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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.

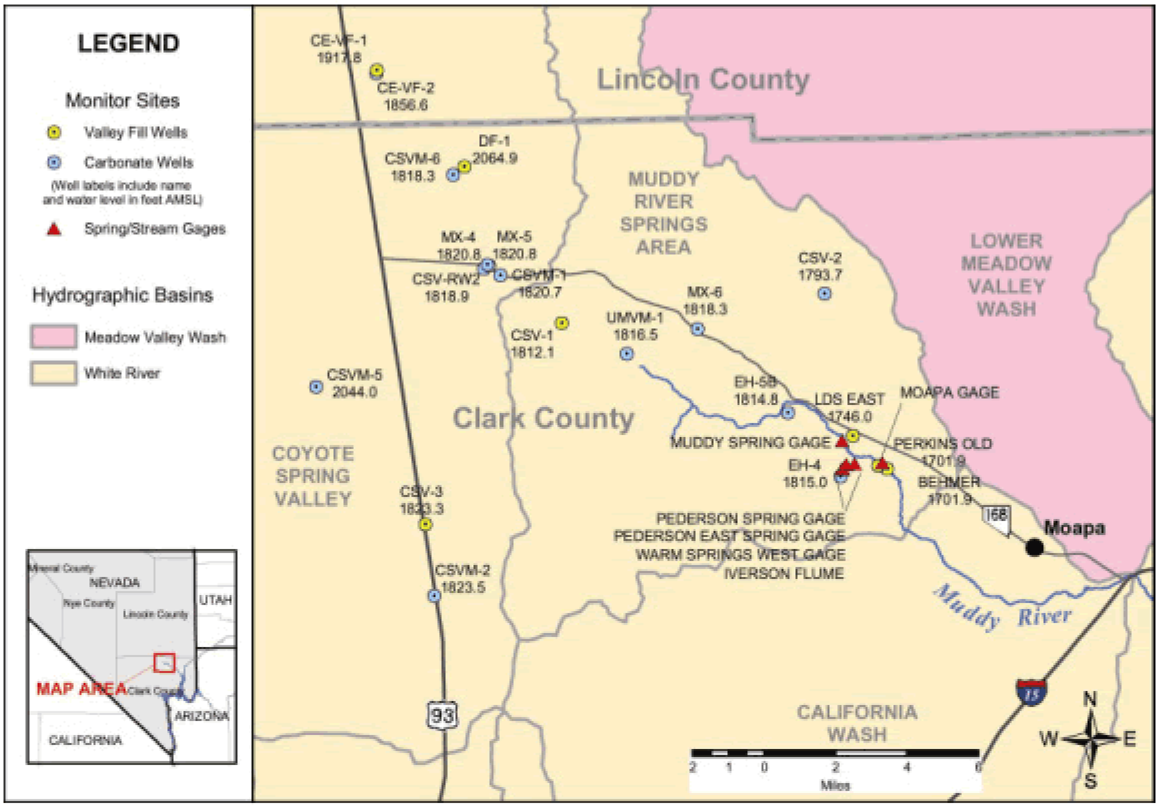

Figure 2 — Wells and springs in Coyote Spring Valley and Muddy Springs Area with potentiometric water surface elevations noted.

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.

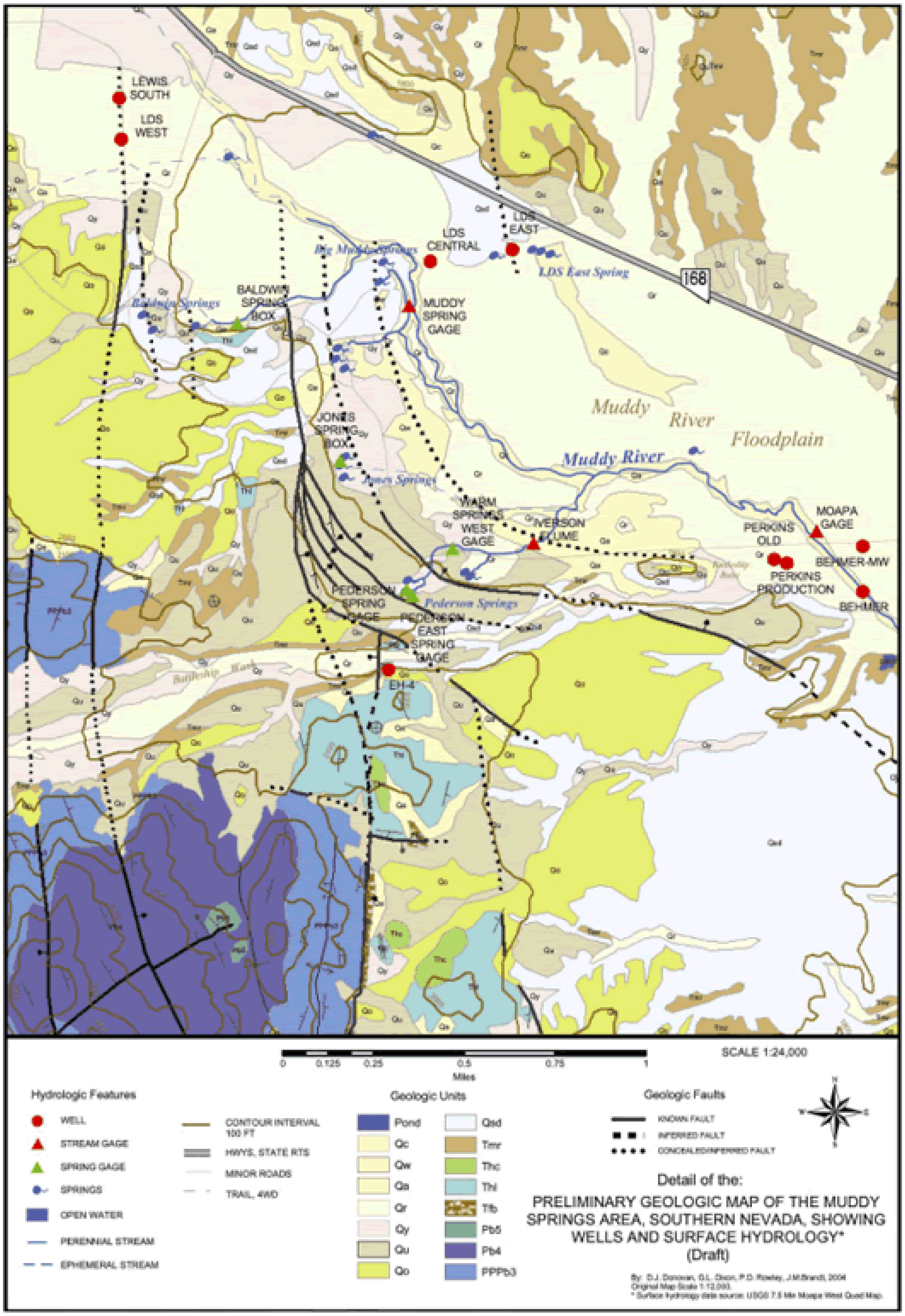

Figure 3 — Geologic Map of the Muddy Springs area.

