Connections between Climate and Groundwater in Arivaca, Arizona

Final Report

Zack Guido and Michael Crimmins
Climate Assessment for the Southwest (CLIMAS)

6-July-2010

Introduction

Water management is a central issue for many communities in the arid Southwest where supplies are limited and population growth and development will likely increase future demand. In many rural communities in Arizona water used for irrigation, business, and domestic activities is principally drawn from groundwater aquifers where limited information on recharge and withdrawals calls into question the sustainable use of these supplies. While detailed studies illuminating the water budget are often impractical for these communities, rapid assessments of the groundwater character and connection to climate has the potential to offer valuable information to aid local water managers and citizen groups. The connection between groundwater and climate plays a central role in determining sustainable water use. In some basins, for example, the current stores of groundwater accumulated thousands of years ago or more (ref?), implying that the water withdrawn will not be replenished naturally. In other basins groundwater has been recharged recently, suggesting that a portion of the groundwater recharge is sustainable. In these situations the inquiry becomes more nuanced, branching into questions such as how much precipitation is recharged, during what season does it occur, and how might climate changes alter future supplies.

In the spring of 2010, the Climate Assessment for the Southwest (CLIMAS) and the Water Resources Research Center (WRRC) at the University of Arizona partnered with the community of Arivaca to provide a rapid assessment of the climate and groundwater connections. This report provide a brief literature review of relevant scientific understanding, describes the data sources and methodology used, characterizes the climate-groundwater connections, summarizes current scientific understanding of changes in future climate in the region, and offers preliminary interpretations.

Background—briefly

Climate directly influences the amount of water recharged into groundwater aquifers by controlling the amount and seasonality of precipitation and evapotranspiration. Most studies focused in arid Southwest suggest that recharge occurs in three physic-geographic regions within a basin. Mountain-block recharge occurs where precipitation infiltrates directly into bedrock, usually located within the terrains elevated regions above the valleys; mountain-front recharge occurs where surface runoff accumulated on the mountain block flows over and infiltrates into the less consolidated sediments at the mountain-valley interface; and stream channel recharge occurs throughout the length of the water way (Flint and Flint, 2007a).

Precipitation that infiltrates into sediments in the valleys but outside of the stream channels is often cited as contributing insignificant amounts to recharge because of high evaporation, low precipitation, and consumption by desert vegetation (Anderson and others, 1992; Scott and others, 2000). Rare basin-floor recharge could, however, be a significant source of recharge during extended periods of high precipitation and low evapotranspiration (Coes and Pool, 2007), which can happen in the Southwest in the fall and winter seasons.

Evapotranspiration plays a large role in limiting the amount of water that recharges aquifers. In many regions in the Southwest, evapotranspiration often greatly exceeds precipitation, which prevents direct recharge from rain infiltration in vegetated portions of alluvial basin floors (Phillips, 1994). Water-chemistry data for the Sierra Vista watershed and the adjacent Tucson Basin also indicate that a greater percentage of precipitation infiltrates during winter streamflows than during summer streamflows when evapotranspiration peaks (Keith, 1981; Pool and Coes, 1999); the longer-lasting, lower intensity storms in the winter also likely contributes to higher infiltration in the winter. During periods with lower precipitation, a greater fraction of precipitation is lost to evapotranspiration and soil-moisture replenishment, while the opposite is true for periods with higher precipitation.

Numerous studies have quantified the amount and percentage of recharge occurring in stream channels. Across diverse areas in the West, these values are similar despite the considerable heterogeneity in the factors the influence streamflow infiltration, which include vegetation type, hydraulic properties of soils, geology, streambed characteristics, and the hydraulic gradient between ground water and surface water (Flint and Flint, 2007a). In twelve basins in carbonate-aquifer system in the Basin and Range province, for example, results indicated that about 15 percent of runoff typically becomes recharge (Flint and Flint, 2007b). Stonestrom and others (2004) also calculated that 12–15 percent of ephemeral runoff became recharge in the Amargosa River in southern Nevada, while in the Walnut Gulch watershed in southeastern Arizona, recharge from ephemeral-stream flow constituted 15–40 percent of total flow during a high runoff year (Goodrich and others, 2004).

Studies in the Sierra Vista watershed and Walnut Gulch have also shown that significant recharge can occur through the beds of ephemeral streams far from mountain fronts in both summer and winter (Coes and Pool, 2007). This reinforces the notion that each of the physiographic regions within a basin is important contributors to recharge. In the Sierra Vista subwatershed, for example, ephemeral-channel infiltration during 2001 and 2002 was estimated to account for approximately 12 to 19 percent of the estimated total annual recharge (Coes and Pool, 2007). The amount of recharge is strongly influenced by the thickness and hydraulic properties of stream alluvium (Coes and Pool, 2007) and the character of the climate. The stream channels often become focal points of recharge because infiltration is often rapid, can penetrate deep into the sediments, and occurs over long distances. For example, in the Sierra Vista watershed, infiltration in ephemeral-stream channels during streamflow events was very high, measuring at about 0.4 to 2.8 meters/hour (Coes and Pool, 2007). Also, in this study, infiltration occurred to depths of at least 20 meters and took place from the edge of the mountain front to as far as 25.6 km downstream (Coes and Pool, 2007). The high infiltration rates suggest that in systems where the aquifer is far beneath the surface, water will percolate past depths where it is consumed by evapotranspiration and remain in the unsaturated zone until it is vertically displaced by infiltrated water from subsequent streamflows (Coes and Pool, 2007).

Description of Data Sources and Methods

Climate and water-related data were obtained from numerous sources that consist of daily and monthly values for temperature, precipitation, evapotranspiration, streamflow, and depth to groundwater (see Table 1).

Precipitation data for Arivaca was obtained from the National Weather Service (NWS) Cooperative Observer Program (Coop) station currently located at the post office in Arivaca (Figure 1). The NWS administers the Coop network but the National Oceanic and Atmospheric Administration's National Climate Data Center (NCDC) archives it. NCDC also conducts limited quality control on the data that includes flagging anomalous measurements of temperature and precipitation, assuring that values are reported in the correct columns, and assuring that daily minimum temperatures are not greater than the maximum temperatures.

The Arivaca Coop station is located at the post office in town. Continuous data measurements began on January 1, 1956 and continued through February 28, 2005, at which point there was confusion between the NWS Tucson office and the NCDC. As a result, measurements following February 28, 2005 were never submitted to NCDC although they were archived in their original written format at the NWS Tucson office. Upon inquiry, the NWS Tucson office provided to this study the unofficial daily measurements that covered the period August 1, 2005 to February 28, 2010.

