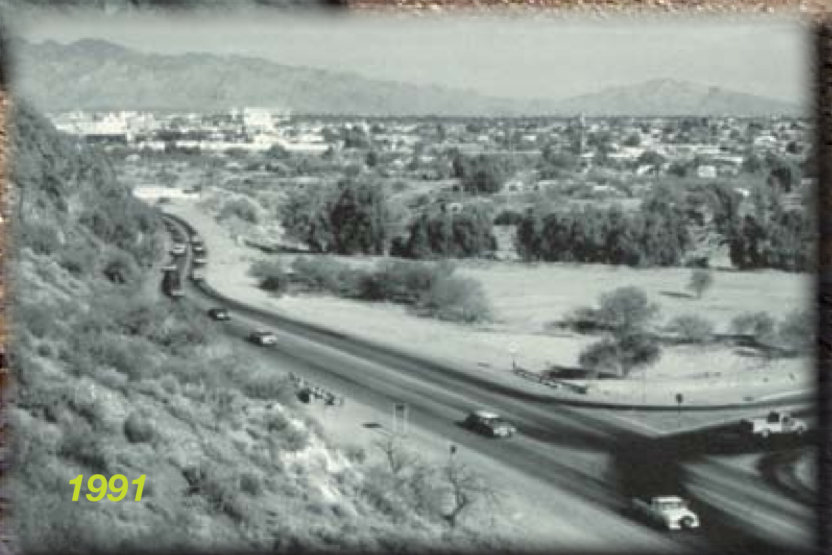
Aquifer Monitoring for Groundwater-Dependent Ecosystems, Pima County, Arizona



Julia Fonseca,
Office of Conservation Science

Pima County
Natural Resources,
Parks and Recreation

Tucson, Arizona

Table of Contents

Introduction 1

Purpose And Scope 2

Geologic Setting 3

Ecosystem Relationships 5

Ecosystem Responses To Change 8

Technical Challenges To Monitoring 11

Costs Of Monitoring 13

Regional Groundwater Reporting 16

Geographic Priorities For Monitoring 19

Groundwater Monitoring Plans 21

Conclusions 23

Acknowledgments 24

References 24

Appendix A. Hydrogeologic Basins In Eastern Pima County 26

Appendix B. Evaluation Of Priorities For Groundwater Monitoring In Pima County 33

Introduction

The medical field uses measures such as temperature, pulse and blood pressure as important indicators of human health. As blood circulates in the body and assists in regulating our temperature, so does groundwater circulate in riparian ecosystems, thereby providing important ecological functions. Groundwater moves into streams, moistens soils, and irrigates vegetation. It also carries nutrients needed for animal and plant health.

The Sonoran Desert Conservation Plan (SDCP) recognizes the important links between groundwater, streamflow, and vegetation that still exist along some streams and springs in Pima County. Unfortunately, depletion of aquifers has altered streamflow and associated groundwater-dependent vegetation along the Santa Cruz River and other streams (Figure 1). Effects of declining groundwater levels upon local flora and fauna have been described in previous County reports (e.g. Behan and Fonseca, 1999).

These effects are not just historic, but continue, in some cases at an accelerated rate, in parts of eastern Pima County (e.g. Hill and Fonseca, 2001).

To promote regional economic and ecological sustainability, the Pima County Board of Supervisors (Board) adopted a set of new policies to evaluate the potential impact of rezonings and other Board-approved land-use changes. The evaluation considers impacts that could be caused by additional groundwater pumping, which can include subsidence of the land surface, loss of water to domestic wells in the area, and effects upon ecosystems. The Board's approach is notable because, as a whole, the State of Arizona has no jurisdiction or legal authority to regulate groundwater pumping as it relates to the fate of the springs, streams and riparian forests that provide critical wildlife habitat. In addition, there is no state agency responsible for maintaining healthy riverine ecosystems in Arizona (Arizona Riparian Council, 2003)

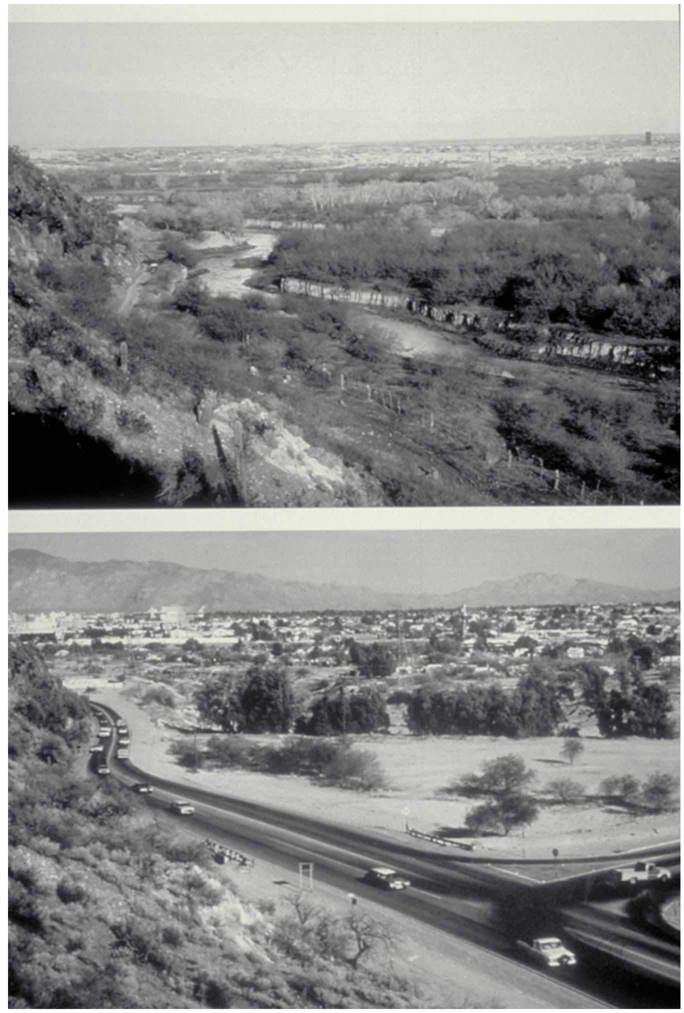


Figure 1. Santa Cruz River at 22nd Street and Mission Road, from Sentinel Peak (upper photo 1904, lower photo 1991) (Desert Laboratory, USGS)

PURPOSE AND SCOPE

The main purpose of this report is to establish priorities for potential expansion of Pima County's existing aquifer monitoring for groundwater-dependent ecosystems. Existing monitoring efforts by other agencies are also reviewed, along with specific methods for collecting data. The information will be used in the Pima County Ecological Monitoring Plan (EMP) to develop monitoring protocols, prioritize areas for other types of monitoring, and to develop cost estimates for implementing a monitoring program. To date, the EMP, one of the last elements of the SDCP, may provide the best opportunity for monitoring this precious resource.

Though the EMP may include groundwater monitoring, it is important to note that groundwater monitoring is not new to eastern Pima County. The Regional Flood Control District initiated groundwater monitoring at wetlands in its Natural Preserve units a decade before the beginning of the Sonoran Desert Conservation Plan by entering into partnerships with other local entities. A number of other federal, state and local non-governmental entities have also recently launched riparian monitoring efforts which include groundwater measurements. This report examines communication needs and partnership opportunities with agencies and citizen groups so as to capitalize on these new initiatives by pooling resources.

This report is written for land managers and biologists who may have relatively little background in hydrology. It contains a brief primer on groundwater-dependent ecosystems, and provides hyper-links to additional web-accessible resources. It describes a variety of approaches to measuring change in aquifers thought to be linked to the health of riparian and aquatic ecosystems. As will be explained, this is a different challenge than monitoring for municipal water supply purposes.

This report focuses solely on groundwater monitoring and does not evaluate other types of hydrologic or ecologic indicators of riparian health that land managers might want to use. For instance, the persistence of native species, the chemical or physical quality of surface flows, or the condition or extent of riparian vegetation may be deemed more appropriate measures for groundwater-dependent ecosystems during the development of the EMP. Pima County and the SDCP Science Technical Advisory Team's (STAT) monitoring subcommittee will need to weigh the significance of the information that can be gained from expanding groundwater monitoring against the other measures of ecosystem health. These decisions will also be influenced by information about the cost and variability of different measures of ecosystem health to be presented at future meetings and reports.

Geologic Setting

Pima County's landscape is characterized by deep valleys filled with sediment and bordered by high mountains, which can be organized into hydrogeologic basins for the purposes of groundwater studies. Hydrogeologic basins are distinct areas of bedrock and valley fill, often separated from each other on the basis of either different directions of groundwater movement, different depths to water, faults, bedrock outcrops, or subsurface ridges. The hydrogeologic basin divides are somewhat analogous to watershed divides, but they are not always coincident. For example, the hydrogeologic basin for the upper Cienega area extends underneath the Babocomari River in Santa Cruz County. Some basins are small and, therefore, easily depleted due to pumping. Others, like the Tucson and Avra Basins are exceptionally large (see Figure 2).

Some groundwater basins have places where groundwater is pushed up to the surface creating streams and springs that run on what is essentially groundwater discharge (Figure 3). These places have provided the basis for human economies

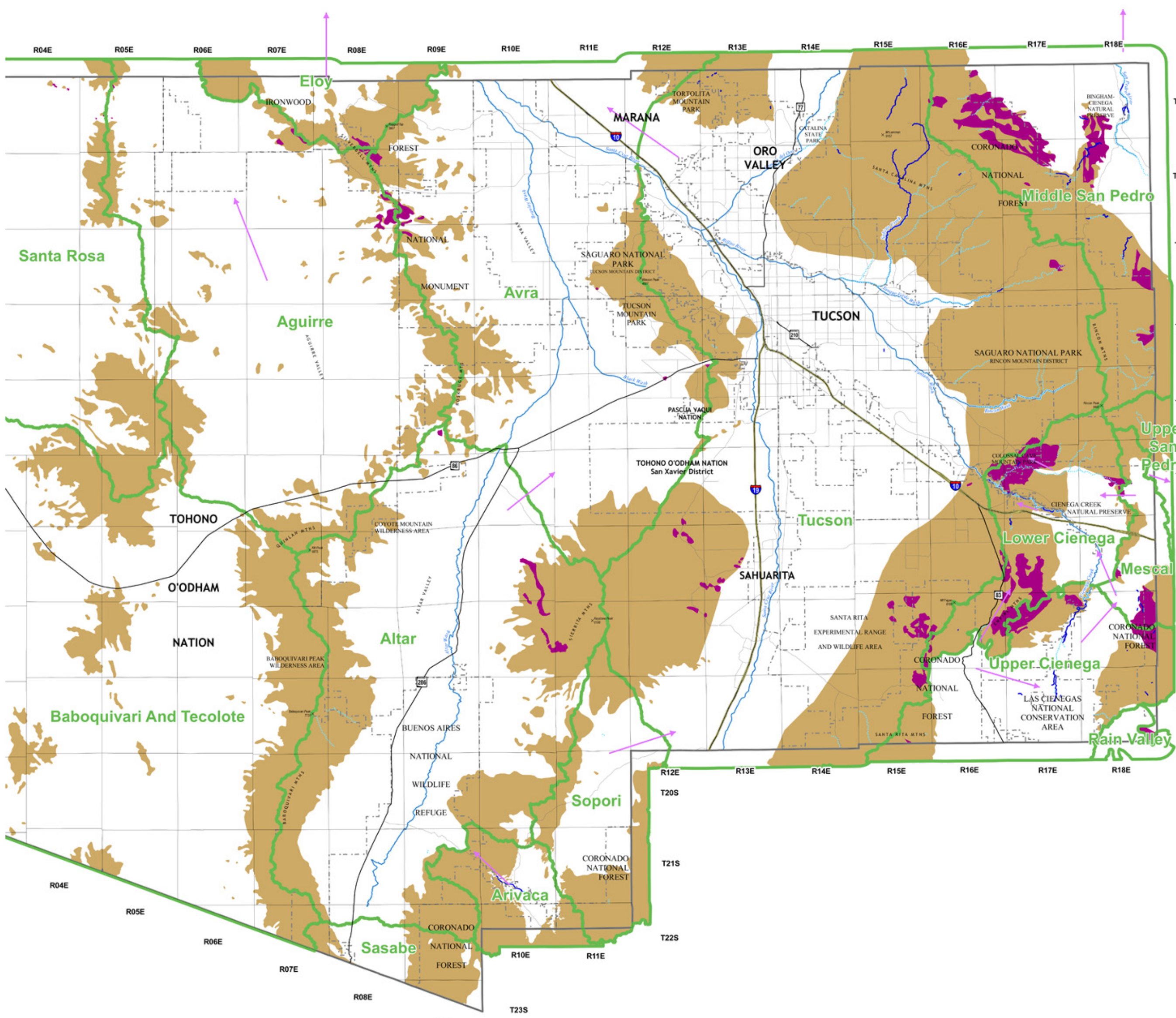


Figure 2. Hydrogeologic basin boundaries in eastern Pima County are shown in green. Bedrock exposed at surface or shallowly buried is tan, carbonate outcrops are purple, perennial and intermittent streams are blue. Arrows show general direction of groundwater movement.

for thousands of years and aquatic and riparian ecologies for hundreds of thousands of years. Tucson at the Santa Cruz River was one example of such a place. The presence of the historic stream at the base of Sentinel Peak was related to the position of underground bedrock and clay which kept groundwater at or near the surface. In other basins, such as central Avra Valley, groundwater levels never rose close enough to the surface to support riparian vegetation or perennial streamflow.