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.

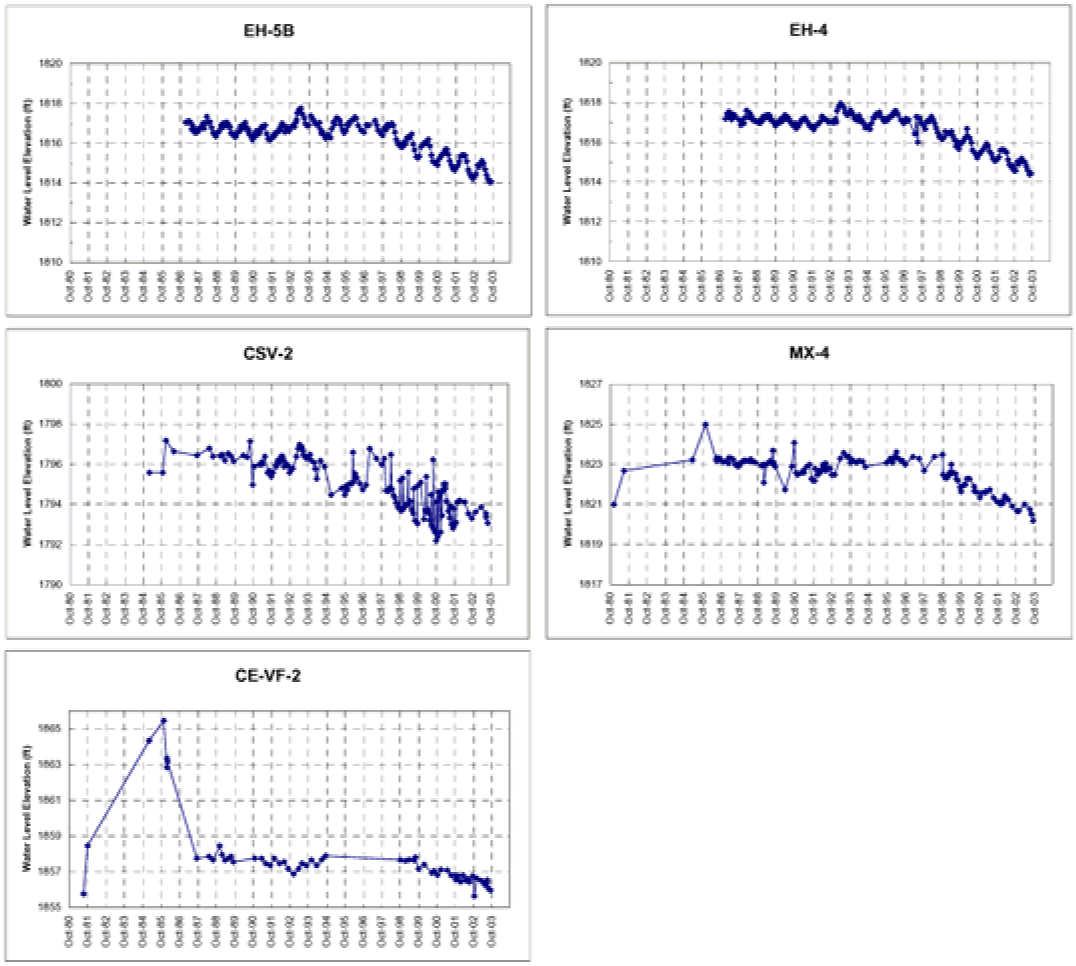

Figure 4 — Carbonate aquifer water level hydrographs, Coyote Spring Valley and Muddy Springs Area. Water level data reported by USGS, SNWA, Nevada Power Company, and MVWD.

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.

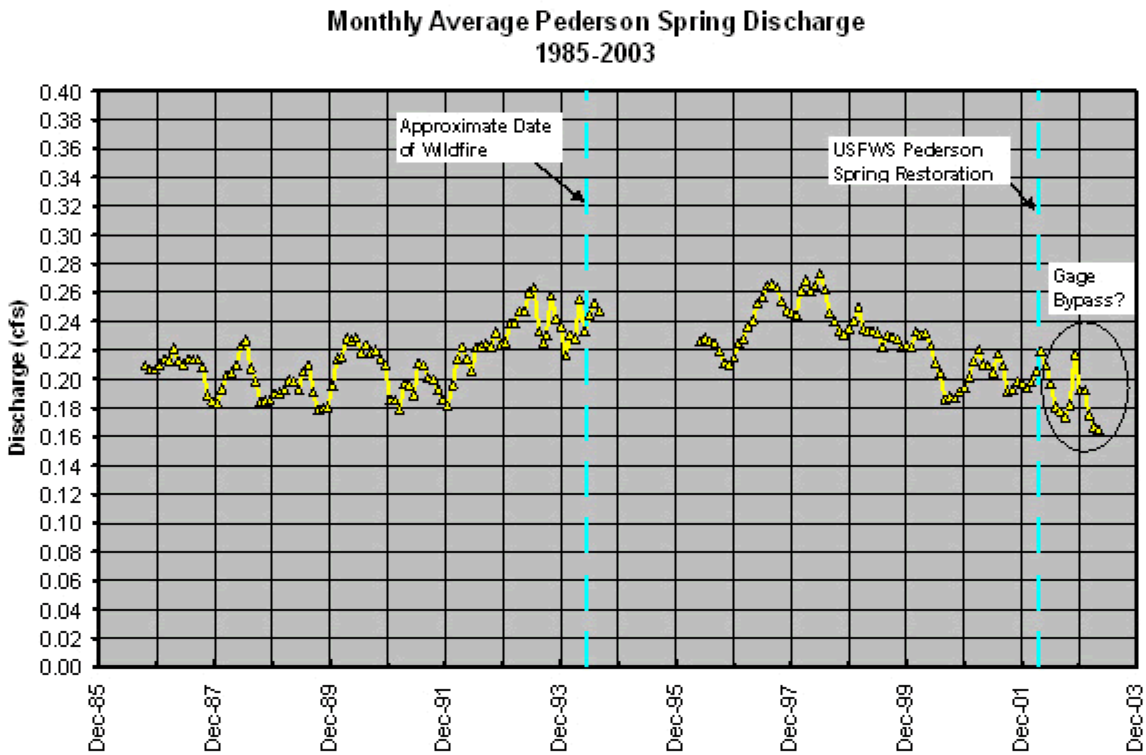

Figure 5 — Pederson Spring Monthly Average Discharge Rates through December 2003. Data source: USGS.