While this record represents the best available precipitation data for the Arivaca area, it is not without blemishes. The Arivaca Coop station did not record temperature measurements and nearly 15 percent of the days between April 1, 2007 and February 28, 2010—the time frame that corresponds to the period of analysis—had missing precipitation values. Also, close inspection of the original data sheets revealed that precipitation measurements were often not made on Sundays when the Post Office was closed. Precipitation values for these days were often labeled with a zero instead of being left blank or designated with an appropriate label. This likely caused confusion for the NCDC and the NWS, which is evident because the NCDC published data have zeros on most Sundays. However, this may not be a problem for research that does not need date-specific values because the precipitation was likely recorded in the following day's time slot.

Monthly data was needed from Coop stations in the vicinity of Arivaca was needed for part of the analysis. Precipitation data was obtained from the Western Regional Climate Center for four stations near Arivaca: the University of Arizona in Tucson, Anvil Ranch, Tumacocori National Monument, and Nogales [I should create a map for this].

To compensate for the lack of temperature measurements at the Arivaca Coop station, average monthly temperatures for Arivaca was obtained from interpolated data generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM utilizes an observation-based statistical algorithm developed by the PRISM group at the Oregon State University that uses measurements made at monitoring stations from several data networks, including Coop stations. PRISM generates climate data for a 2.5 by 2.5 mile (or 4 by 4 kilometer) grid that covers the continental United States. Data was obtained through the on-line Web interface Westmap: http://www.cefa.dri.edu/Westmap.

Evapotranspiration is another important component of the water balance impacting both the demand and supply of water. Evapotranspiration (ET) is a measure of the water lost from a vegetated surface through the combined processes of soil evaporation and plant transpiration. Data for reference evapotranspiration (ETo)—which measures changes in ET principally caused by changing weather conditions—was obtained from the Arizona Meteorological Network (AzMet) station located in Marana about 60 miles northwest of Arivaca. The Marana station is the closest source of ETo data to Arivaca and serves as an estimation for ETo rates in Arivaca.

Daily depth to groundwater data was obtained from an Arivaca citizen, Richard Conway, and from the Arizona Department of Water Resources (ADWR). Conway has monitored five groundwater wells with an automated Level Troll data logger (Figure 1). Measurements from these wells began in March, 2007. Wells RC3, ABR, KAS, and RGN are located in the Arivaca Creek floodplain and drilled in the floodplain alluvium that is characterized as being younger and more porous as the surrounding surface geology (Pima Association of Governments, 2006). The fifth well, CON, is located in the older alluvium outside the modern arroyo floodplains. It is described as being the principal water being geologic unit in the area (Pima Association of Governments, 2006) and in which the majority of the groundwater wells in Arivaca are drilled. RC3 and CON wells are not pumped, according to Conway. KAS is also not pumped but is only a few feet from a well that is irregularly pumped, according to Conway. Water is pumped from RGN and ABR. RGN has been pumped at weekly intervals to supply water to the owner's orchard, while ABR is pumped irregularly for a pasture uses.

Three wells have been monitored by ADWR since about mid-September 2007. Each of these wells is located within the floodplain (Figure 1). Continuous measurements for R-1 and R-4 began on September 22 and December 6, 2007, respectively; measurements for R-11 began on January 1, 2008.
Daily streamflow data were obtained by the U.S. Geological Survey (USGS) gauging station located in Arivaca Creek northwest of the central part of town. Continuous measurements of average daily streamflow began on May 1, 2002 and continue presently. At the USGS gauging station Arivaca Creek is ephemeral. A few miles upstream of the gauging station, however, local citizen describe this Cienega section as experiencing near-constant flows; locals suggest that only recently this section has been periodically dry.

The RC-3 floodplain groundwater well was primarily analyzed for connections between the climate and groundwater. RC-3 was selected because it has the longest continuous record—April 1, 2007 to February 28, 2010—and because it has a similar water level pattern through time as the three other floodplain wells.

Precipitation was principally used to compare with groundwater fluctuation because precipitation events do not always produce measureable streamflows at the USGS gauging stations yet groundwater fluctuation nonetheless occur. Streamflow, which is often used in other studies to compare with groundwater, does not record all possible groundwater recharge episodes in the Arivaca Basin.

Climatology of Arivaca and surrounding region

The temperature pattern in Arivaca is similar to the southwestern region and is characterized by mild winter temperatures and hot summers (Figure 2). July is the hottest month. Monsoon storms help cool ambient temperatures slightly in July, August, and September.

The precipitation pattern of southeast Arizona is characterized by a bimodal distribution. More than half of the total annual precipitation falls during the monsoon season between June and September and most of the remaining precipitation occurs in the winter between November and March (Figure 3). Southeast Arizona experiences its driest period during the two to three months prior to the onset of the monsoon.

Most of the monsoon rains that drench the study area tap moisture from the tropical Pacific, although the Gulf of Mexico contributes as well (Michaud and others, 1995; Diem and Brown, 2006). Monsoon storms are characterized by short, intense episodes that can be isolated in spatial extent. The region most influenced by the monsoon extends from north-central Mexico into southern Arizona with the amount of summer rainfall diminishing to the north and south of this core area. Arivaca is located on the fringes of the core monsoon area and receives slightly more precipitation than areas to its north and less rain than Nogales to the south (Figure 4). Winter rains have a different flavor. They are the product of regional frontal storms and are generally lower in intensity and larger in spatial extent.

Arivaca received about 17.3 inches of precipitation per year between 1956 and 2009 (Figure 3). July and August experience the most precipitation, averaging around four inches per month. Monthly variability is also highest during July and August and lowest during the drier months prior to the onset of the monsoon. The fall months also exhibit high precipitation variability which is in part caused by landfalling tropical storms from the Pacific Ocean during the period between September and November. When a large tropical storm wafts into the region, the amount of precipitation in a single event can account for a large percentage of total annual precipitation.

Seasonal precipitation has also exhibited large interannual variability since 1956, particularly the June-September period (Figure 5). All seasons except October–December exhibit a positive slope, but none of the precipitation trends, including the negative October–December trend, is significant at the 0.1 confidence level. Seasonal temperatures, however, do show significant warming trends. Both winter (December–March) and monsoon (June–September) temperatures since 1950 have significant trends at the 0.05 confidence level (Figure 6). Temperatures during the summer have increased about 1.0 degrees per decade during the winter and 0.3 degrees per decade during the summer; the increasing trends for both seasons begin in earnest in the mid-1970s.

Connections between Groundwater and Climate

Connections between groundwater and climate were evaluated by comparing daily fluctuations of groundwater levels in five wells to precipitation, streamflow, and evapotranspiration between April, 1 2007 and February 28, 2010. Groundwater recharge likely occurs from both infiltrations in the floodplains and directly in the stream channels during streamflow events. Precipitation is principally used to compare with groundwater levels instead of streamflows because groundwater fluctuations in all wells occur when there is no flow at the gauging station. The Streamflow record that exists begin located miles from some of the groundwater monitoring wells would therefore not record all possible recharge events.

