ground water

Evaluating Climate Variability and Pumping Effects in Statistical Analyses

by Timothy D. Mayer[1], and Roger D. Congdon[2]

Abstract

As development of ground water resources reaches the limits of sustainability, it is likely that even small changes in inflow, outflow, or storage will have economic or environmental consequences. Anthropogenic impacts of concern may be on the scale of natural variability, making it difficult to distinguish between the two. Under these circumstances, we believe that it is important to account for effects from both ground water development and climate variability. We use several statistical methods, including trend analysis, cluster analysis, and time series analysis with seasonal decomposition, to identify climate and anthropogenic effects in regional ground water levels and spring discharge in southern Nevada. We discuss the parameterization of climate and suggest that the relative importance of various measures of climate provides information about the aquifer system response to climate. In our system, which may be characteristic of much of the arid southwestern United States, ground water levels are much more responsive to wet years than to dry years, based on the importance of selected climate parameters in the regression. Using cluster analysis and time series seasonal decomposition, we relate differences in amplitude and phase in the seasonal signal to two major forcings—climate and pumping—and distinguish between a regional recharge response to an extremely wet year and a seasonal pumping/evapotranspiration response that decays with distance from the pumping center. The observed spring discharge data support our hypothesis that regional spring discharge, particularly at higher elevation springs, is sensitive to relatively small ground water level changes.

Introduction

Ground water sustainability is defined as "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley et al. 1999). Increasingly, attention is being placed on how to manage ground water resources in a sustainable manner (Bredehoeft 2002, 1997; Sophocleous 1997; Alley and Leake 2004). Many areas of ground water development in the United States are approaching or exceeding their limits of sustainability. Under these conditions, it is likely that even small changes in inflow, outflow, or storage will affect water supply or biological resources. Anthropogenic impacts of concern may be on the scale of natural variability, a condition that confounds analyses and makes it difficult to distinguish between the two. Moreover, it is often the variability of flows and water level fluctuations that determines the extreme conditions limiting water availability and threatening biological resources.

Ground water systems tend to react more slowly than surface water systems to short-term climate variability. Because of this, many past studies on ground water flow have neglected climate variability and used long-term average climate conditions or recharge, particularly in temporal simulations of ground water flow (Hanson et al. 2004). At short time scales of interest or where there is extensive aquifer development, this approach has provided acceptable simulations and predictions of large-scale changes in ground water storage (Hanson et al. 2004). However, it is becoming apparent that climate variability and change need to be accounted for in the

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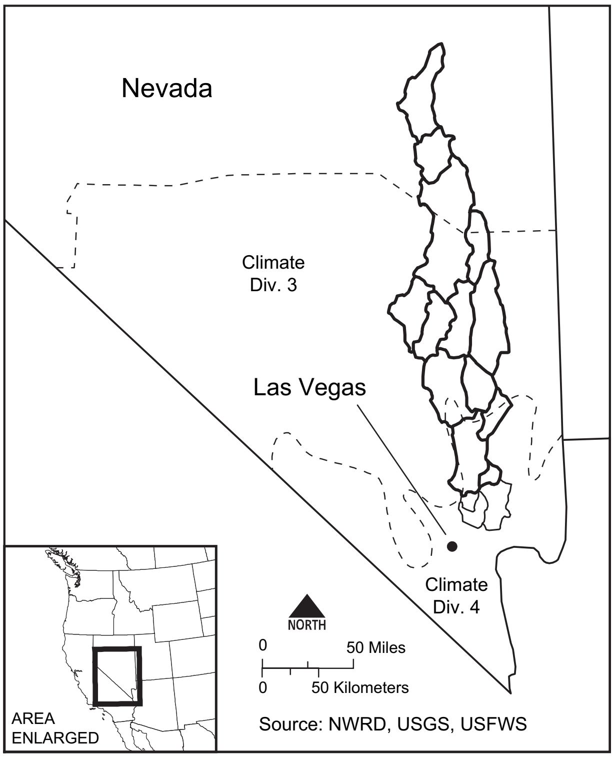
management and analyses of ground water resources (Winter et al. 1999; Alley et al. 1999; Gleick and Adams 2000; Hanson et al. 2004; Weber and Stewart 2004; Scanlon et al. 2005). We believe that this is especially true in systems where the effects of ground water development and climate variability are approximately equal in scale and where these effects have economic or environmental consequences.

When considering climate variability explicitly, one of the first and most important questions is how to represent climate. There are a number of measures available to parameterize climate, including raw precipitation data and several precipitation and drought indexes (Hayes 2006). The indexes differ in their statistical distribution and centering and how they measure deviations from historical norms. Our study examines issues regarding climate parameterization while investigating the effects of climate variability and ground water development on the Muddy River Springs area (MRSA), a regional spring system about 100 km north of Las Vegas, Nevada (Figures 1 and 2). We use statistical analyses to examine water levels and spring discharge for a period that includes a significant increase in ground water development and several years of drought and record precipitation. We begin by examining and characterizing temporal and spatial trends in ground water levels in the system. The long-term well records in the area integrate the combined effects of multiple factors such as climate, seismic activity, barometric pressure, earth tides, evapotranspiration (ET), confined or unconfined conditions, and pumping from different aquifers. The effect of each of these factors varies in frequency and magnitude, but our preliminary analyses indicated that the two main factors affecting the system at scales of concern appear to be climate and ground water pumping.

After identifying and evaluating trends in ground water levels, we examine the relationship between ground water levels in the carbonate rock aquifer and regional spring discharge in the MRSA. We show that in this system, spring discharge is affected by rather small changes in ground water levels resulting from climate and pumping effects. We hypothesize that changes in spring discharge will be proportional to those in hydraulic head at each spring. The higher the elevation of the spring, the smaller the initial hydraulic head and the more sensitive the spring is to water level changes. Our examination of changes in spring discharge in relation to spring elevation and ground water level changes validates our hypothesis. The methods and results we present here are useful in quantifying and assessing climate variability and pumping-related impacts to ground water levels and springs in other regional spring systems, especially where those impacts are at similar scales.

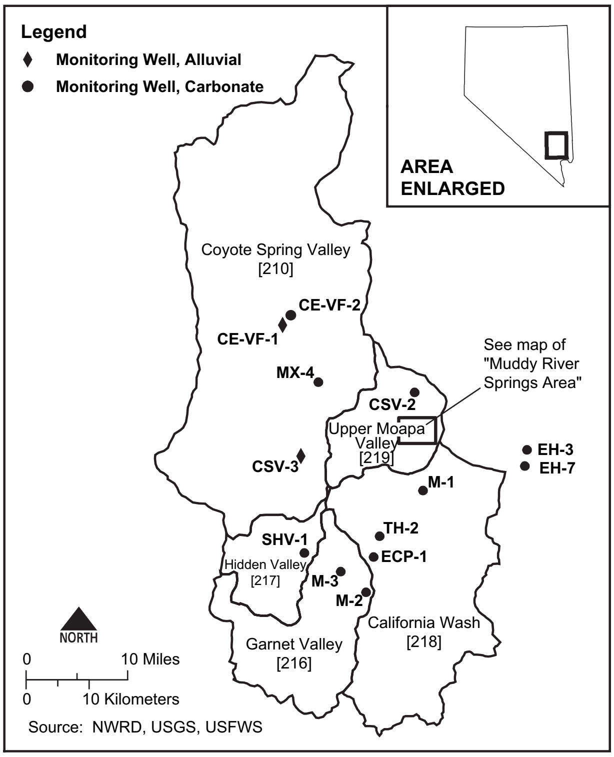
Study Site and Setting

Much of the eastern Great Basin is underlain by a thick sequence of limestone and dolomite rocks known as the carbonate rock province (Harrill and Prudic 1998). Beneath southern Nevada, these carbonate rocks are



Source: NWRD, USGS, USFWS

Figure 1. Map of southeastern Nevada showing Eakin's (1966) original White River ground water flow system (bold outline), adjacent southern basins (narrow outline), and the boundaries of Nevada Climate Divisions 3 and 4.



Source: NWRD, USGS, USFWS

Figure 2. Map of five hydrographic basins within, or adjacent to, the southern portion of the White River ground water flow system, with carbonate and alluvial wells discussed in the text.

widely distributed and permeable enough to facilitate ground water flow at a regional scale. One such regional flow system is the White River ground water flow system, originally defined by Eakin (1966) to encompass 13 topographic basins, extend more than 400 km, and terminate at the MRSA (Figure 1). The flow system consists of numerous local basin fill aquifers underlain by a large regional carbonate rock aquifer that transmits ground water from basin to basin, beneath topographic divides. Much of the flow in the regional carbonate rock aquifer occurs where rocks have been fractured or where openings have been enlarged by dissolution (Prudic et al. 1993; Dettinger et al. 1995). Eakin (1966) identified the regional ground water flow system based on (1) the hydrologic properties of the rocks in the area; (2) the movement of ground water inferred from hydraulic gradients; (3) the relative distribution and quantities of estimated recharge and discharge in the system; (4) the relative uniformity of the discharge of the principal springs; and (5) the chemical composition and warm temperature of the discharge from the principal springs. Additional geologic, isotopic, and numerical studies have confirmed the existence of the regional flow system with minor differences (Harrill et al. 1988; Kirk and Campana 1990; Dettinger et al. 1995; Thomas et al. 1996; GeoTrans Inc. 2001, 2003; Johnson and Mifflin 2006).