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).

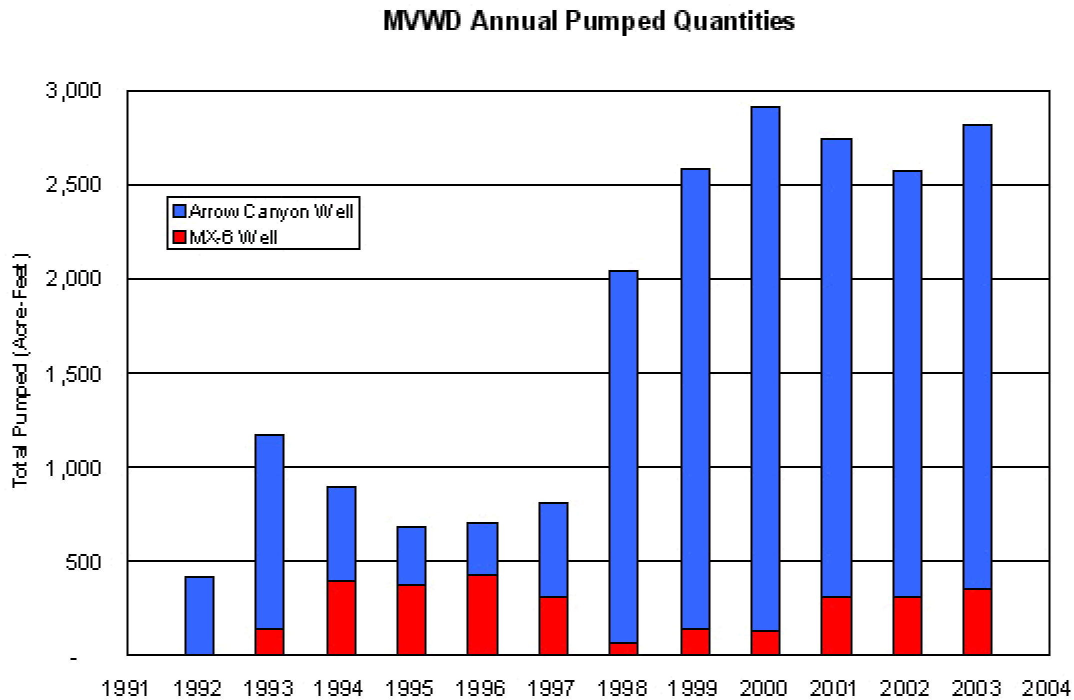

Figure 7 — Annual Total and Seasonal Pumping from MVWD Arrow Canyon and MX-6 Wells. Data source: MVWD.

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).

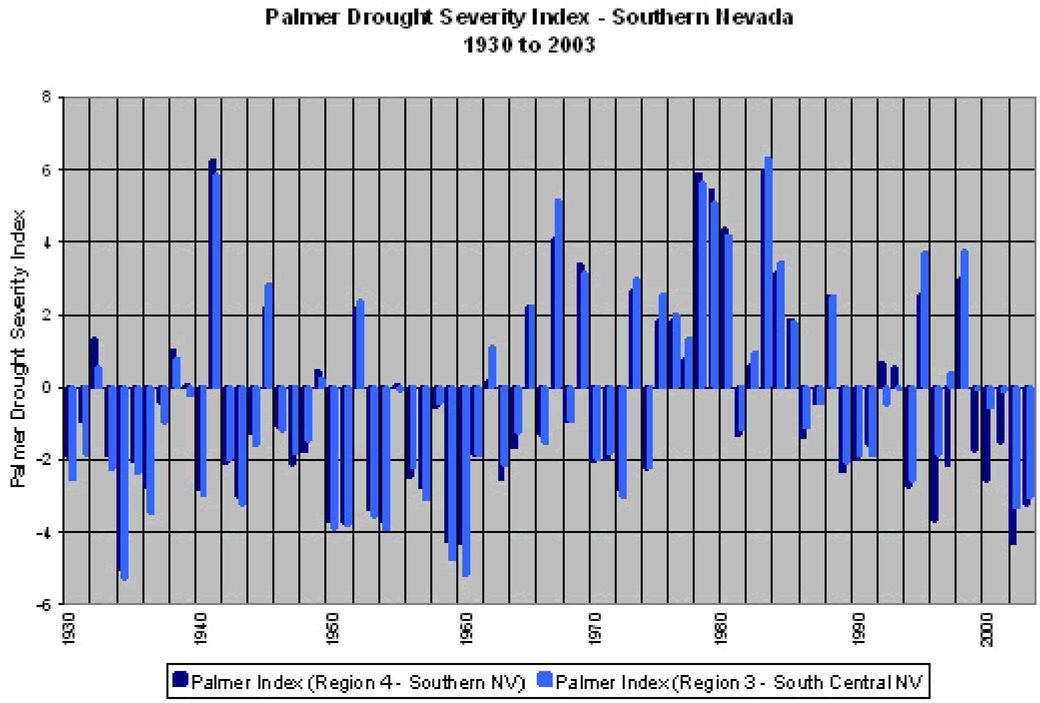

Figure 8 — Palmer Index Bar Plot. Data source: National Climate Data Center, 2003.

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.

