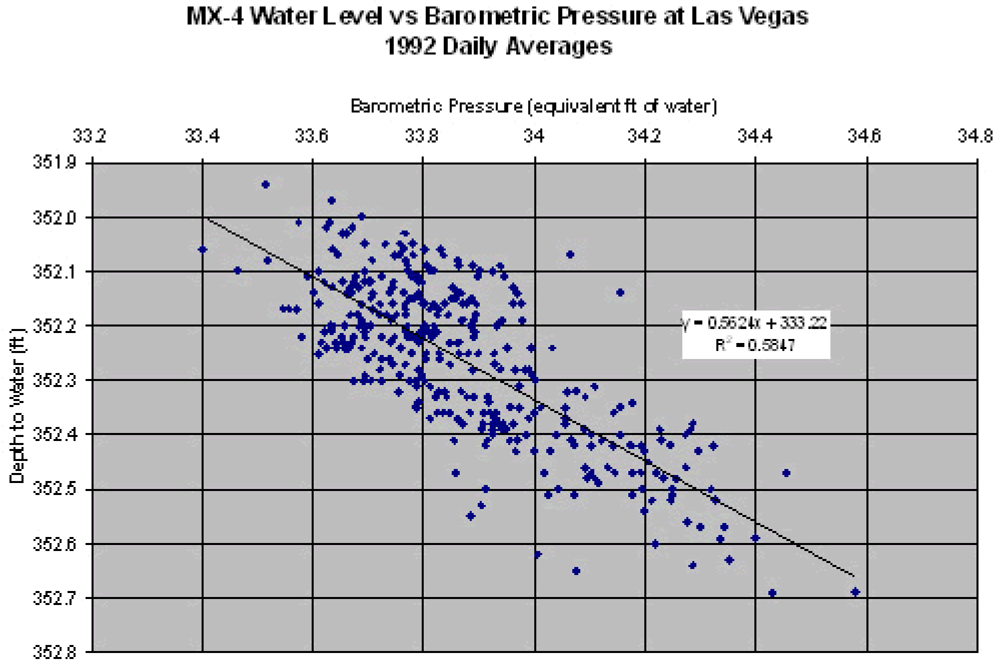


Figure 18 — Average Daily Barometric Pressure at Las Vegas versus Average Daily Water Level at Well MX-4. Data sources: Barometric pressure from the National Climate Data Center, MX-4 water levels from USGS.

Since August 2003, barometric pressure data have been locally collected by SNWA on 15-minute intervals at monitoring well UMVM-1, allowing for more rigorous barometric efficiency computations. The barometric efficiency at well UMVM-1 is calculated as 0.60 (Figure 19). Preliminary barometric efficiencies for MX-4, EH-4, and EH-5b are calculated at 0.42, 0.25 and 0.50, respectively (Table 5, and Figure 20). The barometric efficiency for MX-4 is noticeably lower at 0.42 than calculated using 1991 to 1995 average daily data, and further data collection and analysis is needed to refine the estimates, thus all reported values are considered preliminary.

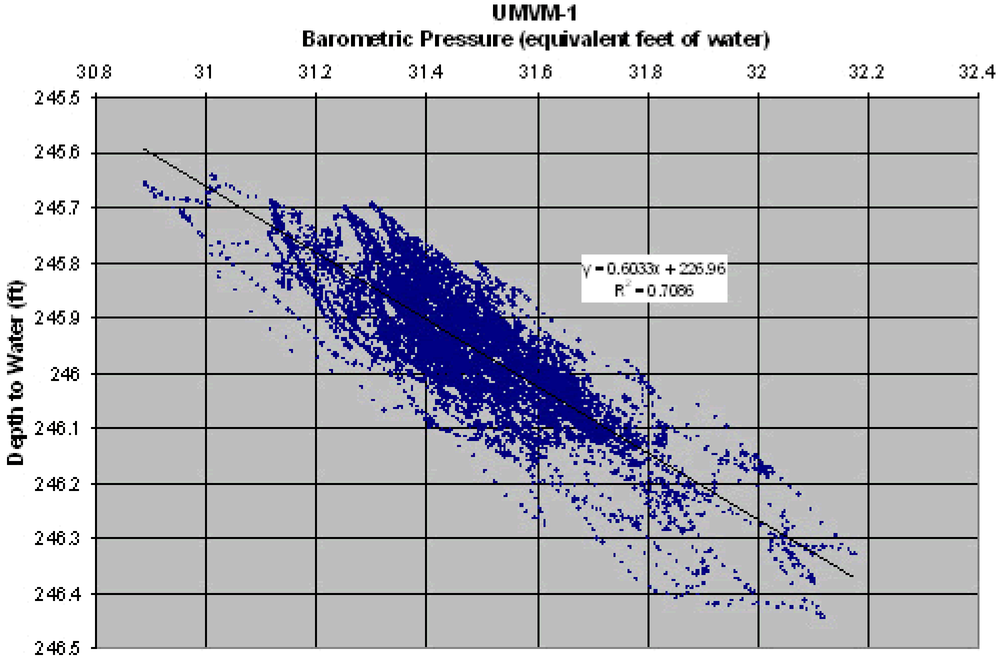


Figure 19 — Barometric Pressure vs. Water Levels recorded at monitoring Well UMVM-1 (15-minute data from August 13, 2003 to December 17, 2003), unadjusted for earth tide effects.

Table 5 – Summary of Barometric Efficiency Calculations using UMVM-1 Barometric Pressure Data, August to December 2003.

| Site | Location of Barometric Pressure Data | Time Period | Time Interval | Barometric Efficiency | $R^2$ |
|---|---|---|---|---|---|
| UMVM-1 | UMVM-1 | Aug. 13 to Dec. 17, 2003 | 15-minute | 0.60 | 0.71 |
| MX-4 | UMVM-1 | September 2003 | Hourly | 0.42 | 0.61 |
| EH-5b | UMVM-1 | September 2003 | Hourly | 0.50 | 0.58 |
| EH-4 | UMVM-1 | September 2003 | Hourly | 0.25 | 0.59 |

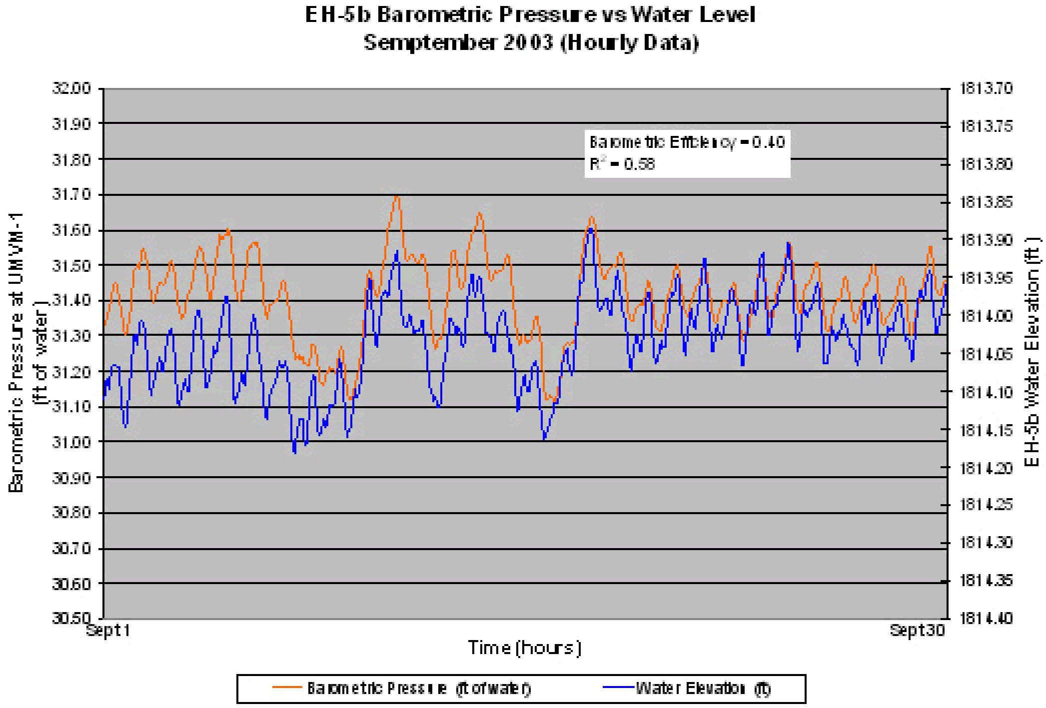


Figure 20. — Barometric Pressure at UMVM-1 versus Potentiometric Water Level at Well EH-5b for Hourly September 2003 Dataset.

**Pederson Spring Discharge Responses to Barometric Pressure Fluctuations**

Assuming Pederson Spring responds similarly to a piezometer tapping the confined carbonate aquifer and the discharge response to barometric pressure change is significant enough to be measured, a spring discharge barometric efficiency may be defined. At Pederson Spring, a visual correspondence between seasonal barometric pressure change (Las Vegas data) and spring discharge appears present in the time period of 1987 to 1990, prior to significant local pumping from the carbonate aquifer (Figure 21). A preliminary barometric efficiency of 0.04 cfs/ft has been derived using average weekly and average monthly datasets, which relies predominantly upon the longer-term annual cycle in local barometric pressure. With the recent repair of the Pederson Spring weir and on-going barometric pressure data collection at well UMVM-1, continued examination of the apparent discharge response to barometric pressure fluctuation will be possible.

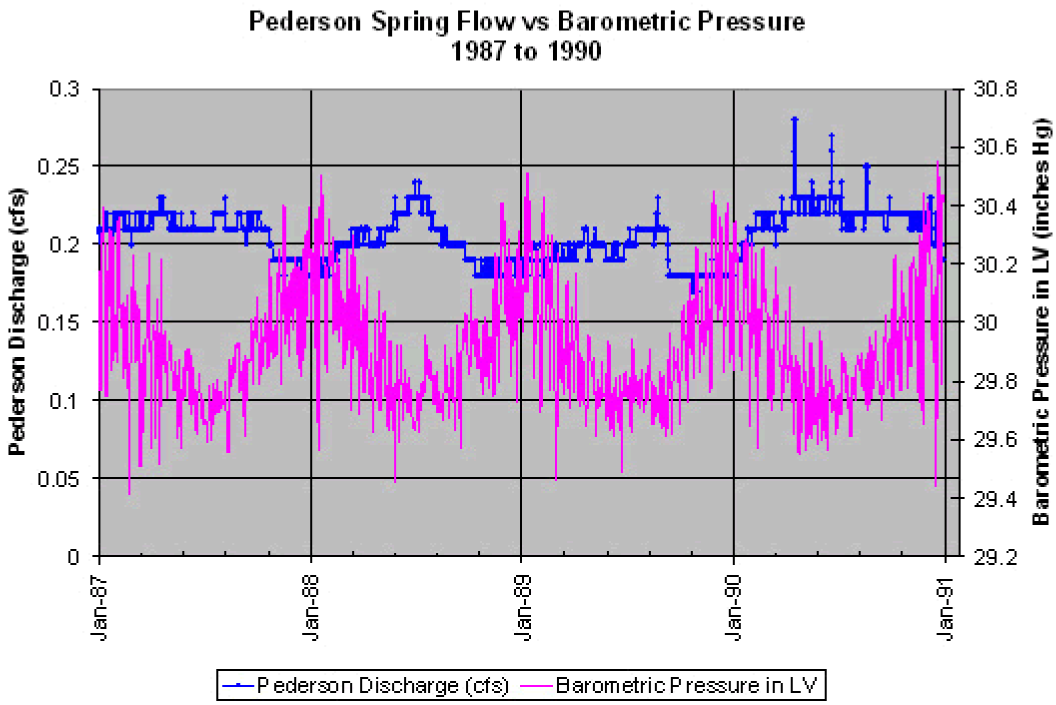


Figure 21 — Pederson Spring Discharge versus Daily Average Barometric Pressure Recorded in Las Vegas. Data sources: barometric pressure from the National Climate Data Center, Pederson Spring discharge from USGS.

The preliminary barometric efficiencies in the carbonate aquifer up-gradient of the Muddy Springs and at Pederson Spring can be combined to define a Pederson Spring discharge response function to potentiometric water level change in the carbonate aquifer, as follows:

(1) $\Delta H_{aquifer} = BE_{aquifer} \ x \ \Delta H_{pressure\text{-}H2O}$

(2) $\Delta Q_{Pederson} = BE_{sping} \ x \ \Delta H_{pressure\text{-}H2O}$

Combining equation 1 and 2 with the common variable of $\Delta H_{pressure\text{-}H2O}$ yields:

(3) $\Delta Q_{Pederson} = (BE_{sping}/BE_{aquifer}) \ x \ \Delta H_{aquifer}$

where,

- $\Delta H_{aquifer}$ is the differential potentiometric head change (feet) caused by barometric pressure fluctuation;
- $\Delta H_{pressure\text{-}H2O}$ is the barometric pressure expressed in equivalent height (feet) of water;
- $\Delta Q_{Pederson}$ is the differential discharge change (cfs) caused by barometric pressure fluctuation;
- $BE_{aquifer}$ is the barometric efficiency of the carbonate aquifer, and
- $BE_{spring}$ is the barometric efficiency of Pederson Spring.

Applying a unit value for $\Delta H_{aquifer}$ of 1, $BE_{spring}$ of 0.04 cfs/ft, and $BE_{aquifer}$ of 0.50 (as defined at EH-5B, and as a general average for the carbonate aquifer up-gradient of the Muddy Springs), one foot of potentiometric head change in the carbonate aquifer equals approximately 0.08 cfs of discharge change in Pederson Spring.

From the derived spring response function, the observed discharge decline in Pederson Spring from 1999 to early 2003 (prior to significant weir leakage) of approximately 0.06 cfs (see Figure 5) is estimated to reflect a 0.75 feet potentiometric head decline in the portion of the carbonate aquifer feeding the spring. This is significantly less than the observed potentiometric head decline in well EH-4, which is approximately 2.0 feet during the same time period, indicating a disconnection between aquifer water levels and spring flows. Faulting between the springs and EH-4 (Figure 3) may be creating a hydraulic discontinuity between these two locations within the aquifer. It should also be noted that well EH-4 may be completed in younger carbonate rocks of the Horse Springs Formation rather than Paleozoic carbonate rocks which hosts the regional flow system (Figure 3).

**SUMMARY**

Regional climate in White River Flow System and Muddy Springs has exhibited dry conditions from 1999 through 2004. Climate appears to have a degree of effect on the local carbonate aquifer, however, declining water level trends began in 1998, one year prior to the dry climate cycle, and appear to be more dramatic than previous responses to climate, based on the limited period of record from the mid-1980s to present. Pumping from the carbonate aquifer at the Arrow Canyon well is believed to be responsible for a portion of the declining trend in potentiometric water levels, with distance-drawdown interpretations generally consistent with Theis theory. However, distance-drawdown interpretations are uncertain due to a strong dependence on the interpretation of drawdown at a single well (CE-VF-2) located 14.7 miles from the Arrow Canyon well.

Several discordances support the presence of hydraulic discontinuities within the carbonate aquifer in the vicinity of the Muddy Springs. Pederson Spring discharge did not commence a declining trend until 1999, an observation which is more consistent with response to a dry climate cycle. Secondly, the magnitude of spring discharge response does not appear consistent with the magnitude of potentiometric water level decline measured in nearby well EH-4. The predicted potentiometric decline at Pederson Spring is approximately 0.8 feet from 1999 to early 2003 as derived using preliminary barometric pressure response relationships, versus 2.0 feet of potentiometric water level decline observed in nearby well EH-4. Other discordances include a less than expected potentiometric drawdown response in well EH-5b due to Arrow Canyon well pumping, based on Theis drawdown theory, and a barometric efficiency reduction from approximately 0.5 up-gradient of the springs to 0.25 adjacent to Pederson Spring at well EH-4.