Each groundwater basin has its own "water budget", or inflow and outflow (Table 1). Under natural conditions, and averaging over a period of years, inflows will equal outflows. Stream discharge from a high water table and water loss from the leaves of groundwater-dependent plant life are two of the principal ways that the water budget is used in a natural system. People can deplete or add to the basin's water budget when they pump water for use, alter recharge, or remove or foster groundwater-dependent vegetation.

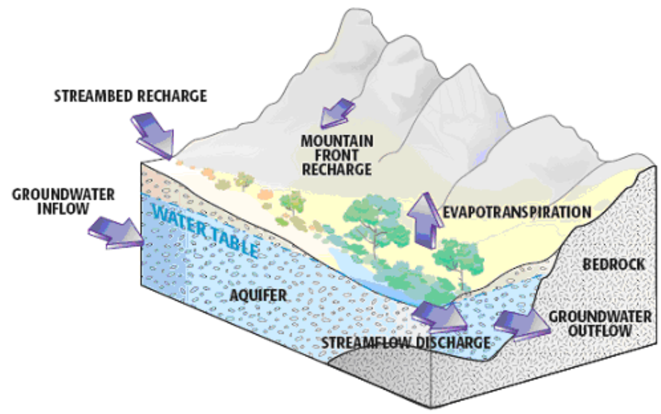


Figure 3. Sources of inflow and outflow to a basin. A high water table can support streamflow discharge and plant water needs (evapotranspiration) during the driest times of the year. Illustration by Everett Acosta, Pima County Graphic Design.

Table 1. Potential sources of water inflows and outflows for a water budget. Natural components in normal typeface, anthropogenic components in italics.

Inflows	Outflows
1. Recharge along washes, wetlands. 3. Recharge that moves into bedrock faults and fractures in mountainous regions 4. Flow from an adjacent aquifer 5. *Artificial recharge at effluent and CAP recharge basins* 6. *Other altered inflows(from waste streams at industrial, agricultural, or urban sites, or removal of land cover)* 7. Recharge from precipitation that percolates through to the water table (usually very low in semi-arid regions)	1. Discharge of water to streams, wetlands, springs and seeps 2. Evaporation from moist soil and plant transpiration (evapotranspiration) 3. Flow to an adjacent aquifer 4. *Pumping of wells* 5. *Mine pit dewatering*

Ecosystem Relationships

The biological goal of the SDCP is to "ensure the long-term survival of the full spectrum of plants and animals that are indigenous to Pima County through maintaining or improving the habitat conditions and ecosystem functions necessary for their survival." One of the key habitat conditions affecting the distribution and abundance of native species is the availability of water and riparian vegetation. (Johnson and Jones 1977). Arizona Riparian Council (ARC) estimates that 60 to 75 percent of Arizona's wildlife species depend on streamside vegetation at some point in their life cycle (ARC, 1994).

Many wetland and riparian ecosystems are dependent upon near-surface water tables to provide a source of moisture for plants, allowing special riparian and aquatic species to persist even when surface flow is absent[1] (Figure 3). The aquifer is a wonderful storage and release device, providing water to root systems during the times when surface flow is absent, and even in times of drought. In our region, streamflow that persists during mid-summer, before the monsoon rains arrives, is often the result of the water table being at the surface.

Hydrologists often use definitions like the following to characterize how long a stream flows:

Perennial: A stream or portion of a stream which flows year-round.

Intermittent: A stream where portions flow continuously only at certain times of the year, for example, when it receives water from a spring, groundwater source or from a surface source, such as melting snow (i.e. seasonal). At low flow, there may be dry segments alternating with flowing segments (*interrupted* flow).

Ephemeral: A stream or portion of a stream which flows briefly in direct response to precipitation in the immediate vicinity, and whose channel is at all times above the water table elevation.

Unlike the classification system above, the length of time a stream flows is, in fact, a natural continuum. Even along the same river, we have situations that defy simple classifications. Consider that water demands of a dense riparian forest in dry regions such as southern Arizona can draw down the water table enough to make streamflow disappear for several hours during a hot summer day!

Streamflow is a visually prominent aspect of the hydrological character of a stream, but it is seldom the only habitat feature of biological significance supported by an aquifer. The water table provides water for lush vegetation and special types of vegetation that provide habitat for wildlife. The hyporheic (subsurface) zone of flow under the stream bed may harbor a distinct invertebrate fauna. Moist banks fed by capillary flow from the water table offer sites for turtle or insect reproduction. Flooding, erosion, or man-made excavations into the water table give rise to off-channel pools where amphibians breed. Springs may also exist at the margins of the floodplain. Springs, wherever they occur, can offer thermal refugia from the main stream or distinct chemical compositions. Groundwater chemistry can also be distinct from surface waters, providing nutrients or other essential minerals needed for organisms. Together, these hydrological and vegetative features provide a wide variety of habitat conditions for aquatic and terrestrial organisms.

One of the major accomplishments of the SDCP has been the identification of various components of groundwater-dependent ecosystems: shallow groundwater zones, perennial and intermittent streams segments, and springs (Pima Association of Governments, 2000; Fonseca, et al., 2000). To my knowledge, no other local jurisdiction has developed this understanding of the relationship between their local ecosystems and the varied geologic and hydrologic conditions that prevail over such a large region. Figure 4 shows the location of known shallow water tables, springs, and natural intermittent and perennial streams. Riparian vegetation communities have also been mapped and classified for the SDCP (Harris et al., 2000).

[1] Not all riparian vegetation is dependent on groundwater. Some riparian vegetation is dependent only on ephemeral runoff, in the same way that your local park might have groves of cottonwoods or cattails if it were irrigated enough.

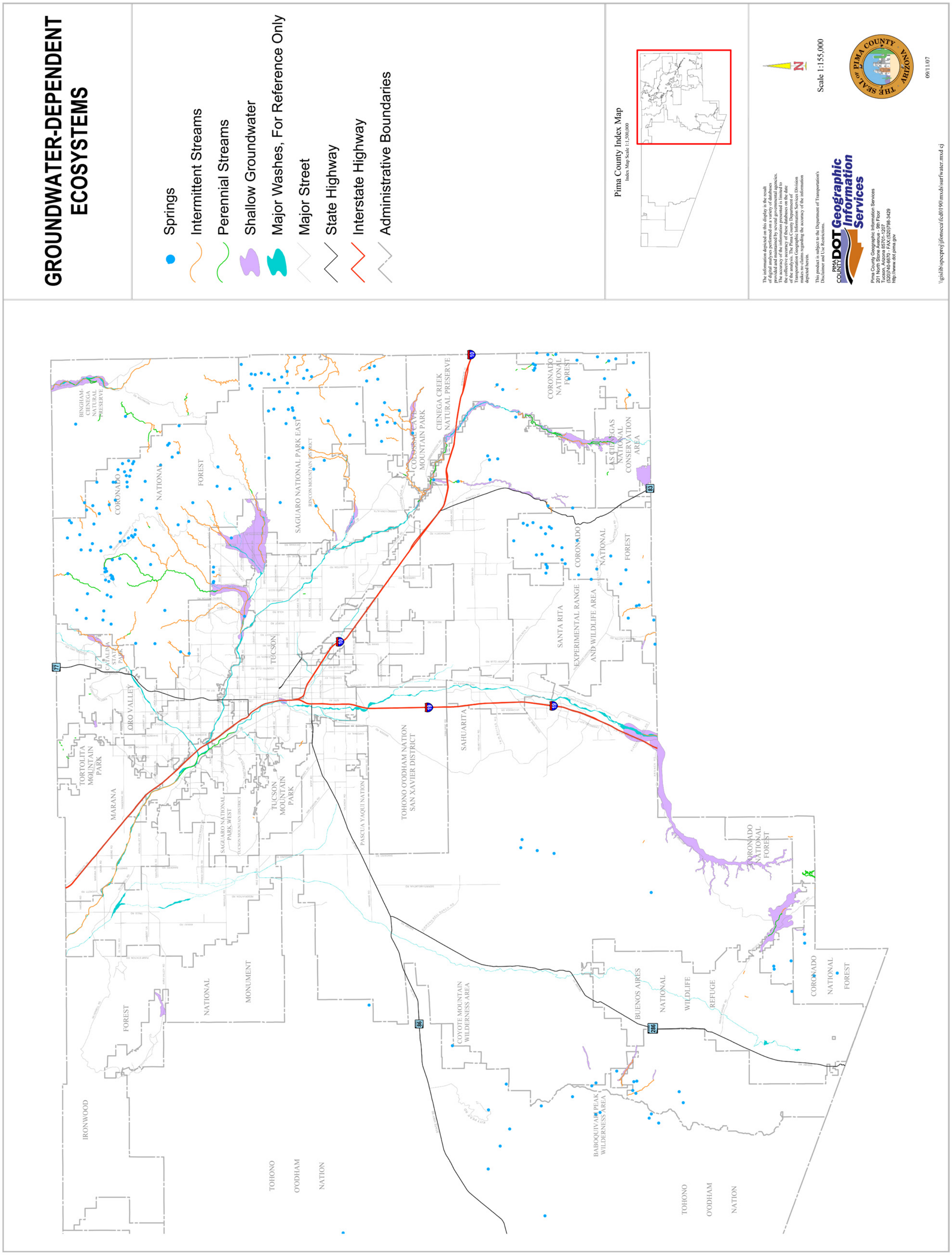


Figure 4. Groundwater-Dependent Ecosystems.

For the ecological monitoring program, we want to know about changes in the groundwater conditions that are capable of affecting our groundwater-dependent streams, springs and vegetation. The position of the water table and the presence of sustained discharges from streams and springs can foreshadow changes in the condition or composition of these ecosystems.

Figure 4 represents the preferred depth to groundwater for a variety of riparian plant communities. Note that relatively small changes in water level can drive big changes in plant communities. If the water level change is gradual (years to decades), the type of canopy and herbaceous cover may shift toward a different plant community as indicated in the right hand column. With sustained reductions in the depths to water, a riparian area that is dominated by cattail may give way to cottonwood, then shift to tamarisk and mesquite and finally to upland types of vegetation (Stromberg in ADWR, 1994).

Relatively small differences in shallow groundwater elevations can be of great significance ecologically, particularly in the first several feet below land surface. Beyond about 50 feet below land surface, the connection between the water table and groundwater-dependent ecosystems is broken. Riparian vegetation is present but it will depend largely on surface flows.

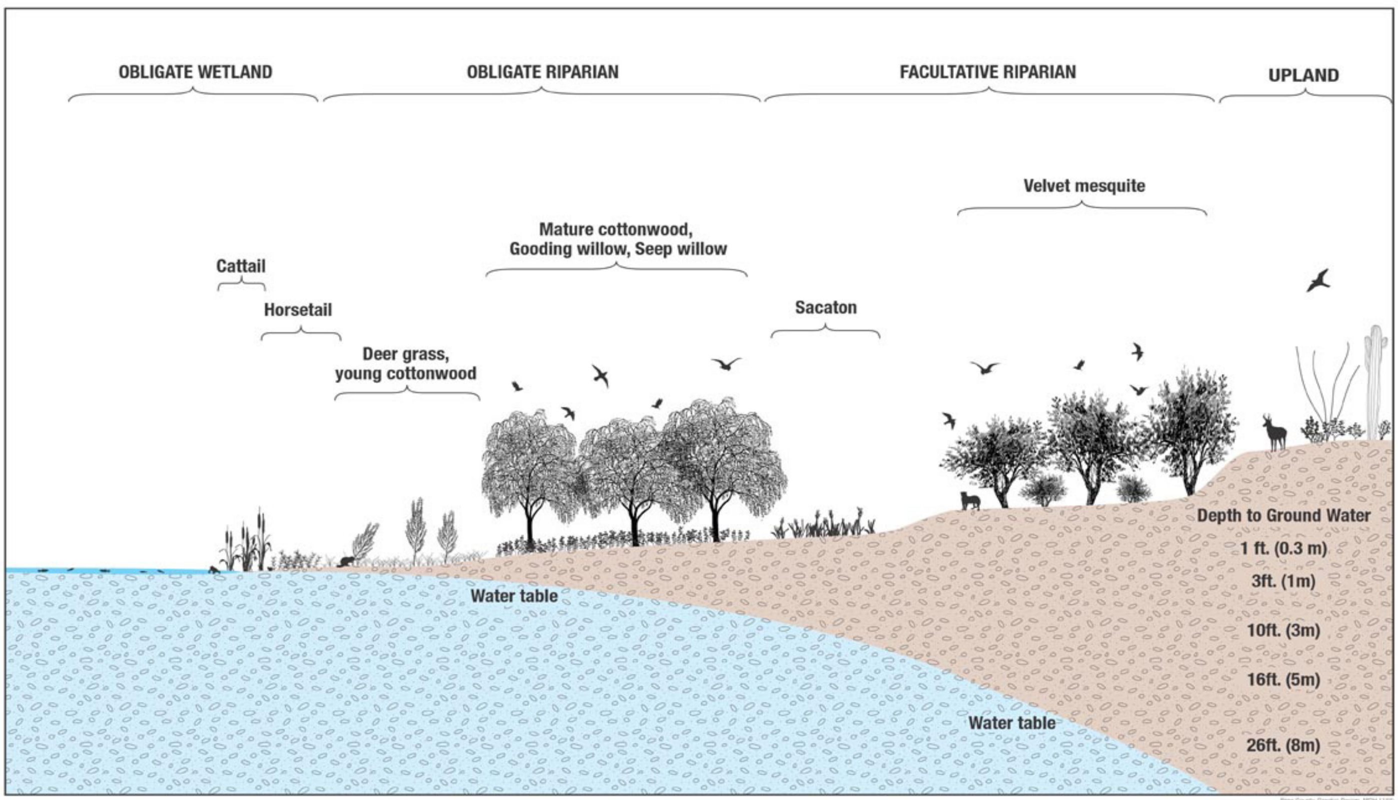


Figure 5. Cross-sectional view of river valley showing relationship between water table and common aquatic and riparian biotic communities (Illustration by Julie Stromberg, Barbara Tellman and Julia Fonseca, based on data in ADWR 1994)

ECOSYSTEM RESPONSES TO CHANGE

Figure 6 represents simplified relationships between changes in climate and/or land use, and changes in water levels. A changing climate affects the temperature and precipitation. Higher temperatures promote more rapid evaporation from water bodies and moist soil, and also increase the transpiration or water demand of upland and riparian vegetation. Increased temperatures in both urban and rural Pima County (Balling, 1988) and longer growth seasons (Weiss and Overpeck, 2005) have contributed to increased water demands of groundwater-dependent ecosystems in recent decades. Climatic stresses can change upland vegetation resulting in increased or decreased runoff.