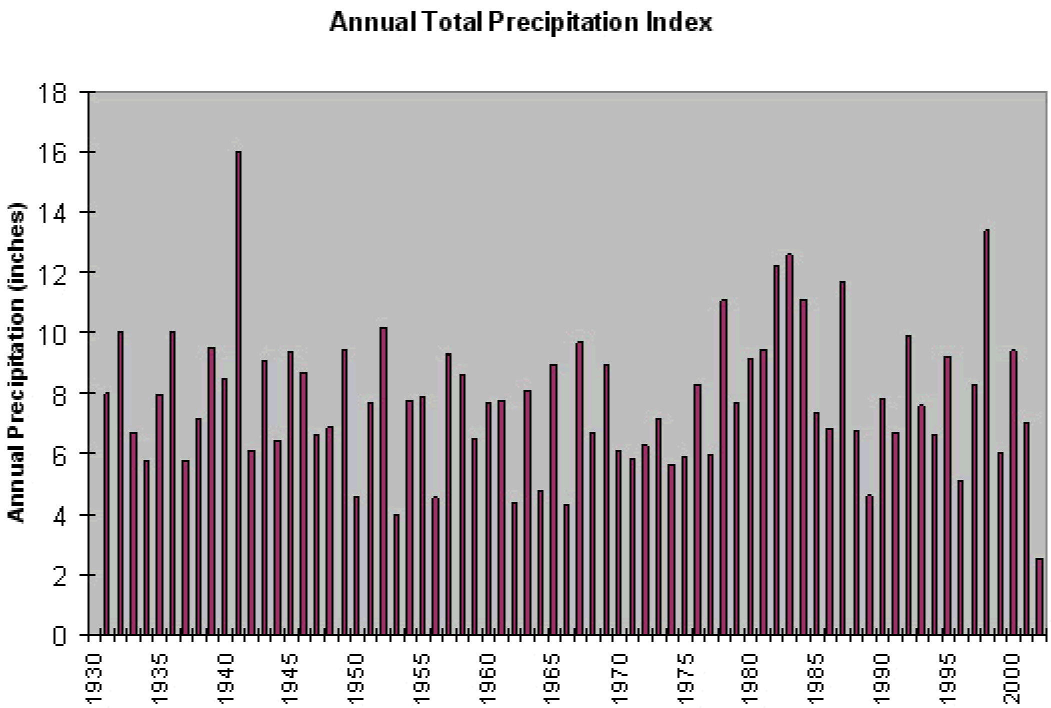

Figure 9 — WRFS Regional Precipitation Index based on records from Las Vegas, Desert Game Range, Pahranagat, Sunnyside, Lund, and Caliente stations. Individual station data source: Western Region Climate Center (WRCC).

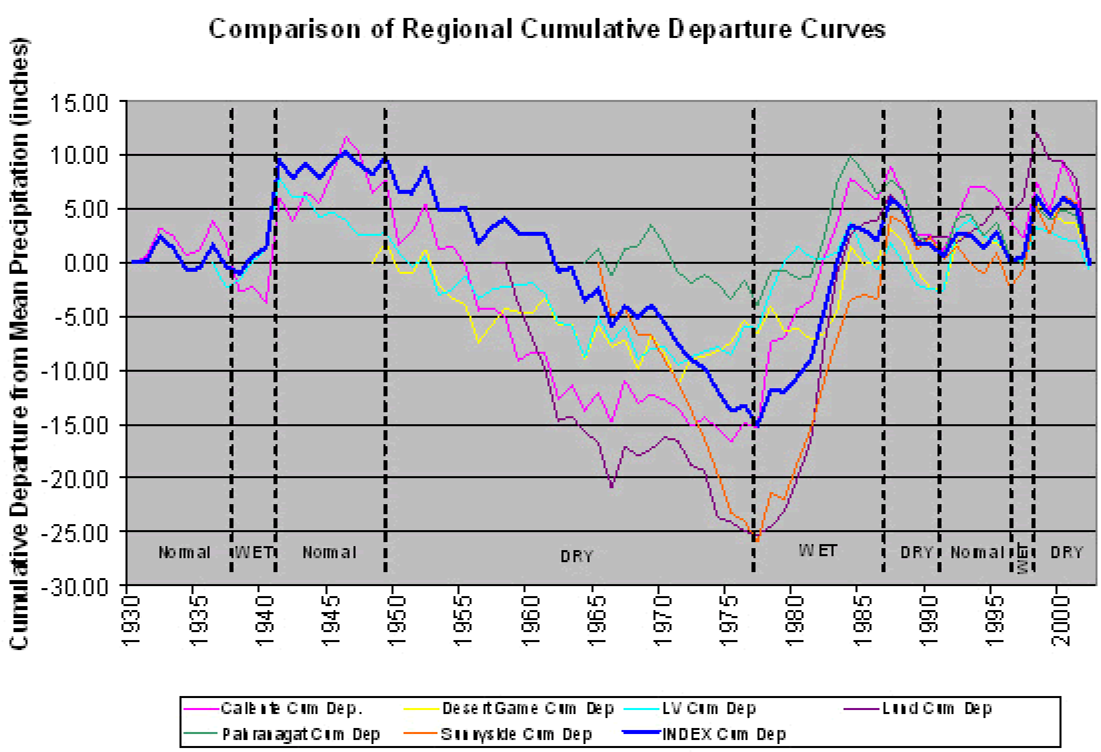

Figure 10 — Cumulative Departure from Mean Precipitation, Comparison for Regional Precipitation Stations. Precipitation data source: WRCC

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.