Four of the five wells are located in the floodplain (R-11, R-4, R-1, and RC-3) and the other well (CON) is drilled in alluvial sediments outside the floodplain. Climate factors, however, are not the only influence on groundwater levels. Pumping for irrigation and domestic uses are often a major component of the water balance. Unfortunately, detailed pumping data in the Arivaca area is unavailable on a daily level and this study did not analyze the limited existing pumping data to assess the influence of human withdrawals on water levels. However, a qualitative assessment of the water levels in the floodplain wells and deeper well provides descriptive and defensible information that the shallow groundwater in the floodplain wells responds rapidly to climate, typically within three days. The groundwater in the well outside the floodplain, however, does not show a discernable response to climate over the two and a half years analyzed—the groundwater in this well may indeed respond to climate with a lag time greater than 2.5 years.

Groundwater Hydrographs

The five analyzed wells are not pumped. Water level fluctuations, therefore, principally reflect climate variations and the influence of pumping in nearby wells. Due to limited data and time, this analysis did not document and assess the impact of pumping from surrounding wells. The CON well is the only groundwater well with daily data that lies outside the floodplain (Figure 1).

Groundwater has fluctuated between 35 and 5 feet below the surface during the period of study in the floodplains wells. Of these wells, R-4 has the shallowest depth to groundwater with a water table hovering around between 5 and 10 feet below the land surface (Figure 7; it is unclear if depth to water was measured from land surface or below the top of the well head). The groundwater fluctuations in all of these wells generally have the same pattern, suggesting that the main control of this pattern is similar to all four wells. The floodplain well with the deepest water table, however, shows more muted fluctuations than the wells with shallower water levels. Only R-11 exhibits a declining trend in depth to water. However, the short study period precludes robust trend analysis.

The depth to groundwater in the CON wells is nearly five times deeper than the floodplain wells. The depth to water pattern during the study period is dissimilar to the floodplain wells, predominantly displaying decreasing depths to water that had a maximum change of about 6 feet (Figure 8).

Seasonal Climate Influence on Groundwater Levels

Groundwater responds rapidly after precipitation events. In the three wells with the shallowest water levels—R-1, R-4, RC-3—changes in depth to water has the highest correlation to precipitation with a two and three day lag. The correlation coefficients are also relatively high, registering -0.55, -0.42, and -0.31, respectively. The floodplain well with the deepest groundwater has the highest correlation coefficient between rain and groundwater response with a 12 day lag, but the coefficient is relatively low with a value of -0.12.

Groundwater recharge appears to occur in both the monsoon and winter seasons (Figure 9). In the summer of 2007, for example, several storms in July caused depth of groundwater to decrease by about 5 feet, from 15 feet to 10 feet below the surface (Figure 9). Similarly, in January 2010 depth to water quickly rose about five feet. In fact, in two of the three monsoon seasons and all three winter seasons, groundwater exhibited recharge. The general pattern during the study period was groundwater rebound during both rainy seasons and declines during the drier spring and fall.

A closer look at the records reveals that the groundwater response to climate is complex. The season, magnitude of the event, duration, and storm density all seem to influence the character of the groundwater response. For example, the 2007 and 2008 monsoon seasons produced recharge, while the water level declined in the 2009 monsoon. The likely primary cause of this is that the total amount of rainfall in 2009 was less than both the 2008 and 2007 seasons. But that is not the whole story. The character of the rainfall was also different. Groundwater did not rebound in 2007 until after 4.3 inches had fallen, while in 2008 recharge occurred after 3.4 inches had fallen. This suggests that the storm intensity and frequency are important players in creating a saturated soil horizon that can rapidly and effectively transmit water from the surface to the groundwater. In the hot summer season, both evaporation and water used by plants draw water from of the soils and are seasonally at their peaks (Figure 9). One large rain event followed by a protracted dry period may cause the soils to completely dry, preventing rain from infiltrating into the aquifer during the subsequent storm. Because more rainfall events occurring in 2008 than in 2007 over a similar time period, this may explain why less total rainfall was needed in 2008 before recharge occurred (Figure 10).

Lower evapotranspiration in the winters also helps explain why less rainfall produces a proportionally larger groundwater response than in the summer. In each of the three winters, groundwater recharge occurred in December and January, although with different magnitudes (Figure 8).

Precipitation does not appear to have a rapid influence on the water level in the CON well located outside the floodplain. In fact, it's difficult to establish a qualitative relationship between climate and water levels in this well given the relatively short water level observational record. It is possible, however, that CON is responding to climate variations that operate on long timescales that are not decipherable given the short record.

With continued monitoring a relationship may become evident. Of particular interest is that switch in water level trends around January 2010. After a period of about 22 continuous months, water levels began to decline shortly during the onset of the relatively dry 2009 summer monsoon season. If this change in pattern is a climate signal, it suggests that water in this well is indeed rapidly responsive to climate changes, but in a much more murky way than the response of the floodplain wells to precipitation. This synchronicity between the change in pattern and dry monsoon season could also be coincidental.

Climate and Groundwater Interpretations

Precipitation and depth to water measurements suggest that the groundwater in the floodplain aquifers respond relatively quickly to precipitation and streamflow events, likely within three days after the rain event.

Groundwater recharge occurs in both the summer and winter and is impacted by the character of the rain event and resulting streamflow—the character of the events is likely more important during the summer when evapotranspiration is highest and exerts an influence on soil moisture.

Water levels in the floodplain of Arivaca Creek are shallower than in the wells drilled outside this area and therefore are likely the primary location for recharge from precipitation. Research in the Southwest suggests that infiltration outside the floodplains contribute negligible amounts to groundwater recharge (Anderson and others, 1992; Scott and others, 2000; Coes and Pool, 2007). Since recharge is evident during the monsoon season (Figure 9) and the depth to water in the well outside the floodplain is around 90 feet, it is unlikely that infiltration of monsoon rain outside the floodplain causes recharge. The floodplain area likely acts as a conduit for surface water recharge, with streamflow and precipitation infiltrating here and diffusing toward lower hydraulic gradients.

The seasonal isotopic signatures and seasonal precipitation totals suggest that summer rain is more important to groundwater recharge. However, the isotopic signature combined with the seasonal precipitation amounts suggest that winter precipitation is *more efficient* at recharge. In other words, it takes less rain in the winter to cause a unit increase in recharge than in the summer. This is because precipitation in the summer (June–October) accounts for about 64 percent of the annual rainfall (deduced from the 1971-2000 record), yet the isotopic data suggests monsoon rain is only *slightly* more important than winter precipitation for recharge. Qualitatively, the seasonal proportion of rain is not equal to the seasonal proportion of isotopes in the groundwater—64 percent monsoon rain, less than 64 percent monsoon isotopes. This implies that every unit decline in precipitation during the winter will have a greater impact on reducing groundwater than unit declines in summer precipitation. This has implications for declining water resources since climate change projections suggest winter precipitation may decrease (see Climate Change Projections section). There is, however, a silver lining. Because monsoon rains contribute a large fraction of the recharge, this aquifer is not as susceptible to climate-driven declines in winter precipitation as other aquifers less influenced by summer rains.