Using a water budget approach, Eakin (1966) estimated that 78% of the recharge to the regional flow system occurs as precipitation in the higher elevation mountain ranges of the four northern basins in the flow system and 62% of the discharge from the regional flow system occurs from springs in the Pahranagat and Upper Moapa valleys in the southern part of the flow system. The MRSA in the Upper Moapa Valley (Figure 2) was reported to be the terminal discharge of the regional flow system (Eakin 1966; Harrill et al. 1988; Prudic et al. 1993), although other researchers hypothesize that additional subsurface flow continues beyond the springs to the southeast (Johnson and Mifflin 2006). The springs are located upgradient of a normal fault that juxtaposes low-permeability rock of the Muddy Creek Formation against the carbonate rock aquifer (Dettinger et al. 1995). Eakin (1966) estimated that approximately 1.4 m^3/s of discharge occurs here from about 20 springs. The springs are thermal, discharging at a nearly constant temperature of 32°C (Scoppettone et al. 1992). They occur within a 2-km radius and form the headwaters of the Muddy River. The occurrence of spring discharge at the terminus of regional ground water flow systems is characteristic of the carbonate rock province (Harrill and Prudic 1998).

The MRSA supports eight rare, endemic, aquatic species, including the Moapa dace (*Moapa coriacea*), a federally listed endangered fish since 1967 (U.S. Fish and Wildlife Service, 1996; Scoppettone et al. 1998). The Moapa dace is thermophilic and occurs typically in water temperatures ranging from 26°C to 32°C (Deacon and Bradley 1972). Because the Muddy River cools as it flows downstream, the fish are restricted to the thermal headwater springs (Cross 1976). Like many native fish of the southwestern United States, the Moapa dace have declined due to habitat alteration and introduction of non-native fish (Deacon and Bradley 1972; Scoppettone et al. 1998). The Moapa Valley National Wildlife Refuge, a 47-ha area of springs and wetlands located in the MRSA, was established in 1979 for the protection of Moapa dace (Figure 3).

The transmissivity of the carbonate rock aquifer in the MRSA and surrounding area is quite variable but can be extremely high. Estimated transmissivities range from 200 m^2/d in several carbonate wells in Coyote Spring Valley to 20,000 m^2/d or higher in wells directly upgradient or adjacent to the springs in the MRSA (Bunch and

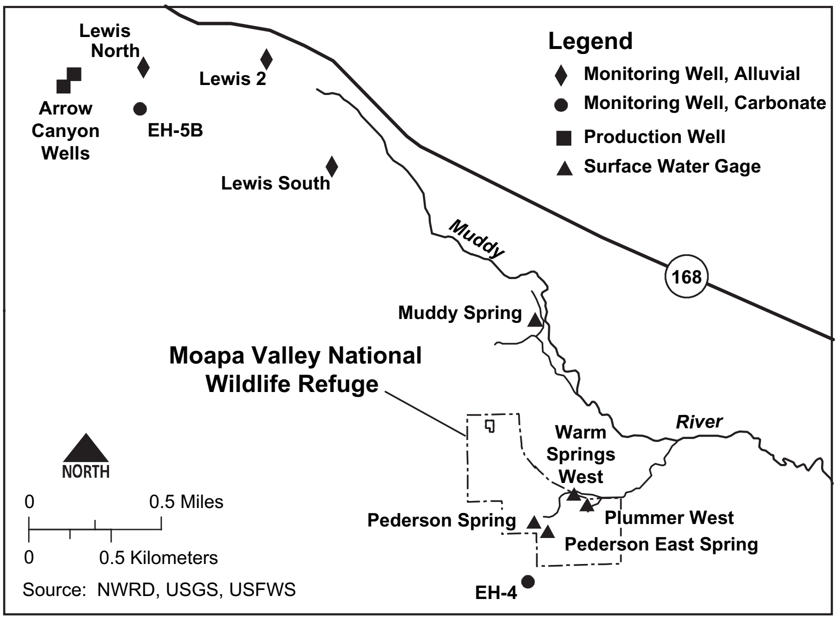


Figure 3. Close-up of MRSA showing Moapa Valley NWR boundaries, Muddy River and tributaries, carbonate production wells, carbonate monitoring wells, alluvial monitoring wells, and spring monitoring sites.

Harrill 1984; Buqo 1994; Dettinger et al. 1995). High-permeability zones such as this are commonly found upgradient of areas of regional spring discharge. Dettinger et al. (1995) analyzed 39 well tests in southern Nevada and found that wells located up to 16 km upgradient of regional springs show transmissivities about 10 to 20 times greater, on average, than those located farther away. The high transmissivity of the carbonate rock aquifer has resulted in a fairly uniform potentiometric surface over an extensive area in and around the MRSA.

There are three primary hydrogeological units in the Upper Moapa Valley: the Quaternary alluvial fill, the Tertiary Muddy Creek Formation, and the Paleozoic carbonate system (Pohlmann 1994). The alluvial fill material provides a shallow, high-yield aquifer that is recharged from the underlying carbonate aquifer. The Muddy Creek Formation underlies the alluvial fill in much of the valley and is considered a semiconfining unit. The Paleozoic carbonates extend below and underlie the other units and are part of the regional carbonate rock aquifer of the White River flow system. Vertical hydraulic gradients in this area are upward from the carbonate rock aquifer to the alluvial fill aquifer.

Like many areas of the southwestern United States, southern Nevada is experiencing tremendous population growth. Municipalities and other water users are turning to the regional carbonate rock aquifer to meet future demand. Ground water in both the shallow alluvial aquifer and the deeper carbonate rock aquifer in the MRSA has been developed. Pumping in the alluvial aquifer for irrigation has been ongoing since World War II, with many of the irrigation water rights being acquired and changed to industrial purposes by power interests since the 1960s. Pumping in the carbonate rock aquifer for municipal supply purposes started in 1986 and increased significantly beginning in 1998. Most of the carbonate pumping now occurs at two adjacent wells: the Arrow Canyon wells 1 and 2, located about 3.5 km northwest of the wildlife refuge (Figure 3).

Theoretical Ground Water Level/Spring Discharge Relationships

Many public agencies and private organizations are concerned that ground water development of the carbonate rock aquifers may negatively impact regional spring systems like the MRSA and the biological resources associated with those systems. It is well established that spring discharge in the MRSA emanates from the regional carbonate aquifer (Eakin 1966; Prudic et al. 1993; Thomas et al. 1996). The potentiometric surface of the carbonate rock aquifer is greater than the land surface elevation of the springs. This hydraulic head differential causes ground water in the carbonate rock aquifer to rise to the land surface, through fissures and fractures, manifesting itself as spring discharge. We are assuming that the flow at a spring is governed by Darcy's law, or some similar proportionality, which states that flow through a porous medium is proportional to the hydraulic head differential or hydraulic gradient (Fetter 1994). The greater the hydraulic head differential between the elevation of the spring orifice and the hydraulic head of the aquifer, the greater the spring discharge, other factors being equal.

All ground water pumping leads to the development of a drawdown cone around the pumping center. As the drawdown cone extends to the springs, the hydraulic head differential at the springs will be reduced. Darcy's law states that a reduction in the hydraulic head differential will result in a proportional decrease in flow. The elevations of spring pool orifices in the MRSA vary by more than 20 m (Southern Nevada Water Authority 2003). The uniform potentiometric surface of the carbonate rock aquifer underlying the MRSA means that the head differential at the various springs decreases with increasing elevation of the spring orifice. We hypothesize that the springs in the system with the smallest head differential, the highest elevation springs, will be proportionately most sensitive to any decline in the potentiometric surface of the carbonate rock aquifer resulting either from ground water pumping or climate effects.