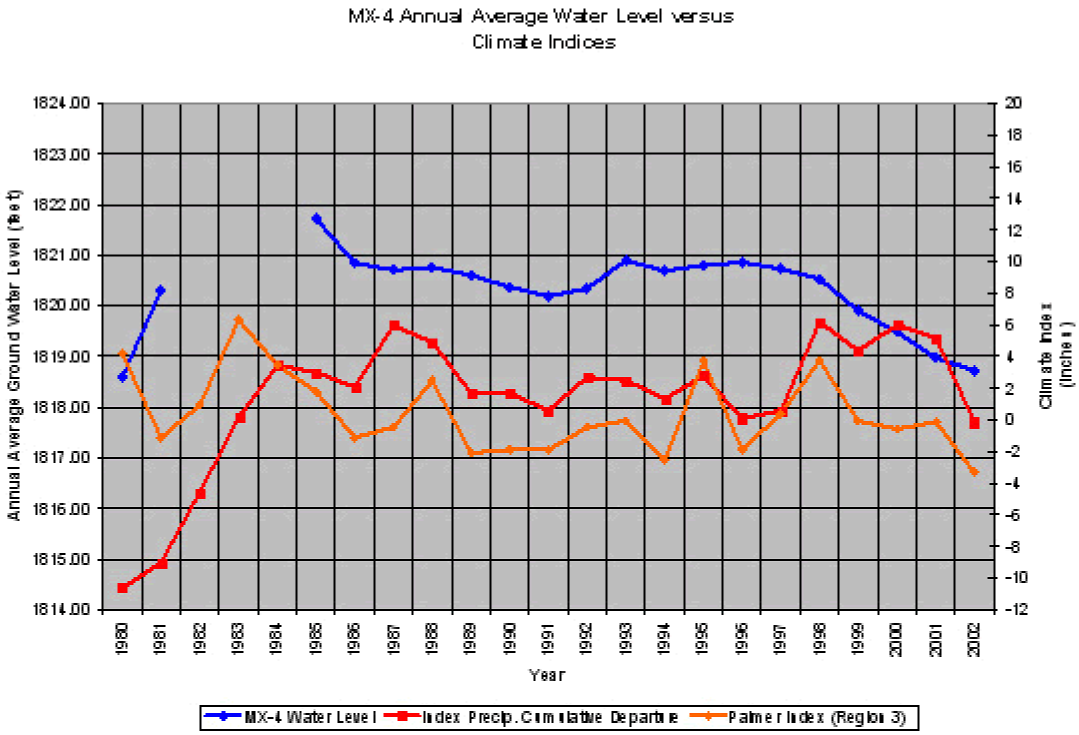

Figure 11 — MX-4 Water Level Elevation versus Regional Climate Trend

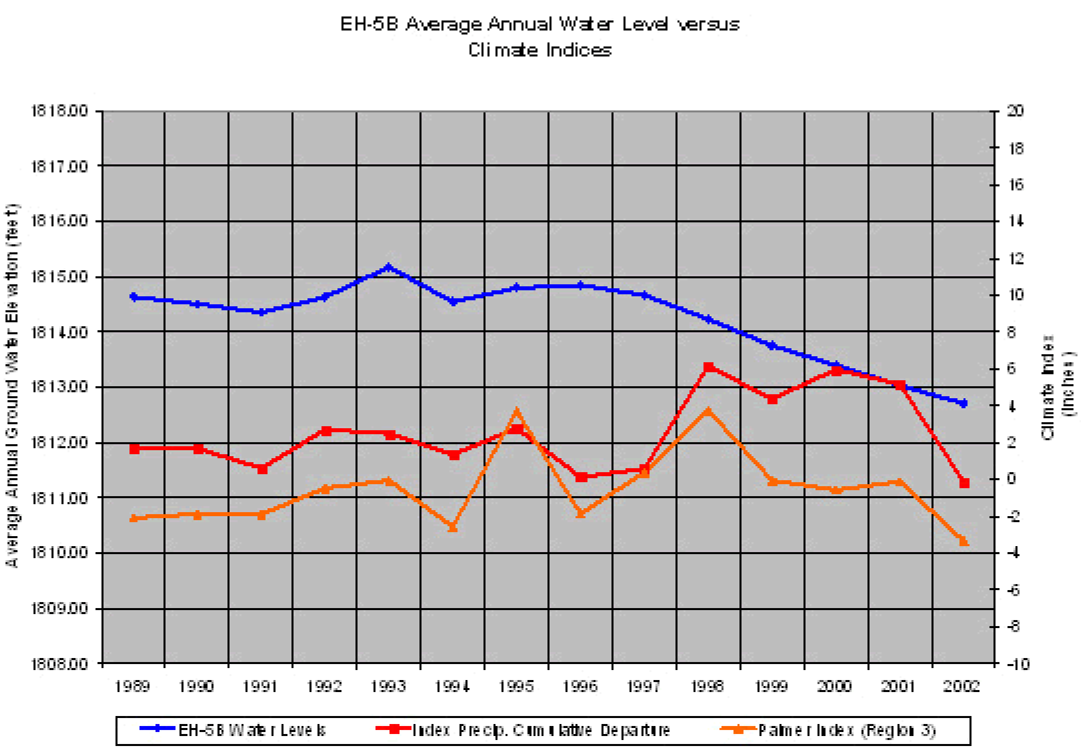

Figure 12 — EH-5B Water Level Elevation versus Regional Climate Trend.

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).

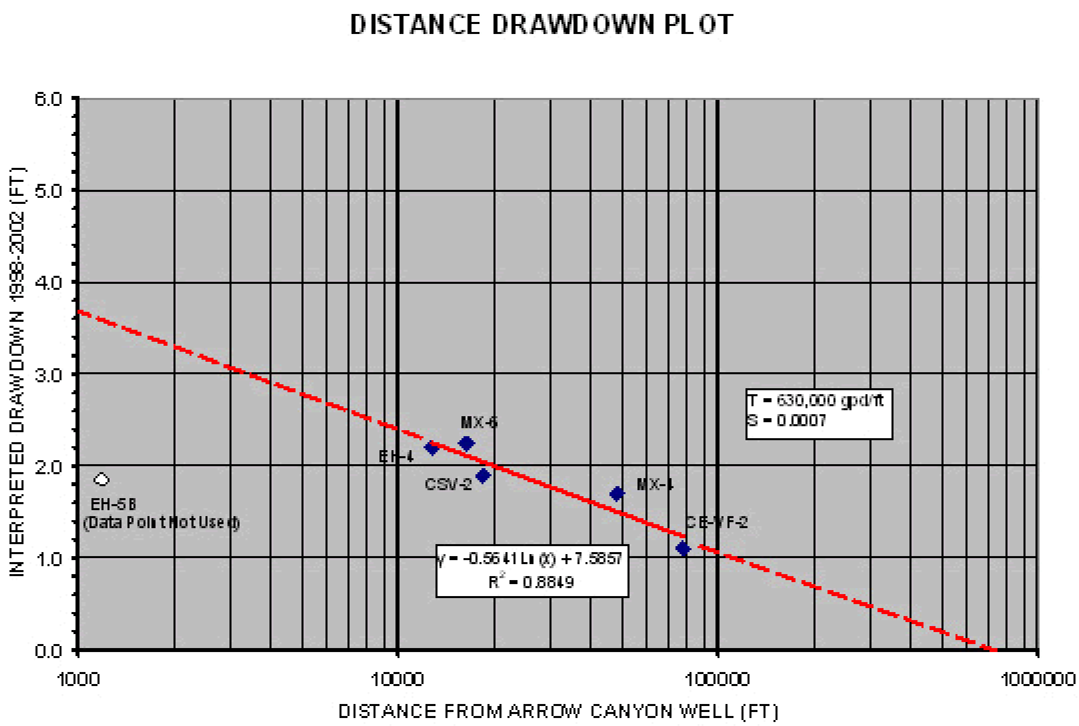

Figure 13 — Distance Drawdown Interpretation for Carbonate Aquifer Wells in the Vicinity of the Arrow Canyon Well.