North-south trending faults are mapped crossing the Muddy Springs in the vicinity of Pederson Spring and well EH-4. Also, well EH-4 is suspected to be completed in the Horse Springs Formation, a much younger fresh water carbonate rock formation, rather than the Paleozoic carbonate rocks that constitute the regional carbonate aquifer, although drawdown responses in EH-4 appear in line with carbonate aquifer wells up-gradient of the Muddy Springs. Hydraulic connections between formations in the vicinity are unclear, and faulting appears to form conduits for discharge of deeper carbonate aquifer water, but may constitute hydraulic barriers to lateral spread of pumping drawdown effects.

Interpretations of climate versus pumping responses in the local carbonate aquifer will gain confidence with continued water level and spring discharge monitoring, and with the undertaking of the planned long-term carbonate aquifer test at well MX-5. The recent replacement of the Pederson Spring weir along with the addition of carbonate aquifer monitoring wells and collection of local barometric pressure data will aid in future interpretations and refinement of the preliminary barometric efficiencies and Pederson Spring discharge responses.

**ACKNOWLEDGEMENTS**

The authors wish to acknowledge the assistance of Judy Brandt, GIS Specialist and Colby Temple, Hydrologist Intern, both with SNWA, for their assistance with data collection and graphics.

**REFERENCES**

Avon, L., Durbin, T., 1994. Hydrologic evaluation of recent water-level decline at Devils Hole: Las Vegas Valley Water District, Cooperative Water Project, Series Report No. 12, 54 p.

Belcher, W. R., Elliott, P. E., Geldon, A. L., 2001, Hydraulic-Property Estimates for use with Transient Ground-Water Flow Model of the Death Valley Regional Ground-Water Flow System, Nevada and California, USGS WRI 01-4120, 28p. with electronic data table.

Bright, D.J., Watkins, S.A., and Lisle, B.A., 2001, Analysis of Water Levels in the Frenchman Flat Area, Nevada Test Site, USGS WRIR 00-4272.

Buqo, T.S., 2004, Allometric Responses in Coupled Groundwater-Surface Water-Reservoir Systems, Abstract and presentation at the 2004 Nevada Water Resources Association Annual Conference.

Converse Consultants, 2003, Water level data for wells EH-4 and EH-5b collected on behalf of Nevada Power Company.

Deming, D., 2002, Introduction to Hydrogeology, published by McGraw Hill.

Donovan, D.J., Dixon, G.L., and Rowley, P.D., 2004, Detailed Geologic Mapping in the Muddy Springs Area, Clark County, Nevada, Abstract and presentation at the 2004 Nevada Water Resources Association Annual Conference.

Driscol, F.G., 1986, Groundwater and Wells, Second Edition, Published by Johnson Division, St. Paul, Minnesota.

Dunne, T., and Leopold, L.B., 1978, Water in Environmental Planning, published by W.H. Freeman and Company.

Eakin, T.E., 1964, Ground-water Appraisal of Coyote Spring and Kane Spring Valleys and Muddy River Springs Area, Lincoln and Clark Counties, Nevada, Nevada Department of Conservation and Natural Resources, Ground-water Reconnaissance Series, Report No. 25.

Eakin, T.E., 1966, A Regional Inter-basin Ground-water System in the White River Area, Southeastern Nevada, published in Water Resources Research, Vol. 2, No. 2, pp. 251-271.

Ertec Western, 1981, MX Sitting Investigation, Water Resources Program, Results of Regional Carbonate Testing, Coyote Spring Valley, Nevada, Prepared for USAF, Ballistic Missile Office, Norton AFB, California, 189 p.

Fenelon, J.M., and Moreo, M.T., 2002, Trend Analysis of Ground-Water Levels and Spring Discharge in the Yucca Mountain Region, Nevada and California, 1960-2000, USGS WRIR 02-4178.

Harrill, J.R., and Bedinger, M.S., 2000, Ground Water Fluctuations in Devils Hole, 1962-1999, Regional Stresses and Water-Level Changes in the Death Valley Region, consultant report prepared for the National Park Service.

Kilroy, K.C., 1992, Aquifer Storage Characteristics of Paleozoic Carbonate Rocks in Southeastern Nevada Estimated from Harmonic Analysis of Water Level Fluctuations, University of Nevada, Reno, PhD. Thesis.

LVVWD, see Las Vegas Valley Water District.

Las Vegas Valley Water District, 2001, Water Resources and Ground-water Modeling in the White River and Meadow Valley Flow Systems, Clark, Lincoln, Nye and White Pine Counties, Nevada.

Longwell, C.R., Pampeyan, E.H., Bowyer, Ben, and Roberts, R.J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology Bulletin 62, 218 p., map scale 1:250,000.

National Climate Data Center, 2003, Published data for historic Palmer Drought Severity Indices (1930 to 2003) and historic daily barometric pressure data recorded in Las Vegas (1981 to 2003).

Palmer, W.C., 1965, Meteorological Drought, published by U.S. Weather Service, Research Paper No. 45

Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for changes in water-table near Yucca Mountain, Nevada, during Quaternary time: Geological Society of America Bulletin, v. 109, p. 219-230.

Schmidt, D. L., Page, W. R., Workman, J. B. 1996, Preliminary geologic map of the Moapa West quadrangle, Clark County, Nevada, U. S. Geologic Survey Open File Report 96-521, 33p. map scale 1:24,000

Thomas, J.M., Calhoun, S.C., Apambire, W.B., 2001, A Deuterium Mass-Balance Interpretation of Groundwater Sources and Flows in Southeastern Nevada, Desert Research Institute Publication No. 41169.

Todd, D.K., 1980, Groundwater Hydrology, 2nd edition, published by John Wiley & Sons, Inc.

USGS, 2003, Annual Water Resources Data, Nevada, Water Year 2003.

USGS, 2003b, Letter from Kimball E. Goddard, District Chief, USGS Nevada to Kay Brothers, SNWA Deputy General Manager; regarding status of Pederson Spring discharge measurements.

Western Regional Climate Center, 2003, Monthly historic precipitation data for several stations in south-central Nevada.

Winograd, I.J., Riggs, A.C., and Coplen, T.B., 1998, The Relative Contributions of Summer and Cool-season Precipitation to groundwater Recharge, Spring Mountains, Nevada, USA, published in Hydrogeology Journal, Volume 6, pp. 77-93.

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# Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona

By William R. Page, Daniel S. Scheirer, Victoria E. Langenheim, and Mary A. Berger

Open-File Report 2006–1040

Revised June, 2011

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Suggested citation: Page, W.R., Scheirer, D.S., Langenheim, V.E., and Berger, M.A., 2011, Revised geologic cross sections of parts of the Colorado, White River, and Death Valley regional groundwater flow systems, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 2006–1040, Denver, CO, 80225.

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1. Relationship between bedrock units in cross sections and Page and others, 2005a

## Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Flow rate | |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| millimeter (mm) | 0.03937 | inch (in.) |

# Revised Geologic Cross Sections of Parts of the Colorado, White River, and Death Valley Regional Groundwater Flow Systems, Nevada, Utah, and Arizona

By William R. Page, Daniel S. Scheirer, Victoria E. Langenheim, and Mary A. Berger

## Abstract

This report presents revisions to parts of seven of the ten cross sections originally published in U.S. Geological Survey Open-File Report 2006–1040. The revisions were necessary to correct errors in some of the original cross sections, and to show new parts of several sections that were extended and (or) appended to the original section profiles. Revisions were made to cross sections *C–C'*, *D–D'*, *E–E'*, *F–F'*, *G–G'*, *I–I'*, and *J–J'*, and the parts of the sections revised or extended are highlighted below the sections on plate 1 by red brackets and the word "revised", or "extended." Sections not listed above, as well as the interpretive text and figures, are generally unchanged from the original report. Cross section *C–C'* includes revisions in the east Mormon Mountains in the east part of the section; *D–D'* includes revisions in the Mormon Mesa area in the east part of the section; *E–E'* includes revisions in the Muddy Mountains in the east part of the section; *F–F'* includes revisions from the Muddy Mountains to the south Virgin Mountains in the east part of the section; and *J–J*' includes some revisions from the east Mormon Mountains to the Virgin Mountains. The east end of *G–G'* was extended about 16 km from the Black Mountains to the southern Virgin Mountains, and the northern end of *I–I'* was extended about 45 km from the Muddy Mountains to the Mormon Mountains, and revisions were made in the Muddy Mountains part of the original section.

This report contains 10 interpretive cross sections and an integrated text describing the geology of parts of the Colorado, White River, and Death Valley regional groundwater flow systems in Nevada, Utah, and Arizona. The primary purpose of the report is to provide geologic framework data for input into a numerical groundwater model. Therefore, the stratigraphic and structural summaries are written in a hydrogeologic context.

The oldest rocks (basement) are Early Proterozoic metamorphic and intrusive crystalline rocks that are considered confining units because of their low permeability. Late Proterozoic to Lower Cambrian clastic units overlie the crystalline rocks and are also considered confining units within the regional flow systems. Above the clastic units are Middle Cambrian to Lower Permian carbonate rocks that are the primary aquifers in the flow systems. The Middle Cambrian to Lower Permian carbonate rocks are overlain by a sequence of mainly clastic rocks of late Paleozoic to Mesozoic age that are mostly considered confining units, but they may be permeable where faulted.

Tertiary volcanic and plutonic rocks are exposed in the northern and southern parts of the study area. In the Clover and Delamar Mountains, these rocks are highly deformed by north- and

northwest-striking normal and strike-slip faults that are probably important conduits in transmitting groundwater from the basins in the northern Colorado and White River flow systems to basins in the southern part of the flow systems.

The youngest rocks in the region are Tertiary to Quaternary basin-fill deposits. These rocks consist of middle to late Tertiary sediments consisting of limestone, conglomerate, sandstone, tuff, and gypsum, and younger Quaternary surficial units consisting of alluvium, colluvium, playa deposits, and eolian deposits. Basin-fill deposits are both aquifers and aquitards.

The rocks in the study area were complexly deformed by episodes of Mesozoic compression and Cenozoic extensional tectonism. Some Cretaceous thrust faults and folds of the Sevier orogenic belt form duplex zones and define areas of maximum thickness for the Paleozoic carbonate rocks. Cenozoic faults are important because they are the primary structures that control groundwater flow in the regional flow systems.

## Introduction

The 10 geologic cross sections (pl. 1) were constructed to better understand the hydrogeologic framework for parts of the Colorado, White River, and Death Valley regional groundwater flow systems in southern Nevada, southwestern Utah, and northwestern Arizona. The main purpose of the cross sections is to provide the National Park Service with geologic framework data for input into a numerical groundwater model. Rapid urbanization and commercial development in the region has increased demand for water from surface-water sources and from local and regional aquifers in these flow systems. As a result, the geology in the area needs to be defined to assist in understanding the complex hydrologic processes that govern groundwater recharge, movement, storage, and discharge.

The study area includes part of the Colorado groundwater flow system (Harrill and Prudic, 1998), the southern part of the White River groundwater flow system (Eakin, 1964, 1966; Thomas and Welch, 1984; and Kirk, 1987), and the eastern part of the Death Valley groundwater flow system (Winograd and Thordarson, 1975; Laczniak and others, 1996; Harrill and Prudic, 1998; D'Agnese and others, 2002; Workman and others, 2002a, 2002b) (fig. 1). The White River flow system is a subset of the Colorado flow system (fig. 1).

The principal discharge for the White River flow system is Muddy River springs (Dettinger and others, 1995) (fig. 2), a series of springs that discharge 36,000 ac-ft/yr to form the Muddy River. Movement of groundwater in the study area is generally southward as indicated by potentiometric maps based on water levels in wells (Thomas and others, 1986; Wilson, 2001). The flow is driven by the hydraulic head parallel to the southward topographic gradient.

Aquifers in the flow systems consist of Paleozoic carbonate rocks, volcanic rocks, and basin-fill sediments (Plume and Carlton, 1988; Dettinger and others, 1995; Prudic and others, 1995; Burbey, 1997; Harrill and Prudic, 1998). The importance of the Paleozoic carbonate-rock aquifer to the flow systems that cover much of southern Nevada and adjacent States is so significant that many regional hydrologic reports have focused on the distribution and features of this aquifer (Dettinger and others, 1995; Burbey, 1997; Wilson, 2001).

## Methods

The 10 interpretive cross sections (pl. 1, fig. 3) were hand drawn at 1:250,000-scale using Page and others (2005a) as a geologic base. Many of the units shown in the cross sections are combined from two or more units from the map. This generalization was necessary to portray stratigraphic relations appropriately for the cross section scale. Table 1 shows the relationship between the cross section bedrock units in this report and those in Page and others (2005a). The hand-drawn sections were scanned and converted to digital vector files. The topographic profiles were made using a 90 meter Digital Elevation Model. Most of the sections (*A–A′*, *B–B′*, *C–C′*, *D–D′*, *E–E′*, and *G–G′*) are oriented east-west (fig. 3), perpendicular to major structures in the study area. The east-west sections on plate 1 were hung on longitude 114°40'00" as a reference line (fig. 3) to visually extrapolate the geology between the section lines in a north-south progression.

A systematic unit color scheme was applied to the cross sections for a broad translation of geologic units into hydrostratigraphic units. Proterozoic and Lower Cambrian confining units are shades of brown and orange; Middle Cambrian to Lower Permian carbonate aquifer rocks in shades of blue; upper Paleozoic and Mesozoic confining units are shades of green; Cenozoic volcanic and intrusive rocks are shades of pink and red, respectively; and Tertiary to Quaternary basin-fill rocks are yellow.

The cross sections integrate data from existing maps and reports, geophysical investigations, and well data, and are progressively more interpretive with depth because of the lack of data at deeper levels. Page and others (2005a) provided a comprehensive list of geologic map sources and reports used in their compilation and in this study, and they presented detailed lithologic description and thickness of individual units in the map and cross section region. Data from several deep petroleum exploration wells were used to constrain thickness of basin-fill sediments and bedrock geology along several cross sections. These wells were tied into the cross section lines (fig. 3) and include the Texaco Federal #1 well (*C–C′*), Mobil Virgin River no. 1–A well (*D–D′*), and the Grace Petroleum Arrow Canyon #1 well (*G–G′*). Stratigraphic and structural data from these wells were from well logs and from Garside and others (1988).

The geology of the Virgin Valley area (*B–B′*, *C–C′*, and *D–D′*) was based on seismic-reflection and well data from Bohannon and others (1993), seismic-reflection data from Carpenter and Carpenter (1994), gravity data from Langenheim and others (2000), and magnetic data from Jachens and others (1998). Much of the subsurface geology in the Meadow Valley Wash (*A–A′*, *B–B′*, *C–C′*, and *D–D′*) and Tule Desert (*A–A′*) areas was based on seismic-reflection and gravity data acquired and analyzed by the USGS, and is summarized in Scheirer and others (2006). The subsurface geology in the central part of California Wash (*E–E′* and *F–F′*) was based on Langenheim and others (2001b, 2002). The subsurface geology of Coyote Spring Valley (*B–B′*, *C–C′*, *D–D′*, *E–E′*, and *F–F′*) was partly based on Phelps and others (2000). Cenozoic basin-fill thickness and geometry shown for basins in the western part of the study area (west of Coyote Spring Valley) is based on Blakely and Ponce (2001). Regional and detailed gravity data (fig. 4) were used to constrain Cenozoic basin geometry and depth to crystalline basement in much of the cross section area.