Methods

Climate Data

Each state in the nation has been divided into 1 to 10 climate divisions. These are areas of climate uniformity with water resource data aggregately assessed through principal component analysis, based on information from 10 to 50 individual stations (Guttman and Quayle 1996). Monthly divisional climate data and indexes, including monthly temperature and precipitation, Standard Precipitation Index (SPI), and various Palmer Drought Index (PDI), are compiled back to 1895 for each climate division in the country. We evaluated two climate parameterizations in the study: precipitation and SPI. Monthly precipitation data and SPI were obtained for two of Nevada's four climate divisions: Climate Divisions 3 (South Central) and 4 (Extreme Southern) (Western Regional Climate Center, 2006). Divisions 3 and 4 encompass the north-central and south portions, respectively, of the White River flow system (Figure 1). We calculated moving averages of the monthly precipitation, defined back from points in time, for various time scales for each division.

The SPI is a recently developed normalized index of drought (McKee et al. 1993), designed to explicitly express the fact that it is possible to simultaneously experience wet and dry conditions on multiple time scales. For SPI, historical precipitation data are used to compute the probability distribution of the monthly and seasonal observed precipitation totals (the past 2, 3, 6 months, etc., up to 72 months), and the probabilities are normalized to a cumulative normal distribution. The mean of SPI is then 0 for any particular location and time scale, and the units are normalized variates or standard deviations away from the mean. Positive SPI values indicate greater than average precipitation, while negative values indicate less than average precipitation. Values of 2.0 and −2.0 are defined as extremely wet and extremely dry conditions, respectively. Because SPI is a standardized measure of precipitation, SPI values from different climate divisions are comparable.

Ground Water and Surface Water Data

Water level data are available for a number of carbonate and alluvial monitoring wells for varying periods (Berger et al. 1988; Southern Nevada Water Authority 2006; USGS 2006). Figures 2 and 3 and Table 1 give the location, aquifer type (carbonate or alluvial), well level elevation, period of record, and frequency of measurements of all monitoring wells investigated in this study. Of particular interest are two carbonate monitoring wells, EH-5B and EH-4, located in the MRSA near the pumping center and the springs (Figure 3). Both wells have monthly measurements dating back to 1987, with continuous measurements beginning in 1997.

Monthly pumping data are available for the alluvial production wells from 1983 through 2005 and for the carbonate production wells from 1992 to 2005 (Las Vegas Valley Water District 2001; Moapa Valley Water District 2005; Nevada Power Co., unpublished data). Annual carbonate pumping from 1987 to 1992 was estimated by Las Vegas Valley Water District (2001). We grouped and averaged annual volumes for both carbonate and alluvial pumping for an 11-year period (1987 to 1997) and a 9-year period (1998 to 2005), based on the availability of pumping and monitoring data and the significant increase in pumping from the carbonate rock aquifer that began in 1998.

Four USGS surface water gauging stations in the MRSA are considered in this study: Pedersen Spring (site no. 09415910), Pedersen East Spring (site no. 09415908), Muddy Springs (site no. 09415900), and Warm Springs West (site no. 09415920) (Table 1; Figure 3). All four sites record spring discharge continuously. The gauges at Pedersen Spring and Pedersen East Spring are V-notch weirs that measure two small springs on the wildlife refuge. These are the highest elevation springs in the area. The weir at the Pedersen Spring gauge developed a leak in 2003, and we use flow data only from 1998 through water year 2002. The gauge at Pedersen East Spring was recently installed, in April 2002.

The gauges at Warm Springs West and Muddy Springs are Parshall flumes that were installed in 1985 and have operated since that year, except for a 21-month gap from October 1994 to June 1996. Warm Springs

Table 1

Monitoring Site Name, Basin, Aquifer, Period of Record, and Frequency of Measurements

Well Name	Hydrographic Basin	Aquifer	Water Level Elevation[1] (m)	Period of Record	Frequency of Measurements
EH-5B	Upper Moapa Valley	Carbonate	553.4	1987–2005	Periodic[2] to 1997, continuous from 1997
EH-4	Upper Moapa Valley	Carbonate	553.4	1987–2005	Periodic to 1997, continuous from 1997
CSV-2	Upper Moapa Valley	Carbonate	547.4	1985–2005	Periodic, continuous from 1991 to 1994 and 1999 to 2005
Lewis North	Upper Moapa Valley	Alluvial	552.3	1987–2005	Periodic
Lewis South	Upper Moapa Valley	Alluvial	546.8	1987–2005	Periodic
Lewis 2	Upper Moapa Valley	Alluvial	547.9	1988–2005	Periodic
EH-3	Lower Moapa Valley	Carbonate	Unknown	1987–2005	Periodic
EH-7	Lower Moapa Valley	Carbonate	Unknown	1987–2005	Periodic
MX-4	Coyote Spring Valley	Carbonate	555.2	1985–2005	Periodic, continuous from 1990 to 1996 and 1999 to 2005
CE-VF-2	Coyote Spring Valley	Carbonate	566.0	1987–2005	Periodic, continuous from 2004
CE-VF-1	Coyote Spring Valley	Alluvial	584.3	1988–2005	Periodic
CSV-3	Coyote Spring Valley	Alluvial	556.0	1987–2005	Periodic
SHV-1	Hidden Valley	Carbonate	554.2	1985–2005	Periodic, continuous from 2001
M-1	California Wash	Carbonate	553.5	2001–2005	Continuous
ECP-1	California Wash	Carbonate	553.5	2001–2005	Continuous
TH-2	California Wash	Carbonate	553.1	2001–2005	Continuous
M-2	Garnet Valley	Carbonate	552.5	2001–2005	Continuous
M-3	Garnet Valley	Carbonate	553.1	2001–2005	Continuous

Spring Name	Hydrographic Basin	Aquifer	Spring Orifice Elevation (m)	Period of Record	Frequency of Measurements
Pedersen Spring	Upper Moapa Valley	Carbonate	552	1998–2002	Continuous
Pedersen East Spring	Upper Moapa Valley	Carbonate	551	2002–2005	Continuous
Warm Springs West	Upper Moapa Valley	Carbonate	548 (average elevation)	1998–2005	Continuous
Muddy Springs	Upper Moapa Valley	Carbonate	535	1998–2005	Continuous
Plummer West	Upper Moapa Valley	Carbonate	536	1998–2004	Periodic

[1] Water level elevation as of January 2001.
[2] Periodic means one or two measurements a month.

West measures the collective discharge from five spring groups upstream on the refuge, including the Pedersen Spring and Pedersen East Spring groups. The Muddy Springs gauge measures the outflow from Muddy Springs, the largest and lowest elevation spring in the area.

Several factors affected the quality of records at these surface water stations prior to 1998, including an unmeasured irrigation diversion above one station, a fire that may have affected another station, a gap in the records because of lack of funding, and some unexplained variability or discontinuities in the flow records. For these reasons, we use data only from 1998 on for these sites. In addition to these four sites, the U.S. Fish and Wildlife Service made monthly measurements of spring discharge at the Plummer West spring (Table 1; Figure 3) from June 1998 to November 2004 using a 45° V-notch weir installed at the outflow of the spring pool. This spring is lower in elevation relative to other springs in the immediate area and does not contribute to the collective flow measured at the Warm Springs West site. A theoretical rating was used to convert stage to discharge at this site. The measurements stopped when the weir was removed because of habitat restoration at the spring.

Elevation Data

The Southern Nevada Water Authority completed a comprehensive elevation survey of numerous wells and stream gauges in the MRSA and surrounding basins, including several of the monitoring sites in this study (Southern Nevada Water Authority 2003, 2005). We referenced elevations from the survey and used a level to determine the elevations of spring monitoring sites not included in the survey (Table 1). The spring elevations were used in combination with the ground water elevations in carbonate monitoring wells to estimate the hydraulic head differential at each spring or spring group.

Statistical Analyses

We used a *t*-test to compare the average pumping volumes for two periods, pre- and post-1998, based on a fourfold increase in pumping from the carbonate rock aquifer that occurred beginning in 1998. Temporal trends in the two carbonate monitoring wells, EH-5B and EH-4, in the MRSA were analyzed pre- and post-1998 periods as well. We evaluated three main stressors: climate, alluvial pumping/ET, and carbonate pumping. We excluded seismic activity, barometric pressure, and earth tides on the grounds that effects from these factors are minor and short term, at least for our scales of interest (Pohlmann 1994; Fenelon and Moreo 2002; Waddell and Roemer 2006).

Explanatory variables for the multiple regressions used in the trend analysis were initially evaluated through automated stepwise procedures (Helsel and Hirsch 1992; Ott 1993) using the statistical software SPSS. We then used regression diagnostics, regression statistics, and residual plots to select variables, to test regression assumptions, and to evaluate multicollinearity among variables, which can cause the values of coefficients to be unstable or their signs to be unreasonable (Helsel and Hirsch 1992). These steps were done iteratively, using the data from the EH-5B and EH-4 carbonate monitoring wells, different explanatory variables, and different periods of record, until we developed a common subset of explanatory variables that applied to both wells. We relied on the variance inflation factor, standardized coefficients, PRESS statistic, and adjusted r^2 to help us evaluate variables and regressions. Candidate explanatory variables for the multiple regressions included a wide range of divisional climate statistics from Divisions 3 and 4, including monthly precipitation, 6- to 36-month moving averages of monthly precipitation, 4- to 72-month SPI, and higher order transforms of all moving averages and SPIs. We address some of the differences and implications of using various climate parameterizations in a later section.