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

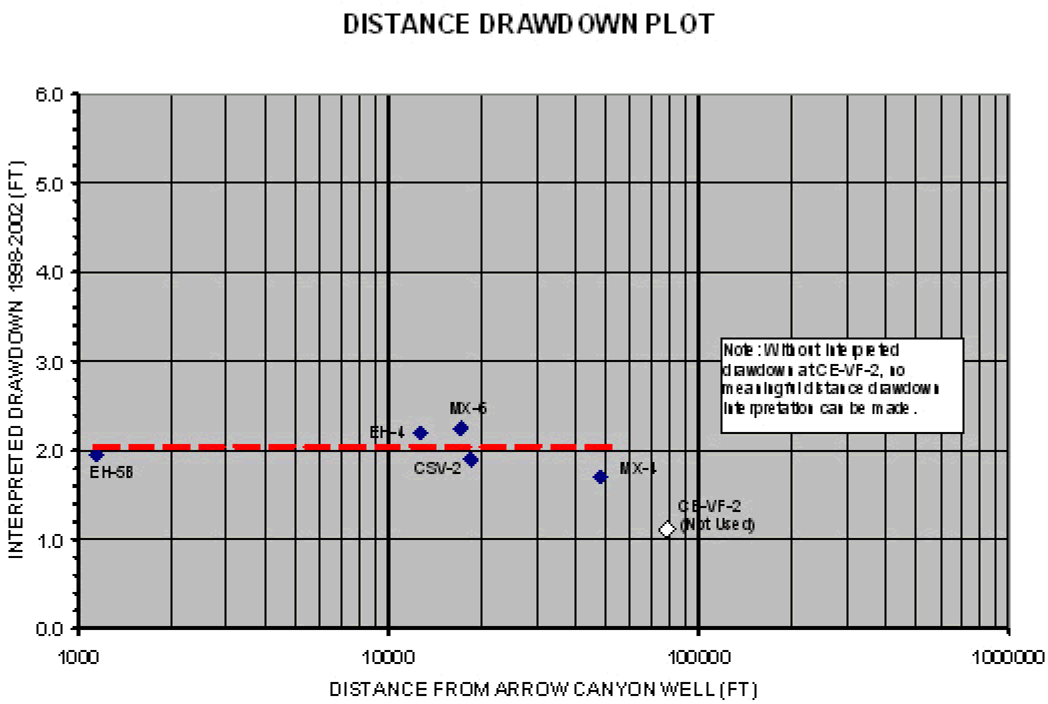

Figure 14 — Alternative Interpretation of Distance Drawdown Data if Well EH-5B is Included andWell CE-VF-2 is Removed from Consideration.

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).

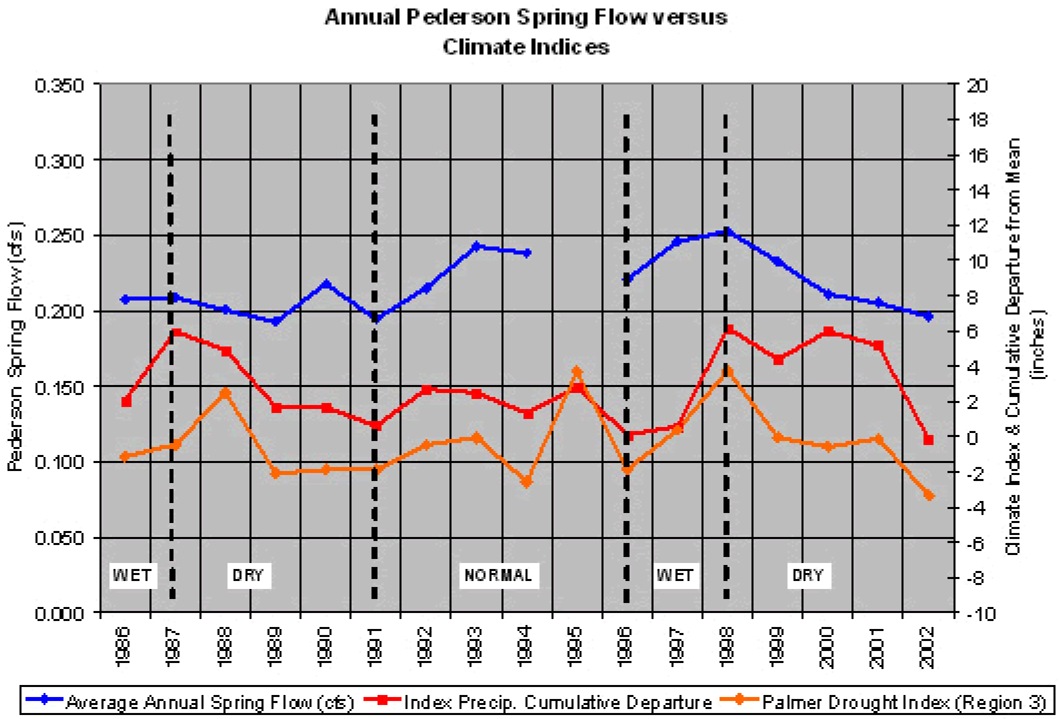

Figure 15 — Comparison of Pederson Spring Flows with Regional Climate Trends. Data source for spring discharge: USGS.

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).

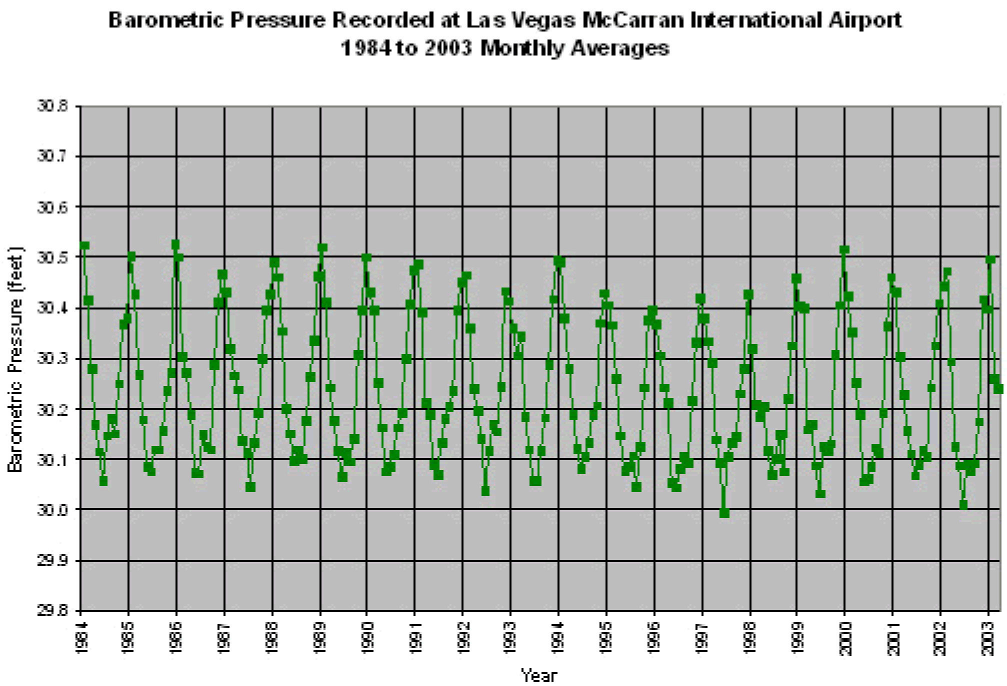

Figure 16 — Monthly Average Barometric Pressure recorded at Las Vegas McCarran Airport. Data Source: National Climate Data Center.