Climate Change Projections

A recent report produced by the U.S. Global Change Research Program indicates that temperatures are projected to increase across the southwest U.S. while precipitation amounts are expected to decrease over the next several decades (USGCRP, 2009). Projections on changes in precipitation are difficult to produce given the complexity in modeling the hydrologic cycle, but have converged consistently over the past several years on a relatively high-confidence scenario of a drying trend during the winter and spring seasons over much of Arizona (USGCRP, 2009, Seager et al. 2007). This is due primarily to a northerly retreat of the winter jet stream due to a strengthening of the Hadley Cell circulation and expansion of sub tropical high pressure systems in the sub-tropics around the globe (Lu et al. 2007). Precipitation projections for the summer and fall seasons are less clear due to the lack of a robust portrayal of the North American Monsoon System responsible for summer convection across Arizona and the lack of resolution necessary to model tropical storms in the fall season (USGCRP, 2009).

Temperature increases are expected during all seasons but are expected to be greatest during the summer season under all emission scenarios and may exceed 4 to 6 °F by 2050. Higher temperatures during the summer season will drive higher evapotranspiration rates, potentially impacting the amount of water that is available to move through the soil to recharge shallow aquifers.

Analysis Limitations

The relatively short period of record also precludes establishing seasonal relationships between climate and groundwater since only 3 monsoon and winter seasons were captured in the record.
It was difficult to assess the effect of streamflows on recharge. The USGS gauging station is located below Arivaca and displays only periodic flows. It is likely that rain events create channelized flow in portions of the basin above the gauging station that is not sustained for the length of Arivaca Creek. Therefore, the USGS streamflow record does not record all the events that cause recharge.

Recommendations and Future Work

Survey local water managers to understand important climate and groundwater management issues and questions
Continue monitoring groundwater wells
Take advantage of the hourly precipitation measured at the Arivaca community garden in order to analyze the hourly character of storms and relate that to recharge
Conduct a broader literature review

References

Coes, A.L., and Pool, D.R., 2007, Ephemeral-stream channel and basin-floor infiltration and recharge in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona, in Stonestrom, David A., Constantz, Jim, Ferre, Ty P.A., and Leake, Stanley A., eds., Ground-water recharge in the arid and semiarid southwestern United States: U.S. Geological Survey Professional Paper 1703-J, p. 253-311 [http://pubs.usgs.gov/pp/pp1703/j/].

Diem J.E., and Brown, D.P., 2006, Tropospheric moisture and monsoonal rainfall over the southwestern United States. Journal of Geophysical Ressearch 111(D16):16112. doi:10.1029/2005JD006836

Flint, L. E., and Flint, A. L., 2007a, Regional analysis of ground-water recharge, in Stonestrom, David A., Constantz, Jim, Ferre, Ty P.A., and Leake, Stanley A., eds., Ground-water recharge in the arid and semiarid southwestern United States: U.S. Geological Survey Professional Paper 1703-B, p. 29-60 [http://pubs.usgs.gov/pp/pp1703/b/].

Flint, A.L., and Flint, L.E., 2007b, Application of the basin characterization model to estimate in-place recharge and runoff potential in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007–5099, 20 p.

Goodrich, D.C., Williams, D.G., Unkrich, C.L., Hogan, J.F., Scott, R.L., Hultine, K.R., Pool, D., Coes, A.L., and Miller, S., 2004, Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona, *in* Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater recharge in a desert environment, the Southwestern United States: American Geophysical Union, Water Science and Applications Series, v. 9, p. 77–99.

Lu, J., Vecchi, G. A., and Reichler, T., 2007, Expansion of the Hadley cell under global warming. Geophys. Res. Lett. 34, no. 6.

Keith, S.J., 1981, Stream channel recharge in the Tucson Basin and its implications for groundwater management: Tucson, Ariz., University of Arizona, M.S. thesis, 84 p.

Michaud, J. D., Avine, B. A. , and Penalba, O. C., 1995: Spatial and elevational variations of summer rainfall in the southwestern United States. *J. Appl. Meteor.*, 34:2689–2703.

Pima Association of Governments, 2006, *Hydrogeologic assessment of Arivaca.* Unpublished report, 89 p.

Pool, D.R., and Coes, A.L., 1999, Hydrogeologic investigations of the Sierra Vista subwatershed of the Upper San Pedro Basin, Cochise County, Southeast Arizona: U.S. Geological Survey Water-Resources Investigations Report 99−4197, 41 p.

Scott, R.L., Shuttleworth, W.J., Keefer, T.O., and Warrick, A.W., 2000, Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest: Water Resources Research, v. 36, no. 8, p. 2233−2247.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.-P., Harnik, N., Leetmaa, A., Lau, N.-C., Li, C., Velez, J., and Naik, N., 2007, Model projections of an imminent transition to a more arid climate in southwestern North America. *Science*, 316(5828), 1181-1184.

Stonestrom, D.A., Prudic, D.E., Laczniak, R.J., and Akstin, K.C., 2004, Tectonic, climatic, and land-use controls on ground-water recharge in an arid alluvial basin: Amargosa Desert, U.S.A., *in* Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater recharge in a desert environment, the Southwestern United States: American Geophysical Union, Water Science and Applications Series, v. 9, p. 29–47.

The University of Arizona Cooperative Extension (UACE), Basics of Evaporation and Evapotranspiration. http://ag.arizona.edu/pubs/water/az1194.pdf (last accessed on June 30, 2010).

Global Climate Change Impacts in the United States (USGCRP), Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009.