We did not quantitatively model pumping or ET in the statistical analysis. The alluvial pumping/ET signal was assumed to be seasonal and was represented with the periodic functions, sine and cosine, with the time variable used to test the assumption that there were no long-term changes resulting from alluvial pumping/ET. We interpreted coefficients from the sine and cosine terms in the regressions to define the amplitude and phase of the seasonal periodicity (Helsel and Hirsch 1992). These authors suggest always adding both sine and cosine terms, even if one of the pair is not statistically significant, to allow the regression to determine the phase shift from the data rather than arbitrarily.

Carbonate pumping was represented with a binary variable, which was changed from zero to one during periods of increased carbonate pumping. This was done for two reasons. First, we did not have actual monthly pumping data for the entire record; only annual pumping data were available. Second, this approach permitted us to use analysis of covariance to quantify any statistically significant changes that occurred coincident with periods of increased pumping (Helsel and Hirsch 1992; Ott 1993). The key variables in the analysis of covariance approach are the interaction terms or the products of the binary variable with time, sine, and cosine. The regression coefficients and statistics associated with these terms indicate changes in time, amplitude, or phase during periods of increased carbonate pumping. Our approach implicitly assumes that a threshold level of carbonate pumping exists below which there are no measurable effects. Preliminary statistical analysis showed this assumption to be acceptable in our system for the period of interest, but such an approach would not be appropriate in all cases.

For the analysis of spatial trends in carbonate and alluvial monitoring wells throughout the system, we considered the period January 2001 to September 2005, a period encompassing extreme climate variability and increased carbonate pumping. Continuous data, when available, were averaged to monthly values. Several months of data were missing in 2004 for some of the carbonate wells in California Wash. We estimated these missing data based on regressions with TH-2, a carbonate well located in the same basin with a complete record for the period. Spatial trends in all wells in the southern portion of the flow system were compared through hierarchical cluster analysis, using average linkage and correlation coefficient distance, and through time series seasonal decomposition. We tested for statistically significant seasonality through regression analysis using the sine and cosine of time, as mentioned previously. In those wells with seasonality, we used a seasonal decomposition procedure in the time series analysis in SPSS to compute and compare the amplitude and phase of the seasonality at all wells for four complete years, January 2001 to December 2004. In the seasonal decomposition procedure, the time series is separated into seasonal, trend, and cycle components. The seasonal index is the average deviation of each month's water level from the level that was due to the other components that month, expressed in the original measurement units. The seasonal index provided an objective measure to compare the relative amplitude and phase of the seasonality for all wells. We also examined the recharge response to the extremely wet year in 2005 for all wells.

For the analysis of spring discharge/ground water relationships, we considered the period 1998 to 2005, when spring discharge data are most reliable. For each spring, we normalized flow to the initial flow value in the period of record and then plotted the normalized flow as a function of carbonate water levels at EH-5B. The slopes for linear regressions of normalized flow vs. ground water elevation were computed and compared, based on the elevations of the spring orifices and the assumed hydraulic head differential at each spring.

Results and Discussion

Climate Data

Figure 4a shows total winter precipitation in Climate Divisions 3 and 4 for the period 1985 to 2005. Winter precipitation and late spring snowmelt, rather than summer precipitation, have been shown to be the principal sources of recharge in the fractured carbonate rock of this area (Winnograd et al. 1998). Winter precipitation was quite variable during this period, particularly in Climate Division 4. The winter totals of 2005, 1993, and 1992 were the highest, second highest, and third highest October to March precipitation totals, respectively, in Climate Division 4 since recordkeeping began in 1895. The winter total of 2002 was the second lowest October to March total in Division 4 since 1895.

The 12-, 24-, and 60-month SPI for Nevada Climate Divisions 3 and 4 from 1980 through 2005 are shown in Figure 5. The SPI plots show that both wet and dry conditions have been experienced simultaneously in each division, depending on the time scale of interest. There is less variability in the SPI values at longer time scales.

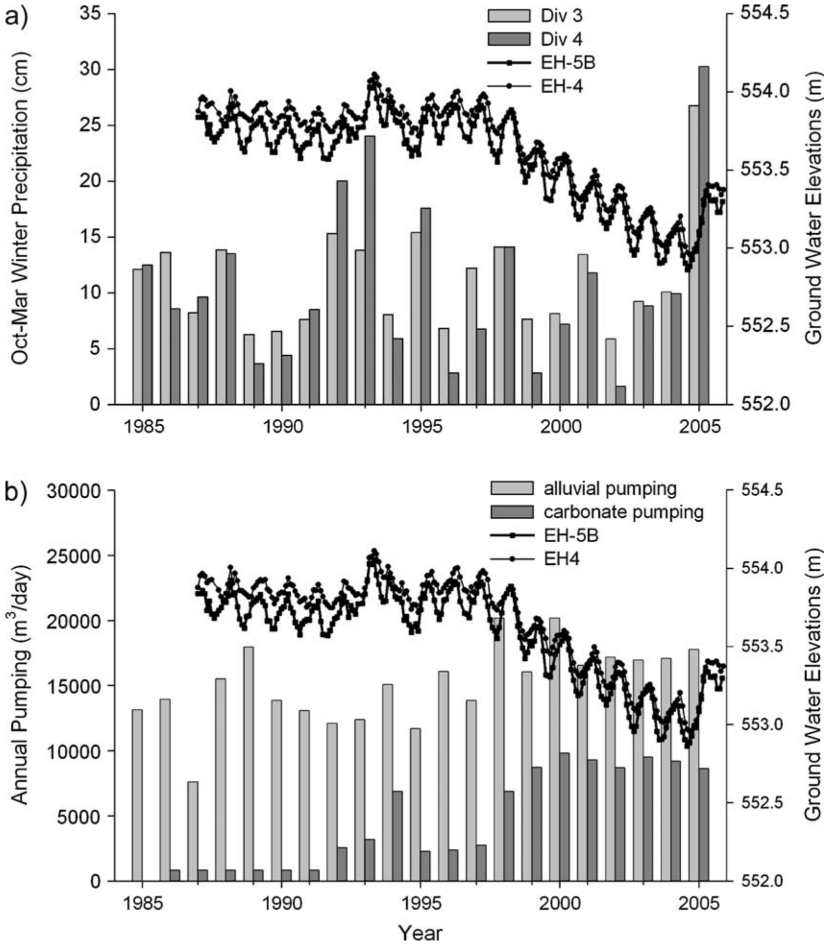


Figure 4. Water levels in carbonate monitoring wells EH-5B and EH-4 for the period 1985 to 2005 with October to March winter precipitation in Nevada Climate Divisions 3 and 4 (a, top plot) and annual alluvial and carbonate pumping (b, bottom plot).

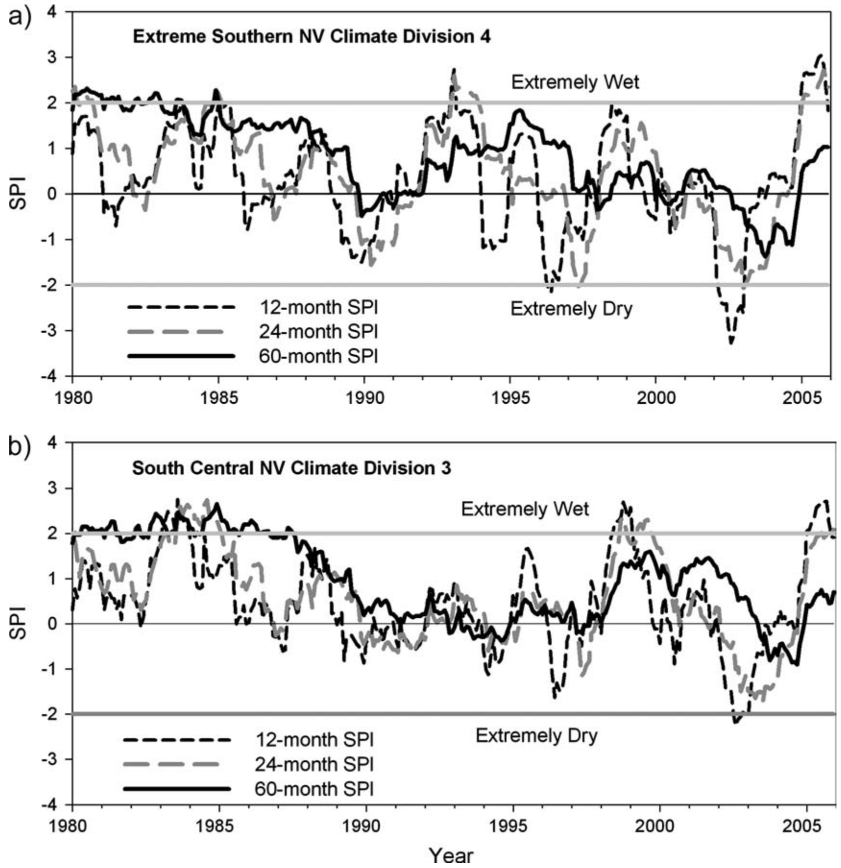


Figure 5. The 12-, 24-, and 60-month SPI for Nevada Climate Divisions 4 (a, top plot) and 3 (b, bottom plot) for 1980 to 2005. The definition of the terms *extremely wet* and *extremely dry* is discussed in the text.