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.

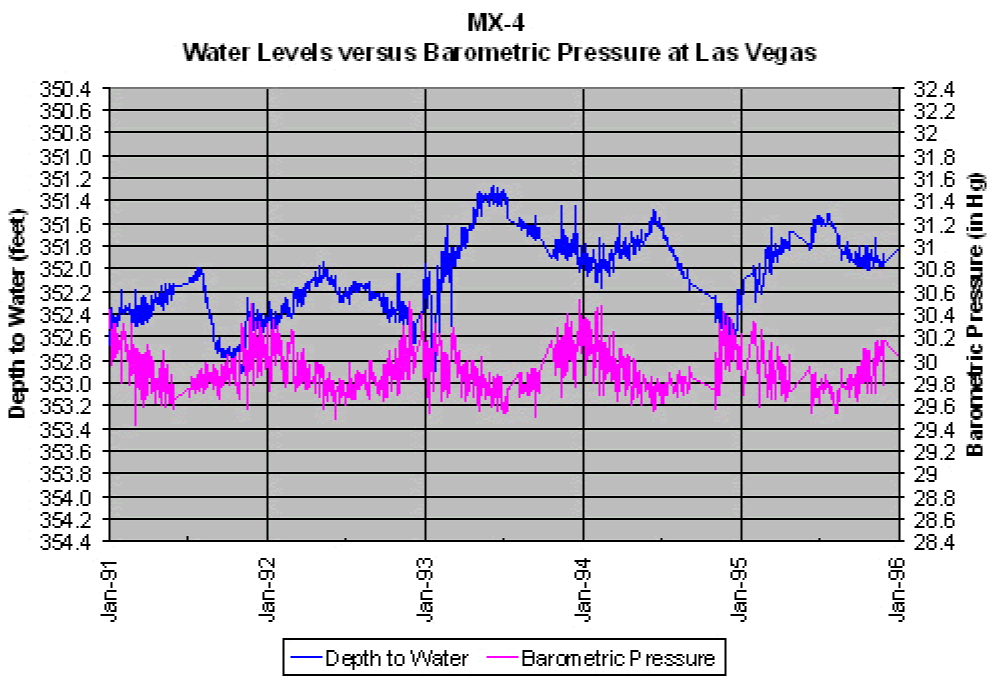

Figure 17 — Depth to water at monitoring well MX-4 versus barometric pressure at Las Vegas. Data sources: Barometric pressure from the National Climate Data Center, MX-4 water levels from USGS.

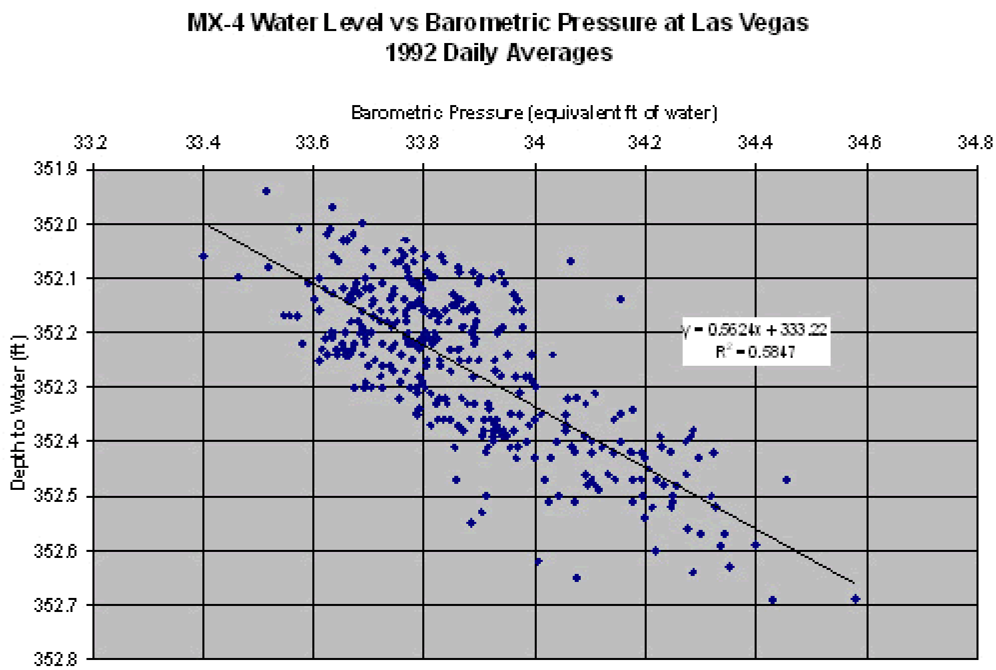

Figure 18 — Average Daily Barometric Pressure at Las Vegas versus Average Daily Water Level at Well MX-4. Data sources: Barometric pressure from the National Climate Data Center, MX-4 water levels from USGS.

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.

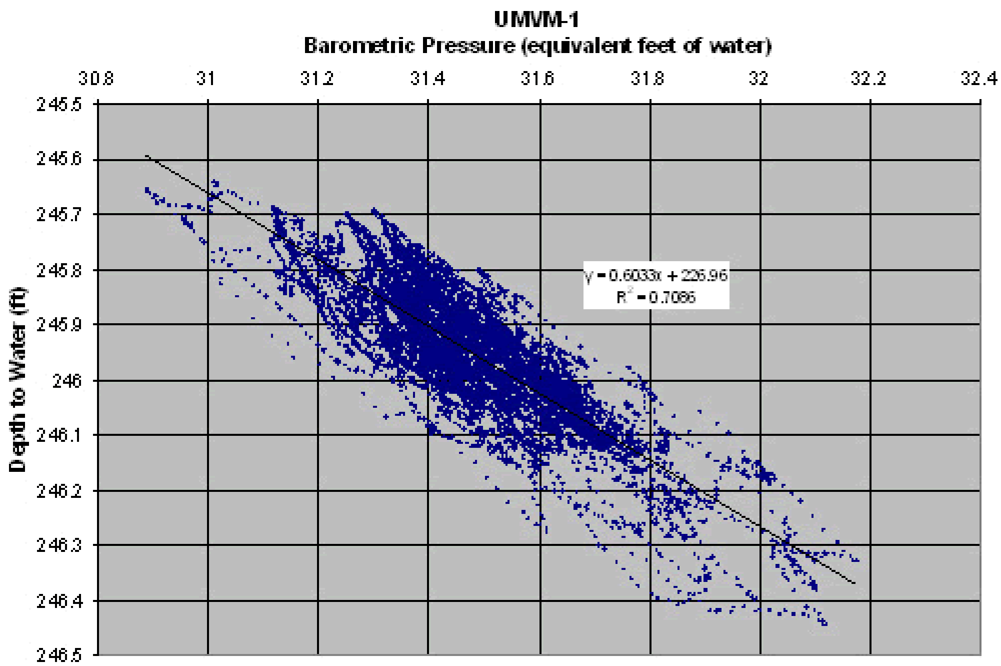

Figure 19 — Barometric Pressure vs. Water Levels recorded at monitoring Well UMVM-1 (15-minute data from August 13, 2003 to December 17, 2003), unadjusted for earth tide effects.