Figures 1

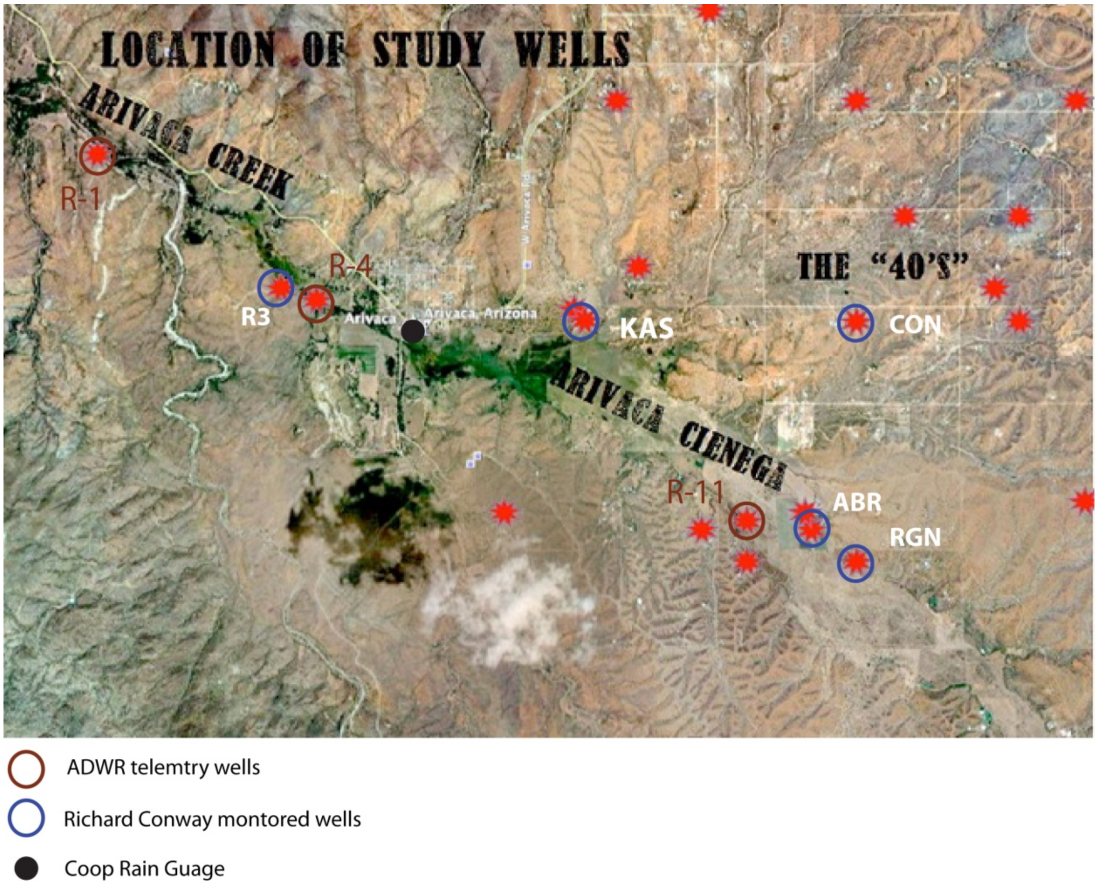


Table 1. Data Sources

Data Source	Climate Variable	Location	Time Period Used	Notes
National Weather Service Coop Network	Daily and monthly Precipitation	Arivaca 1E Tucson-Univ. of Arizona Anvil Ranch Tumacocori Nat. Monument Nogales 6E	1/1/1956–2/28/2005 1971–2000 1971–2000 1971–2000 1971–2000	
Arizona Meterological Network	Monthly evapotranspiration	Marana	1/1/2007–2/28/2010	This station is the closest one to Arivaca and is located in an area most similar to Arivaca
www.Rainlog.org	Daily precipitation	Arivaca	4/1/2007–2/28/2010	Suppliments missing Coop values during this time period
PRISM – Oregon State University	Interpolated monthly temperature	Arivaca	1950–2009	Used because Arivaca Coop station does not have a temperature record
U.S. Geological Survey	Daily streamflow	Arivaca	5/1/2002–2/28/2010	
ADWR groundwater measurments	Daily depth to groundwater	Arivaca	9/22/2007–2/28/2010	Data is for 3 floodplain wells
Richard Conway groundwater measurements	Daily depth to groundwater	Arivaca	4/1/2007–2/28/2010	Local citizen measured depth to groundwater using a Level Troll data logger in 5 wells

PRISM = Parameter-elevation Regressions on Independent Slopes Model
ADWR = Arizona Department of Water Resources