Large or sustained flows, such as those that occur during El Niño winters that are characterized by frequent and heavy rainfall, also increase recharge rates. Increased recharge will cause the water table to rise, resulting in greater, longer or more sustained stream discharges. As noted earlier, a higher water table can assist the establishment of new riparian deciduous forests, and create more or improved aquatic habitat conditions.

The water cycle in the western U.S. has already changed significantly during the last half century and a majority of this change has been induced by climate change resulting from greenhouse gases and aerosols (Barnett, 2008).

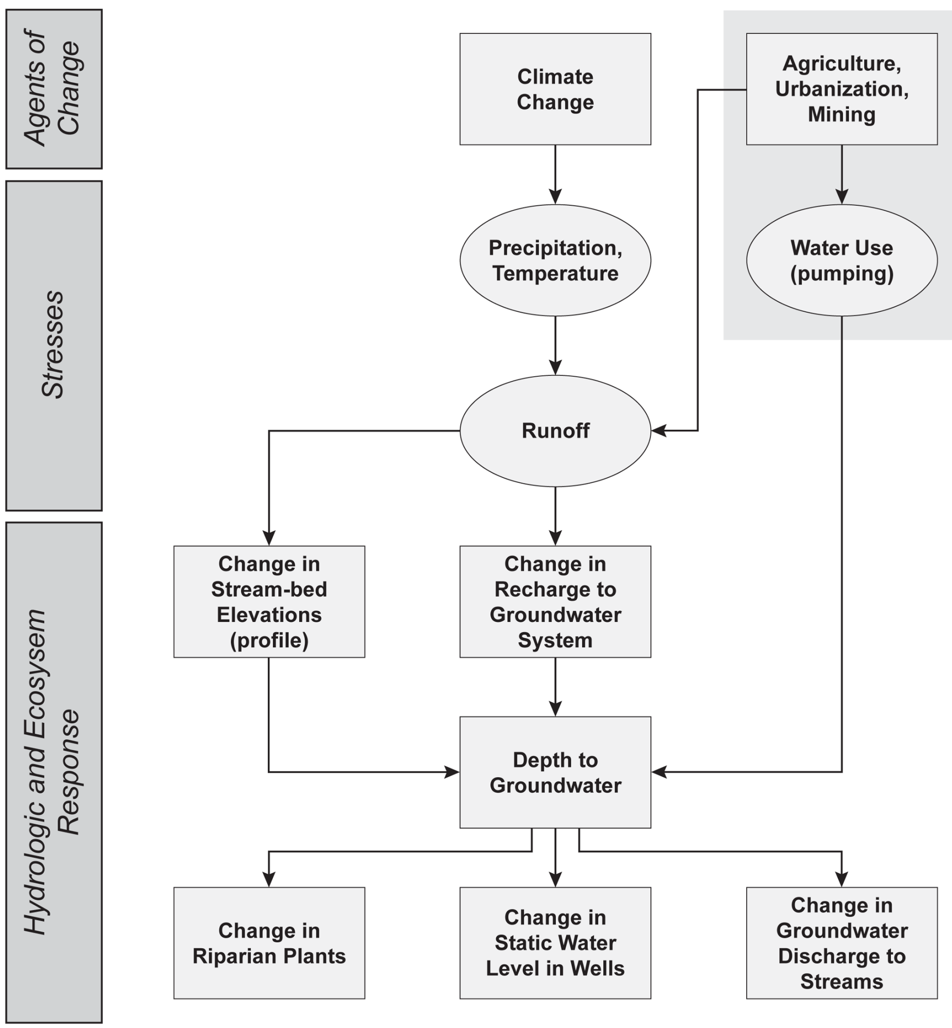


Figure 6. Climatic variation has always affected groundwater-based ecosystems, but global warming and the increased scale of human activities constitute new agents of change. (Modified from McCobb and Weiskel, 2002)

Climate models predict continued warming and more variability in precipitation (Seager, Ting et al. 2007). Warming trends increase evapotranspiration and human demands. Drier winters diminish recharge to some but not all of our groundwater-dependent ecosystems. Actual effects will vary according to the relative importance of summer to winter recharge for that watershed, the biophysical characteristics of the watershed, and the human use patterns for water. If changes in summer precipitation occur as a result of global warming, the vegetation response would be greater because most vegetative growth occurs during summer. But the response would be hard to predict because summer precipitation patterns are much more variable in Pima County than are winter patterns (Scalero et al., 2001). Regardless, precipitation changes will necessarily affect riparian vegetation and the duration and magnitude of groundwater-supported discharges. One might surmise that groundwater levels will become more variable and more rapid changes in riparian vegetation states will be observed.

When runoff moves large amounts of sediment, we may see the formation of an arroyo. Arroyos or headcuts may locally change the depths to groundwater in ways that simultaneously reduce accessibility of riparian trees on the former channel bed to water while also exposing the water table to the surface again for aquatic species. Conversely, the channel may fill with sediment and the depth to water may increase. This phenomenon happened in many streams following high precipitation in the Santa Catalina Mountains during July 2006. Filling and lowering of the channel can occur simultaneously along different reaches of the same stream.

Rates of change also matter. When the changes occur over decades, the vegetation community adjusts with episodes of plant mortality, recruitment, and replacement that are subtle to human perception. The differing depth-to-water tolerances exhibited by plants leads to dominance of one species over another across the floodplain, based on the relative height of different surfaces above the water table (as illustrated in Figure 5 and discussed at greater length in Haney et al., 2008). Figure 7 portrays these preferences graphically, by species, for the Verde River in Arizona. The overall trajectory will be toward a plant and animal community that is more in keeping with the local depth to water.

Figure 8 illustrates changes in stream flow and riparian vegetation which accompanies a rapidly declining water table that persists below a critical threshold for riparian vegetation. In this case, there is no gradual shift in species composition as shown in Figure 5. Instead, as ecological thresholds such as those in Figure 7 are passed, losses in plant diversity and cover are observed without obvious signs of vegetative replacement.

During the development of the SDCP, STAT developed scenarios that might affect species or ecosystem processes (RECON, 2006). Reasonably foreseeable "changed circumstances" that were anticipated included sustained depletion of groundwater due to urbanization, mining and climate change, and these changes were thought to particularly affect Bingham Cienega and Cienega Creek. Diseases affecting the health of riparian woodlands may also result from sustained drought stress. More positive, though less likely, scenarios included increased base flows on the San Pedro River due to retirement of agriculture and mining, and development of a shallow water table along the Santa Cruz River at Martinez Hill due to CAP-supported agriculture and recharge.

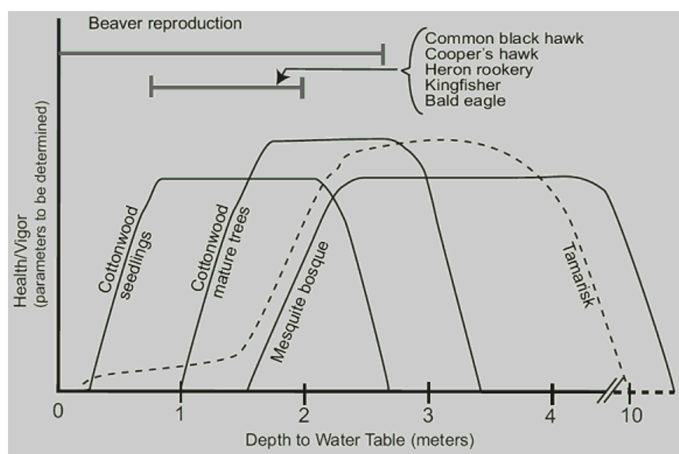


Figure 7. Thresholds of health or vigor exist for different species. These hypothetical flow-ecology response models for cottonwood saplings, mature cottonwoods, tamarisk and mesquite represent the range of tolerances exhibited by different trees to depth to water. (From Haney et al., 2008)

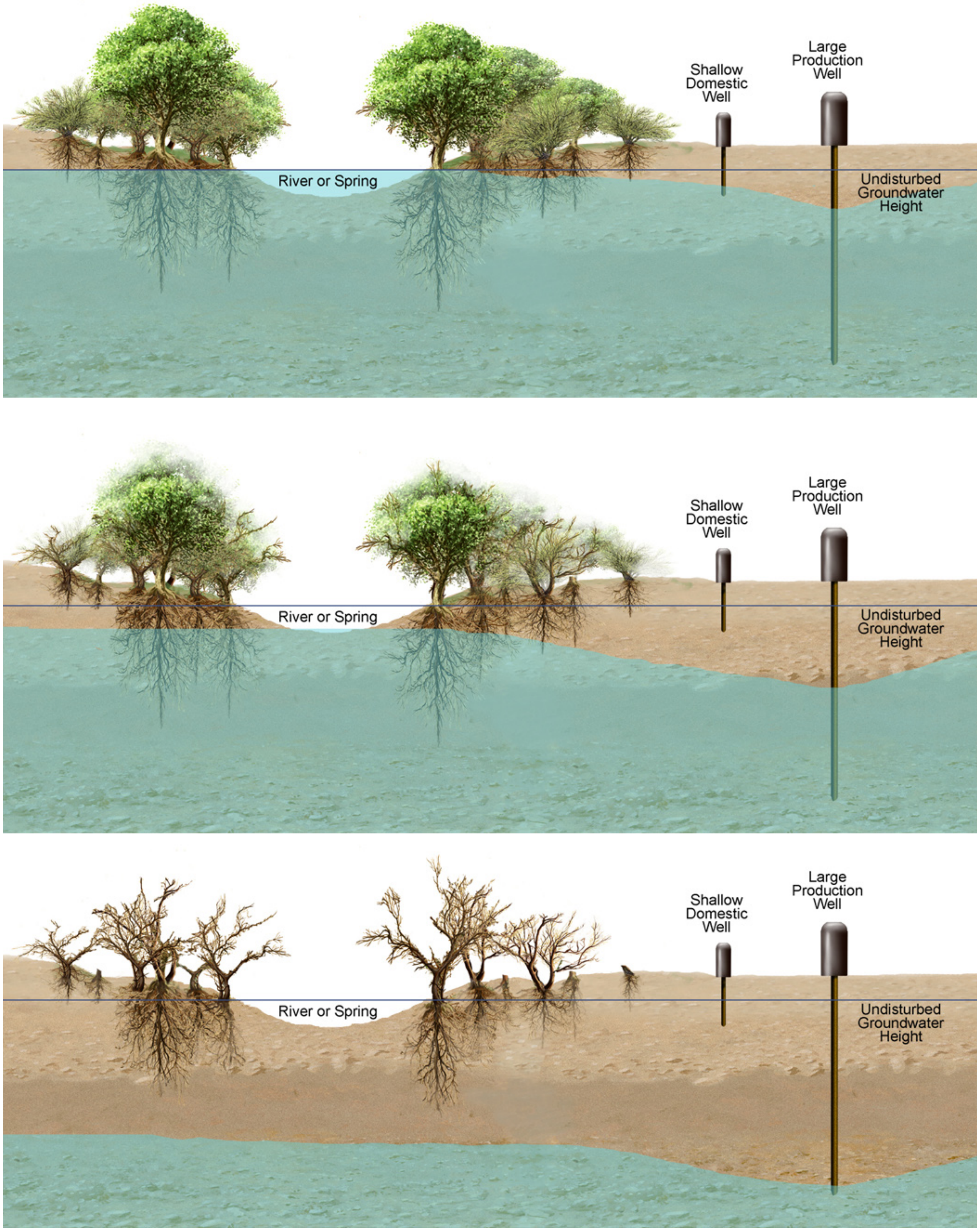


Figure 8. Effects of rapid groundwater decline upon riparian vegetation. The first effects include reduced canopy foliage and reduced herbaceous vegetation diversity and cover. Loss of base flows to stream is shown in second panel, followed by death of characteristic woody riparian trees as groundwater declines below the root zone. In this example, groundwater pumping draws down the aquifer, however reduced streambed recharge rates caused by upstream dams could have similar effects. (Illustration by Bill Singleton and Julia Fonseca)

TECHNICAL CHALLENGES TO MONITORING

An understanding of the complexity of aquifers is fundamental to understand the challenge of monitoring groundwater-dependent ecosystems. Aquifers are fully saturated zones of rock or unconsolidated earth that will yield water to a well. The soil beneath our feet also has water but typically not so much that it will yield water to an open hole (well). Thus, hydrologists distinguish water in soil (the unsaturated zone) from the aquifer (the saturated zone) (Figure 9). The water table is the surface of the aquifer.