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

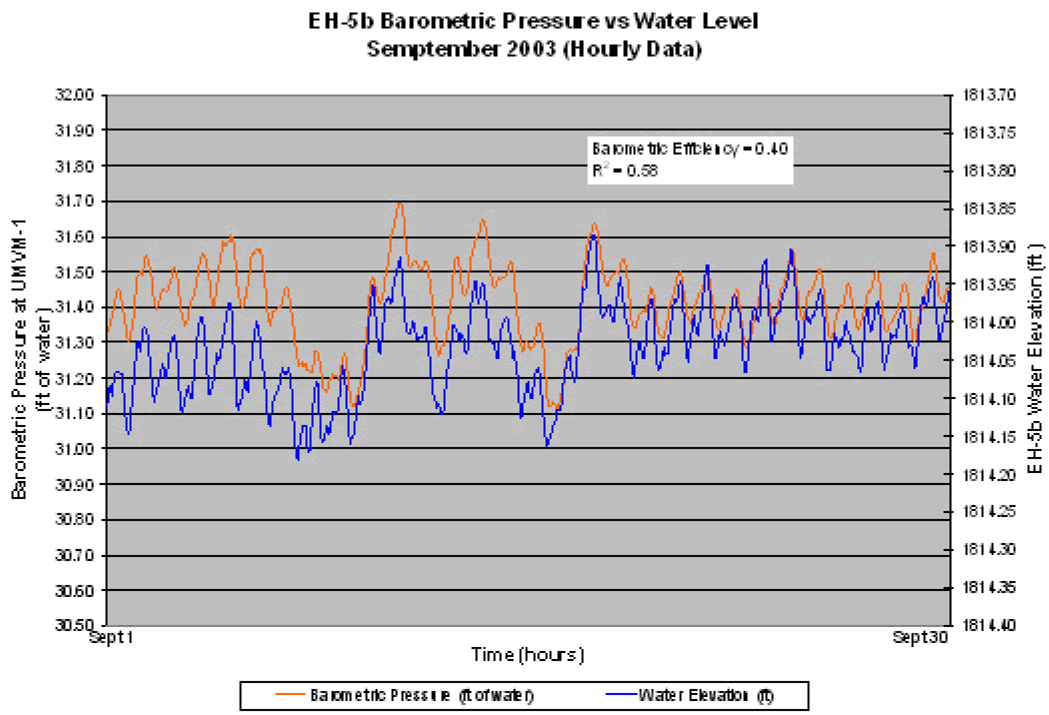

Figure 20. — Barometric Pressure at UMVM-1 versus Potentiometric Water Level at Well EH-5b for Hourly September 2003 Dataset.

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.

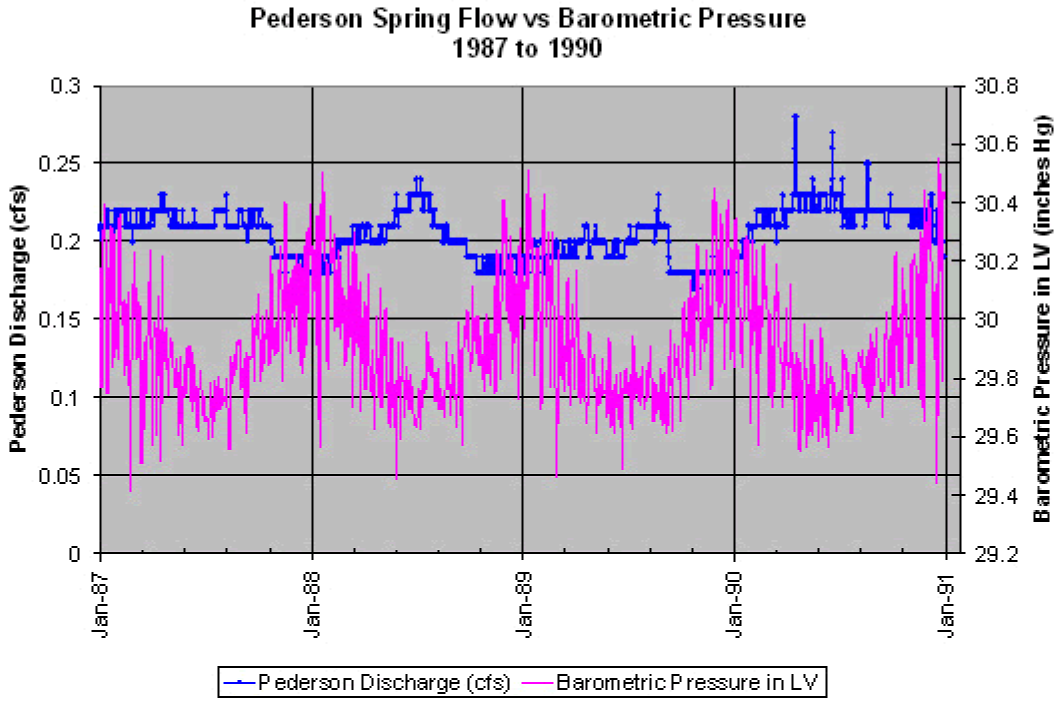

Figure 21 — Pederson Spring Discharge versus Daily Average Barometric Pressure Recorded in Las Vegas. Data sources: barometric pressure from the National Climate Data Center, Pederson Spring discharge from USGS.

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) $\Delta H_{aquifer} = BE_{aquifer} \times \Delta H_{pressure\text{-}H2O}$

(2) $\Delta Q_{Pederson} = BE_{sping} \times \Delta H_{pressure\text{-}H2O}$

Combining equation 1 and 2 with the common variable of $\Delta H_{pressure\text{-}H2O}$ yields.

(3) $\Delta Q_{Pederson} = (BE_{sping}/BE_{aquifer}) \times \Delta H_{aquifer}$

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.

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