Figure 2

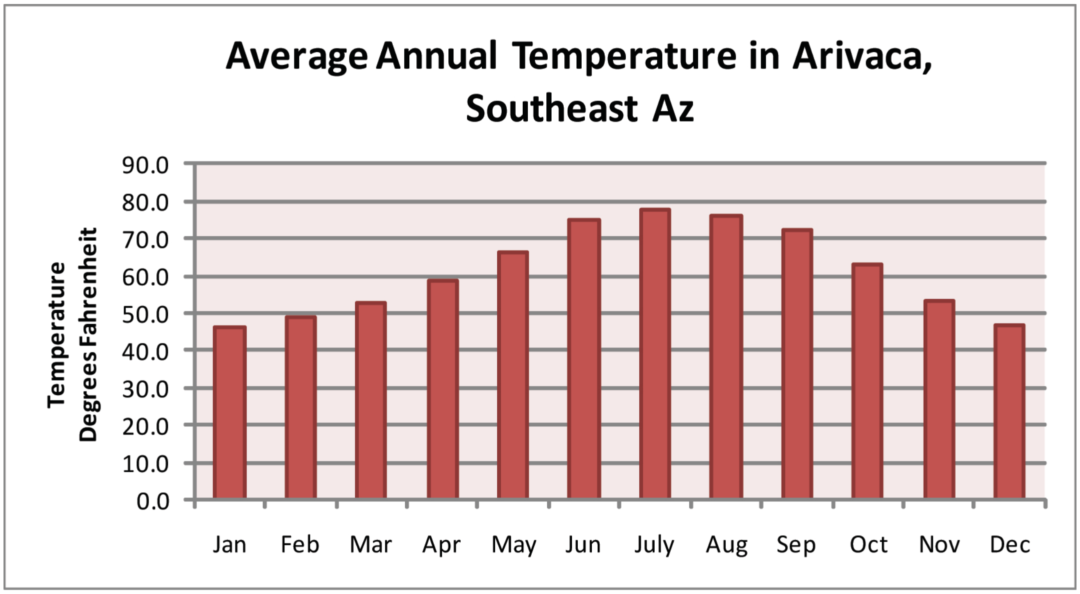


Fig 3

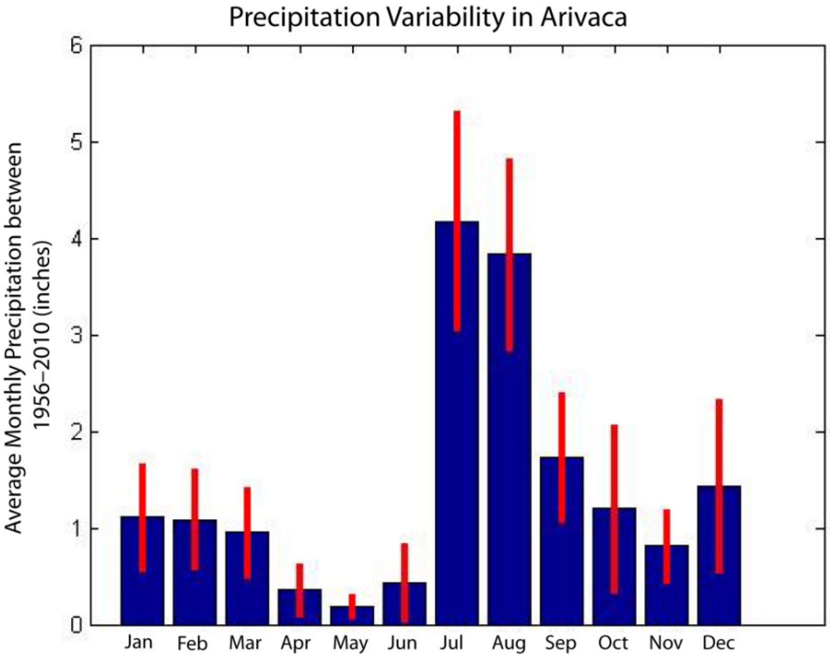


Figure X. Seasonal precipiation recorded at the National Weather Service Cooperative Observer Program station in Arivaca. Red bars correspond to one standard deviation of the total monthly precipitation and are a measure of monthly precipitation variability. Total annual precipitation measured between January 1956 and February 2010 is about 17.3 inches.

Fig. 4

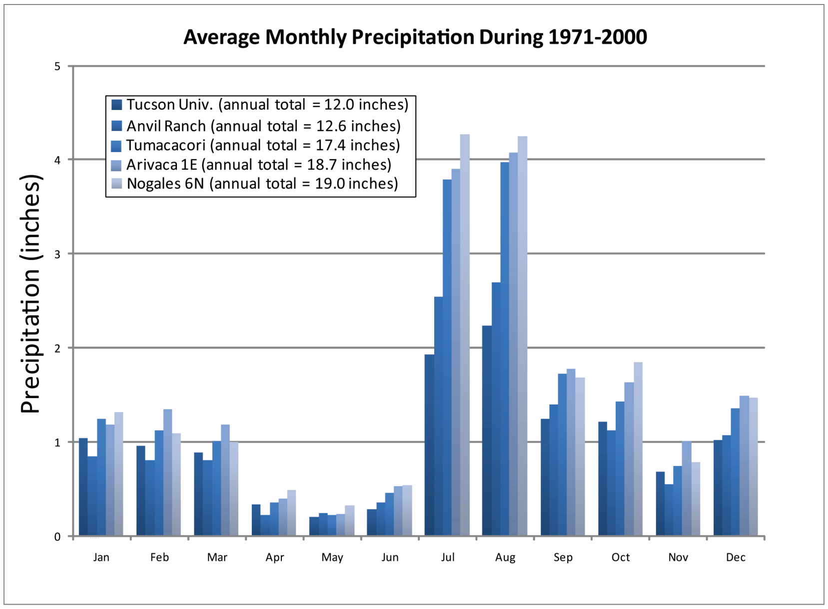

Average Monthly Precipitation During 1971-2000
Precipitation (inches)
0
1
2
3
4
5
Tucson Univ. (annual total = 12.0 inches)
Anvil Ranch (annual total = 12.6 inches)
Tumacacori (annual total = 17.4 inches)
Arivaca 1E (annual total = 18.7 inches)
Nogales 6N (annual total = 19.0 inches)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Fig. 5

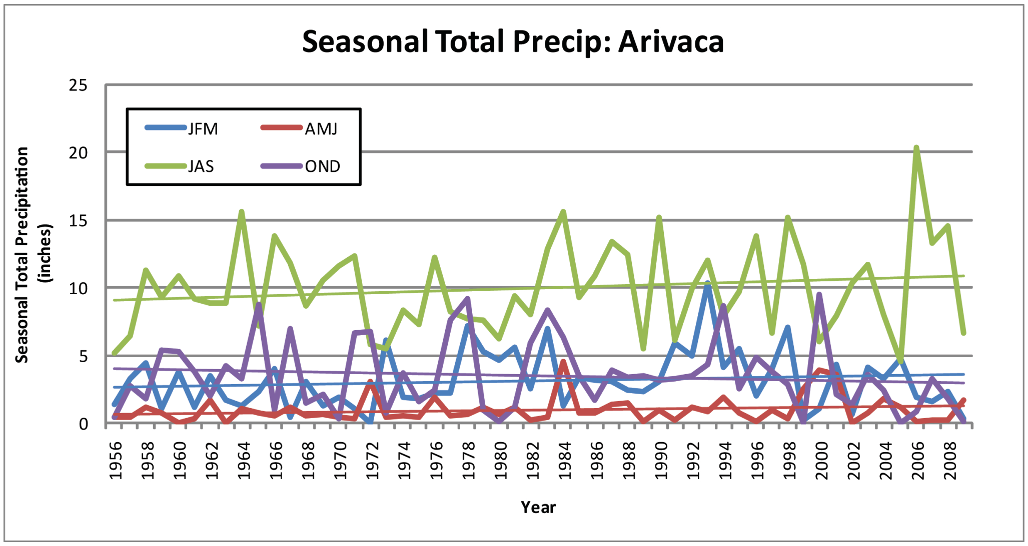

Seasonal Total Precip: Arivaca
Seasonal Total Precipitation (inches)
0
5
10
15
20
25
JFM
AMJ
JAS
OND
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year