Sometimes the shallow aquifer supporting a stream is naturally disconnected from a larger regional aquifer by abrupt changes in the character of the geologic materials below the streambed. In the example shown in Figure 10, infiltrating water creates and maintains an isolated aquifer in the younger floodplain alluvium. The disconnection from an aquifer of regional extent can also artificial. Drawdown around pumped wells can cause the regional aquifer to decline and "stranding" the riparian ecosystem to depend only on a "perched" aquifer. Perched aquifers are smaller in volume and extent and may be present only seasonally. Such aquifers will be less resilient to drought.

Knowing to what degree an ecosystem is dependent on multiple aquifers is critical to designing an effective monitoring system. Inspection of materials and measurement of water levels encountered during well drilling can help understand whether multiple aquifers are present but often special types of wells are needed to be sure.

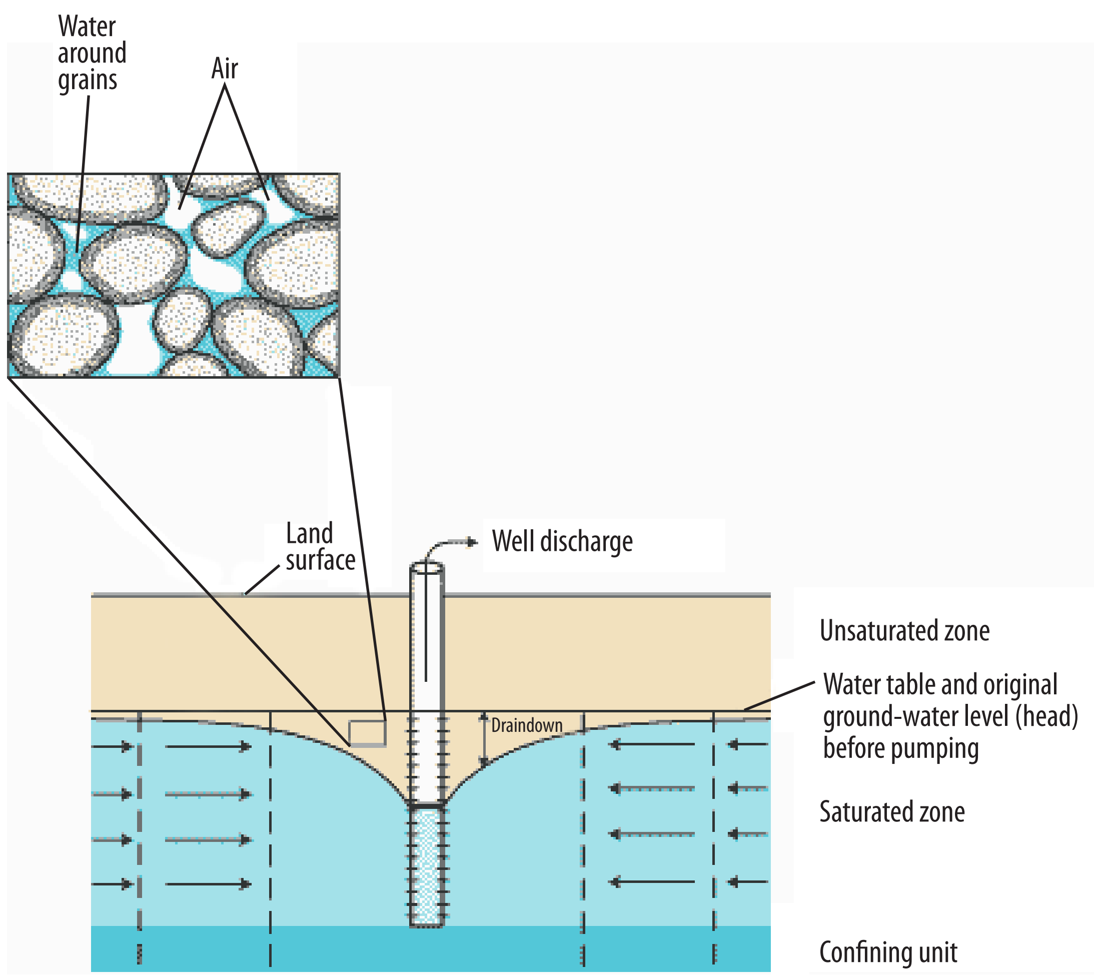


Figure 9. An aquifer is saturated with water, such that it yields water to wells. Inset shows unsaturated soil. Note drawdown of the water table around the well. Illustration by U.S. Geological Survey.

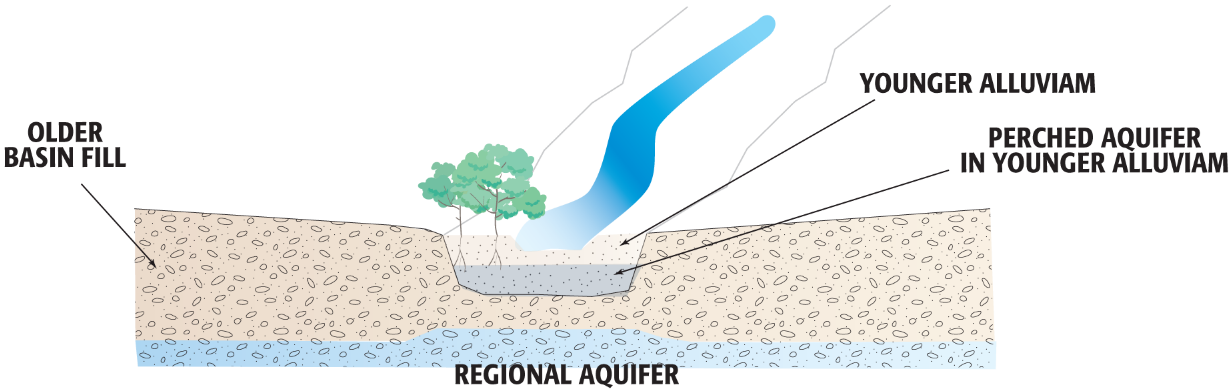


Figure 10. A floodplain aquifer is sometimes separated from a regional aquifer.

Modern wells are usually lined or "cased" with steel. The steel is perforated with small openings (screened) in a water-bearing interval. A well that is designed to detect the pressure that exists in a specific aquifer might not be perforated at all. This type of well is called a piezometer. Piezometers of different depths are useful for understanding the sources and direction of flow of groundwater to a wetland or riparian area, including whether multiple aquifers are present (U. S. Army Corps of Engineers 1993).

Variations in subsurface geology can complicate the interpretation of water-level changes from individual wells. A good understanding of local geology and the construction of the monitoring well is needed to interpret the data. Also, how the well is constructed can affect the water level observed in the well. Wells may be "screened" (perforated) over a single aquifer or multiple aquifers. Where multiple, stacked aquifers exist, care must be taken to ensure depth to water measurements are reflecting changes to the aquifer or aquifers supporting the stream or riparian area.

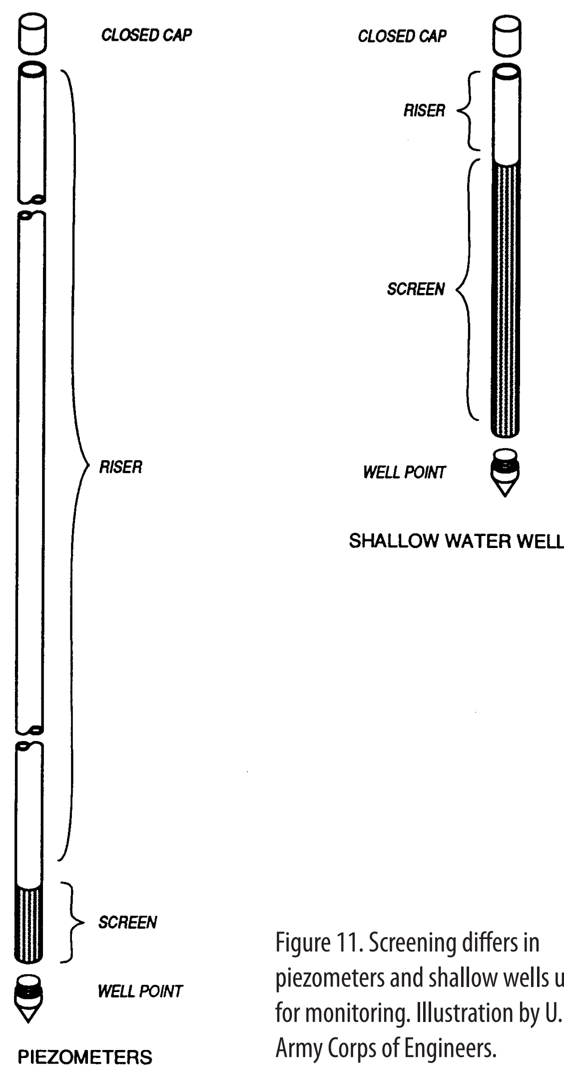


Figure 11. Screening differs in piezometers and shallow wells used for monitoring. Illustration by U. S. Army Corps of Engineers.

Costs Of Monitoring

During Phase 1 of the EMP, a group of water-resource scientists was asked to prioritize various water-related ecosystem indicators for further investigation. Repeated measurement of groundwater depth and gradients (direction of movement) in wells ranked second only to field measurements of water quality for ecological relevance. Land managers also ranked it highly (RECON, 2007).

Shallow piezometers can be driven by hand to depths of 10 to 15 feet in soft sediments. These are quite inexpensive compared to deeper wells. Costs vary depending on labor and materials, but $1200 per well is a recent estimate by The Nature Conservancy (TNC), excluding the cost of data collection devices (Barbara Clark, *personal communication*, 2008). Recent costs for data loggers used in Arivaca wells have been around $350 (John Regan, personal communication, 2008).

Hand-driven piezometers are used for detecting change in the immediate vicinity of the ecological site. Arrays of such wells can be useful in understanding the groundwater movement from streambed recharge and other sources. They can also be used to detect changes in groundwater gradients due to nearby well fields. One of their limitations is that when the sources of stress are more distant, they provide no information about likely aquifer response until it is too late.

Drilled wells are needed to sense changes that are deeper, originating farther away, or have greater variation. These can be much more expensive to install. Costs depend on the difficulty of access, distance from urban areas, depth, diameter, type of construction materials and type of geologic material being penetrated. Costs have ranged from $10,000 to $25,000 per well, though shallow (20-40 feet) wells in soft material could cost less. Cost will vary widely depending on the type of drill rig that can be procured and how competitive the drilling market is at the time. Other components of cost include a $150 permit from ADWR, and archeological and environmental clearance.

Because of the high cost of drilling new wells, hydrologists often rely on existing stock, domestic or irrigation production wells to measure groundwater levels. Measurements must be taken when the well is not being pumped, ideally the well is retired from production. While use of existing wells is advantageous from a cost standpoint, their location and construction can be problematic. There is often very little information about the depth of the screened interval or the geologic materials encountered in old wells. Irrigation and municipal supply wells, in particular, may penetrate a different (deeper) aquifer than the one that provides water to the root zone of riparian vegetation. Nonetheless, monitoring such wells can be essential to understanding groundwater movement in the contributing aquifer or aquifers that surround a stream or riparian area.

The main cost associated with measuring water levels in wells is the vehicle travel cost and time spent by field personnel in accessing the site. These costs are identical whether monitoring groundwater or some other ecological parameter, however only one person need collect the data unless safety concerns dictate otherwise. Other costs include the cost of a device to measure depth to water, and the cost of maintaining records. Pressure transducers linked to automated data loggers can reduce field time, and cost on the order of hundreds of dollars each.

The frequency of measurement is an important consideration, and must be evaluated in conjunction with methods and numbers of sampling points (wells) to be measured. If manual measurements are used, monthly or quarterly measurements can accurately reflect seasonal and interannual changes, but will fail to provide precise information about how the aquifer responds to natural recharge and evapotranspiration demands. The increased data precision provided by pressure transducers collecting daily or even weekly measurements can facilitate understanding the aquifer characteristics and responses to stressors. Alternatively, additional investigations to monitor water levels at a higher resolution can be performed as a supplement to infrequent manual measurements. If the aquifer responds slowly to recharge events along the stream, there is minimal aquifer development, and there is no immediate drive for higher precision, monthly or even quarterly measurements may be sufficient.

Streamflow discharge (flow volume at a given point) and length of observed streamflow measurements were deemed less desirable by Phase 1 workshop participants than depth to water. In part, this ranking is justified because these surface water measurements are usually more variable. Variation in the alluvial aquifer levels will occur more slowly and with less "noise", thereby providing more precise trend estimates (Figure 12).

Another reason groundwater monitoring may be favored over streamflow monitoring is the potential of groundwater depth to be a leading indicator of change. By the time the change in streamflow is detected, the system will have already been altered. Because of the longer time lag in the response of the groundwater table to agents of change, groundwater monitoring can foreshadow changes to the aquatic ecosystem. Groundwater level data can be used to detect changes in direction and magnitude of flow before critical thresholds are passed that might impair stream baseflows or vegetation. Note, however, that this advance notice will not be obtained from one monitoring well in isolation; it will only be possible if the monitoring data from a given site are placed in a broader context of what is happening around the system. Models, aquifer tests, and regional monitoring of climate, aquifer levels and pumping can all help put data from groundwater monitoring into a broader spatial and temporal context.