Generally, conditions have been more variable for Division 4 (Extreme Southern Nevada) than Division 3 (South Central Nevada). Considering the 12- and 24-month SPI, Division 4 (Figure 5a) was extremely wet in 1992 and 1993 and extremely dry in 1996 and 1997. In contrast, Division 3 (Figure 5b) was normal or slightly above normal in 1992 and 1993 and not as dry in 1996 and 1997 but was extremely wet in 1998 and 1999. Both climate divisions experienced extremely dry conditions in 2002 and extremely wet conditions in 2005.

One purpose of this study was to discuss the implications of using various climate parameterizations in this type of statistical analysis. Specifically, we explore the difference in using raw precipitation data, in the form of moving average precipitation, vs. a drought index such as the SPI. Generally, the two parameters track similar trends. Moving averages become normally distributed and linearly related to SPI at longer time scales, as a consequence of the larger sample sizes and the Central Limit Theorem (Ott 1993). Guttman (1998) reported that the SPI spectral characteristics conform to what is expected for a moving average process.

A major difference between the two variables is with their units and frequency distributions. The units of SPI are normalized variates, and the frequency distribution is symmetric and centered about a mean of 0. The absolute value of SPI is 0 under average conditions and increases as conditions become either wet or dry. Any regression term containing SPI, or any of its higher order transforms, is the product of the regression coefficient and the value of SPI at that time step. Such a term will have the least amount of influence on the predicted water level under average conditions, when the product is close to zero, and will be larger and more influential, although opposite in sign, as the conditions become wetter or drier. We characterize the regression response to this parameterization as symmetric, in the sense that both wet and dry years will be influential in determining the simulated water level. The PDI (Palmer 1965) and other standardized precipitation or drought indexes centered on zero (see Hayes [2006] for a description of several common indexes) will have similar characteristics.

By contrast, the units of precipitation are nonstandardized values and are always positive, and the frequency distribution of moving average precipitation at shorter time scales is asymmetric and positively skewed (McKee et al. 1993). The square or cubic transform of this variable increases this skewness. Any product in the regression containing precipitation, or any of its higher order transforms, will have the least amount of influence on the predicted water level under dry conditions, or low values of precipitation, and will be more influential as conditions get wetter and precipitation values increase. We characterize the regression response to this parameterization as asymmetric, in the sense that wet years will be more influential in determining the simulated water level than dry years. We propose that the relative importance of these two parameters, moving average precipitation vs.

SPI, in a regression analysis, will have implications about whether the system responds asymmetrically to only wet or dry conditions or symmetrically to both wet and dry conditions.

We excluded two other common climate parameterizations in this study, the PDI and the cumulative rainfall departure from normal, on the basis of critical reviews of these parameterizations. The PDI is a widely used measure of meteorological drought severity (Palmer 1965). Alley (1984) criticized the PDI as being complex to calculate, using somewhat arbitrary rules to designate droughts or wet periods, and being limited in geographical extent. Guttman (1998) compared the PDI and the SPI and reported that the spectral characteristics of the PDI varied geographically, while those of the SPI did not. He concluded that the PDI is a complex structure with a long memory, while the SPI is an easily interpreted, moving average process.

The cumulative rainfall departure from normal measures the accumulated departure of precipitation from a mean defined for some time period. Weber and Stewart (2004) criticized the measure as being problematic for nonnormally distributed precipitation, a common condition in arid environments. Furthermore, they pointed out that the calculated departure is extremely variable depending on the starting and ending points and the length of the period for which the mean is defined.

Pumping and ET

The pumping from the carbonate rock aquifer increased slowly from 1987 to 1997 and then considerably after 1998 (Figure 4b). Carbonate pumping averaged 2200 m^3/d for the period 1987 to 1997 and 8870 m^3/d for the period 1998 to 2005, a statistically significant fourfold increase ($p = 0.000$). The higher values pumped in 1993 and 1994 compared with other years in the earlier period are partly due to a 121-d aquifer test conducted from December 1993 to April 1994 (Buqo 1994).

Annual alluvial pumping increased slightly over the same period from 13,500 m^3/d for the period 1987 to 1997 to 17,750 m^3/d for the period 1998 to 2005 ($p = 0.005$) (Figure 4b). By comparison, we estimated ground water discharge from the alluvial aquifer through phreatophyte ET in the MRSA to be about 5000 m^3/d, based on preliminary information from a USGS study of ET in the area (G.A. DeMeo, written communication, 2006). Based on these estimates, alluvial pumping seems to place a greater demand on the alluvial aquifer than ET. Ground water discharge through ET does not occur in the southern part of the flow system outside the MRSA because of the greater depths to alluvial ground water in other areas. Both alluvial and carbonate pumping are generally greatest during the months of May through September, when demand is highest. Minimum pumping occurs in January in both aquifers.

Temporal Trends in Two Carbonate Monitoring Wells

Ground water elevations in the carbonate rock aquifer in the MRSA, as measured in wells EH-5B and EH-4, show a strong seasonal trend, with minimum annual elevations usually observed in the fall (Figure 4). Two other trends are evident in the ground water level data: annual increases in 1992, 1993, and 2005 and a multiyear decrease beginning in 1998. The increases in 1992, 1993, and 2005 correspond to years of high winter precipitation, especially in Division 4 (Extreme Southern Nevada) (Figure 4a). The decrease beginning in 1998 coincides with the fourfold increase in pumping from the carbonate rock aquifer that occurred at the same time in the MRSA (Figure 4b). The initial water level elevations and the magnitude of increases and declines in both wells are similar, despite the distance separating the two wells and their varying proximities to the pumping center. This is indicative of the uniformity of the potentiometric surface in the carbonate rock aquifer in the MRSA, as a result of the high transmissivities.

We first examined data statistically from EH-5B and EH-4 data for the years 1987 to 1998, a period of minimal carbonate pumping. For both wells, the optimum explanatory variables determined through stepwise multiple regression analysis were sine, cosine, the cube of the Division 4 24-month moving average monthly precipitation, the Division 3 30-month SPI, the Division 4 60-month SPI, time, and carbonate pumping. These seven explanatory variables explained between 65% and 75% of the variance of the data for the period. The most influential terms in the regression, based on the standardized coefficients and the *t* values, were the sine/cosine, followed by the cubic transform of the Division 4 24-month moving average monthly precipitation. The regression coefficient for time for this period was positive but very small, meaning that there was no long-term decline associated with the alluvial and carbonate pumping that occurred prior to 1998. The effect of the 121-d aquifer test in 1994 in the carbonate rock aquifer, as measured with the carbonate binary pumping variable, was statistically significant but short-lived, appearing to extend about 2 months after the completion of the aquifer test.

The importance of the cubic transform of Division 4 24-month moving average precipitation in the regression is interesting for several reasons. First, the selection of this term, rather than lower order terms of the 24-month moving average, implies that the system is quite responsive to wet years since the cube leads to right skewness in the data and emphasizes wet years. We are using climate division data, which are primarily based on valley floor weather stations, as a surrogate measure of recharge in the system. But the proportion of recharge in mountainous areas during wet years may be much greater than is indicated by the precipitation data from valley floor weather stations. The importance of the cubic transform over lower order terms in the regression may be an indication of the greater proportion of recharge in wetter years.

Second, the fact that a higher order transform of precipitation was selected rather than higher order transforms of SPI means that the system response appears to be asymmetric and more sensitive to wet years than to dry years, as described previously. An example of this asymmetry can be observed in the response of water levels to the extremely wet period in 1992 to 1993 and the lack of a response to the extremely dry period in 1996 to 1997. This sensitivity to wet years, often associated with El Niño events, has been described for other ground water systems in the arid southwestern United States (Hanson et al. 2004; Scanlon et al. 2006).