Fig. 6

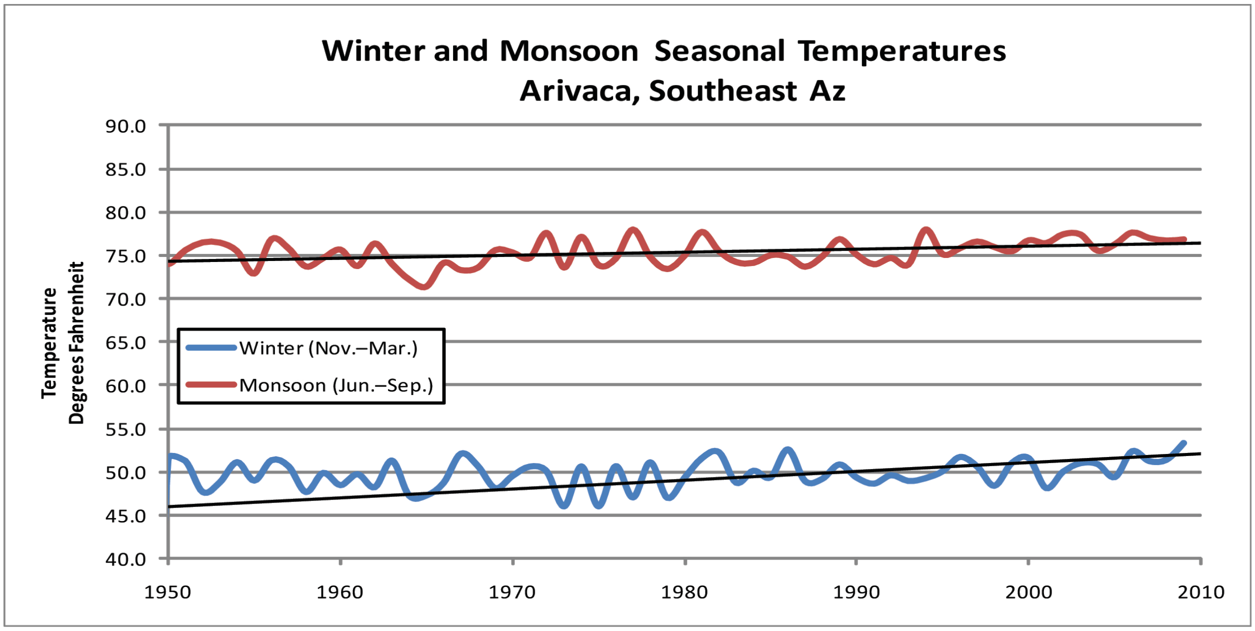

Winter and Monsoon Seasonal Temperatures
Arivaca, Southeast Az
Temperature
Degrees Fahrenheit
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
Winter (Nov.–Mar.)
Monsoon (Jun.–Sep.)
1950
1960
1970
1980
1990
2000
2010

Fig. 7

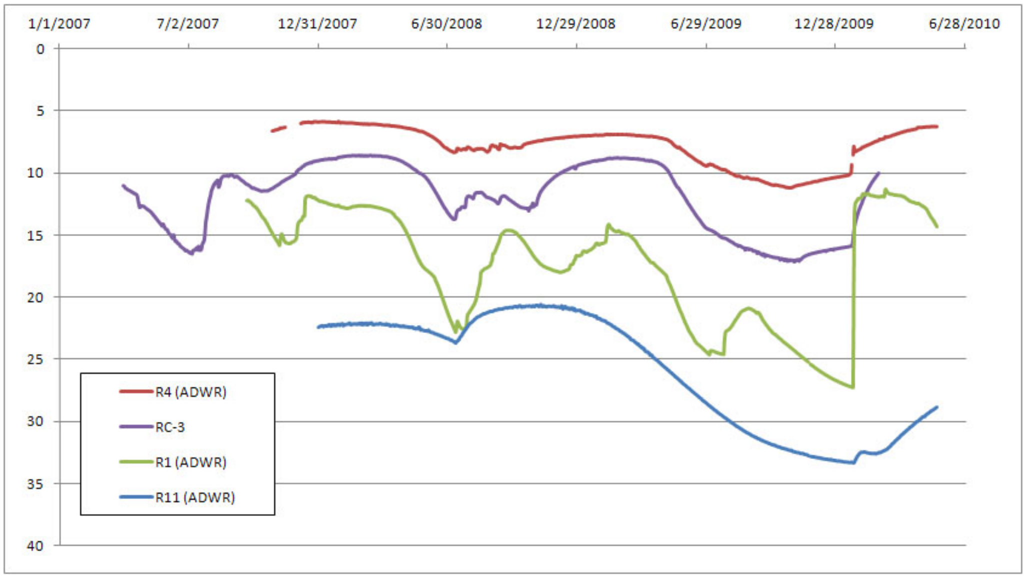

1/1/2007
7/2/2007
12/31/2007
6/30/2008
12/29/2008
6/29/2009
12/28/2009
6/28/2010
0
5
10
15
20
25
30
35
40
R4 (ADWR)
RC-3
R1 (ADWR)
R11 (ADWR)