## Stratigraphy

### Proterozoic and Paleozoic Rocks

Early Proterozoic metamorphic and intrusive rocks consist of gneiss, granite, and schist that are about 1.7 Ga (Quigley and others, 2002). These crystalline rocks form both geologic and hydrologic basement and are considered barriers to groundwater flow because of their low permeability. The crystalline rocks may be locally permeable where highly fractured, but fractures in these rocks are generally poorly connected (D’Agnese and others, 1997). Early

Proterozoic rocks exposed in the Beaver Dam and Virgin Mountains form the eastern boundary of the flow systems (*A–A′*, *B–B′*, *C–C′*, *D–D′* and *E–E′*). Early Proterozoic rocks also form the core of the Mormon Mountains where they act as a local barrier to groundwater flow (Burbey, 1997) (*B–B′* and *C–C′*), although through-going, north-striking faults along the western and eastern Mormon Mountains may provide conduits for some southward groundwater flow through the mountain range.

A north-trending positive gravity anomaly extends from the Meadow Valley Mountains to the central Arrow Canyon Range (fig. 4). We interpret this gravity high to represent a zone of shallow Proterozoic crystalline rocks beneath parts of the Meadow Valley Mountains and Arrow Canyon Range (*C–C′*, *D–D′* and *E–E′*). Termination of the gravity anomaly south of the central Arrow Canyon Range may be due to the development of duplex zones and thicker Paleozoic rocks in the southern Arrow Canyon and Las Vegas Ranges shown along cross sections *F–F′* and *G–G′* (see Mesozoic Thrust Faults section below).

Late Proterozoic sedimentary rocks in the study area consist of quartzite, conglomerate, sandstone, siltstone, and shale, and they contain subordinate amounts of limestone and dolostone. The Late Proterozoic sedimentary rocks are well cemented, contain minimal pore space, and have low permeability. They were deposited in shallow marine waters along a passive continental margin of what is now western North America (Stewart, 1976; Stewart and Poole, 1972) and represent initial deposits of the Cordilleran miogeocline (Stewart and Poole, 1972; Stewart, 1972, 1976).

Lower Cambrian rocks are predominantly well-cemented, clastic units of quartzite, conglomerate, siltstone, and shale with low permeability. Together, the Lower Cambrian and Late Proterozoic sedimentary rocks form a confining unit in the study area. In the Death Valley groundwater flow system, these rocks are referred to as the lower clastic aquitard (Winograd and Thordarson, 1975), or the lower clastic confining unit (Belcher and others, 2002). These rocks are reported to be nearly impermeable and have low transmissivities based on pumping tests and other hydrologic data in the region (Winograd and Thordarson, 1975). Late Proterozoic clastic units are present mostly in the western part of the study area and they pinch out to the east and are absent in the Mormon, Virgin, and Beaver Dam Mountains, and in the Lake Mead area. In these areas, the lower clastic confining rocks include the Lower Cambrian Tapeats Sandstone and the Lower and Middle Cambrian Bright Angel Shale.

Middle Cambrian through Lower Permian rocks record a significant shift in deposition to predominantly carbonate sedimentation, from mostly clastic sedimentation in pre-Bonanza King (and equivalent units) Late Proterozoic and Cambrian units. The carbonate rocks are predominantly limestone and dolostone and form the regional aquifer (Dettinger and others, 1995). The Middle and Upper Cambrian Bonanza King Formation (and partly equivalent Highland Peak Formation and Muav Limestone) forms the basal part of the carbonate aquifer in the White River, Colorado, and Death Valley groundwater flow systems (Winograd and Thordarson, 1975; Laczniak and others, 1996; Belcher and others, 2002; D’Agnese and others, 2002). Groundwater flow through the carbonate rocks is mostly through fractures and faults. Because the rocks are soluble in groundwater, dissolution features are also important in the development of secondary porosity and permeability. Zones of high transmissivity in the carbonate rock aquifer are indicated by large spring discharge (36,000 ac-ft/yr at Muddy River Springs) in areas of low potentiometric gradient, and by water wells exhibiting extremely high hydraulic conductivity (Dettinger and others, 1995).

Middle Cambrian through Lower Permian rocks are predominantly carbonate with the exception of the Upper Cambrian Dunderberg Shale Member of the Nopah Formation (70 to 100 m thick), Middle Ordovician Eureka Quartzite (0 to 120 m), Upper Mississippian Chainman Shale (200 to 285 m), Upper Mississippian Indian Springs Formation (20 to 60 m), and the Lower Permian redbeds (600 m). The Dunderberg Shale Member, Eureka Quartzite, and Indian Springs Formation are probably not thick enough to form regional confining units, but they may act as confining units locally. The Chainman Shale and Lower Permian redbeds are substantially thicker and may be regional confining units in parts of the study area.

The upper part of the carbonate aquifer in the study area consists of Upper Mississippian and Lower Permian units, including the Bird Spring Formation and partly equivalent Callville Limestone and Pakoon Dolomite. Lower Permian redbeds overlie these formations and represent a shift from predominantly carbonate marine to mostly continental sedimentation, although a few carbonate units lie above the Lower Permian redbeds, including the Lower Permian Kaibab and Toroweap Formations, and the Lower Triassic Virgin Limestone Member of the Moenkopi Formation. Continental sedimentation predominated through the Mesozoic and into the lower Tertiary.

## Late Proterozoic-Paleozoic Facies Belts

Late Proterozoic-Paleozoic rock units are separated geographically into facies belts even though they may be partly or entirely correlative. This is because facies changes prevent exact correlations between areas, and different names have been applied to rocks of the same age. In the study area, Late Proterozoic-Paleozoic rocks can be broadly subdivided into western, central, and eastern facies belts (Page and others, 2005a).

Rocks in the western belt include Late Proterozoic through Devonian units deposited as part of the Cordilleran miogeocline in offshore carbonate shelf and intertidal depositional settings, and an overlying Mississippian to Permian sequence deposited mostly in a carbonate platform depositional setting. These rocks are exposed as far east as the Las Vegas Range, Arrow Canyon Range, Meadow Valley Mountains, and Delamar Mountains (fig. 2). From oldest to youngest, these rocks include the following formations: Johnnie Formation (Late Proterozoic); Stirling Quartzite (Late Proterozoic) and Wood Canyon Formation (Late Proterozoic and Lower Cambrian) and their equivalent, the Prospect Mountain Quartzite; Carrara Formation (Lower and Middle Cambrian) and northern equivalents, Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), and Pioche Shale (Lower and Middle Cambrian); Bonanza King (Middle and Upper Cambrian) and partly equivalent Highland Peak Formation (Middle Cambrian); Nopah Formation (Upper Cambrian); Pogonip Group (Upper Cambrian to Middle Ordovician); Eureka Quartzite (Middle Ordovician); Ely Springs Dolomite (Upper Ordovician); Laketown Dolomite (Lower Silurian); Sevy Dolomite (Lower Devonian); Simonson Dolomite (Middle Devonian); Guilmette Formation (Middle and Upper Devonian) and the partly equivalent Sultan Limestone (Middle Devonian to Lower Mississippian); Monte Cristo Group (Lower and Upper Mississippian) and the partly equivalent Joana Limestone (Lower Mississippian); Chainman Shale (Lower and Upper Mississippian) and Scotty Wash Quartzite (Upper Mississippian); and Bird Spring Formation (Upper Mississippian to Lower Permian).

The eastern facies belt includes cratonic platform rocks of the Colorado Plateau region exposed in the Beaver Dam and Virgin Mountains, and in the Lake Mead area including Frenchman Mountain (table 1). The rocks are mostly shallow marine sediments deposited in near-shore, intertidal, shoreline, and continental settings. The facies belt is characterized by a large magnitude unconformity separating Middle Devonian from Upper Cambrian rocks. The cratonic sequence, or eastern facies belt, includes (from oldest to youngest): Tapeats Sandstone (Lower Cambrian); Bright Angel Shale (Lower and Middle Cambrian); Muav Limestone (Middle Cambrian); Nopah Formation (Upper Cambrian); Temple Butte Formation (Middle? and Upper Devonian); Redwall Limestone (Lower and Upper Mississippian); and Callville Limestone (Pennsylvanian) and Pakoon Dolomite (Lower Permian). The central facies belt includes rocks that are transitional between the eastern and western belts; these rocks are exposed in the Muddy Mountains, Mormon Mountains, and Tule Springs Hills (fig. 2).

The thickness of Middle Cambrian to Lower Permian carbonate rocks that form the regional aquifer decreases dramatically across the belts from west to east over a distance of about 100 km; from a maximum of about 7 km thick in the western belt to less than 2 km thick in the eastern belt. Whereas thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton, the greatest thickness variation across the belts is because the Paleozoic rocks were telescoped into a narrower zone during Mesozoic thrusting.

## Mesozoic Rocks

Mesozoic rocks are predominantly continental clastic units consisting of conglomerate, sandstone, siltstone, mudstone, shale, and gypsum, but they also include minor limestone and dolostone. These rocks are exposed mostly in the eastern parts of the study area and were deposited in fluvial, lacustrine, eolian, and marginal marine environments, and they include Triassic, Jurassic, and Cretaceous units. The Mesozoic rocks have low permeability compared with the Paleozoic carbonate rocks because of their high proportion of clastic material. They are generally considered confining units, but they may be permeable where highly fractured. Units containing large amounts of shale and mudstone, such as in the Triassic formations, generally have low permeability. The Jurassic Navajo Sandstone in the Utah part of the study area is an aquifer (Heilweil and others, 2002), but in other parts of southern Nevada, such as in Las Vegas Valley, the Jurassic Aztec Sandstone generally has low permeability. This example illustrates the variability in hydrologic properties of the Mesozoic rocks.

## Tertiary-Quaternary Rocks

Tertiary and Quaternary rocks in the cross sections are mostly basin-fill deposits, which consist of alluvium and colluvium, playa deposits, eolian deposits, spring discharge deposits, and landslide breccias of Miocene to Holocene age. Older basin-fill rocks include the Miocene and Pliocene Muddy Creek Formation and equivalent units in the Lake Mead area, and the Oligocene and Miocene Horse Spring Formation and equivalent units. The Muddy Creek Formation is mostly lacustrine and fluvial mudstone, tuffaceous sandstone, gypsum, halite, and conglomerate. The Horse Spring Formation consists of fluvial and lacustrine rocks, comprised of tuffaceous sandstone, tuff, conglomerate, siltstone, mudstone, limestone, and gypsum.

Basin-fill rocks in the study area are both aquifers and aquitards. Basin-fill deposits in the Mesquite basin of the Virgin Valley reach maximum thicknesses of about 8 to 10 km (Langenheim and others, 2001a, 2000). In the Mesquite, Nev., area, the Muddy Creek Formation is the main aquifer (Johnson and others, 2002; Dixon and Katzer, 2002), where it consists of gravel, sand, silt, and clay, and is moderately deformed by high-angle normal faults.

Dettinger and others (1995) hypothesized that Muddy River Springs partly exist due to thick basin deposits of lower Meadow Valley Wash basin which may form a groundwater barrier to eastward flow from the springs (see cross section *D–D')*. The Muddy Creek Formation is widely exposed in this basin, and unlike the Muddy Creek in the Virgin Valley area, the formation is mildly deformed and is mostly low-permeability lacustrine clay and silt.

Unit Tv in the cross sections includes volcanic rocks of Oligocene to Pliocene age. Most of the volcanic rocks are ash-flow tuffs erupted from calderas, but stratovolcanoes were locally present. These rocks also include basalt and lava flows. In the Delamar and Clover Mountains, the volcanic rocks range from several hundred to several thousand meters thick. Intracaldera tuffs are generally thicker than outflow tuffs. Unit Ti consists of granitic intrusive rocks that generally are the source plutons for the volcanic units in unit Tv.

## Structural Geology

The physiography of the study area reflects late Mesozoic and Cenozoic structural events that produced a Cretaceous fold-and-thrust belt that was subsequently disrupted by Cenozoic extensional and transform tectonics, and accompanying intrusive and volcanic activity.

### Mesozoic Thrust Faults

Major thrust faults in the study area include the Muddy Mountain and Gass Peak thrusts. The Muddy Mountain thrust is exposed in the Muddy Mountains; several equivalent thrusts extend northward (Hintze and Axen, 2001) including: the Glendale thrust in the Glendale, Nev., area; Mormon thrust in the Mormon Mountains; Tule Spring thrust in the Tule Springs Hills, Nevada; and the Square Top Mountain thrust in the northern Beaver Dam Mountains in southwest Utah (fig. 5).

The Gass Peak thrust (Guth, 1980, 1981, 1990) in the Sheep Range is west of and at a structurally higher level than the Muddy Mountain and equivalent thrusts (fig. 5). The thrust faults strike north to northeast and are east to southeast vergent structures of Sevier orogenic belt (Armstrong, 1968; Fleck, 1970). The Muddy Mountain and equivalent thrusts are the frontal thrusts of the Sevier orogenic belt in southern Nevada and southwestern Utah. The Muddy Mountain thrust is reported to be late Albian to Cenomanian(?) in age (Bohannon, 1983; Carpenter and Carpenter, 1994; Fleck and Carr, 1990). Several intermediate thrusts are between the Muddy Mountain (and equivalent thrusts) and Gass Peak thrusts. These include the Delamar thrust in the southern Delamar Mountains (*B–B'*) (Page, 1990), the Meadow Valley and Vigo thrusts in the Meadow Valley Mountains (*B–B'*) (Pampeyan, 1993), and the Dry Lake thrust and other unnamed thrusts in the Arrow Canyon and Dry Lake Ranges (*D–D'*, *F–F'*, and *G–G'*) (Page, 1992; Page and Dixon, 1992). The Summit Willow Tank thrust is a secondary thrust fault below the Muddy Mountain thrust in the Muddy Mountains (*E–E'* and *F–F'*) (Bohannon, 1983).

A commonly accepted model for thrusts in the Sevier belt, which we have conceptually applied to the cross sections, is that of a ramp-flat, decollemont geometry, where thrusts are flat at depth along a basal decollement and detach to ramp at certain stratigraphic levels. We follow Guth (1980) in the interpretation of a flat-ramp-flat geometry for the Gass Peak thrust with decollement zones near the base of the Late Proterozoic-Lower Cambrian sequence (Guth, 1980; fig. 1, case 1, p. 151). East of the Gass Peak thrust, the regional decollement forms an extensive hanging-wall flat near the base of the Middle and Upper Cambrian Bonanza King Formation as indicated by exposure of these rocks at the base of hanging-wall ramps and flats in the Muddy Mountain (*E–E'*, *F–F'*, and *G–G'*), Mormon (*B–B'* and *C–C'*), Tule Spring (*A–A'*), and Delamar (*B–B'*) thrust faults. The eastward transition to a decollement at the base of the Bonanza King Formation is probably controlled by the west to east pinch out of the Late Proterozoic clastic units against the craton (Sweetkind and others, 2001); the pinch out is in a zone between the

Sheep Range and the Arrow Canyon Range/Meadow Valley Mountains because Late Proterozoic rocks at the base of the sedimentary sequence are absent in the Mormon Mountains and Tule Springs Hills, and rocks of the Middle and Lower Cambrian Bright Angel Shale and Lower Cambrian Tapeats Sandstone rest directly on Early Proterozoic crystalline basement.

Duplex zones in the Paleozoic carbonate rocks are interpreted along the Dry Lake and Muddy Mountain thrusts (*F–F′* and *G–G′*). These duplex zones define areas of maximum thickness for the Paleozoic carbonate rocks in the region because the Paleozoic section is essentially repeated along the thrusts. In cross section *G–G′*, these rocks are interpreted to be greater than 7 km thick based on logs from the Grace Petroleum Arrow Canyon no. 1 well. In this well, an upper thrust fault is interpreted at about 2,288 m depth where rocks of the Cambrian Carrara Formation are in the upper plate above rocks of the Cambrian Bonanza King Formation in the lower plate. A lower thrust fault occurs at about 2,800 m depth where rocks of the Bonanza King Formation in the upper plate are above rocks of the Mississippian-Permian Bird Spring Formation in the lower plate, thus repeating the Paleozoic section from the Bird Spring Formation downward. We interpret the upper fault as the Dry Lake thrust and the lower fault as the Muddy Mountain thrust (*G–G′*). The zone between the two faults is characterized by complexly repeated Cambrian units indicating horst blocks and (or) imbrication structures, features commonly associated with thrust fault zones.