Finally, the stepwise selection of a precipitation variable from Climate Division 4 ahead of Division 3 states that precipitation in the southern portion of the flow system is quite important. In the original conceptual flow model (Eakin 1966), most of the recharge was believed to occur in the north and recharge in the southern portion was believed to be minor. Our results may contradict this and support greater recharge in the southern portion of the flow system, as suggested by Johnson and Mifflin (2006). Higher precipitation rates, thin soils, and the exposure of high-permeability carbonates at the surface all likely contribute to greater recharge in the high-elevation areas of the southern portion of the flow system.

Next, we extended the regressions for both carbonate monitoring wells to December 2002. This period includes 5 years of increased carbonate pumping, 1998 to 2002, and the extreme drought of 2002. We used the same seven explanatory variables as in the previous regressions, along with three interaction terms of carbonate pumping with time, sine, and cosine. The interaction terms capture any change in the slope with time and the periodicity, corresponding to the period of increased carbonate pumping after 1998. The regressions explained between 95% and 96% of the variance in the two carbonate monitoring wells for the period 1987 to 2002 (Figure 6). The adjusted r^2 values improved considerably from regressions for the previous 1987 to 1998 period, in part because the long-term decline beginning in 1998 dominates the variance and this trend is simulated very well by the regression equations. The regression equations for the 1987 to 2002 period are shown subsequently:

$$\begin{aligned}\text{EH-5B monthly water level (m)} &= 1.78 \times 10^{-5}(t)\\ &+ 0.085\left[\sin(2\pi t)\right] + 0.048\left[\cos(2\pi t)\right]\\ &+ 1.61 \times 10^{-5}(\text{D4 24 m avg})^3 + 0.039(\text{D3 30 m SPI})\\ &+ 0.023(\text{D4 60 m SPI}) + 6.033(\$\text{bc}\$)\\ &- 1.77 \times 10^{-4}(\$\text{bc}\$ \times t) + 0.013\left[\$\text{bc}\$ \times \sin(2\pi t)\right]\\ &+ 0.027\left[\$\text{bc}\$ \times \cos(2\pi t)\right] + 553.09\end{aligned}$$

$$\begin{aligned}\text{EH-4 monthly water level (m)} &= 8.22\text{E} \times 10^{-6}(t)\\ &+ 0.066\left[\sin(2\pi t)\right] - 0.009\left[\cos(2\pi t)\right]\\ &+ 1.21 \times 10^{-5}(\text{D4 24 m avg})^3 + 0.042(\text{D3 30 m SPI})\\ &+ 0.012(\text{D4 60 m SPI}) + 6.320(\$\text{bc}\$)\\ &- 1.85 \times 10^{-4}(\$\text{bc}\$ \times t) + 0.026\left[\$\text{bc}\$ \times \sin(2\pi t)\right]\\ &+ 0.033\left[\$\text{bc}\$ \times \cos(2\pi t)\right] + 553.55\end{aligned}$$

where t = time (day of year); sin and cos = the sine and cosine terms for the periodicity; D4 24 m avg = the 24-month moving average precipitation (mm) for Climate Division 4; D3 30 m SPI = the 30-month SPI for Climate

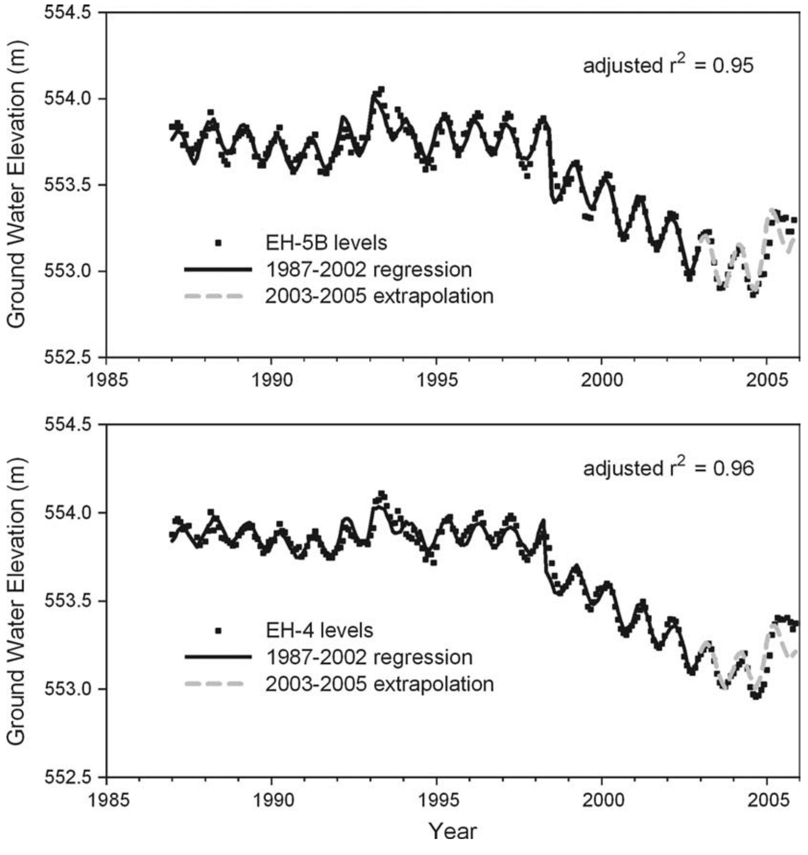


Figure 6. Water levels in carbonate monitoring wells EH-5B and EH-4 for 1987 to 2005 with multiple regressions for 1987 to 2002 and extrapolations of the regression for the period 2003 to 2005.

Division 3; D4 60 m SPI = the 60-month SPI for Climate Division 4; bc = the binary variable for the carbonate pumping; bc × t = the interaction term of the carbonate binary variable and time; and bc × $\sin(2\pi t)$ and bc × $\cos(2\pi t)$ = the interaction terms of the carbonate binary variable and the periodicity.

Coefficients and prediction values from the regressions for each well were basically equal for the two periods, 1987 to 1998 and 1987 to 2002, and the two regressions plot on top of each other during the overlapping years. Only the value of the regression coefficient for the carbonate binary variable changed between the two periods. The coefficient for the interaction term with time was negative and statistically significant, indicating that ground water levels began declining coincident with the increased carbonate pumping in 1998. The interaction terms with sine and cosine indicated that the amplitude of the seasonal pattern increased by 2.7 cm and the phase shifted 2 to 3 weeks earlier in both wells after 1998, although only the phase shift in EH-5B was statistically significant. Extrapolations of the 1987 to 1998 regressions beyond 1998 with climate terms alone were unable to simulate the long-term decline that began in 1998. To simulate this decline, we had to add the binary variable to account for increased carbonate pumping. We infer from these results that the long-term decline in carbonate levels beginning in 1998 is a result of the increased carbonate pumping that began at the same time.

The regressions for the period 1987 to 2002 were extrapolated for 3 years from 2003 to 2005, using the same explanatory variables, in an attempt to validate the statistical model (Figure 6). The regressions appear to simulate the ground water trends in these years for both wells, continuing to decline through 2004 and then increasing in 2005 in response to the extremely wet year. The wet year response in 2005, as predicted by the regressions, is based on the responses observed and fitted statistically in the 1987 to 2002 regressions. While the extremely wet years in 1992, 1993, and 2005 caused large increases in water levels, the extremely dry conditions of 2002 appear to have relatively little effect on water levels. This demonstrates what we interpret to be the sensitivity and asymmetry in the system response to wet years over dry years.

Spatial Trends in Carbonate and Alluvial Monitoring Wells

Most of the carbonate wells examined in this study show similar behavior, with a seasonal pattern imposed over a long-term declining trend from 1998 until 2004 and a large increase in response to the 2005 wet year (Figure 7). We assume that these wells are responding to the same climate and pumping signals as described for EH-5B and EH-4 previously. The multiyear declining trend through 2004 observed in most of the carbonate wells is most likely a result of the increased carbonate pumping in the MRSA. CE-VF-2 and SHV-1, the two more distant carbonate wells, do not appear to start declining until about 2000 rather than 1998.

Figure 8 presents the results from the cluster analysis of all wells examined in this study. Nine of the 11 carbonate wells are very similar to each other, with a similarity level more than 97. However, even within this group, there are subtle but important differences in the amplitude and phase, as indicated by the results from the time series seasonal decomposition (Figure 9). EH-5B has the greatest amplitude and the earliest phase in comparison to the other carbonate wells. It also has more of a characteristic pumping-induced asymmetry, as observed by Johnson and Mifflin (2006), in contrast to the other carbonate wells, which are more symmetric and sinusoidal. The seasonal amplitude, phase, and asymmetry may be related to the proximity of EH-5B to the Arrow Canyon production wells (Figure 3) and other alluvial production wells. MX-4 and M3 have slightly smaller amplitudes and later phases compared with the other carbonate wells. There is a north-south trending thrust fault separating these two wells from the MRSA and California Wash. The stratigraphic position of the carbonate rocks may be shifted across the fault, and this may be part of the reason for the smaller amplitude and later phase in the wells west of the fault. We observed no evidence of pumping-induced asymmetry in the hydrograph for MX-4, in contrast to Johnson and Mifflin (2006). CE-VF-2 and SHV-1, two other carbonate wells farther west of the thrust fault and the MRSA, partitioned quite differently from the main group of carbonate wells because of a lack of seasonality and, in the case of SHV-1, a much smaller decline and recharge response.