An excellent example of the use of groundwater data for adaptive management comes from Tonto National Forest, whose managers exploit these lag times to protect streams and springs. The Forest requires would-be developers of groundwater to perform both short-term and long-term groundwater monitoring on Forest lands (Tonto National Forest, 1999). Occasionally, the Forest Service has seen changes in springs and streams due to test pumping miles away, in a matter of days (Grant Loomis, Tonto National Forest, *personal communication*, circa 2000). These are typically in areas of bedrock fracture flow where mining production wells are used. Lag times can be months, years, or even decades in big alluvial aquifers.

Information derived from repeated measurement of water levels can be used to understand aquifer properties, directions of flow and trends in the water budget. These data in turn can be used when preparing groundwater models. Aquifer models are not a form of monitoring, but when constrained by real data, can be used to analyze how an aquifer will respond to changed conditions and at what rate.

Streamflow extent or length, also known as "wet-dry" mapping, is a special type of indirect groundwater monitoring. It involves the distance that surface water is present along a channel. Typically wet-dry mapping is done in the arid foresummer, when it can be used as a proxy for the position of the water table. Repeated measurements of this type will respond to interannual changes in the water budget, and will help distinguish reaches where the stream is "losing" water to an aquifer versus those where the aquifer is discharging to the stream.

Wet-dry mapping along Cienega Creek takes about the same amount of field trip as a round of measurements at a network of 8 wells, but the data and processing time is about twice as long (Mead Mier, PAG, 2008). If these measurements were collected by citizen scientists instead of PAG staff, training and additional quality control would add to the staffing needed. Instead, PAG invites interested parties to join with them in the effort, and uses the field trips as a means to collect other visual observations relating to biology and management needs. This information is then provided to County land managers.

Changes in surface water extent are easily understood by the public. Knowing what reaches are perennial or intermittent can also be useful in constraining groundwater models. For instance, a model could be calibrated to reproduce observed conditions, including a water table which supports stream flow. Repeated wet-dry mapping may be most appropriate for remote sites on bedrock or bouldery material where installing a well or gage would be too costly, where spatial fluctuations in aquatic habitat are important to understand, or where public engagement is critical.

Stream discharge can be measured as an indirect type of groundwater monitoring. Discharge is a measurement of the rate of surface flow at a given location. June "low flow" measurements (when flow would reach a seasonal minimum) are usually a good indicator of the aquifer's discharge to a stream.

Repeated stream discharge measurements have been used to quantify in-stream flow rights for streamflow protection. Labor costs for obtaining discharge measurement are higher than for groundwater measurement, if a stream gauge is not used, mainly because trained personnel are needed to collect instantaneous measurements.

Automated, fixed location stream gauges have the advantage of collecting many repeated measurements, but this data is much more costly. Pima County currently pays U.S. Geological Survey to collect and analyze streamflow data from ten locations at a cost of $154,000. This is over ten times the cost of the entire Cienega Creek monitoring program. The high cost of maintaining stream flow gauges derives from the desire to record accurately the wide variation in natural flows. A long and accurate record of daily flows would be needed to extract useful information about trends in base flows. Automated gages can be useful in interpreting annual streambed infiltration, and infiltration rates based on flood flows, even if they are not particularly sensitive to base flows. Stream gauge data are not amenable to collection by citizen scientists.

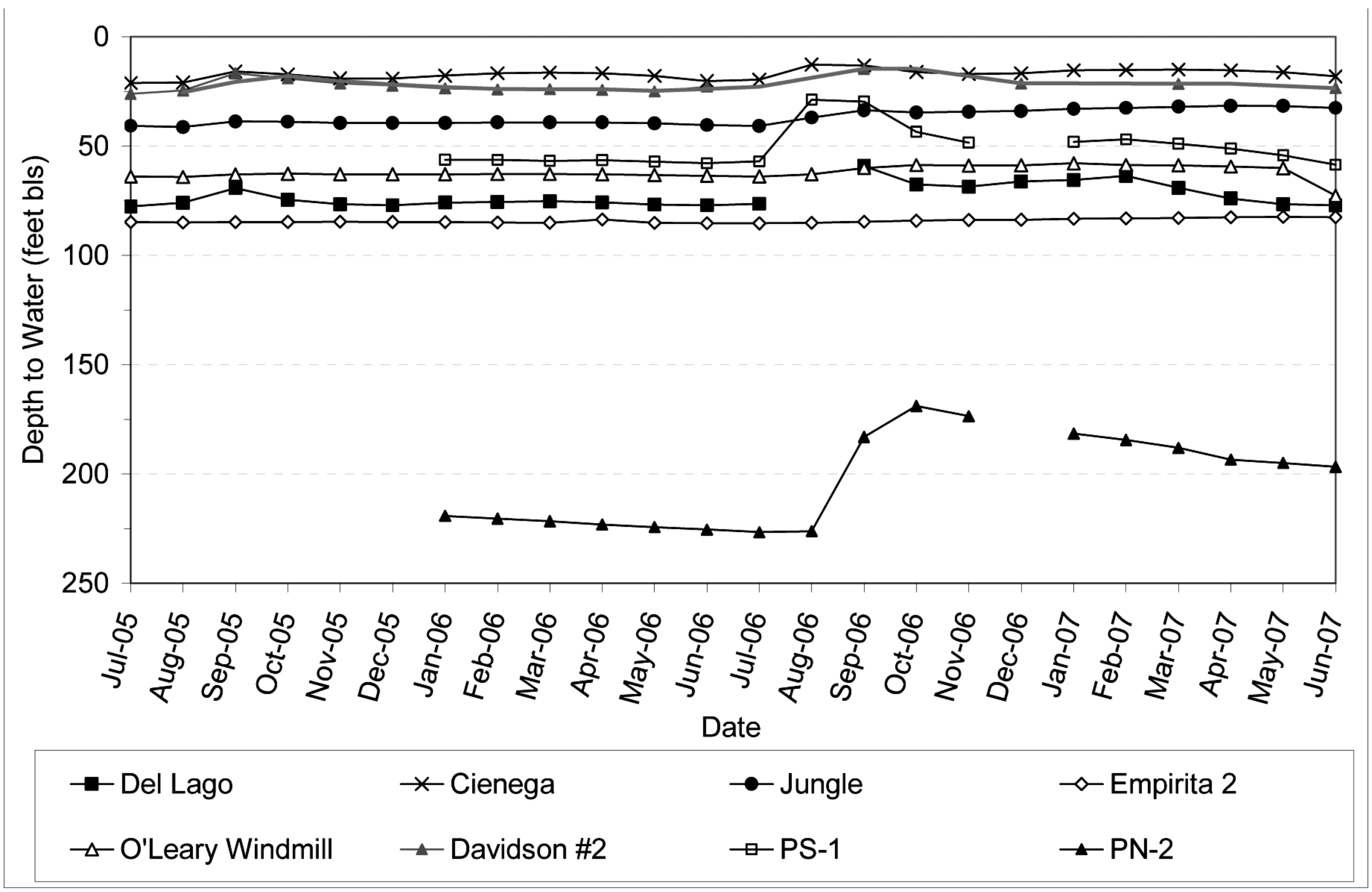


Figure 12. Depths to Groundwater in Cienega Creek Natural Preserve, July 2005 – June 2007. Data is not available for some months due to inaccessibility.

Regional Groundwater Reporting

This section of the report addresses the promise and problems with use of regional groundwater monitoring data for the EMP.

Approximately 1,600 wells are designated as "Index" wells statewide[2]. Typically, index wells are visited once each year by Arizona Department of Water Resources (ADWR) field staff to obtain a long-term record of groundwater level fluctuations. ADWR's network of index wells consists of both automated sites and wells that are measured by manual "conventional" methods. For the wells measured manually, groundwater level data is collected by the use of electric sounders or steel tapes that take a discrete measurement at selected intervals (usually only one measurement per year). Water-level measurements are generally collected during the winter months when water demand is less and aquifer conditions are not as stressed. Data is recorded and uploaded into the Department's Ground Water Site Inventory (GWSI) database. Municipal providers and U. S. Geological Survey (USGS) also coordinate reporting of water levels to ADWR.

Most of the index wells are chosen for an understanding of the water supply for farms and cities. While in some places, the water levels may have been historically shallow, modern water levels monitored in these wells are generally deep--greater than 100 feet below land surface—and, therefore, without direct relevance to the surviving groundwater-dependent ecosystems of Pima County. Furthermore, measurements at frequencies of a year or more apart do not allow for an examination of seasonal effects on water levels, which would be desirable for understanding the aquifer response to stresses.

To provide the public with an interpretation of conditions of groundwater resources, USGS created an interactive map service to present different views of groundwater information. Figure 9 shows a portion of the statewide map. The map uses coloration to allow visualization of *regional* groundwater conditions. Hyperlinks provide access to water level hydrographs to allow more detailed inquiry of individual well observations. The layers of information available on the online map include trends in recent water levels (1997-2006) as well as other information.

Figure 13 shows that in our region, the Tucson basin, Avra Valley, and Altar basins are populated with a number of data points for trends in recent water levels. In general, monitored water levels declined during the period 1997-2006 in most parts of the Tucson and Avra Valley areas. Exceptions exist in the vicinity of incidental and purposeful aquifer recharge and where pumping has been substantially reduced (e.g. central Tucson, northern Avra Valley, near San Xavier).

This type of regional reporting could be useful for indicating trends in the regional aquifers underlying lower parts of the Sabino and Tanque Verde Valleys. It is not useful for most other areas (see Site Monitoring, next): the Cienega Basin has no trend data and the Lower San Pedro, Arivaca and Sopori basins are each represented by only one well. This is because very few wells available to ADWR and USGS are measured frequently enough to derive trends, and of those, some appeared to be influenced by local pumping and not reflective of more regional water-level declines that were the objective of their project (Tillman et al., 2007).

Groundwater levels measured in the vicinity of groundwater-dependent ecosystems is generally lacking in the index well system. However, ADWR recently worked with the Pima County Regional Flood Control District (PCRFCD) and Arivaca Water Education Taskforce to install automated monitoring equipment in wells along Cienega Creek and Arivaca Creek using one-time grant funds. ADWR lacks the resources or statutory mandate to expand the program to create an effective system of monitoring wells for riparian areas in eastern Pima County. As a result, local resources will need to fill the gap.

PAG has taken the lead on providing local governments with information about the distribution and magnitude of groundwater pumping near shallow groundwater areas. As noted earlier, pumping (reported in acre-feet per year), along with drought, can be a source of stress to groundwater-dependent ecosystems. There is no state requirement to report pumping from exempt wells (those pumping less than 35 gallons per minute) or wells outside the active management areas. This impairs data interpretation. Thus, PAG also has

[2] This is a tiny fraction of the number of wells actually present. Pima County estimates that there are 17,528 wells registered with ADWR in Pima County alone.

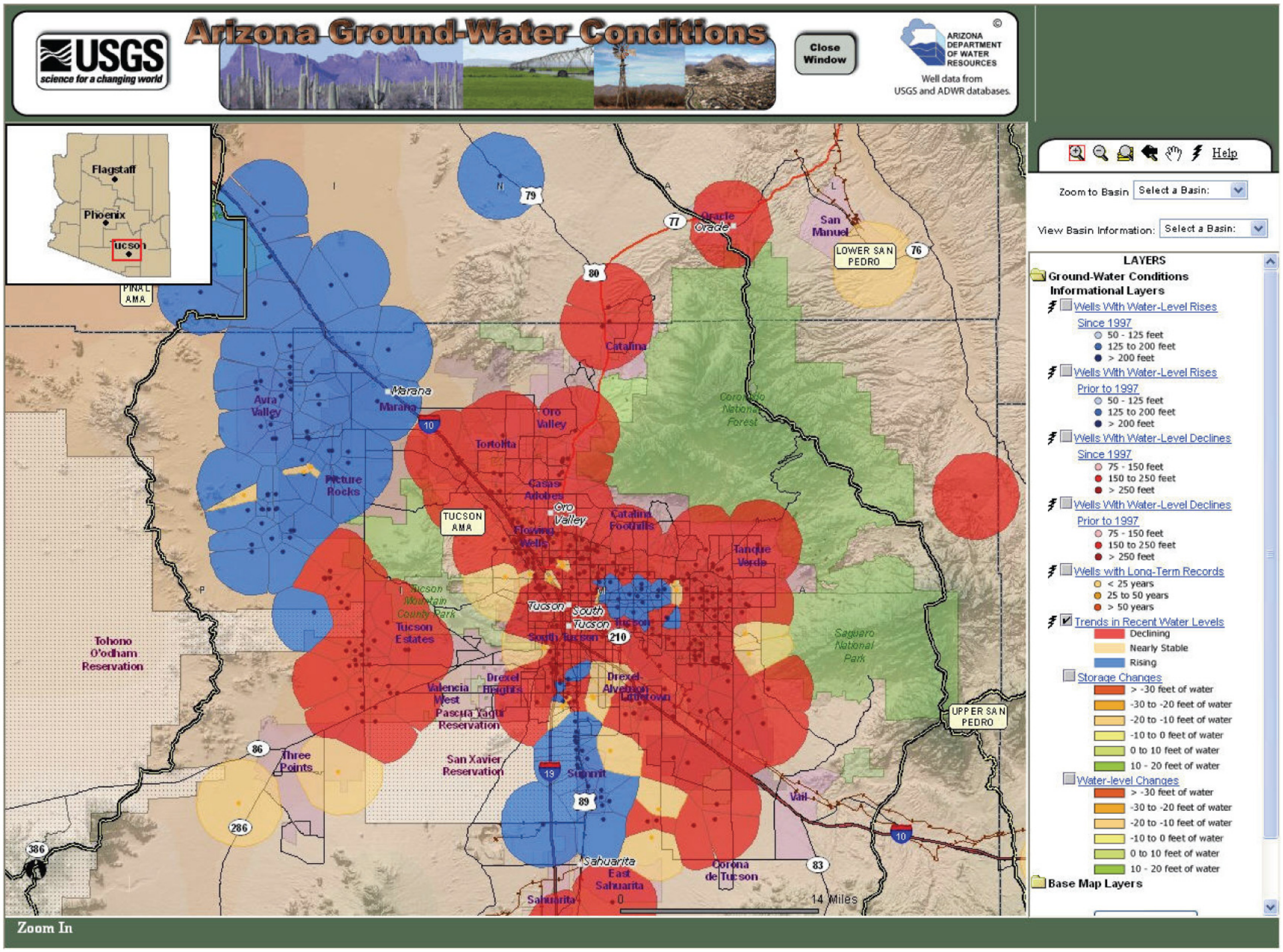


Figure 13. Screen capture of interactive map service (trend layer) http://pubs.usgs.gov/of/2007/1436/of2007-1436.pdf See also Tillman et al., 2007

monitored the number of wells near a given shallow groundwater area.