Burbey (1997) suggested that Late Proterozoic-Lower Cambrian clastic confining units in the upper plate of the Gass Peak thrust may restrict eastward groundwater flow from the Sheep Range and areas to the west. The upper plate confining units are thrust over Mississippian to Permian rocks of the Bird Spring Formation in the lower plate as shown in cross sections *F–F′* and *G–G′*. North of *F–F′*, however, the Gass Peak thrust loses throw and juxtaposes mainly Paleozoic carbonate rocks in upper and lower plates (*B–B′*).

The Muddy Mountain thrust in the Muddy Mountains juxtaposes Paleozoic carbonate rocks in the upper plate against Mesozoic and Paleozoic rocks in the lower plate (*G–G′*); such a relationship suggests that the less permeable Mesozoic rocks below the thrust may act as a groundwater flow barrier, and the thrust has been characterized as a barrier in local groundwater models. Although the lower plate rocks may act as a barrier in localized zones along strike, we think that overprinting of the thrust by Cenozoic faults (Langenheim and others, 2002) provides linkage between rocks in the upper and lower plates, allowing for some groundwater flow across the thrust. This example may apply to other Mesozoic thrust faults in the map area, especially where the thrusts are highly modified by younger Cenozoic extensional faults.

Mesozoic thrusts have been reactivated by normal faults during Cenozoic extension in parts of the study area. The Delamar thrust has been reactivated by high-angle normal faults in the southern Delamar Mountains (Page, 1990). Guth (1990) reported that parts of the Gass Peak thrust may have been reactivated by Cenozoic normal faults, and structural relations illustrated in cross section *B–B′* suggest extensional Cenozoic reactivation on the thrust based on Tertiary volcanic rocks downfaulted on the thrust in the northern Sheep Range. Axen and others (1990) discussed extensional Cenozoic reactivation of the Tule Spring thrust in the Tule Springs Hills.

### Cenozoic Magmatism, Strike-slip Faults, Normal Faults, and Basin Development

Cenozoic tectonics affected the rocks in the study area and includes volcanism and plutonism, normal and strike-slip faulting, and basin development. Cenozoic faults are important because they represent the last major phase of deformation that affected the rocks in the region, and they provide the fractures and faults that control groundwater flow through the Paleozoic carbonate aquifer. Quaternary faults are present in parts of the study area, and faulting is currently active in some areas such as in the Pahranagat shear zone. These younger faults may be especially important in groundwater flow because younger faults and fractures tend to be more open than in older fault systems (Dettinger and others, 1995), and in many cases, they have reactivated older fault zones.

### Magmatism

The northern part of the study area is characterized by numerous Oligocene and Miocene volcanic rocks, mainly ash-flow tuffs erupted from calderas, but also some lava flows and granitic plutons. The southern limit of these rocks occurs at about latitude 37$^{o}$, just north of the Mormon Mountains and Tule Springs Hills, and the negative isostatic gravity anomalies in the northern part of figure 4 reflect low-density volcanic rocks in the Clover Mountains (Scheirer and others, 2006). Volcanic rocks are also exposed in the southeast part of the study area in the southern Virgin Mountains, Black Mountains, and Lake Mead area. These rocks include Miocene andesitic volcanic rocks and calc-alkaline plutons.

The volcanic rocks in the northern part of the study area were erupted mainly from the Caliente caldera complex (Rowley and others, 1995) in the Delamar and Clover Mountains, and the Kane Wash caldera complex (Scott and others, 1995) in the Delamar and Meadow Valley Mountains (fig. 5). The Caliente caldera complex in the Clover Mountains is highly deformed by north- and northwest-striking normal and strike-slip faults (Page and others, 2005a) that may be important conduits in transmitting ground water from basins in the northern part of the Colorado flow system to basins in the southern part of the flow system.

### Strike-slip Faults, Normal Faults, and Basin Development

Major strike-slip fault zones include the northeast-striking, left-lateral Pahranagat shear zone, Kane Springs Wash fault zone, and Lake Mead fault zone, and the northwest-striking, right-lateral Las Vegas Valley shear zone (fig. 5). These fault zones represent transfer or accommodation zones that separate structural blocks within the study area that have undergone different rates and amounts of extension (Guth, 1981; Wernicke and others, 1982; Duebendorfer and Black, 1992; Rowley, 1998). Strike-slip faults are denoted on the cross sections with the letters “T” and “A”, indicating relative fault block movement toward or away from the viewer, respectively (see plate symbol explanation).

The Pahranagat shear system is a zone of steeply northwest-dipping faults that shows evidence of dip-slip and strike-slip offset (fig. 5). Tschanz and Pampeyan (1970) estimated about 6 to 9 km of left-lateral displacement on the shear system. Modern fault scarps and fissures in alluvial deposits in southern Delamar Valley (Swadley, 1995), and current seismicity on faults in the shear system (Rogers and others, 1987) indicate that it is active. Strands of the Pahranagat shear system join together and merge with north-striking range front faults bounding the northern Delamar Mountains to the north, and the southern Delamar Mountains and the Sheep Range to the south (Page and others, 2005a). Cross section *B–B′* transects the southern part of the shear zone, and displays a series of closely-spaced, northwest-dipping faults offsetting primarily Late Proterozoic and Paleozoic rocks. The volcanic rocks in *B–B′* are thin near the southern limit of their exposure, but they thicken to the north within the shear zone (Page and others, 2005a).

The Kane Springs Wash fault zone (fig. 5) is a left-lateral fault system that has about 7 to 11 km of displacement based on offset of the Kane Springs Wash caldera (Harding and others, 1995). Northeast-striking faults of the Kane Springs Wash fault zone merge into the north-striking range front fault system on the west side of the Meadow Valley Mountains. In cross section *A–A′*, the Kane Springs Wash fault zone is 3 km wide and cuts mainly volcanic and plutonic rocks of the Kane Wash caldera complex. Southward (*B–B′*), the fault zone is about 5 km wide and cuts mainly Paleozoic carbonate rocks. Early Proterozoic crystalline rocks are interpreted to be present at shallow depths (less than 4 km) near where the fault zone intersects *B–B′*, based on surface exposure of older Paleozoic rocks (Cambrian) and on regional gravity data (fig. 4). Quaternary faulting has been reported along some strands of the Kane Springs Wash fault zone in Kane Springs Wash (Swadley and others, 1994).

The northwest-striking Las Vegas Valley shear zone (LVVSZ) (fig. 5) is a large-magnitude, right-lateral, strike-slip fault zone that formed during Cenozoic extension (Page and others, 2005b). The shear zone truncates the southern Las Vegas, Sheep, Desert, and Pintwater Ranges, and extends for nearly 150 km from the Lake Mead area to Mercury, Nevada. The LVVSZ played a significant role in the tectonic development of Las Vegas Valley (Page and others, 2005b). The effects of the LVVSZ include oroflexural bending and offset of major Mesozoic thrust faults and folds. Offset of Mesozoic thrust faults across Las Vegas Valley indicate 48±7 km of right-lateral separation (Wernicke and others, 1988); this estimate includes bending of the Las Vegas Range. Paleomagnetic data (Sonder and others, 1994; Nelson and Jones, 1987) indicated a 20-km-wide zone of clockwise rotation as great as $100^{o}$ in rocks as young as 13.5 Ma adjacent to the LVVSZ. The paleomagnetic data, along with other structural data, bracket the principal period of movement along the LVVSZ between 14 and 8.5 Ma (Duebendorfer and Black, 1992; Duebendorfer and Simpson, 1994).

Two strands of the LVVSZ are shown in *H–H′* in the Frenchman Mountain area. The northern strand is concealed by basin-fill sediments between the Dry Lake Range and Frenchman Mountain, and it is shown as a north-dipping fault that juxtaposes a thick section of Paleozoic rocks in the hanging wall against Proterozoic crystalline rocks beneath Frenchman Mountain in the footwall. The southern strand of the LVVSZ juxtaposes cratonic Paleozoic rocks of Frenchman Mountain in the footwall of the fault against presumably thicker, cratonic margin Paleozoic rocks and Tertiary volcanic rocks concealed beneath basin-fill deposits in the hanging wall.

The Lake Mead fault zone (LMFZ) (fig. 5) is a major northeast-striking, left-lateral fault system consisting of about four major fault strands that form a crustal boundary separating the Great Basin to the north from the lower Colorado extensional corridor to the south (Anderson, 1973; Anderson and others, 1994; Bohannon, 1983). The major strands of the fault zone bound structural blocks which have undergone large lateral translations. For example, the Frenchman Mountain block is interpreted to have been displaced 65 km southwestward during Miocene extension (Anderson and others, 1994). Rocks in the lower Colorado extensional corridor (Faulds and others, 2001) consist largely of Proterozoic crystalline rocks, and Tertiary volcanic and plutonic rocks. Paleozoic and Mesozoic rocks are present in isolated blocks on the flanks of crystalline basement uplifts (see east end of *F–F′*). Faults of the LMFZ are shown in the eastern parts of cross sections *F–F′* and *G–G′*. *F–F′* shows the LMFZ juxtaposing Mesozoic and Paleozoic rocks of the Muddy Mountains in the hanging wall against shallow Proterozoic crystalline rocks in the footwall in the South Virgin Mountains. *G–G′* shows near-vertical strands of the LMFZ juxtaposing Paleozoic and Mesozoic rocks in the Muddy Mountains against Proterozoic crystalline rocks and Tertiary volcanic and plutonic rocks in the Lower Colorado extensional corridor.

Strike-slip faults are reported in the Tule Springs Hills and East Mormon Mountains (Anderson and Barnhard, 1993; Hintze and Axen, 2001; Axen and others, 1990). The East Tule

Desert fault (fig. 5) is a left-lateral, strike-slip fault that bounds the west flank of the Tule Springs Hills. In cross section *A–A′* Paleozoic and Mesozoic rocks of the Tule Spring autochthon are offset along the fault, and the downthrown side forms Tule Desert, a shallow basin with less than 500 m of Cenozoic basin-fill deposits (Scheirer and others, 2006). The Sams Camp and Carp Road faults (fig. 5) are probably equivalent to the East Tule Desert fault, and extend farther south along the East Mormon Mountains. These faults juxtapose Paleozoic rocks in the hanging wall against a footwall horst cored by Proterozoic crystalline rocks (*B–B′*). At the south end of the East Mormon Mountains, the Carp Road fault bends southwestward where it merges with the Davidson Peak fault, an east-striking transverse zone composed of highly folded Paleozoic and Mesozoic rocks (fig. 5), and then bends south to bound the west flank of the southern Mormon Mountains (along Candy Peak; *D–D′*; fig. 2). Anderson and Barnhard (1993) interpreted that the large sinistral displacements along these strike-slip faults are kinematically linked to major uplifts and depressions in the Mormon Mountain area that formed during Miocene extension. Alternatively, Axen and others (1990) interpreted that these faults are kinematically linked to the large-magnitude Cenozoic extension on the Tule Spring and Mormon Peak detachment faults (see below).

Locally before 10 Ma, normal block-faulting created north-trending ranges and basins to form the present-day physiography that characterizes the Basin and Range province. These faults, which define the Pintwater, Desert, Sheep, and Arrow Canyon Ranges, and Delamar and Meadow Valley Mountains (fig. 5), are especially prominent in the western part of the study area. These range-bounding faults are predominantly normal faults, but some of them have an oblique-slip component, especially along their margins with transverse structures such as the Las Vegas Valley shear zone and the Pahranagat shear zone. The range-front fault on the west side of the Desert Range juxtaposes Late Proterozoic-Lower Cambrian confining units and overlying Lower Cambrian to Devonian carbonate units in the hanging wall against shallow Proterozoic crystalline and overlying Late Proterozoic confining units in the footwall (*C–C′* and *D–D′*).

The range front fault zone along the west flank of the Sheep Range is characterized by westward tilted blocks of Late Proterozoic and Paleozoic units along a series of west-dipping normal faults extending to the Desert Range (*C–C′*, *D–D’*, and *G-G′*). Guth (1981) estimated 44 percent extension across this area based on restoration of rotated beds in the fault blocks. Faults in this region are interpreted to have a listric geometry to account for tilting, and Wernicke and others (1988) suggested that these faults may sole into a deep regional detachment fault of uncertain depth. Guth (1981) discussed the possibility that a regional detachment may merge with the Mesozoic thrust systems, but we interpret that the normal faults offset the thrusts at depth (rather than merging with them) to produce an irregular basement-sedimentary rock interface.

Range front faults on the west flanks of the southern Delamar Mountains, Meadow Valley Mountains, and Arrow Canyon Range were important in the development of Coyote Spring Valley (*B–B′*, *C–C′*, *D–D′*, and *F–F′*). In general, these fault systems consist of a series of steep, west-dipping normal faults that down-drop Paleozoic strata westward in a step-like pattern (Page, 1998; Page and others, 1990; Page and Pampeyan, 1996). Displacement on individual faults is generally less than 1 km, and cumulative displacements may be as much as 2 km (Page, 1998; Page and others, 1990). Phelps and others (2000) interpreted the subsurface location of some of these faults based on gravity data. Their study also indicates that Cenozoic basin-fill deposits probably reach a maximum thickness of about 1 to 1.5 km in Coyote Spring Valley.

A prominent high-angle normal fault on the west side of the Mormon Mountains is referred to here as the Meadow Valley Wash (MVW) fault (fig. 5). The fault structurally controls Meadow Valley Wash and probably was important in accommodating Miocene uplift of the Mormon Mountains (also see *B–B′* and *C–C′*). Along *A–A′* the fault juxtaposes Paleozoic and Mesozoic rocks of the Tule Spring autochthon in the footwall against Cenozoic basin-fill deposits and underlying Paleozoic rocks of the Tule Spring allochthon in the hanging wall. *B–B′* and *C–C′* show the MVW fault juxtaposing a thick sequence of Paleozoic rocks of the Mormon thrust allochthon in the hanging wall against Proterozoic crystalline rocks in the footwall. South of *C–C′*, the nature of the MVW fault is unknown, although we interpret it to merge with the system of strike-slip faults on the west flank of the southern Mormon Mountains to form the east boundary of lower Meadow Valley Wash basin. Seismic-reflection data (Scheirer and others, 2006) in the northern part of Meadow Valley Wash (in the area of *A–A′*) suggest the MVW fault is a high-angle normal fault.

The MVW fault may be a conduit for north-south groundwater flow beneath Meadow Valley Wash, but the upthrown block of Proterozoic crystalline confining units in the Mormon Mountains probably forms a barrier to eastward groundwater flow across the mountain range. Abundant paleo-spring carbonate deposits fill faults and fractures in bedrock units on the east and south flanks of the Meadow Valley Mountains and in Tertiary basin-fill sediments in Meadow Valley Wash (Page and Pampeyan, 1996; Schmidt, 1994; Schmidt and Dixon, 1995). These spring carbonate features are indicative of groundwater discharge and the existence of a past groundwater flow path through the thick sequence of Paleozoic carbonate rocks concealed beneath the eastern Meadow Valley Mountains and Meadow Valley Wash.

Seismic-reflection and gravity data (Scheirer and others, 2006) indicate that Meadow Valley Wash is partitioned into a series of fault-controlled basins. The deepest basin is between Moapa and Rox, Nev., (figs. 2 and 4). Cenozoic basin-fill deposits in the basin may be 2 to 3 km thick in the central part of the basin, and they are complexly deformed by folds and faults. Basin-fill surface exposures in this area are also complexly deformed. The Permian Kaibab Limestone crops out near Rox (*C–C′*), indicating a bedrock ridge constricts Meadow Valley Wash and bounds a shallower basin to the north. A drill hole in the northern basin (just north of Rox) bottomed out in basin-fill deposits at 730 m, and seismic-reflection data suggest Cenozoic basin-fill deposits may be up to 1 km thick (Scheirer and others, 2006). The northernmost basin of Meadow Valley Wash is between Carp and Leith (fig. 2). Cenozoic basin-fill deposits are interpreted to be 1 to 2 km thick in this basin (Scheirer and others, 2006), and the main basin structure is controlled by the MVW fault.