In general, carbonate wells located closer to the MRSA tend to have larger amplitudes and earlier phase shifts than those farther away, with the most distant wells in Hidden Valley and Coyote Spring Valley showing no seasonality and a delayed drawdown as well. Such a pattern could be suggestive of a muted or attenuated signal with distance from the source, although this is more clearly evident in the upgradient direction than in California Wash or Garnet Valley. Given the complex geology and the fractured nature of the flow system, responses may not be expected to be isotropic or solely a simple function of linear distance. Johnson and Mifflin (2006) postulated the presence of a hydraulic barrier between California Wash and the MRSA based on their modeling results, but we found no evidence here to support the existence of such a barrier.

The alluvial monitoring wells responded and partitioned quite differently from the carbonate wells and from each other (Figures 7 and 8). The three alluvial wells in the MRSA partitioned into two separate clusters, which are quite unique from the carbonate wells in the same basin. The amplitude is much greater and the phase is earlier than in the adjacent carbonate wells (Figure 9). These differences may be due to the different hydraulic properties of the unconfined alluvial aquifer and the fact that the seasonal signal is partly a result of alluvial pumping in the same aquifer. There is also more of a pumping-induced asymmetry observed in the seasonal pattern, particularly in Lewis North, the closest alluvial well to the Arrow Canyon production wells. Only one of these three wells, Lewis North, shows a long-term decline through 2004 (Figure 7). CSV-3, an alluvial well in Coyote Spring Valley, has poorly defined seasonality, a long-term

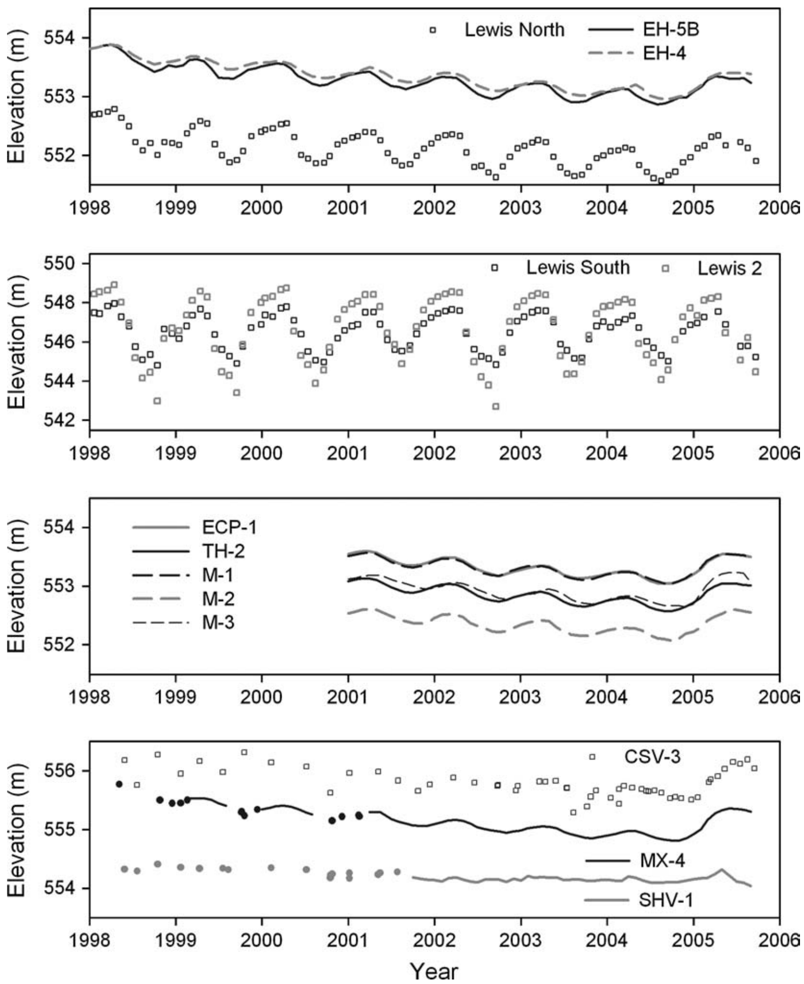


Figure 7. Hydrographs from representative carbonate and alluvial monitoring wells in the MRSA (top two plots), California Wash and Garnet Valley (third plot), and Coyote Spring Valley and Hidden Valley (bottom plot) for the period 1998 to 2005. Lines represent periods of continuous data in the carbonate wells. Symbols represent periodic measurements, open for alluvial wells and closed for carbonate wells. Note the different scales on the vertical axes. Three wells discussed in the text, CSV-2, CE-VF-1, and CE-VF-2, are not plotted.

decline beginning in 2000, and a response to the 2005 wet year. It was partitioned with CE-VF-2, a carbonate well in the same basin with a very similar hydrograph. CE-VF-1, a second alluvial well in northern Coyote Spring Valley, showed no seasonality or long-term decline or recharge response. It partitioned very differently from any of the other wells (Figure 8).

The response to the extremely wet year in 2005 varied by aquifer type. The timing and magnitude of the response are quite uniform in most of the carbonate wells, with the exception of SHV-1 (Figure 7). The 2005 wet year response is more dampened and short-lived in two alluvial wells, Lewis North and CSV-3, and not present at all in the other three alluvial monitoring wells (Figure 7). The widespread and rapid response to the 2005 wet year in the carbonate rock aquifer is surprising. We assumed that climate responses in the regional carbonate aquifer would be attenuated. We believe that the uniform, widespread wet year response, as well as the importance of Division 4 precipitation in the regression analysis, suggests that the carbonate rock aquifer is directly recharged from higher elevation areas in the southern portion of the flow system. The carbonate lithologies are exposed at the surface at higher elevations and are likely quite efficient in capturing recharge, as suggested by others (Winnograd and Thordarson 1975; Winnograd et al. 1998; Johnson and Mifflin 2006). Thomas et al. (1996) postulated that most of the recharge to the Sheep Mountains on the west side of Coyote Spring Valley must flow north and east into the basin and the MRSA because of noncarbonate barriers to westward, southward, and southeastward flow. The results from this study support these conclusions.

The trends described in this study appear to be unique to the southern portion of the White River flow system. They are completely lacking in the records for other wells outside the flow system including EH-7 and EH-3, two carbonate monitoring wells located east of the MRSA (Figure 2), and several other carbonate monitoring wells located to the west of Coyote Spring Valley and the Sheep Mountains. The relevance of these spatial relationships is that they indicate that both climate and pumping impacts are propagated at approximately the same scale throughout much of the southern portion of this system. The area is hydraulically connected through the carbonate rock aquifer. Climate and pumping effects are small but spatially extensive, in part because of the high

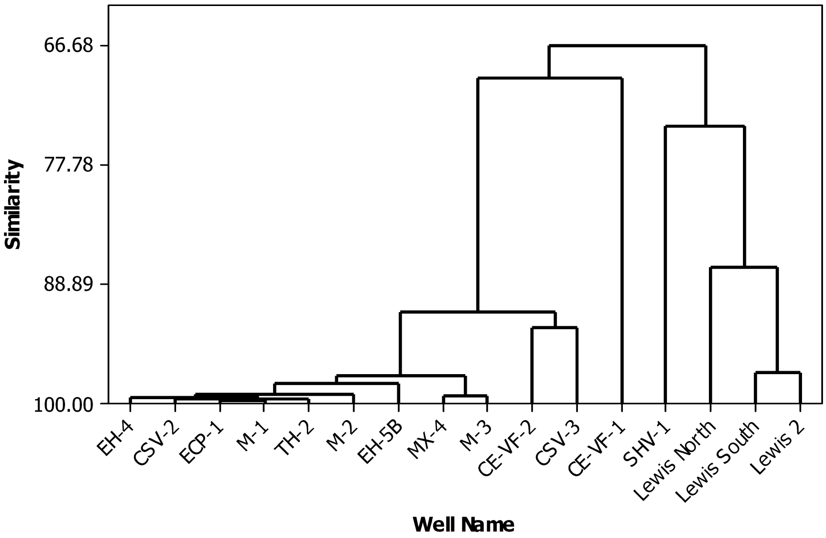


Figure 8. Cluster tree of 11 carbonate and 5 alluvial wells, using average linkage and correlation coefficient distances, with water levels from the period January 2001 to September 2005. The five alluvial wells are Lewis North, Lewis South, and Lewis 2 (all in the MRSA) and CSV-3 and CE-VF-1 (in Coyote Spring Valley).

transmissivity of the carbonate rock aquifer. Next, we examine what these effects mean for regional spring discharge.