PAG's 2000 report presented annual groundwater pumping in acre-feet from non-exempt wells and numbers of wells within a mile of each area. This type of monitoring was repeated again this year (PAG, in press). This year's report found pumping declined at a number of sites, but detected increased pumping in the vicinity of the lower Cienega Creek. Monitoring had already been stepped up in advance of this finding, and analysis of the new data will be necessary before conclusions can be drawn.

Knowing the location, magnitude and trends of groundwater pumping in a region can give managers years of advance notice of changes that may affect a wetland or riparian area. Thus, PAG's monitoring reports are desirable and complementary to monitoring water levels.

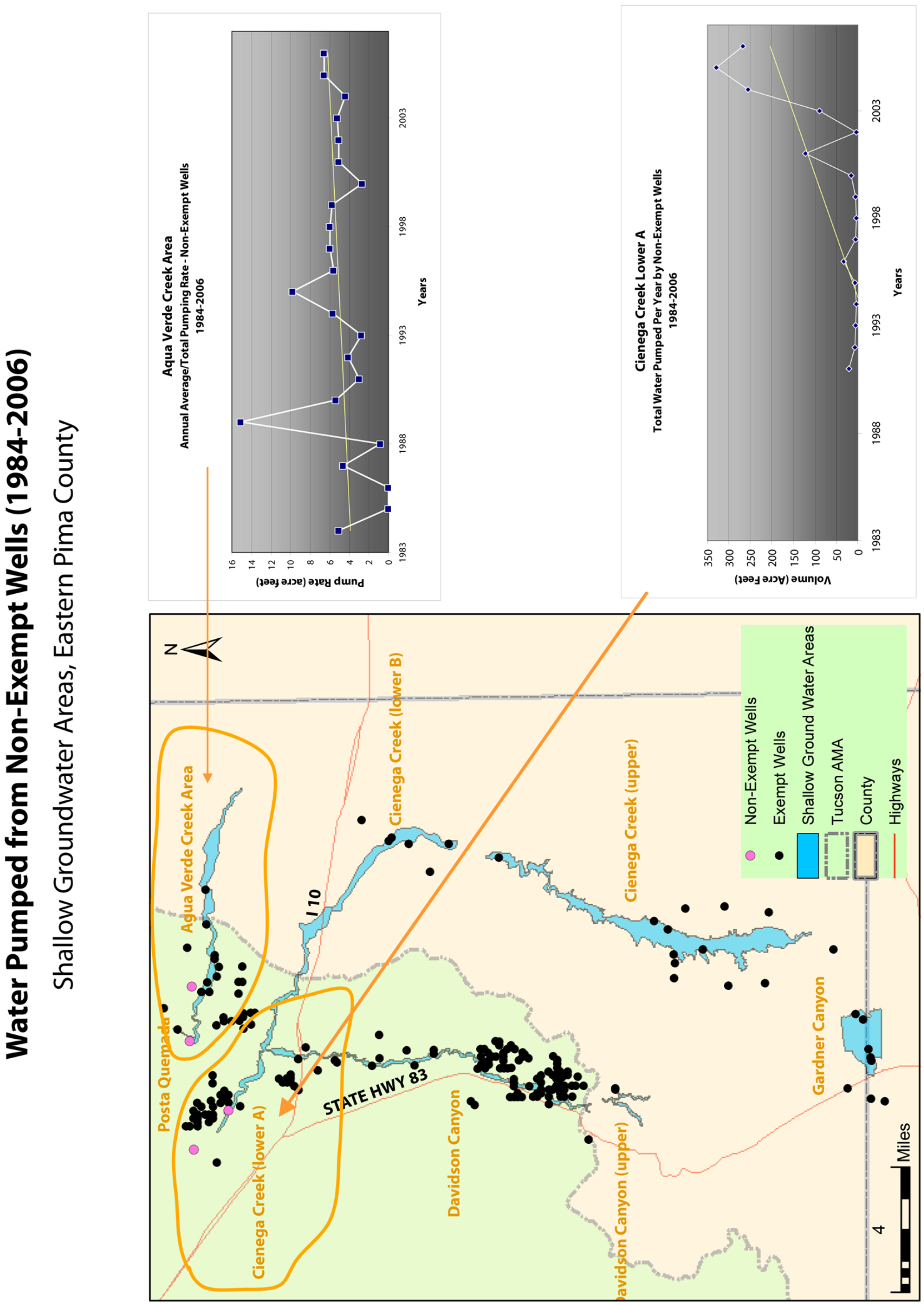


Figure 14. Excerpt from PAG (in press) showing pumping trends for non-exempt wells.

Geographic Priorities For Monitoring

There are many wells in Pima County, but very few were installed for monitoring streams and wetlands. Of the 17,528 wells registered with ADWR in Pima County, 3,307 are considered monitoring wells[3]. Of these, 72 monitoring wells are within a known shallow groundwater area. Most monitoring wells are installed in pollutant contamination areas, or areas at risk of being polluted by mines, landfills and wastewater treatment facilities. Only a handful of the 72 wells are actually installed to provide information about ecological conditions.

During the development of the SDCP, STAT reviewed the Cienega Creek groundwater monitoring data and encouraged staff to also report on conditions at Arivaca Creek and the San Pedro River. Arivaca was added because of the potential for land-use activities permitted by Pima County to affect the fate of the aquifer supporting Arivaca Cienega in Buenos Aires National Wildlife Refuge (AWET, 2000).

Bingham Cienega on the San Pedro was added because of Pima County's 1989 commitment to protect biological resources at the site, and the subsequent discovery of a number of rare wetland species. Collectively, these three sites represent the existing SDCP groundwater monitoring priorities.

The ranking of parameters in Phase 1 of the EMP was independent of any particular location. In Phase 2, we need to consider the nexus of the indicator to adaptive management responsibilities of Pima County. The degree to which County land use decisions can affect groundwater-dependent ecosystems is an important criterion affecting where the County has and will conduct monitoring. Other than the three sites mentioned earlier, what are the priority sites for monitoring?

An earlier report (Scalero and Fonseca, 2000) evaluated ecological priorities for streams and springs in eastern Pima County. This report was done prior to much of the new science developed during the SDCP. A set of 72 streams was derived from this report and analyzed along with all streams with perennial or intermittent flow reaches (PAG, 2001) using GIS. Stream centerlines were intersected with other hydrological, geological, biological and land tenure information to gain a perspective on the relative size of riparian and aquatic ecosystems and their significance for fish, frogs, or other listed species. The overlap between the stream centerline and riparian forest cover was reported in miles. Distance of stream overlap (intersection) with limestone outcrops was included because limestone can serve as an important aquifer, as well as climatic and biological refugia (Fonseca 2007). Species data are derived from Turner and List (2007), Scalero and Fonseca (2000), and Rosen (2000).

Based on this GIS analysis, a subset of streams was chosen for further evaluation. These are discussed in narrative form in Appendix B. Priorities for monitoring are based in part upon whether the County has land or water rights in the area, and whether the County's land use jurisdiction extends to the area, combined with the author's understanding of the significance of the area for aquatic and listed fauna.

Table 2 summarizes with the management challenges and existing monitoring programs as they are currently understood for the higher priority streams. Note, however, that the column listing land ownership and land use jurisdiction area is based on the GIS stream centerline intersection with land ownership information. The GIS analysis understates the significance of the County's influence in some of the areas listed below. The reader is referred to Appendix A and B for more perspective on management challenges for specific groundwater areas.

[3] Index wells include some monitoring wells, but many are wells that were designed for production.

Table 2. Summary of Geographic Priorities for Monitoring (see Appendix B for details)

Stream Name	Surface Flow (miles) Perennial	Intermittent	County Land (miles)	Developable (miles)	Priority (Partner)
Sabino Creek	15.0	3.4	0.1	3.9	1-2 (FS)
Cienega Creek (upper)	7.7	4.6	0.0	0.0	1 (BLM)
Arivaca Creek	2.7	1.0	0.0	2.4	1 (AWET)
Cienega Creek (lower)	2.7	4.8	10.7	7.0	1 (PAG)
San Pedro River	2.2	10.6	1.8	11.7	1 (TNC)
Buehman Canyon	5.2	2.5	0.0	3.0	1 if acquired
Wakefield Canyon	1.1	0.8	0.2	5.7	With legislation
Espiritu Canyon	2.2	4.6	0.3	4.5	2
Youtcy Canyon	0.9	1.9	4.5	3.3	2
Edgar Canyon	0.7	0.0	4.2	1.8	2
Davidson Canyon	0.7	1.3	4.2	11.7	2 (PAG)
Tanque Verde Creek	0.5	17.2	4.7	8.7	2
Rincon Creek	0.0	11.3	0.5	10.0	2 (NPS)

Local government and environmental organizations have attempted to fill the void in reporting on ecologically relevant groundwater levels. Initially, PCRFCD enlisted PAG for the Cienega Creek monitoring (see description in Powell 2008), and TNC at Bingham Cienega. These organizations have internalized these efforts and broadened the scope of their monitoring. Other, smaller community organizations have also monitored groundwater for ecological and domestic purposes. These organizations face bigger challenges in maintaining continuity—the continuation of monitoring efforts on Rincon Creek is completely dependent on successful fundraising by Rincon Institute. The efforts in Arivaca have lapsed at times and then resumed when funding or leadership emerged. Monitoring efforts by federal agencies have also been inconsistent due to budget, staff, or priorities.

There is no overall coordination of reporting among the groups who monitor groundwater for ecological purposes. Common data collection and management protocols and reporting of data could be useful in promoting awareness of the nexus between ecological states and the fate of the water table. Such efforts might also contribute toward drought monitoring for state and local purposes.

Groundwater Monitoring Plans

Once geographic priorities for groundwater monitoring are agreed upon, the next step would be to look more closely at each of the selected areas. Monitoring objectives should be established in relation to management goals and desired future conditions for the groundwater-dependent ecosystem. Is maintaining adequate supplies for the conservation target seen as the main issue, or is maintaining water quality or temperature from groundwater sources an issue as well? Table 3 presents some examples of ways to relate desired future conditions for an ecosystem to monitoring objectives.

Ecological monitoring objectives may have a legal component if the managing agency has surface water rights or intends to use entitlements to groundwater resources for ecological purposes. In some cases, management plans will have been completed, but may not have clearly stated the ecological and legal objectives. If so, additional work is needed to provide a foundation for groundwater monitoring that will effectively inform management.

Subsequent steps include:

1. Examining the distribution and construction of existing wells in relation to hydrogeology, land use, land tenure, location of water resource stressors and monitoring objectives;

2. Analyzing water quality data and literature research for information about the degree of connectivity between surface water, riparian water needs, and groundwater resources. Appendix 1 provides some information sources for hydrogeology in Pima County. Data gaps would be identified in this step as well;

3. Conducting reconnaissance field investigation to understand feasibility of monitoring methods (wells, surface water discharges, and installation of new piezometers) and to close some data gaps;

4. Documenting a conceptual model for the site and the origin of source waters related to the ecosystem;

5. Recommending appropriate methods, locations, budget, and agreements necessary to monitor, manage the data, and report the data. Securing internal and external review;

6. Preparing groundwater monitoring protocol detailing site access, safety, data collection, analysis and storage, presentation of information, and communication to land managers and the public; and

7. Procuring and deploying labor to conduct monitoring.

In practice, hydrologists or citizens often begin groundwater monitoring at step 6 or 7 with collection of data from a few existing wells owned by willing cooperators. This approach, while not ideal, has been a pragmatic one. The data are collected on an ad hoc basis while geological and hydrological research in steps 1 and 2 begin. Years later, when a formal land management or watershed plan is written, sometimes funding is made available to expand or formalize the monitoring program.