Fig. 8

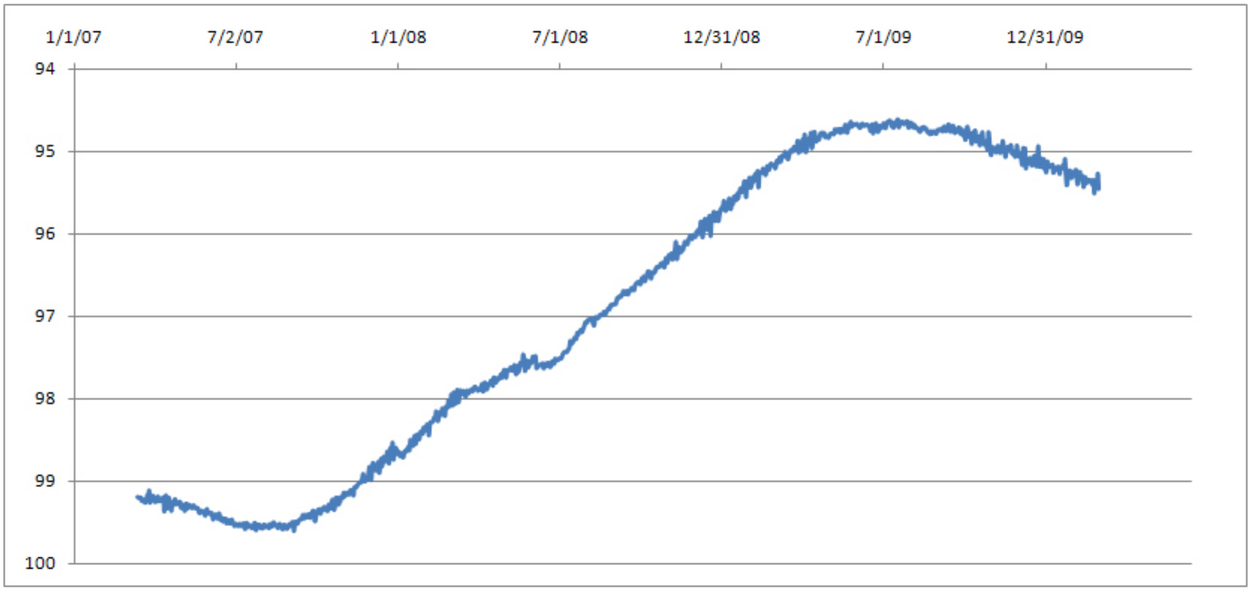

1/1/07
7/2/07
1/1/08
7/1/08
12/31/08
7/1/09
12/31/09
94
95
96
97
98
99
100

Fig. 9

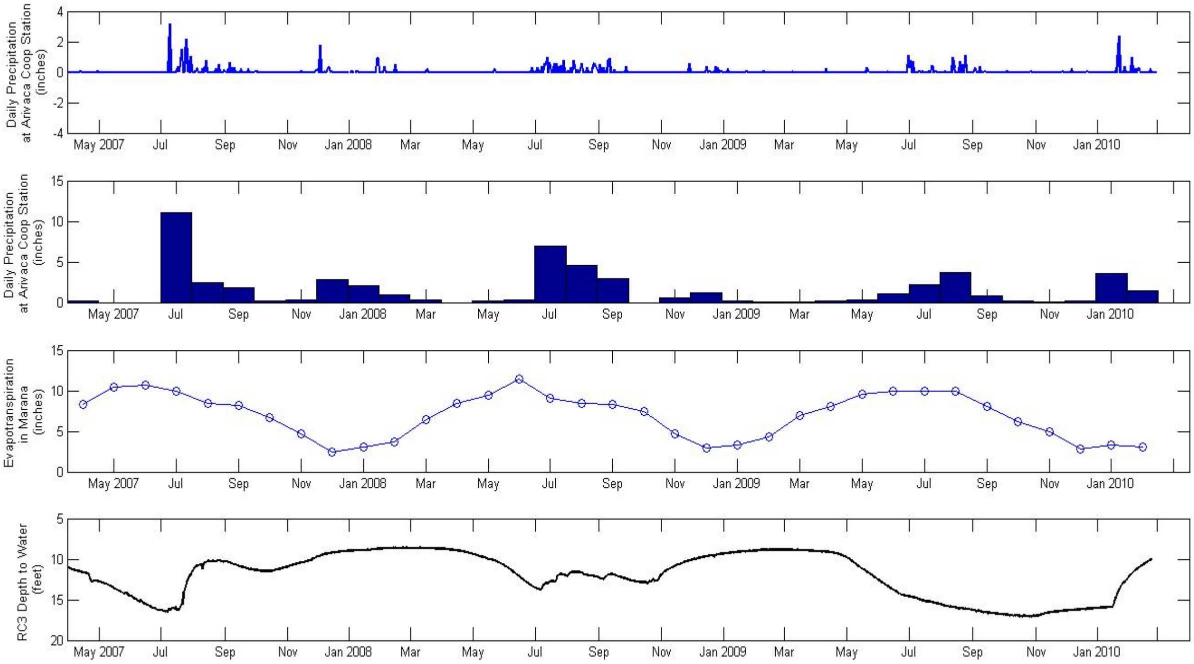
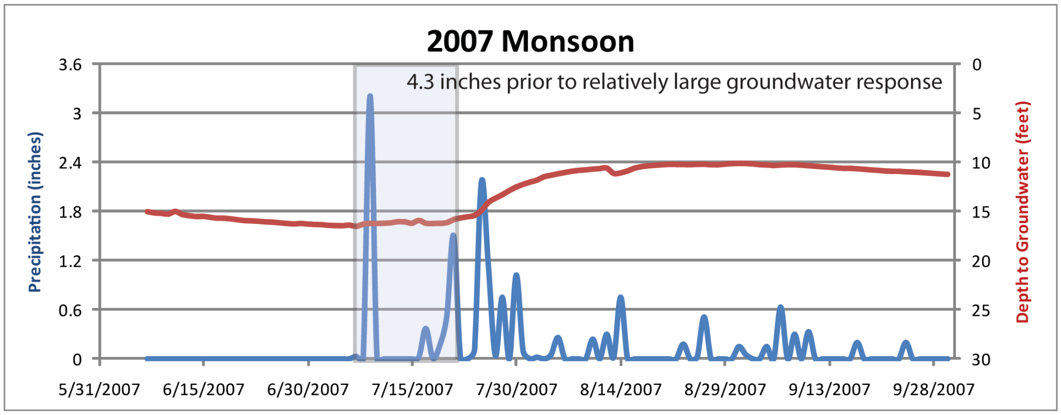
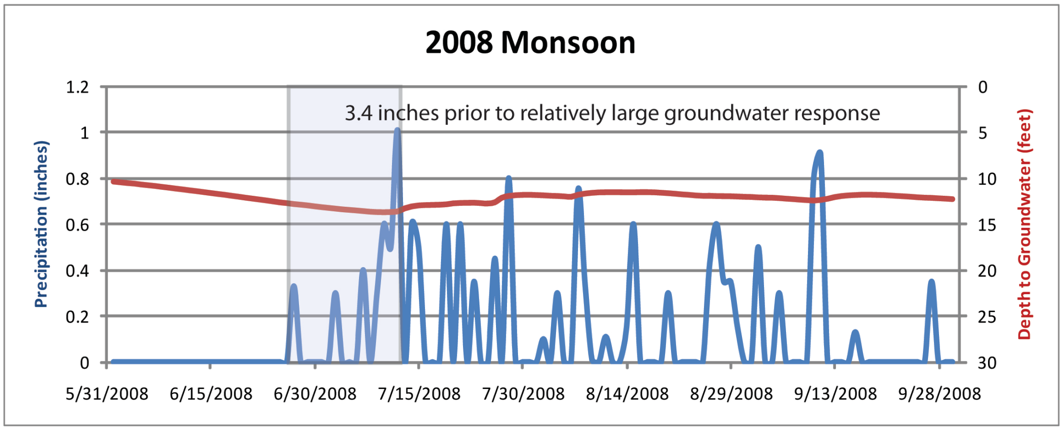

Daily Precipitation at Arivaca Coop Station (inches)
4
2
0
-2
-4
May 2007
Jul
Sep
Nov
Jan 2008
Mar
May
Jul
Sep
Nov
Jan 2009
Mar
May
Jul
Sep
Nov
Jan 2010
Daily Precipitation at Arivaca Coop Station (inches)
15
10
5
0
Evapotranspiration in Marana (inches)
15
10
5
0
RC3 Depth to Water (feet)
5
10
15
20

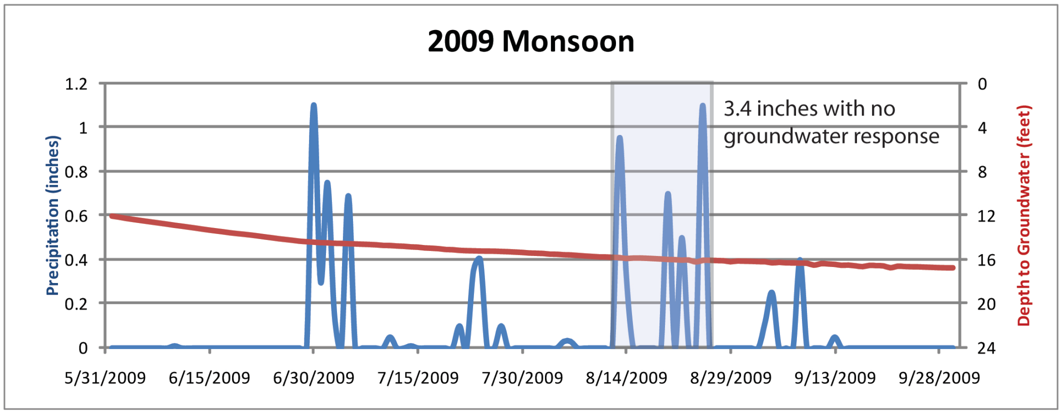
Fig. 10



2007 Monsoon



2008 Monsoon



2009 Monsoon