Trends in Spring Discharge

Ultimately, much of the interest in ground water level trends relates to effects on spring discharge. Since 1998, we have observed a small but widespread pumping-induced decline in carbonate water levels in the MRSA and adjacent basins, followed by a sharp increase in water levels in response to the record precipitation in 2005. Trends in spring discharge are similar to carbonate water level trends, decreasing through 2004 and increasing after that. The springs essentially behave as artesian flowing wells. However, there are differences in the responses among individual springs, as discussed subsequently.

We hypothesized that because the drawdown is widespread and fairly uniform in the carbonate rock aquifer underlying the MRSA, the sensitivity of any one spring to declines in the water level should be related more to the elevation of the spring orifice and the initial hydraulic head rather than the proximity to pumping. Higher

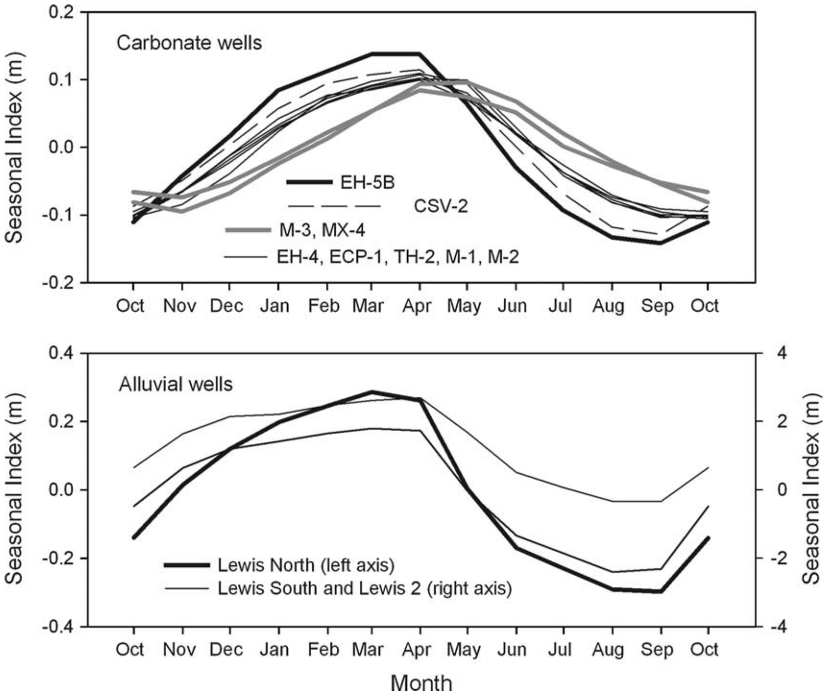


Figure 9. Seasonal indexes for carbonate and alluvial monitoring wells with statistically significant seasonality, based on time series seasonal decomposition of water level data for a 4-year period from January 2001 to December 2004. The seasonal index is the average deviation of each month's water level (in meters), from the level that was due to the other components that month.

elevation springs will be proportionately more sensitive to a uniform decline in ground water levels than lower elevations springs because of their smaller hydraulic head. The elevations of the spring orifices are presented in Table 1. Figure 10 presents normalized spring discharge for several springs of different elevations as a function of ground water elevation at EH-5B. Higher elevation springs have generally steeper regression slopes, meaning that they lose proportionately more flow for a given decline in head than the lower elevation springs. The fairly uniform water level declines or increases observed in the carbonate rock aquifer head result in much greater proportions of head loss or gain at higher elevation springs, with commensurate changes in flow. This indicates that the sensitivity of the various springs to ground water level declines is partly a function of their elevation and initial hydraulic head.

The higher elevation springs may represent some of the most important habitat for thermophilic, aquatic species in the Muddy River Springs ecosystem. Temperatures in the thermal water are warmer at the headwaters of the springs (Cross 1976), and there is generally less habitat disturbance and fewer introduced species in the headwater areas, especially at some of the smaller higher elevation springs. The position of these springs in the landscape means that they are very important in terms of habitat value and more susceptible to pumping-related impacts.

Conclusions

When ground water development approaches the limits of sustainability, even small changes in inflow, outflow, or storage can have economic or environmental consequences. In this study, we explore the premise that under such conditions, anthropogenic impacts of concern may be on the same scale as climate variability and both will need to be accounted for explicitly in any analysis. We use statistical methods to examine the response of water levels and spring discharge in a regional flow system in southern Nevada to climate and pumping. We consider the issue of climate parameterization and evaluate the use of several measures of climate variability, including raw precipitation data and several precipitation and drought indexes. Ultimately, the cubic transform of 24-month moving average precipitation was the most useful measure in our system because it captures the integrated water level response to precipitation over time and the asymmetric response of the system to wet conditions over dry conditions. This sensitivity to wet years, often

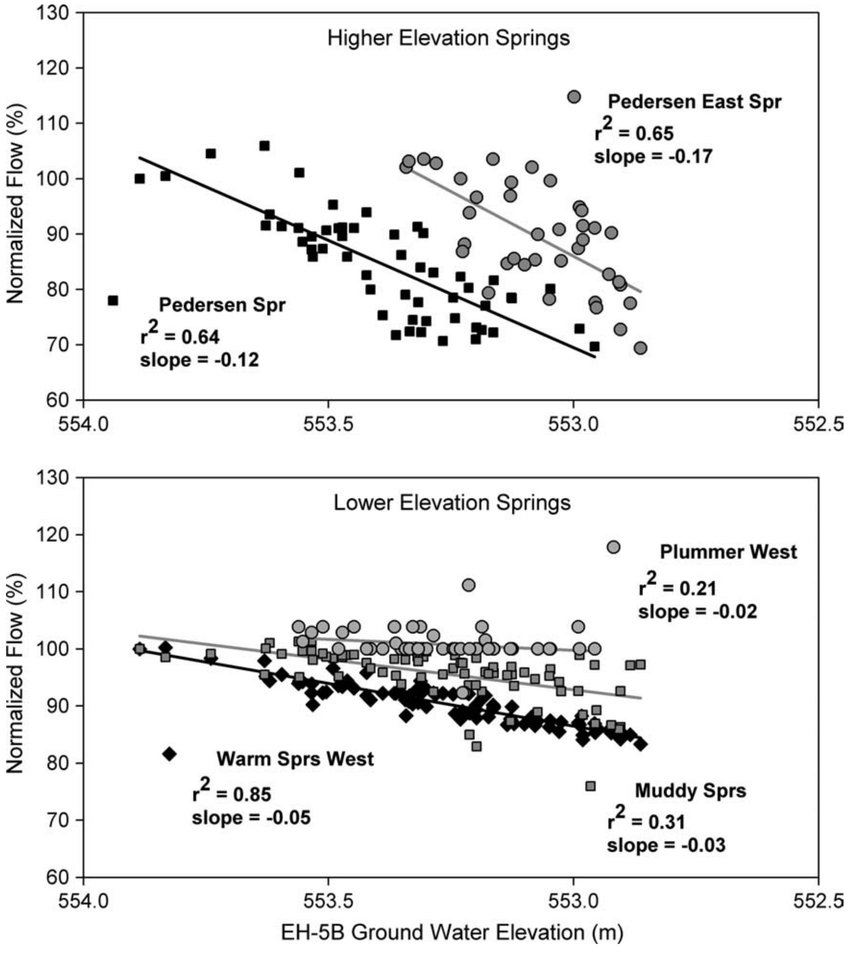


Figure 10. Normalized flow at various springs in the MRSA as a function of EH-5B levels. Values on the *x* axis are from high to low. Periods of record for each spring are given in the text.

associated with El Niño events, has been described for other ground water systems in the arid southwestern United States (Hanson et al. 2006; Scanlon et al. 2006).

Using cluster analysis and time series seasonal decomposition, we show that both climate and pumping impacts are propagated at approximately the same scale throughout much of the flow system. Relatively small changes in carbonate water levels are observed to cause corresponding changes in regional spring discharge. The sensitivity of any one spring to changes in water levels is, in part, related to the elevation and hydraulic head at the spring. The higher the elevation of the spring, the less hydraulic head at the spring initially and the more sensitive the spring is to ground water level changes. This is important since these springs represent some of the most important habitat for aquatic species in the Muddy River Springs ecosystem. Our statistical results give strong inference that the carbonate rock aquifer and the regional springs are well connected and responding to changes in climate and pumping and that the system is reaching the limits of sustainability.

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