Wernicke and others (1985) and Axen and others (1990) interpreted that three stacked, west-dipping, low-angle normal (detachment) faults (Mormon Peak, Tule Springs, and Castle Cliff detachments) between the Meadow Valley Mountains and the Beaver Dam Mountains are the first order Cenozoic extensional structures in the region. Axen and others (1990) interpreted the Castle Cliff detachment as the lowest-level fault that projects westward in the subsurface beneath Tule Springs Hills as a continuation of the Castle Cliff fault exposed on the west flank of the Beaver Dam Mountains. The Tule Springs detachment is the intermediate fault interpreted by Axen and others (1990) as a breakaway zone on the west flank of the East Mormon Mountains to project westward below the main part of the Mormon Mountains. Wernicke and others (1985) interpreted the Mormon Peak detachment as the highest-level fault exposed in the Mormon Mountains to project westward beneath the Meadow Valley Mountains. Wernicke and others (1985) and Axen and others (1990) interpreted these as large-magnitude extensional faults that root into crystalline basement and were activated from west to east by processes of simple uniform shear.

Anderson and Barnhard (1993) noted low-angle normal faults in the area but on the basis of fault kinemetics and careful geologic mapping, they challenged the idea that these detachments had large lateral extent, and, alternatively, they viewed detachments as localized structures that accommodated strain associated with extreme vertical uplift. Carpenter and Carpenter (1994) also downplayed the role of detachments as first order Cenozoic extensional structures on the basis of seismic-reflection data and geologic mapping, and they reinterpreted many of the detachments in the Mormon Mountains as localized gravity-slide slip-surfaces. The cross sections in this report are conceptually in agreement with Anderson and Barnhard (1993) and Carpenter and Carpenter (1994), and portray detachments as more localized structures and high-angle normal and strike-slip faults as the first order extensional structures in this region.

The Piedmont fault (fig. 5) is the major fault bounding the west flanks of the Beaver Dam and Virgin Mountains (Bohannon and others, 1993), and it forms the boundary between the Colorado Plateau and Basin and Range provinces (*A–A′*, *B–B′*, *C–C′*). In most areas, the fault juxtaposes an east-tilted section of Paleozoic and Mesozoic rocks overlain by thick Tertiary-Quaternary basin-fill deposits in the hanging wall against Proterozoic crystalline rocks in the footwall (*B–B′*, and *C–C′*). The fault is estimated to have about 12 km of normal separation (Bohannon and others, 1993) and was most active from 13 to 10 Ma (Quigley and others, 2002). Quigley and others (2002) suggested that Cenozoic uplift in the Virgin-Beaver Dam Mountains along the Piedmont fault may have been controlled by older Proterozoic shear zones along a former accretionary crustal boundary. Carpenter and Carpenter (1994) reported the southern end of the fault, south of Mesquite (fig. 1), to have a left-lateral component as illustrated in sections *D–D′*, *E–E′*, and *J–J′*.

Virgin Valley is segmented into two deep northeast-trending basins (fig. 4), the Mormon basin to the southwest and the Mesquite basin to the northeast (Bohannon and others, 1993; Langenheim and others, 2000, 2001a). The basins formed by subsidence caused by Miocene extension mainly along the Piedmont fault. Cenozoic basin-fill deposits in the Mesquite basin are estimated to have maximum thicknesses of about 8 to 10 km, with the deepest part of the basin beneath the Littlefield, Ariz., area (Langenheim and others, 2000, 2001a) (fig. 2). Cross sections *B–B′* and *C–C′* extend across the Mesquite basin and show an east-dipping sequence of deformed Paleozoic and Mesozoic rocks overlain by moderately deformed Cenozoic basin-fill rocks. The subsurface stratigraphy and structure portrayed in the cross sections are derived mostly from seismic-reflection data from Bohannon and others (1993) and Carpenter and Carpenter (1994), and gravity data from Langenheim and others (2000, 2001a). Cross sections *D–D′* and *E–E′* extend across the Mormon basin where Cenozoic basin-fill deposits reach maximum thicknesses of 5 to 6 km. The subsurface stratigraphy and structure portrayed in the cross sections in the Mormon basin is mostly from seismic-reflection data from Bohannon and others (1993), gravity data from Langenheim and others (2000, 2001a), and the Mobil Virgin River no. 1–A deep petroleum test well on Mormon Mesa. The Mobil well encountered the base of Cenozoic basin fill at about 2 km, and the well bottomed out in Proterozoic crystalline rocks at about 5.9 km depth (Bohannon and others, 1993).

Muddy River Springs (fig. 2 and *D–D′*) are structurally controlled by a broad north-striking fault zone that forms the east range front of the southern Meadow Valley Mountains and Arrow Canyon Range (Schmidt and Dixon, 1995; Schmidt and others, 1996; Page and others, 2005a). The fault zone is informally referred to here as the east Arrow Canyon Range fault zone (fig. 5). Faults in the fault zone are exposed in the Paleozoic carbonate rocks on the east flanks of the Meadow Valley Mountains (Schmidt, 1994) and Arrow Canyon Range (Page, 1992; Schmidt and others, 1996), and in the Cenozoic basin-fill deposits in lower Meadow Valley and California Wash. East-striking faults intersect the north-striking faults (Schmidt and others, 1996; Schmidt, 1994; Page and others, 2005) and potentially enhance permeability. Seismic-reflection data (Scheirer and others, 2006) indicate an east-trending buried bedrock ridge separates lower Meadow Valley Wash basin from California Wash basin (fig. 4). The ridge is structurally controlled by east-striking faults (Scheirer and others, 2006), and it connects the Paleozoic carbonate rocks in the subsurface between the Arrow Canyon Range and Muddy Mountains. Near Ute (fig. 2), along the east flank of the Arrow Canyon Range, spring carbonate mounds represent past spring discharge from the fault zone (Schmidt and Dixon, 1995). Quaternary faults are exposed in this area, which may have increased permeability in the fault zone.

Cenozoic basin-fill deposits in California Wash basin are estimated to be 2 to 3 km deep based on gravity and seismic-reflection data (Langenheim and others, 2001b, 2002). The basin is bounded by the California Wash fault zone, a zone of west-dipping normal faults on the west flank of the Muddy Mountains (*E–E′*, *F–F′*, and *G–G′*). Bidgoli and others (2003) reported Quaternary faulting in the fault zone.

The Rogers Spring fault is located on the southeast side of the Muddy Mountains where it bounds a moderately deep basin in the Lake Mead Overton Arm area (fig. 5, *F–F′*); Cenozoic basin-fill deposits are 2 to 3 km thick in the Overton Arm basin. The fault dips from $60^{o}$ to $70^{o}$ southeast and juxtaposes Paleozoic carbonate rocks of the Muddy Mountain thrust allochthon against deformed Tertiary basin-fill deposits that overlie autochthonous Mesozoic rocks (*F–F′*). Bohannon (1983) interpreted the fault as a normal fault, but he reported local evidence of strike-slip displacement suggesting multiple stages of movement. We agree with Bohannon’s interpretation of strike-slip and normal movement on the fault, but a reverse component of displacement is also indicated because the Paleozoic allochthon of the Muddy Mountain thrust on the northwest side of the fault is presumably downdropped against autochthonous Mesozoic rocks on the southeast side (*F–F′*) based on exposure of the Jurassic Aztec Sandstone farther to the southwest along the fault. Rogers and Blue Point Springs are probably both structurally controlled by the Rogers Spring fault, and warm water discharging from the springs ($85^{o}$–$86^{o}$ F) suggests a relatively deep source. The springs may exist partly due to juxtaposition of the Paleozoic-Mesozoic sequence in the fault footwall against Early Proterozoic crystalline rocks in the hanging wall, and the presence of thick basin-fill sediments containing impermeable evaporate deposits in the fault hanging wall (Laney and Bales, 1996).

## Summary

The oldest rocks in the study area are Early Proterozoic crystalline rocks. These rocks form basement and are confining units in the regional groundwater flow systems. Late Proterozoic to Lower Cambrian rocks are predominantly clastic rocks and are also considered confining units in the region.

Above the Late Proterozoic to Lower Cambrian clastic rocks are Middle Cambrian to Lower Permian units that are predominantly carbonate rocks, and they form the main aquifer in the regional groundwater flow systems. The Paleozoic carbonate rocks thin from west to east in the study area, from as much as 7 km in the western part to less than 2 km in the eastern part.

Much of the thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton.

Above the Paleozoic carbonate rocks are mainly clastic units of late Paleozoic to Mesozoic age that are generally considered confining units in the flow systems, but they may be permeable where fractured. Tertiary volcanic and plutonic rocks are exposed in the extreme northern and southern parts of the study area and may be aquifers where they are highly faulted, such as in the Delamar and Clover Mountains. Basin-fill deposits consist of middle to late Tertiary sediments of variable lithologies, and younger Quaternary surficial units consisting mainly of alluvium. Basin-fill sediments are both aquifers and aquitards in the region.

Movement of groundwater through the aquifers is through fractures and faults, and through solution channels formed in the carbonate rocks. The rocks in the area were complexly deformed by episodes of Mesozoic compression and Cenozoic extension. Cretaceous thrust faults and folds in the area formed during the Sevier orogeny. Duplex zones along some of the thrust faults resulted in structural thickening and define areas of maximum thickness of the Paleozoic carbonate rocks.

Cenozoic extensional tectonics affected the rocks in the region and included normal and strike-slip faulting, volcanism, and plutonism. Cenozoic faults are significant because they are the primary structures that control groundwater flow in the regional groundwater flow systems.

## Acknowledgments

We thank William P. VanLiew, National Park Service, Water Resources Division, Fort Collins, Colo., for funding this work. Robert G. Bohannon and Robert B. Scott provided comprehensive technical reviews for the original report (U.S. Geological Open-File Report 2006-1040); Sue Beard and Kenzie Turner reviewed the revised report.

## References Cited

Anderson, R.E., 1973, Large magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.

Anderson, R.E., and Barnhard, T.P, 1993, Aspects of three-dimensional strain at the margin of the extensional orogen, Virgin River depression area, Nevada, Utah and Arizona: Geological Society of America Bulletin, v. 105, p. 1019–1052.

Anderson, R.E., Barnhard, T.P., and Snee, L.W., 1994, Roles of plutonism, midcrustal flow, tectonic rafting, and horizontal collapse in shaping the Miocene strain field of the Lake Mead area, Nevada and Arizona: Tectonics, v. 13, no. 6, p. 1381–1410.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Axen, G.J., Wernicke, B.P., Skelly, M.F., and Taylor, W.J., 1990, Mesozoic and Cenozoic tectonics of the Sevier thrust belt in the Virgin River Valley area, southern Nevada, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 123–154.

Belcher, W.R., Faunt, C.C., and D'Agnese, F.A., 2002, Three-dimensional hydrogeologic framework model for use with a steady-state numerical ground-water flow model of the Death Valley regional flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 01–4254.

Bidgoli, T.S., Fossett, E., Knudsen, T.R., Kubart, Dano, Mcewan, D.J., and Taylor, W.J., 2003, Surface rupture, paleoseismology, and seismic hazard assessment of the Holocene California

Wash fault, southern Nevada: implications for risk to greater Las Vegas area [abs.]: Geological Society of America Abstracts with Programs, v. 35. no. 6, p. 476.

Blakely, R.J., and Ponce, D.A., 2001, Map showing depth to pre-Cenozoic basement in the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2381-E, scale 1:250:000.

Bohannon, R.G., 1983, Geologic map, tectonic map, and structure sections of the Muddy and northern Black Mountains, Clark County, Nevada: U.S. Geological Survey Miscellaneous Investigations Map I–1406, scale 1:62,500.

Bohannon, R.G., Grow, J.A., Miller, J.J., and Blank, R.H., Jr., 1993, Seismic stratigraphy and tectonic development of Virgin River depression and associated basins, southeastern Nevada and northwestern Arizona: Geological Society of America Bulletin, v. 105, p. 501–520.

Burbey, T.J., 1997, Hydrogeology and potential for ground-water development, carbonate-rock aquifers, southern Nevada and southeastern California: U.S. Geological Survey Water-Resources Investigations Report 95–4168, 65 p.

Carpenter, J.A., and Carpenter, D.G., 1994, Structural and stratigraphic relations in a critical part of the Mormon Mountains, Nevada, *in* Dobbs, S.W., and Taylor, W.J., eds.: Nevada Petroleum Society 1994 Conference Volume II, (Book 1), p. 95–126.

D'Agnese, F.A., Faunt, C.C., Turner, K., and Hill, M.C., 1997, Hydrogeologic evaluation and numerical simulation of Death Valley regional ground-water flow system, Nevada and California: Water-Resources Investigations Report 96–4300, 124 p.

D'Agnese, F.A., O'Brien, G.M., Faunt, C.C., Belcher, W.R., and San Juan, Carma, 2002, A three-dimensional numerical model of predevelopment conditions in the Death Valley regional ground-water flow system, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 02–4102, 114 p.

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

Dixon, G.L., and Katzer, T.L., 2002, Geology and hydrology of the lower Virgin River Valley in Nevada, Arizona, and Utah: Virgin Valley Water District, Mesquite, Nevada, Report no. VVWD–01, 126 p.

Duebendorfer, E.M., and Black, R.A., 1992, Kinematic role of transverse structures in continental extension: an example from the Las Vegas Valley shear zone, Nevada: Geology, v. 20, p. 1107–1110.

Duebendorfer, E.M., and Simpson, D.A., 1994, Kinematics and timing of Tertiary extension in the western Lake Mead region, Nevada: Geological Society of America Bulletin, v. 106, p. 1057–1073.

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

Eakin, T.E., 1966, A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p. 251–271.

Faulds, J.E., Feuerbach, D.L., Miller, C.F., and Smith, E.I., 2001, Cenozoic evolution of the northern Colorado River extensional corridor, southern Nevada and northwest Arizona, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The geologic transition,

High Plateaus to Great Basin—A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 239–272.
Fleck, R.J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: Geological Society of America Bulletin, v. 81, p. 1705–1720.
Fleck, R.J., and Carr, M.D., 1990, The age of the Keystone thrust: Laser-fusion $^{40}Ar/^{39}Ar$ dating of foreland basin deposits, southern Spring Mountains, Nevada: Tectonics, v. 9, p. 467–476.
Garside, L.J., Hess, R.H., Fleming, K.L., and Weimer, B.S., 1988, Oil and Gas development in Nevada: Nevada Bureau of Mines and Geology Bulletin 104, 136 p.
Guth, P.L., 1980, Geology of the Sheep Range, Clark County, Nevada: Boston, Massachusetts, Institute of Technology, Ph.D. dissertation, 189 p.
Guth, P.L., 1981, Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada: Geological Society of America Bulletin, v. 92, p. 763–771.
Guth, P.L., 1990, Superposed Mesozoic and Cenozoic deformation Indian Springs quadrangle, southern Nevada, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 123–154.
Harding, A.E., Scott, R.B., Mehnert, H.H., and Snee, L.W., 1995, Evidence of the Kane Springs Wash caldera in the Meadow Valley Mountains, southeastern Nevada, *in* Scott, R.B., and Swadley, WC, eds., Geologic Studies in the Basin and Range–Colorado Plateau Transition in Southeastern Nevada, Southwestern Utah, and Northwestern Arizona: U. S. Geological Survey Bulletin 2056, p. 135–167.
Harrill, J.R., and Prudic, D.E., 1998, Aquifer systems in the Great Basin region of Nevada, Utah and adjacent states—Summary report: U.S. Geological Survey Professional Paper 1409A, 61 p.
Heilweil, V.M., Watt, D.E., Solomon, D.K., and Goddard, K.E., 2002, The Navajo aquifer system of southwestern Utah, *in* Lund, W.R., ed., Field Guide to Geologic Excursions in Southwestern Utah and Adjacent areas of Arizona and Nevada, Geological Society of America Rocky Mountain Section Meeting, Cedar City, Utah, May 7th–9th, 2002: U.S. Geological Survey Open-File Report 02–172, p. 105-130.
Hintze, L.F., and Axen, G.J., 2001, Geologic map of the Lime Mountain Quadrangle, Lincoln County, Nevada: Nevada Bureau of Mines and Geology Map 129, scale 1:24,000.
Jachens, R.C., Dixon, G.L., Langenheim, V.E., and Morin, R., 1998, Interpretation of an aeromagnetic survey over part of Virgin Valley, Tule Desert, and the valley surrounding Meadow Valley Wash, southeastern Nevada: U.S. Geological Survey Open-File Report 98–804, 16 p.
Johnson, M., Dixon, G.L., Rowley, P.D., Katzer, T.L., and Winters, M., 2002, Hydrology and ground-water conditions of the Tertiary Muddy Creek Formation in the lower Virgin River basin of southeastern Nevada and adjacent Arizona and Utah, *in* Lund, W.R., ed., Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada, Field trip guide, Geological Society of America, Rocky Mountain section meeting, Cedar City, Utah: U.S. Geological Survey Open-File Report 02–172, p. 284–315.
Kirk, S.T., 1987, Analysis of the White River groundwater flow system using a deuterium-calibrated discrete-state compartment model: Reno, University of Nevada, M.S. thesis, 81 p.