Groundwater monitoring programs ideally should be initiated with broad community engagement and resulting data should be broadly accessible. In practice, monitoring often results from a specific conflict or state-mediated permit granted to develop an aquifer. Local communities of interest are often prevented from engaging in the development of water policies and decisions, and monitoring data are often difficult to access or understand. Groundwater monitoring required as a condition of permits is often too limited to provide the information needed for understanding the ecosystem.

As in most conservation work, opportunities to achieve social objectives are highly relevant. Some communities of interest see a value in ecological monitoring to inform their local endeavors, while others do not. At a county-level of government, there is an opportunity to combine reporting of groundwater monitoring data with local drought monitoring. Data from site-specific groundwater-monitoring networks can represent the local effects of drought upon many aquatic and riparian ecosystems much more accurately than any regional drought indicators can. However, because the scope of inference for local groundwater-level monitoring in some cases may be quite limited, data must be carefully interpreted when making inferences concerning drought effects for uplands or unrelated aquifers.

Table 3. Examples of Monitoring Objectives for Different Ecosystems

Ecosystem	Desired future condition	Parameter	Monitoring objective
River	Water for aquatic species	Discharge at a station	No days with zero flows
	Maintain/restore flood recharge	Timing and total annual volume of flood flows	Volume does not drop below 1 std dev of gage record, and flows occur at appropriate season
	Maintain base flows for fish/wildlife	Extent of flow in June	Presence of flow in June
	"	Discharge at a station	Min flows above x cfs
	"	Discharge at a station	No declining trends in low flows
	Maintain riparian forest	Depth to water	No depths to water less than x for y time
	Maintain riparian forest	Species composition	Presence of seedling/sapling stage trees
	Maintain water quality of underflow	Total dissolved solids (TDS)	Depths to water, TDS, and gradient of underflow maintained
	Maintain thermal refugia	Temperature of upwelling	Min. winter temp not less than x; summer max. temp not less than y
GW-dependent riparian (no flow)	Recruitment of willow	Stage of vegetation	Seedling and sapling life stages represented in system
	Maintain deciduous riparian forest	Depth to water, evidence of recruitment pulses	No depths below x feet longer than y time; rate of declines in water table less than x cm/day; seedling/sapling stage trees
	Maintain bosque Depth to water	Depth to water	No depths below x feet longer than y time
	Maintain herbaceous understory	Species composition	Presence of characteristic species; species richness
Cienega wetland	Wetland vegetation	Depth to water	No depth below x feet longer than y time
	Maintain habitat for amphibian breeding	Duration of surface water	Surface water for X weeks during warm season
Wet Cave	Deposition of CaCO3	Movement of water	No days of zero seepage at x sites
	Humidity and Temp.	Relative humidity	X relative humidity and temp not varying more than y
Tinaja (Bedrock pool)	Maintain habitat for amphibian breeding	Depth-duration of water	Not less than X depth for Y time during monsoon
Ephemeral pool (Alluvial)	Maintain habitat for amphibian breeding	Duration of water	Not less than x depth for y weeks during monsoon

CONCLUSIONS

Regional groundwater monitoring reports are not sufficiently resolved to be useful for understanding and protecting groundwater-dependent ecosystems. Monitoring for human water supplies is not geared to measure the small changes in near-surface water levels or gradients that are critical ecologically.

Variation in near-surface groundwater levels affects biodiversity in groundwater-dependent ecosystems. New challenges in the form of global climate change and additional human groundwater demands portend greater fluctuations in the water table, which may drive rapid ecosystem changes.

Cienega Creek, San Pedro River and Arivaca Creek are the top ecological treasures in Pima County, and they all are affected by County land and water resource planning. All have existing monitoring programs except upper Cienega Creek. Tanque Verde Creek, Buehman Creek, and possibly Sabino Creek also merit attention. These streams are the highest priority for inclusion in the EMP groundwater monitoring program. Ideally, identification of key resources to be protected at the each new site and a statement of management objectives should precede and help to frame monitoring needs.

Pima County should:

1. support PAG's leadership in the lower Cienega Creek monitoring program through the continued allocation of PCRFCD funding;
2. provide technical assistance to U. S. Bureau of Land Management (BLM) with the development of their groundwater monitoring plan for upper Cienega and include reporting of data in the EMP;
3. support TNC's monitoring efforts at Bingham Cienega Natural Preserve, and see that data are reported in a broader middle San Pedro context for the EMP;
4. assist and coordinate with reporting by Arivaca Water Education Task Force and U.S. Fish and Wildlife Service at Arivaca Creek as part of the EMP;
5. identify willingness of potential partners Metropolitan Domestic Water Improvement District, Tucson Water, Tucson Audubon and others to cooperate in monitoring and reporting along Tanque Verde/Agua Caliente Creek or along Sabino Creek;
6. host discussions with interested parties in promoting consistency in collecting and formatting of data and in formulating how the EMP will communicate results for high priority streams;
7. review PAG's periodic regional assessment of pumping stress and regional reporting by ADWR and USGS in interpreting data from these and other sites, and assist in communication with land managers; and
8. estimate the costs of expanding to other important ecological sites recommended for further consideration (these include the Colossal Cave complex, Buehman [if property interests are acquired by Pima County], Rincon Creek, and Davidson, Espiritu, Edgar and Youtcy Canyons).

Because of the overlap with a distinct County preserve and the lack of obvious threats of groundwater depletion, ecosystem management and monitoring objectives should be established for Espiritu, Edgar and Youtcy, in conjunction with County land management plans for Six Bar and A7 Ranches. The other sites have more mixed ownerships that suggest the potential for partnerships with other entities, including citizen groups. If Congressional legislation enables a land exchange near the Whetstone Mountains, require the Empirita Water Company to monitor groundwater and adjacent springs.

Other organizations can help by:

1. Identifying funding for capital expenses, such as piezometers, or water resource management plans for specific areas that may lack them;
2. Collecting and sharing data on key ecosystems identified in the report; and
3. Communicating information to citizens.

Scientists can help by:

1. Investigations of source waters for key groundwater-dependent ecosystems; and
2. Development of conceptual models and aquifer models.

ACKNOWLEDGMENTS

John Regan, Mike List, and Cory Jones provided GIS analyses to support the report. Brian Powell reviewed and improved the drafts. Neva Connolly, Kathy Chavez, John Regan, Locana de Souza, Kerry Baldwin, Annette Plicato and Megan Bell also assisted in providing internal quality control. External peer reviewers Russell Scott, Dale Turner, Mark Briggs, and Gita Bodner kindly provided their expertise and ideas to improve the manuscript. Information from Claire Zucker, Mead Mier, Mike List, Kendall Kroesen, Megan Bell, Don Swann, Richard Conway, John Regan, Robert Pape, Mike Block and others was incorporated and greatly appreciated. The layout and graphics were greatly improved by Edie Price and Graphic Design.

REFERENCES

Arivaca Water Education Task Force. 2000. Arivaca Resources. Sonoran Desert Conservation Plan. Pima County Administrator's Office.

Arizona Department of Water Resources. 1994. Arizona riparian protection program legislative report. Report to the Governor, President of the Senate and Speaker of the House. Arizona Department of Water Resources, Phoenix, Arizona.

Arizona Riparian Council, 2003. Letter of Comment on Advance Notice of Proposed Rulemaking on the Clean Water Act Regulatory Definition of "Waters of United States". http://azriparian.asu.edu/cwaletter.pdf

Arizona Riparian Council, 1994. Riparian Fact Sheet #1. Center for Environmental Studies, Tempe, Arizona.

Balling, R. C., Jr., 1988. The climatic impact of a Sonoran vegetation discontinuity. Climate Change 13, 99-109.

Barnett, Tim P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the Western United States. Science Express, 31 January, pp. 1-3. www.sciencexpress.org

Behan, M. and J. Fonseca. 1999. Water resources and the Sonoran Desert Conservation Plan. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/001WAT.PDF

Bodner, G, J. Simms, and D. Gori. 2007. State of the Las Cienegas National Conservation Area: Gila Topminnow population status and trends, 1989-2005. A report prepared by The Nature Conservancy, Tucson, AZ. http://azconservation.org/dl/TNCAZ_LasCienegas_Gila_Topminnow_Status.pdf

Brown, J., A. Wyers, A. Aldous and L. Bach, 2007. Groundwater and Biodiversity Conservation: a Methods Guide for Integrating Groundwater Needs of Ecosystems and Species into Conservation Plans in the Pacific Northwest. The Nature Conservancy.

Fonseca, J., D. Scalero, and N. Connolly. 2000. Springs in Pima County, Arizona. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/006SPR.PDF

Fonseca, J. 2007. Limestone and its relationships to sky island biodiversity. Pages 6-7 In Sky Island Alliance. Restoring connections. Newsletter of the Sky Island Alliance v.10 no.1. www.skyislandalliance.org/images/newsletters/07-Spring-SIANewsletter-geology.pdf

Haney, J.M., D.S. Turner, A. E. Springer, J. C. Stromberg, L. E. Stevens, P. A. Pearthree, and V. Supplee, 2008. Ecological Implications of Verde River Flows. The Nature Conservancy, Arizona Water Institute, and Verde River Basin Partnership. http://azconservation.org/dl/TNCAZ_VerdeRiver_Ecological_Flows.pdf

Harris, L. K., J. A. Wennerlund, and R. B. Duncan, 2000. Riparian vegetation mapping and classification. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/012SDC.PDF

Hill, E. and J. Fonseca, 2001. Groundwater level changes in the Tanque Verde Valley. A report to the Pima County Board of

Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/013GRO.PDF

Johnson, R. R. and D. A. Jones, 1977. Importance, preservation, and management of riparian habitat: A symposium, Tucson, Arizona, July 9, 1977. Fort Collins, CO, Rocky Mountain Forest and Range Experiment Station: 217 p. :.

McCobb, T.D. and P. K. Weiskel, 2002. Long-term Hydrologic Monitoring Protocol for Coastal Ecosystems, U. S. Geological Survey Patuxent Wildlife Research Center, Rhode Island. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Pima Association of Governments, 2000. GIS coverage of perennial streams, intermittent streams and areas of shallow groundwater. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/002GIS.PDF

Pima Association of Governments, 2000. Water usage along selected streams in Pima County. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/008WAT.PDF

Pima Association of Governments, in press. Groundwater withdrawals in shallow groundwater areas, Eastern Pima County, Arizona, 1984-2006.

RECON, 2006. Pima County Multi-Species Conservation Plan. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d51/mscp_iv.pdf

RECON, 2007. Ecological Effectiveness Monitoring Plan for Pima County: Phase 1. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d30/EEMP.pdf

Rosen, P., 2000. Aquatic vertebrate conservation in Pima County: Concepts and planning development. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d7/007AQU.PDF

Scalero, D. and J. Fonseca. 2000. Historical occurrence of native fish in Pima County. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, Arizona. http://www.pima.gov/cmo/sdcp/reports/d7/011HIS.PDF

Scalero, D., J. Fonseca, and D. Ward, 2001. Climatic Variability in Pima County. A report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ. http://www.pima.gov/cmo/sdcp/reports/d10/018CLI.PDF

Seager, R., M. F. Ting, et al. (2007). "Model projections of an imminent transition to a more arid climate in southwestern North America." Science 316(5828): 1181-1184.

Tonto National Forest. 1999. Ground water use from National Forest System lands, Tonto National Forest, Policy and Procedures

Turner, Dale S. and M. D. List, 2007. Habitat mapping and conservation analysis to identify critical streams for Arizona's native fish. Aquatic Conservation: Marine and Freshwater Ecosystems 17: 737-748.

http://azconservation.org/dl/TNCAZ_Habitat_Mapping_Critical_Streams.pdf U. S. Army Corps of Engineers, 1993. Installing monitoring wells/piezometers in wetlands. WRP Technical Note HY-IA-3.1.

Weiss, J. L. and J. T. Overpeck, 2005. Is the Sonoran Desert losing its cool? Global Change Biology 11, 2065-2077.

Appendix A. Hydrogeologic Basins In Eastern Pima County

By Julia Fonseca, Pima County Regional Flood Control District, John Regan, Pima County Geographic Information System, and Andrew Schwarz, 2006 Planning Intern

Background

Pima County and PCRFCD have sponsored numerous studies over the past 20 years to augment knowledge about groundwater conditions in Pima County and the location and relationships between groundwater conditions and groundwater-dependent ecosystems. It is now possible, on the basis of these studies and others, to differentiate physical boundaries of the groundwater basins in Pima County using Pima County's Geographic Information Systems and to describe, in general terms, the location and direction of inflows and outflows. This effort is part of Pima County water resources inventory and will be used for county planning purposes.

Alluvial Basins

Alluvial basins are important physical features in Pima County because they store and transmit large quantities of groundwater. Alluvial basins are distinguished from each other by a bedrock boundary at the surface or below the surface of the ground, or by physical features that produce abrupt differences in groundwater levels or flow directions, such as a constriction in the lateral extent of alluvial sediments by bedrock at the surface or in the shallow subsurface, an abrupt transition in aquifer properties, an abrupt change in depth to bedrock, and/or geologic structures like faults.

The concept of basins as defined herein is useful to aquifer modelers to define limits to assumptions common to a given area. Indeed, this coverage utilizes geologic reports and geophysical models as a basis for differentiating portions of alluvial basins from each other, or from bedrock units.