Laczniak, R.J., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96–4109, 60 p.

Laney, R.L., and Bales, J.T., 1996, Geohydrologic reconnaissance of Lake Mead National Recreation area—Las Vegas Wash to Virgin River, Nevada: U.S. Geological Survey Water Resources Investigations Report 96–4033, 29 p.

Langenheim, V.E., Glen, J.M., Jachens, R.C., Dixon, G.L., Katzer, T.C., and Morin, R.L., 2000, Geophysical constraints on the Virgin River depression, Nevada, Utah, and Arizona: U.S. Geological Survey Open-File Report 00–407, 26 p.

Langenheim, V.E., Bohannon, R.G., Glen, J.M., Jachens, R.C., Grow, J.A., Miller, J.J., Dixon, G.L., and Katzer, T.L., 2001a, Basin configuration of the Virgin River depression, Nevada, Utah, and Arizona—A geophysical view of deformation along the Colorado Plateau-Basin and Range transition, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The geologic transition, High Plateaus to Great Basin—A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 205–226.

Langenheim, V.E., Miller, J.J., Page, W.R., and Grow, J.A., 2001b, Thickness and geometry of Cenozoic deposits in California Wash area, Nevada, based on gravity and seismic reflection data: U.S. Geological Survey Open-File Report 01–393, 24 p.

Langenheim, V.E., Page, W.R., Miller, J.J., and Grow, J.A., 2002, Geophysical and geological constraints on the hydrogeologic framework of the California Wash region, southern Nevada: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A–16.

Nelson, M.R., and Jones, C.H., 1987, Paleomagnetism and crustal rotations along a shear zone, Las Vegas Range, southern Nevada: Tectonics, v. 6, no. 1, p. 13–33.

Page, W.R., 1990, Effects of Tertiary extension on the Mesozoic Delamar thrust plate, southern Nevada [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 74.

Page, W.R., 1992, Preliminary geologic map of the Arrow Canyon Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 92–681, scale 1:24,000.

Page, W.R., 1998, Geologic map of the Arrow Canyon NW quadrangle, Clark County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ–1776; scale 1:24,000.

Page, W.R., and Dixon, G.L., 1992, Northern terminus of the Mesozoic Dry Lake thrust fault, Arrow Canyon Range, southeastern Nevada: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 56.

Page, W.R., Dixon, G.L., Rowley, P.D, and Brickey, D.W., 2005a, Geologic map of parts of the Colorado, White River, and Death Valley groundwater flow systems, Nevada, Utah, and Arizona: Nevada Bureau of Mines and Geology Map 150, scale 1:250,000.

Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Workman, J.B., Mahan, S.A., Paces, J.B., Rowley, P.D., Dixon, G.L., Burchfiel, B.C., Bell, J.W., and Smith, E.I., 2005b, Geologic and geophysical maps of the Las Vegas 30' x 60' Quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, scale 1:100,000.

Page, W.R., and Pampeyan, E.H., 1996, Preliminary geologic map of the Paleozoic rocks in the Wildcat Wash SE and Wildcat Wash SW Quadrangles, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Open-File Report 96–26, 18 p., scale 1:24,000.

Page, W.R., Swadley, W C, and Scott, R.B., 1990, Preliminary geologic map of the Delamar 3 SW quadrangle, Lincoln County, Nevada: U.S. Geological Survey Open-File Report 90–336, scale 1:24,000.

Pampeyan, E.H., 1993, Geologic map of the Meadow Valley Mountains, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I–2173, scale 1:50,000.

Phelps, G.A., Jewel, E.B., Langenheim, V.E., and Jachens, R.C., 2000, Principal facts for gravity stations in the vicinity of Coyote Spring Valley, Nevada, with initial gravity modeling results: U.S. Geological Survey Open-File Report 00–420, 18 p.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–A, scale 1:1,000,000.

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409–D, 102 p.

Quigley, M.C., Karlstrom, K., Beard, S., and Bohannon, R.G., 2002, Influence of Proterozoic and Laramide structures on the Miocene extensional strain field, north Virgin Mountains, Nevada/Arizona, *in* Lund, W.R., ed., Field Guide to Geologic Excursions in Southwestern Utah and Adjacent areas of Arizona and Nevada, Geological Society of America Rocky Mountain Section Meeting, Cedar City, Utah, May 7th–9th, 2002; U.S. Geological Survey Open-File Report 02-172, p. 86–104.

Rogers, A.M., Harmsen, S.C., and Meremonte, M.E., 1987, Evaluation of the seismicity of the southern Great Basin and its relationship to the tectonic framework of the region: U.S. Geological Survey Open-File Report 87–408, 196 p.

Rowley, P.D., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, western United States--their tectonic and economic implications, *in* Faulds, J.E., and Stewart, J.H., eds., Accommodation zones and transfer zones--the regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, p. 195–228.

Rowley, P.D., Nealey, L.D., Unruh, D.M., Snee, L.W., Mehnert, H.H., Anderson, R.E., and Gromme, C.S., 1995, Stratigraphy of Miocene ash-flow tuffs in and near the Caliente Caldera complex, southeastern Nevada and southwestern Utah, *in* Scott, R.B., and Swadley, WC, eds., Geologic studies in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S Geological Survey Bulletin 2056, p. 43–88.

Scheirer, D.S., Page, W.R., and Miller, J.J., 2006, Geophysical studies based on seismic and gravity data of Tule Desert, Meadow Valley Wash, and California Wash basins, southern Nevada: U.S. Geological Survey Open-File Report 2006–1396, 42 p.

Schmidt, D.L., 1994, Preliminary geologic map of the Farrier Quadrangle, Lincoln and Clark Counties, Nevada: U.S. Geological Survey Open File Report 94–625, scale 1:24,000.

Schmidt, D.L., and Dixon, G.L., 1995, Geology and aquifer system of the Coyote Spring Valley area, southeastern Nevada: U.S. Geological Survey Open-File Report 95–579, 47 p.

Schmidt, D.L., Page, W.R., and Workman, J.B., 1996, Preliminary geologic map of the Moapa West Quadrangle, Clark County, Nevada: U.S. Geological Survey Open-File Report 96–521, scale 1:24,000.

Scott, R. B., Unruh, D.M., Snee, L.W., Harding, A.E., Nealey, L.D., Blank, H.R., Jr., Budahn, J.E., and Mehnert, H.H., 1995, Relation of peralkaline magmatism to heterogeneous extension during middle Miocene: Journal of Geophysical Research, v. 100, p. 10381–10401.

Sonder, L.J., Jones, C.H., Salyards, S.L., and Murphy, K.M., 1994, Vertical axis rotations in the Las Vegas Valley shear zone, southern Nevada: paleomagnetic constraints on kinematics and dynamics of block rotations: Tectonics, v. 13, p. 769–788.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345–1360.

Stewart, J.H., 1976, Late Precambrian evolution of North America: plate tectonics implication: Geology, v. 4, p. 11–15.

Stewart, J.H., and Poole, F.G., 1972, Lower Paleozoic and uppermost Precambrian Cordilleran Miogeocline, Great Basin, western United States, *in* Dickinson, W.R., ed., Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 28–57.

Swadley, W.C., Page, W.R., Scott, R.B., and Pampeyan, E.H., 1994, Geologic map of the Delamar 3 SE Quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map–GQ–1754, scale 1:24,000.

Swadley, W.C., 1995, Maps showing modern fissures and Quaternary faults in the Dry Lake Valley area, Lincoln County, Nevada: U.S. Geological Survey Miscellaneous Field Investigations Series, Map I–2501, scale 1:50,000.

Sweetkind, D.S., Dickerson, R.P, Blakely, R.J., and Denning, P.D., 2001, Interpretive cross sections for the Death Valley regional flow system and surrounding areas, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2370, 32 p., one map sheet.

Thomas, J.M., Mason, J.L., and Crabtree, J.D., 1986, Ground-water levels in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–B, scale 1:1,000,000.

Thomas, J.M., and Welch, A.H., 1984, Isotope hydrology and aqueous geochemistry of the White River Groundwater basin, a regional carbonate aquifer in eastern Nevada: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 689.

Tschanz, C.M., and Pampeyan, E.H., 1970, Geology and Mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology Bulletin 73, 188 p.

Wernicke, Brian, Guth, P.L., and Axen, G.J., 1988, Tertiary extensional tectonics in the Sevier thrust belt of southern Nevada, *in* Weide, D.L., and Faber, M.L., eds., This Extended Land; Geological journeys in the southern Basin and Range; Geological Society of America Cordilleran Section Field Trip Guidebook: University of Nevada at Las Vegas Geoscience Department Special Publication no. 2, p. 473–499.

Wernicke, Brian, Spencer, J.E., Burchfiel, B.C., and Guth, P.L., 1982, Magnitude of crustal extension in the southern Great Basin: Geology, v. 10, p. 499–502.

Wernicke, Brian, Walker, D.J., and Beaufait, M.S., 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, Central Mormon Mountains, Southern Nevada: Tectonics, v. 4, no. 2, p. 213–246.

Wilson, J.W., 2001, Potentiometric surface, carbonate-rock province, southern Nevada and southeastern California, 1998–2000: U.S. Geological Survey Open-File Report 01–335, 15 p.

Winograd, I.J., and Thordarson, W., 1975, Hydrologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712C, p. C1–C126.

Workman, J.B., Menges, C.M., Page, W.R., Ekren, E.B., Rowley, P.D., and Dixon, G.L., 2002a, Tectonic map of the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2381–B, 58 p.

Workman, J.B., Menges, C.M., Page, W.R., Taylor, E.M., Ekren, E.B., Rowley, P.D., Dixon, G.L., Thompson, R.A., and Wright, L.A., 2002b, Geologic map of the Death Valley ground water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies MF–2381–A, scale 1:250,000.

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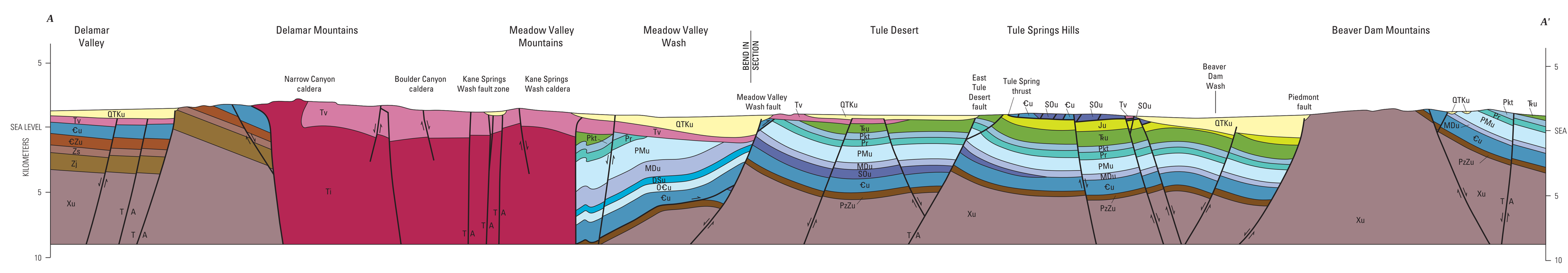
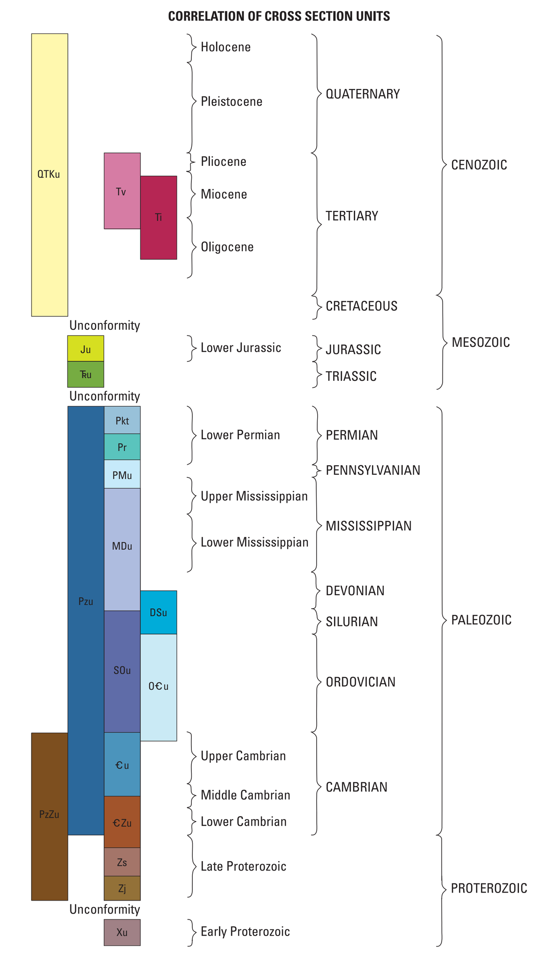
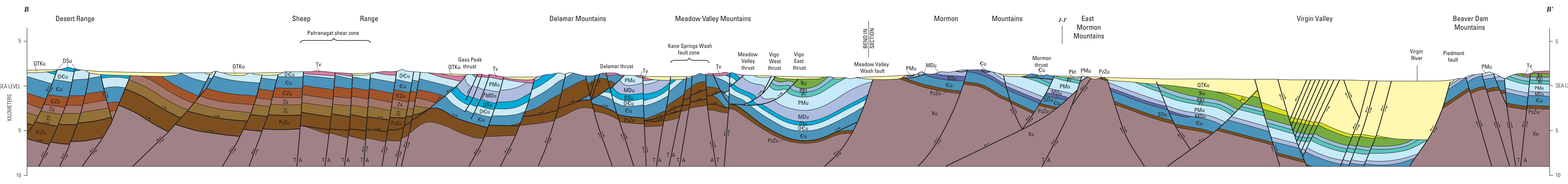
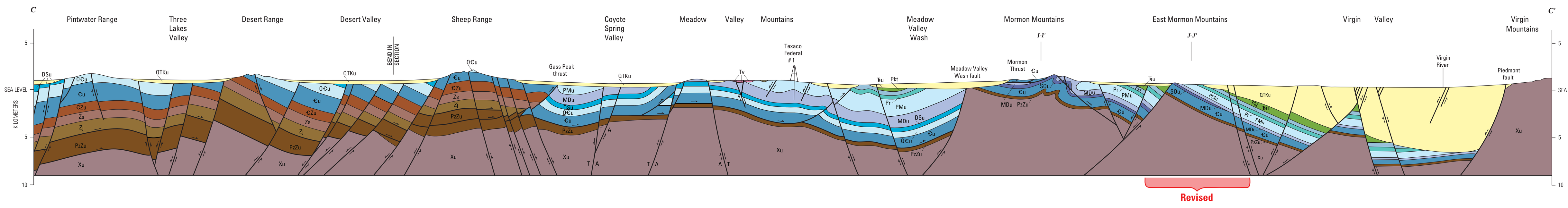
Prepared in cooperation with the
National Park Service

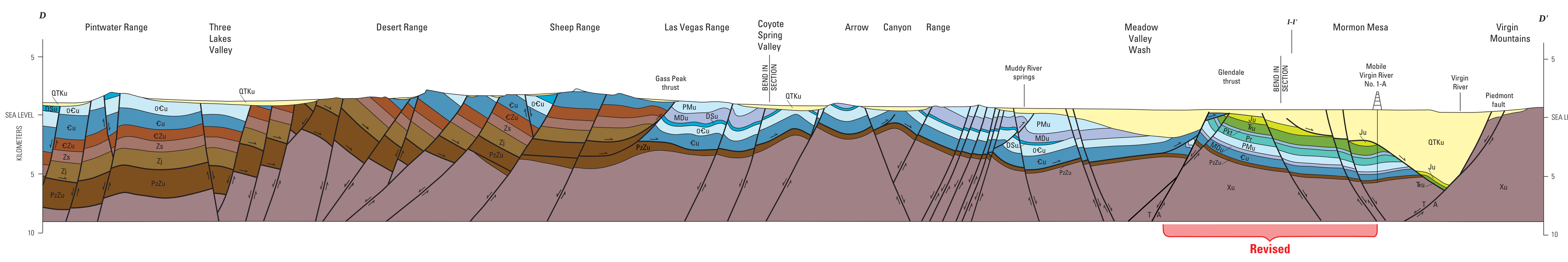
Open-File Report 2006–1040
*Pamphlet accompanies Map*
Revised June, 2011

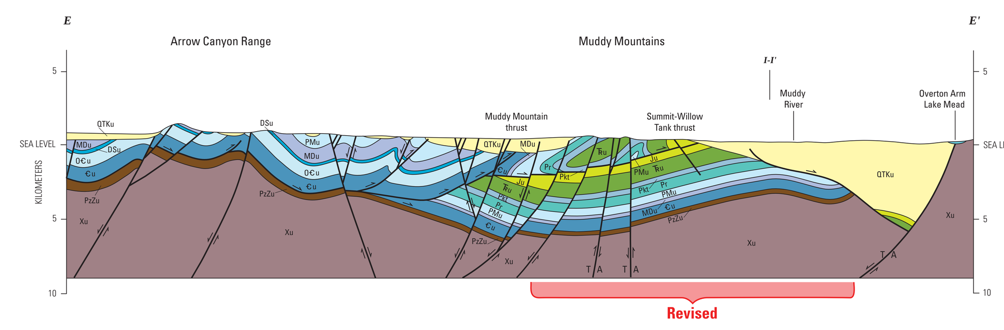


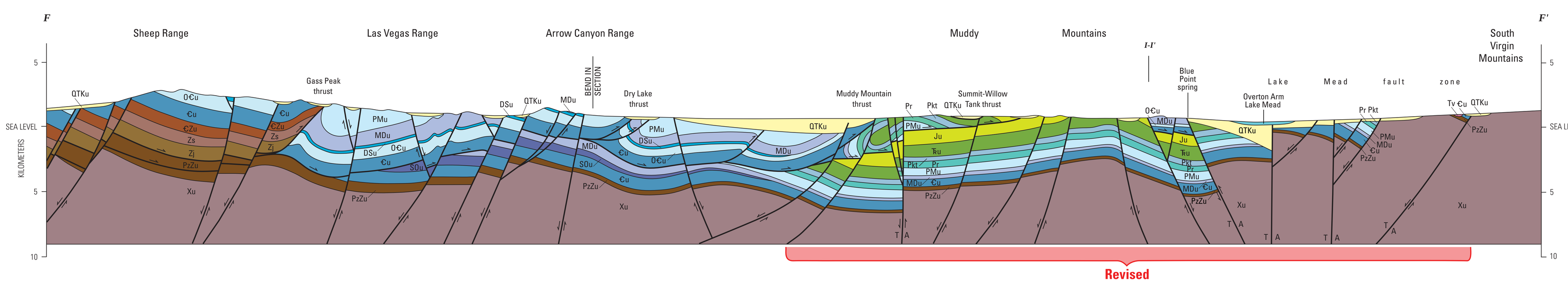


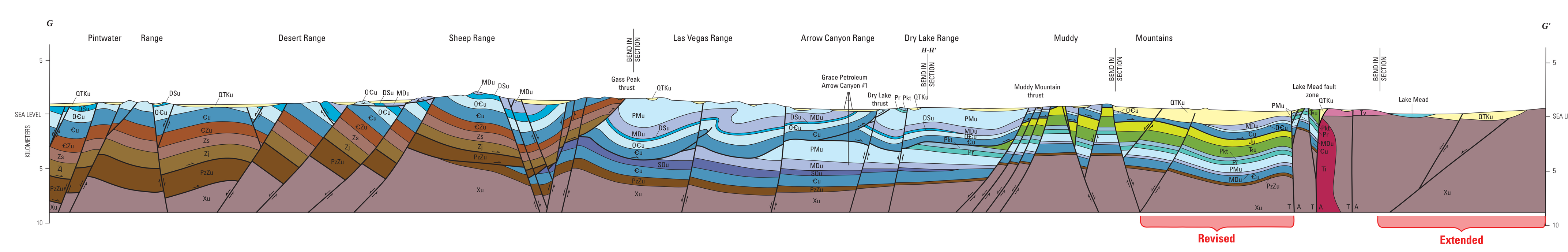



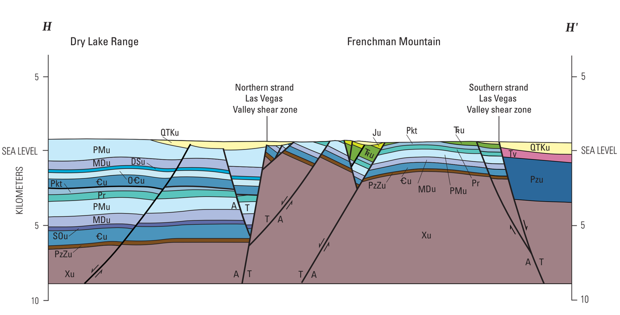


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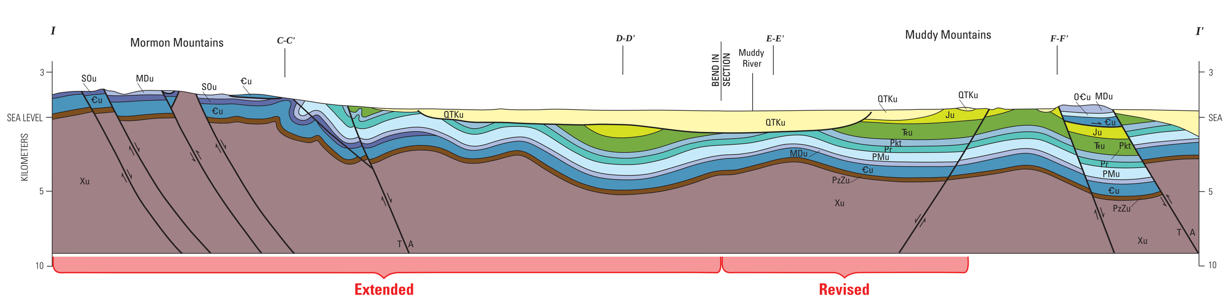


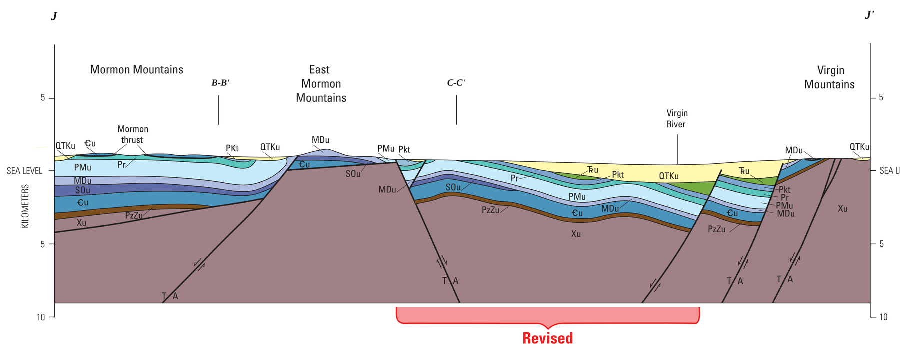


## DESCRIPTION OF CROSS SECTION UNITS

**QTKu** **Quaternary to Cretaceous rocks, undivided (Holocene to Cretaceous)**—Alluvium (Holocene to Pliocene), playa deposits (Holocene to Pleistocene), eolian deposits (Holocene), spring discharge deposits (Holocene to Pleistocene), calcrete (Pleistocene to Pliocene), and landslide megabreccia deposits (Pleistocene to Miocene). Includes sedimentary rocks of the Muddy Creek Formation (Pliocene-Miocene), and the Horse Spring Formation (Miocene and Oligocene). Unit locally includes Cretaceous synorogenic basin-fill deposits in the Muddy Mountains area, which consist of the Baseline Sandstone (Upper and Lower Cretaceous), and Willow Tank Formation (Lower Cretaceous). Unit from 0 to greater than 8,000 m thick

**Tv** **Tertiary volcanic rocks, undivided (Pliocene to Oligocene)**—Ash-flow tuff, airfall tuff, lava flows, and basalt flows. Exposed in the Delamar Mountains (A-A') and in the Lake Mead area (G-G'). Several hundred meters to greater than several thousand meters thick

**Ti** **Tertiary intrusive rocks, undivided (Miocene and Oligocene)**—Granitic or silicic intrusive rocks in the Delamar Mountains (A-A') and in the Lake Mead area (G-G')

**Ju** **Lower Jurassic rocks, undivided**—Includes the Aztec Sandstone in most of southern Nevada (Basin and Range province), and the correlative Navajo Sandstone in southwest Utah and northwest Arizona (Colorado Plateaus Province). Unit also includes the Kayenta and Moenave Formations, which underlie both the Aztec Sandstone and Navajo Sandstone. Exposed in Tule Springs Hills, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit has combined thickness of 1,000 to 2,200 m

**Ʀu** **Triassic rocks, undivided**—Chinle (Upper Triassic) and Moenkopi (Middle? and Lower Triassic) Formations exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit has combined thickness of about 1,000 m

**PzZu** **Paleozoic rocks undivided (Lower Permian to Cambrian)**—May include parts of all Paleozoic units listed below. Shown in H-H' south of Frenchman Mountain

**Pkt** **Kaibab and Toroweap Formations, undivided (Lower Permian)**—Exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit is 300 to 500 m thick

**Pr** **Lower Permian redbeds**—Unit defined by Longwell and others (1965) and correlated with parts of the Queantoweap and Esplanade Sandstones and the Hermit Formation. Exposed in the eastern Meadow Valley Mountains, Tule Springs Hills, Mormon Mountains, Muddy Mountains, Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Unit is 400 to 800 m thick

**PMu** **Lower Permian to Upper Mississippian rocks, undivided**—Bird Spring (Lower Permian to Upper Mississippian) and Indian Springs (Upper Mississippian) Formations in west and central parts of the study area as far east as the Muddy Mountains, Tule Springs Hills, Mormon Mountains, and Callville Limestone (Pennsylvanian) and Pakoon Dolomite in the eastern part of the study area in the Lake Mead area and in the Virgin and Beaver Dam Mountains. Combined thickness of unit from about 460 to 2,500 m thick

**MDu** **Upper Mississippian to Middle Devonian rocks, undivided**—In the west and central parts of the study area includes the Joana Limestone (Lower Mississippian) or Monte Cristo Group (Upper and Lower Mississippian), Crystal Pass Limestone or Pilot Shale (Lower Mississippian to Upper Devonian), Guilmette Formation (Upper and Middle Devonian) or Sultan Limestone (Upper and Middle Devonian). Also includes Scotty Wash Quartzite and Chainman Shale (Upper Mississippian) in the northern Meadow Valley Mountains and Delamar Mountains. In the eastern part of the study area, in the Lake Mead area and the Virgin and Beaver Dam Mountains, includes the Redwall Limestone (Upper and Lower Mississippian) and Temple Butte Formation (Upper and Middle?) Devonian). Combined thickness of unit is from about 300 to 1,800 m

**DSu** **Middle Devonian to Silurian rocks, undivided**—Rocks equivalent to parts of the Simonson Dolomite (Middle Devonian), Sevy Dolomite (Lower Devonian), and Laketown Dolomite (Silurian). Combined thickness from 200 to 780 m

**SOu** **Silurian and Ordovician rocks, undivided**—Rocks equivalent to the Laketown Dolomite (Silurian), the Ely Springs Dolomite (Upper Ordovician), Eureka Quartzite (Middle Ordovician), and the Pogonip Group (mostly Upper and Middle Ordovician, but includes Cambrian rocks in the Sheep Range area). These rocks extend as far east as the Muddy Mountains, Mormon Mountains, and Tule Springs Hills. Unit only includes Ordovician rocks in the Muddy Mountains; Silurian and Ordovician rocks are absent in the Beaver Dam Mountains, Virgin Mountains, and Lake Mead area. Combined thickness of unit from 0 to 1,500 m

**OЄu** **Upper Ordovician to Upper Cambrian rocks, undivided**—Rocks equivalent to the Ely Springs Dolomite (Upper Ordovician), Eureka Quartzite (Middle Ordovician), and Pogonip Group (Middle Ordovician to Upper Cambrian). Combined thickness from about 550 to 1,200

**Єu** **Upper and Middle Cambrian rocks, undivided**—Includes Nopah (Upper Cambrian) and Bonanza King (Upper and Middle Cambrian) Formations in most parts of the study area. Equivalent rocks along the west end of A-A' in the northern Delamar Mountains include the Nopah Formation and Highland Peak Formation (Middle Cambrian). In the eastern part of the study area in the Beaver Dam and Virgin Mountains, and in the Lake Mead area, includes the Nopah and Muav Formations (Middle Cambrian). Combined thickness of unit from about 500 to 2,300 m

**PzZu** **Paleozoic and Late Proterozoic rocks, undivided**—In western part of study area unit may consist of Cambrian and Late Proterozoic units including the Nopah Formation (Upper Cambrian), Bonanza King Formation (Upper and Middle Cambrian), Carrara Formation (Middle and Lower Cambrian), Wood Canyon Formation (Lower Cambrian and Late Proterozoic), Stirling Quartzite (Late Proterozoic), and Johnnie Formation (Late Proterozoic). Late Proterozoic rocks pinch out in the eastern part of the study area where unit includes only the Bright Angel Shale (Middle and Lower Cambrian) and Tapeats Sandstone (Lower Cambrian) in the Mormon Mountains, Tule Springs Hills, Beaver Dam and Virgin Mountains, and Lake Mead area. Combined thickness of unit from 125 to greater than 2,000 m

**ЄZu** **Middle Cambrian and Late Proterozoic rocks, undivided**—In Pintwater, Desert, and Sheep Ranges includes the Carrara (Middle and Lower Cambrian) and Wood Canyon (Lower Cambrian and Late Proterozoic) Formations. In northern Delamar Mountains (west side of A-A') includes the Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), and Pioche Shale (Middle and Lower Cambrian) and Wood Canyon Formation. Combined thickness of unit from 360 to 1,000 m

**Zs** **Late Proterozoic rocks, undivided**—Includes the Stirling Quartzite in the Pintwater, Desert, and Sheep Ranges, and northern Delamar Mountains (western part of A-A'). Unit is 600 to 800 m thick

**Zj** **Johnnie Formation (Late Proterozoic)**—In the Pintwater, Desert, and Sheep Ranges includes Johnnie Formation; in northern Delamar Mountains includes rocks partly equivalent to the Johnnie Formation. About 1,000 m thick but greater than 1,000 m in northern part of study area

**Xu** **Early Proterozoic crystalline rocks**—Gneiss, schist, and granite exposed at Frenchman Mountain, Lake Mead area, Virgin Mountains, Beaver Dam Mountains, and Mormon Mountains

### Explanation of Cross Section Symbols

Contact

**Normal fault**—Arrows indicate direction of fault block movement

**Oblique-slip fault**—Arrows indicate direction of vertical movement; T indicates fault block movement toward the viewer, A indicates fault block movement away from viewer

**Strike-slip fault**—T indicates fault block movement toward the viewer; A indicates fault block movement away from viewer

**Low-angle fault (low-angle normal or thrust fault)**—Arrow indicates relative movement of overriding plate

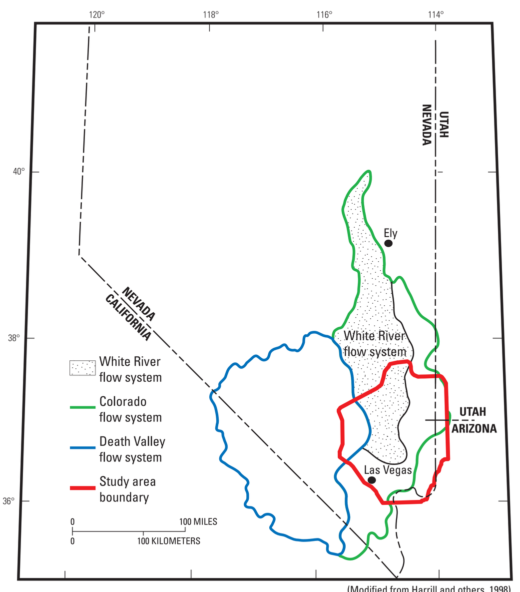


**Figure 1.** Map showing Death Valley, White River, and Colorado flow systems, and study area boundary.

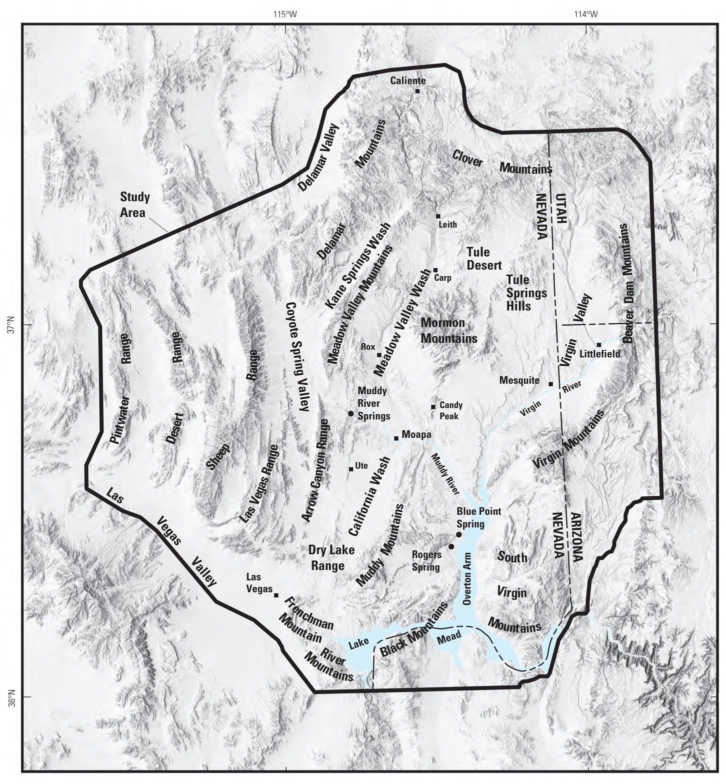

**Figure 2.** Index map showing major physiographic features in the study area.

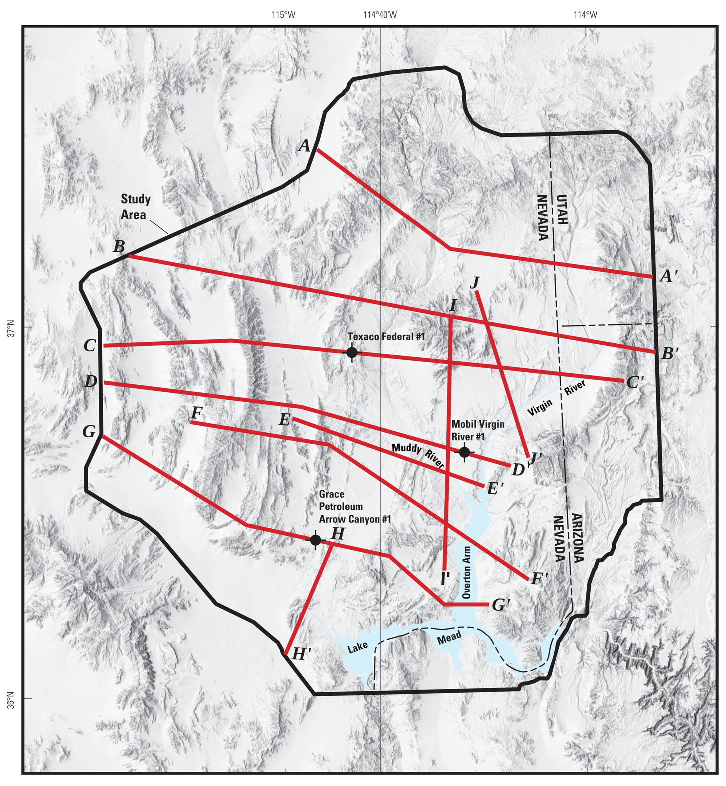

**Figure 3.** Location of cross sections and oil wells in the study area. East-west cross sections are hung on longitude 114°40'00'' as a reference line to visually extrapolate the geology between the section lines in a north-south progression.

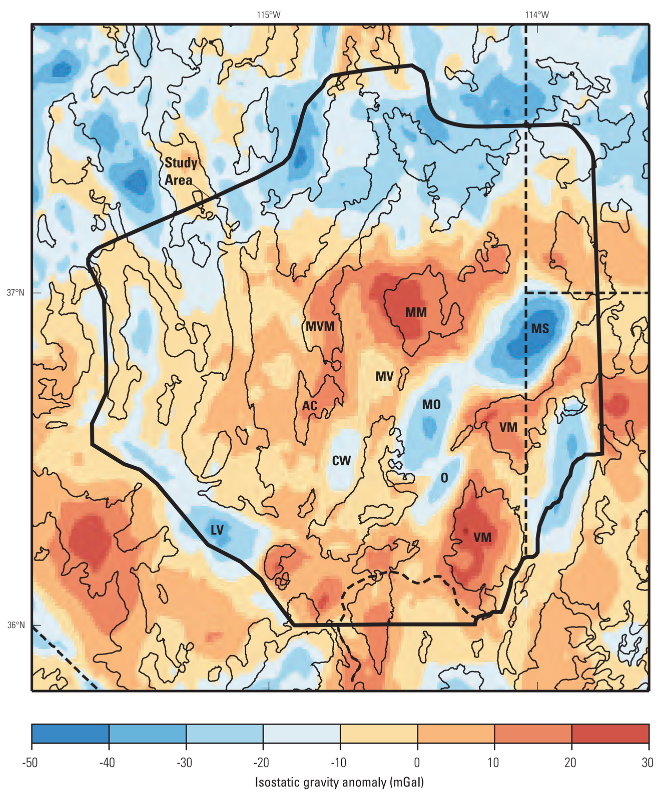


**Figure 4.** Isostatic gravity anomalies of the study area that reflect shallow crustal density variations. Blue colors indicate mass deficits (for example, accumulations of low-density material such as Cenozoic basin-fill deposits and/or volcanic rocks) and red colors indicate mass excesses, generally in ranges comprised and underlain by dense units. MS, Mesquite basin; MO, Mormon basin; O, Overton Arm basin; CW, California Wash basin; LV, Las Vegas basin; MV, Lower Meadow Valley Wash basin; MVM, Meadow Valley Mountains; AC, Arrow Canyon Range; MM, Mormon Mountains; and VM, Virgin Mountains. Blue colors in northern part of study area are low-density volcanic rocks. Dark-red colors in Mormon Mountains, Virgin Mountains, and Lake Mead area are Early Proterozoic crystalline rock. Thin black solid lines are range outlines.

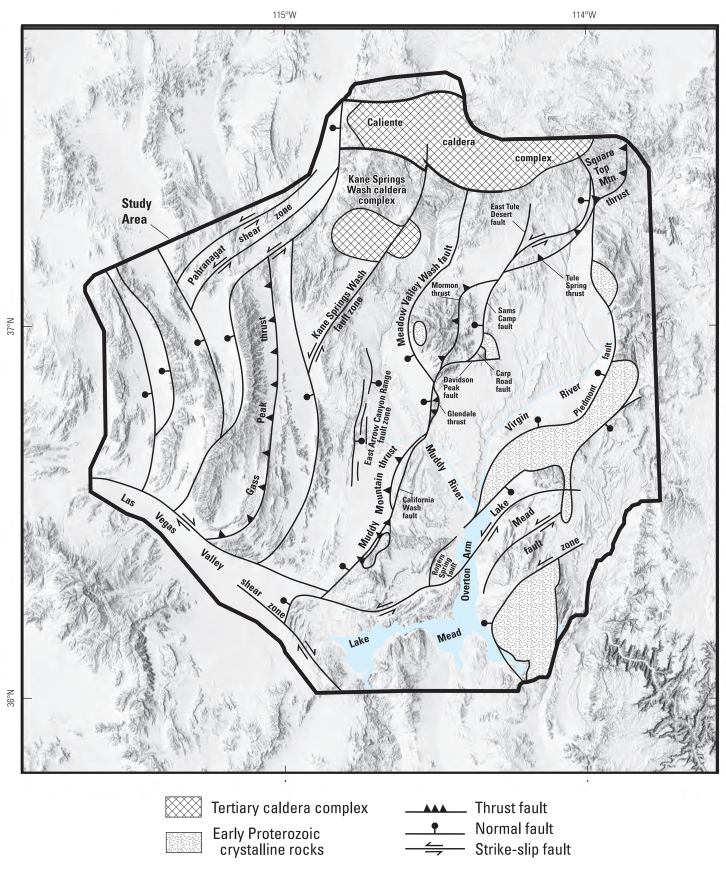


**Figure 5.** Generalized map of the principal structural features in the study area.

| This Report | | Page and others (2005): Pintwater, Desert, Sheep, and Las Vegas Ranges | Clover and N. Delamar Mountains | S. Delamar and N. Meadow Valley Mountains | Arrow Canyon Range and S. Meadow Valley Mountains | Tule Springs Hills, Mormon and Muddy Mountains | Beaver Dam and Virgin Mountains, and Lake Mead area |
|---|---|---|---|---|---|---|---|
| Ju | | Not Exposed | Jam Aztec Ss. Kayenta Fm. Moenave Fm. | Not Exposed | Not Exposed | Jam Aztec Ss. Kayenta Fm. Moenave Fm. | Jct Carmel Fm. Temple Cap Fm. (UT); Jam Aztec Ss. (NV) Navajo Ss. (UT, AZ) Kayenta Fm. Moenave Fm. |
| Ʀu | | Not Exposed | Ʀu Chinle Fm. Moenkopi Fm. | Ʀu Chinle Fm. Moenkopi Fm. | Not Exposed | Ʀu Chinle Fm. Moenkopi Fm. | Ʀu Chinle Fm. Moenkopi Fm. |
| Pkt | | Not Exposed | Pkt Kaibab Fm. Toroweap Fm. | Pkt Kaibab Fm. Toroweap Fm. | Not Exposed | Pkt Kaibab Fm. Toroweap Fm. | Pkt Kaibab Fm. Toroweap Fm. |
| Pr | | Not Exposed | Pr Lower Permian redbeds | Pr Lower Permian redbeds | Not Exposed | Pr Lower Permian redbeds | Pr Lower Permian redbeds |
| PMu | | Not Exposed | PMb Bird Spring Fm. Indian Springs Fm. | PMb Bird Spring Fm. Indian Springs Fm. | PMb Bird Spring Fm. Indian Springs Fm. | PMb Bird Spring Fm. Indian Springs Fm. | PIPc Pakoon Dol. Callville Ls. |
| MDu | | MDu Joana Ls. Pilot Sh. Guilmette Fm. | Not Exposed | Msc Scotty Wash Qtz. and Chainman Sh.; MDu Joana Ls. Guilmette Fm. | Mm Monte Cristo Gp.; MDu Crystal Pass Ls. Guilmette Fm. | Mm Monte Cristo Gp.; MDu | Mr Redwall Ls.; Dtb Temple Butte Fm. |
| DSu | | DSu Simonson Dol. Sevy Dol. Laketown Dol. | Not Exposed | DSu Simonson Dol. Sevy Dol. Laketown Dol. | DSu Simonson Dol. Sevy Dol. Laketown Dol. | Absent | Absent |
| OЄu | SOu | Oes Ely Springs Dol.; Oe Eureka Qtz.; OЄp Pogonip Gp. | Not Exposed | Oes Ely Springs Dol.; Oep Eureka Qtz. Pogonip Gp. | Oes Ely Springs Dol.; Oep Eureka Qtz. Pogonip Gp. | SOu Laketown Dol. Ely Springs Dol. Eureka Qtz. Pogonip Gp.; Op Pogonip Gp. (Muddy Mtns.) | Absent |
| PzZu | Єu | Єn Nopah Fm.; Єbk Bonanza King Fm. | Єn Nopah Fm.; Єhp Highland Peak Fm. | Єn Nopah Fm.; Єbk Bonanza King Fm. | Єn Nopah Fm. | Єnb Nopah Fm. Bonanza King Fm. | Єn Nopah Fm.; Єm Muav Ls. |
| PzZu | ЄZu | Єc Carrara Fm.; ЄZw Wood Canyon Fm. | Єcp Lyndon Ls. Chislom Sh. Pioche Sh.; ЄZw Wood Canyon Fm. | Not Exposed | Not Exposed | Єbt Bright Angel Sh. Tapeats Ss. | Єbt Bright Angel Sh. Tapeats Ss. |
| PzZu | Zs | Zs Stirling Qtz. | Zs Stirling Qtz. | Not Exposed | Not Exposed | Absent | Absent |
| PzZu | Zj | Zj Johnnie Fm. | Not Exposed | Not Exposed | Not Exposed | Absent | Absent |
| Xu | | Not Exposed | Not Exposed | Not Exposed | Not Exposed | Xu | Xu |

**Table 1.** Relationships between bedrock map units (Mesozoic-Proterozoic) in the cross sections and geologic map of Page and others (2005).

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Publishing support provided by:
Denver Publishing Service Center
Manuscript approved for publication May 26, 2011

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# REVISED GEOLOGIC CROSS SECTIONS OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY REGIONAL GROUNDWATER FLOW SYSTEMS, NEVADA, UTAH, AND ARIZONA

By
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Victoria E. Langenheim, and
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2011

*Suggested Citation:*
Page, W.R., Scheirer, D.S., Langenheim, V.E., and Berger, M.A., 2011, Revised geologic cross sections of parts of the Colorado, White River, and Death Valley regional groundwater flow systems, Nevada, Utah, and Colorado: U.S. Geological Survey Open-File Report 2006–1040, 1 sheet, 25 p. pamphlet. [Available at URL *http://pubs.usgs.gov/of/2006/1040*].