The term "basin" has also been used in defining subsets of Active Management Areas (AMA), e.g. the Tucson or Avra subbasins. AMA groundwater basins or subbasins differ from the areas defined herein both in definition and location. AMA boundaries are based on political or cadastral units, watershed boundaries, and geological features known at the time of their designation. They define areas administered by ADWR.

Hydrogeologic Bedrock

Bedrock outcrops are by definition not part of the alluvial basins of Pima County. Bedrock units in this map (in white) are those that are exposed at the land surface, or pediments (shallowly buried shelves of bedrock). The original bedrock geology coverage used is called bedrock2. It is derived from the SDCP's 2000 digital composite of geology originally based on mapping by the U.S. Geological Survey. The viewing scale is smaller than 1:125,000. This was modified by adding more detailed information in the Arivaca area, excluding all of the Qs and QTs units from "bedrock", and then dissolving the unit boundaries.

Most bedrock units have relatively little groundwater in storage. Carbonate bedrock is economically important because it is known to form local aquifers, and may also form important recharge areas. The Vail area, in particular, has a known carbonate –rock aquifer that locally supports wet caves, as does the northeast flank of the Catalina Mountains. In the SDCP, this rock type is identified as a special target for conservation. It can be differentiated from other types of bedrock using the "limestone outcrops" data layers in the SDCP MapGuide site.

Pediments are included with bedrock unit in this map, in those locations where there is evidence to define them. The edge of pediments are based on the 400 foot depth to bedrock contour of Oppenheimer and Sumner[4] as modified by the work of Saltus and Jachens[5] or as suggested by inselbergs in the Arizona Geological Survey mapping, or by overlays of depth to bedrock contours provided by Steve Richard at Arizona Geological Survey.

Pediment areas sometimes have shallow depths to water. Wells on pediments often have low productivity. The pedi-

[4] Oppenheimer, J.M., and Sumner, J.S.,1981. Gravity modeling of the basins in the Basin and Range province, Arizona: Arizona Geological Society Digest, v. 13, p. 111—116; Tucson.

[5] Saltus, R.W., and Jachens, R.C., 1995, Gravity and basin-depth maps of the Basin and Range Province, western United States: U.S. Geological Survey Geophysical Investigations Map GP-1012, 1 sheet, scale 1:2,500,000.

ment aquifers often possess relatively little storage. Local discharges to springs or streams are not uncommon. For the most part, the thin alluvial aquifers sitting on pediments are tributary to their downgradient basins. At the scale of this analysis, it is possible that there are microbasins or structural troughs within the pediment shelves that are entirely self-contained or that possess depths to bedrock in excess of 400 feet.

Pediments along the eastern margin of the Upper Santa Cruz Basin share a geologic history related to the chevron folds derived from detachment faulting from the Rincon metamorphic core complex. The Vail fault, also known as the Pantano fault, is associated with the boundary between the pediment and the Tucson basin to the southeast[6]. Tanque Verde Creek, Cienega Creek and Rincon Creek are zones of groundwater discharge in the pediment, as are a number of springs[7].

Boundaries between hydrogeologic areas that cross bedrock units are based primarily upon surface watersheds and information from Anning, D.W., and Konieczki, A.D., 2005[8].

[6] Johnson, A.T., 1994. Geohydrology of the Pantano Feature, Southeastern Arizona. Prepublication manuscript for a Master's of Science degree from the University of Arizona, Department of Geosciences;

[7] Hill, Elizabeth; Fonseca, Julia, 2001. Groundwater Level Changes in the Tanque Verde Valley.; Pima Association of Governments, 2004. Groundwater Conditions in Rincon Valley.

[8] Anning, D.W., and Konieczki, A.D., 2005. Classification of hydrogeologic areas and hydrogeologic flow systems in the Bason and Range Physiographic Province, Southwestern United States: U. S. Geological Survey Professional Paper 1702.

[9] Pima Association of Governments, 2000. *Sonoran Desert Conservation Plan- GIS Coverage of Perennial Streams, Intermittent Streams, and Areas of Shallow Groundwater*.

[10] Anning, D.W., and Konieczki, A.D., 2005.

[11] Oppenheimer, J., 1980. Gravity Modeling of the Alluvial Basins, Southern Arizona. Unpublished Master's Thesis, University of Arizona,

[12] Fonseca, J., 2000. Cocio Wash and the Gila Topminnow. Prepared for the Sonoran Desert Conservation Plan.

Streams and Springs

Perennial and intermittent streams and springs are plotted based on the work of PAG for the SDCP[9] and subsequent modifications. In some cases, these features constitute discharges from one basin to the other. They may represent the position of the water table in a given area.

Avra Basin

The Avra Valley basin is differentiated from the Altar Basin using the work of Anning and Konieczki[10]. The division between the Avra Valley and Altar Valley Basins is delineated by a subsurface bedrock high separating two geologic basins containing thick basin fill deposits (~8000 ft in the north, ~5000 ft in the south). However, there is evidence in Oppenheimer that such a transition may actually occur farther north[11].

Groundwater underflow in the Avra Valley is generally south to north. Groundwater enters the basin from the Rillito Narrows between the Tortolita and Tucson Mountains and from the Altar Basin. There are no perennial surface outflows of water in the Avra basin anymore. Discharge of groundwater at a spring in the pediment of the Silverbell Mountains ceased in the 1980s[12].

Avra Valley receives a large amount of imported surface water from the Colorado River. Much CAP water is being stored in the central and northern Avra Basin for later withdrawal using the technique of artificial groundwater recharge. This work is causing the water table to rise back after an era of heavy groundwater depletion in the 20th century.

Water supply infrastructure is dominated by the CAP and related projects. There are a number of existing agricultural developments with extensive irrigation delivery systems. There are also several existing water companies in the Avra Valley.

Altar Basin

The Altar Basin is defined based on depth to bedrock contours. The division between the Avra and Altar Basins is delineated by a subsurface bedrock high separating two geologic basins containing thick basin fill deposits (~8000 ft in the north, ~5000 ft in the south) defined by Anning and Konieczki.

The Altar Valley could be further subdivided into an upper and lower basin based on depth to bedrock contours, but it is not known if these divisions are meaningful from a water supply standpoint. The upper Altar hydrogeological basin appears to extend south into Mexico across a surficial drainage divide. The Arivaca Basin is considered a distinct basin based on bedrock outcrops located between the two areas[13].

The alignment of the basin boundary between the Tucson and Altar Basins is based on structural fabric in the area, in the approximate vicinity of the topographic divide. There was no evidence identified for outflow or inflow across this boundary.

Groundwater in the Altar Valley generally flows south to north. Groundwater enters the basin from the Arivaca Basin via Arivaca Creek as well as underflow. Groundwater exits the Altar Basin in the north in to the Avra Basin. There are no surface outflows of groundwater from the Altar basin to other basins. Discharge of groundwater at streams and springs at the base of the Baboquivari Mountains in the pediment flow into the deeper alluvial basin. Groundwater also supports riparian habitats such as the riparian woodlands along Brown Canyon.

Existing groundwater uses are relatively low in the Altar Valley and are dominated by irrigation for pasture. Groundwater use reported for stock is highly variable (EM&A, 2008)[14]. There are no alternative supplies of water. Infrastructure to deliver and move water is minimal.

Tucson Basin

The Tucson Basin extends beyond both the northern and southern boundaries of Pima County. To the west, the basin is bounded by pediments of the Sierrita Mountains and the Tucson Mountains. Between the Tortolita Mountains and the Tucson Mountains is a structural high that defines the line between the Tucson and Avra Basins, which is aligned with one lonely bedrock outcrop in the Tortolita pediment. The Tucson Basin is one of the deepest basins in eastern Pima County. It could be further subdivided into a tributary subbasin in the vicinity of Catalina, based on depth to bedrock contours, but it is not known if this boundary would have significance for water supply purposes. There is no obvious basis for a segmentation of the Tucson Basin from the rest of the Upper Santa Cruz area in the vicinity of SCAMA boundary, so none is noted in this work within Pima County. However, the Canoa-Amado area has a shallow groundwater zone and there are seasonal discharges intermittent flows along the Santa Cruz River north of Elephant Head Road. The work of Keith Nelson, ADWR was used to define the lateral boundaries near Amado[15].

To the east the Santa Catalina Mountains and Santa Rita Mountains form the boundary of the basin. Groundwater flows through the Upper Santa Cruz basin from south to north and then northwest. Groundwater also enters the basin from the Lower Cienega basin and from the Tubac area of the Santa Cruz basin. There are surface discharges associated with the groundwater flows at these locations. Groundwater exits the Tucson basin at the Rillito Narrows between the Tucson Mountains and Tortolita Mountains[16]. Depths to groundwater change dramatically across the Rillito Narrows. Although there is a surface stream at that location, supported by effluent, it is not known to be hydraulically connected to the regional aquifer, based on water-level data from Pima County Water Reclamation Department monitoring wells. There were historic discharges of groundwater at Sentinel Peak and San Xavier del Bac, and many other locations.

[13] Pima Association of Governments, 2006. Hydrologic Assessment of Arivaca. Pima Association of Governments-Watershed Planning Program, Staffan Schorr.

[14] Errol Montgomery and Associates, 2008. Technical Memorandum to Julia Fonseca from Staffan Schorr regarding Hydrogeologic Investigation of Altar Valley Subbasin, Pima County, Arizona.

[15] Nelson, Keith, 2007. Groundwater flow model of the Santa Cruz Active Management Area along the Effluent-dominated Santa Cruz River, Santa Cruz and Pima Counties, Arizona. Modeling report no. 14, Arizona Department o f Water Resources, accessed on May 19, 2007 http://www.azwater.gov/WaterManagement_2005/Content/AMAs/SantaCruzAMA/SCAMA_gw_flow_model_report14_030807.pdf

[16] Davidson E. S., 1973. Geohydrology and water resources of the Tucson Basin, Arizona. United States Geological Survey Water Supply Paper 1939-E.

Notable groundwater discharges within the basin today are primarily at springs along the Catalina Mountains, and along Sabino Creek. Stream base flows are diverted from Cienega Creek and imported across a basin divide to the golf course at Del Lago (Vail).

The Tucson basin has a large alternative supply of water, in the form of CAP water. The Central Arizona Project and Tucson Water have developed a great deal of infrastructure to recharge and deliver CAP in the Tucson Basin. Tucson Water and Pima County have infrastructure to reclaim and deliver effluent for re-use. Other providers have substantial infrastructure to deliver groundwater supplies.

Arivaca Basin

This alluvial basin is defined based on recent work by Staffan Schorr for Pima County, and depth to bedrock contours. The Arivaca Basin is an isolated basin with little or no inflow of groundwater. Groundwater flow in the basin is generally from the northeast, east and southeast to the center of the basin and then west under the cienega. Arivaca Creek is a perennial stream originating in the basin and fed by a groundwater outflow in the cienega. Other groundwater-dependent ecosystems include a wetland, sacaton grasslands, springs, and deciduous riparian forest.

Arivaca groundwater is tributary to the Altar Valley Basin, and flows across bedrock below the Arivaca Cienega. Because the stream flows extend across this boundary, the hydrogeological basin boundary was chosen to include the entire surficial watershed downstream to the junction of Arivaca with Altar. North of Arivaca basin is a shallow basin fill area that contributes surface water flow toward the Altar Valley. It is mapped as bedrock. Presumably this area contributes groundwater toward the same direction but this assumption should be tested.

The Arivaca basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is minimal.

Sopori Basin

The Sopori Basin is defined based on recent data evaluated by Staffan Schorr for Pima County[17] and depth to bedrock contours. The Sopori groundwater Basin is an isolated, shallow alluvial basin that is tributary to the Tucson Basin. The Sopori Wash Fault delineates the boundary between the Sopori Basin and Tucson Basin at Sopori Wash. Basin depth increases significantly on the Tucson side of the fault. The fault may cause a major hydrologic disconnect between the two basins. Groundwater in the Sopori Basin generally follows the Sopori Wash, flowing from south to northeast and east. The boundary between the Sopori and Tucson Basins in the Sierrita piedmont and across the Tumacacori Mountains was based on watershed data.

This basin has groundwater discharges in the form of springs along the creek and riparian evapotranspiration.

The Sopori Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is minimal. The lower end of the Valley, near the Santa Cruz River, is where groundwater depletion has been heaviest. Significant exurban development has been proposed in this basin.

Lower Cienega Basin

The Lower Cienega Basin is defined based on depths to bedrock and the presence of bedrock outcrops interposed between it and the adjacent Tucson and Upper Cienega Basins. Estimated depths of basin fill are as great as 1200 feet[18]. This basin receives surface discharges of groundwater across "the Narrows" from Cienega Creek as well as groundwater underflow. Underflow moves northeast toward the Tucson Basin. It is possible that there are "microbasins" within this area that are self-contained.

Cienega Creek and Agua Verde Creek are surface discharges from the underlying aquifer in the Lower Cienega Basin caused by bedrock outcrops and areas of shallower stream alluvium. The streamflow goes below the surface in areas of thicker alluvium and deeper bedrock as it enters the Tucson

[17] Pima Association of Governments, 2005. *Groundwater Conditions in Sopori Basin*.

[18] William Jess Ellett, 1994. Geologic Controls on the Occurrence and Movement of Water in the Lower Cienega Creek Basin. Masters Thesis submitted to the Department of Hydrology and Water Resources, University of Arizona.

Basin. Other groundwater-dependent ecosystems include wet caves, springs, wetlands, mesquite bosques, and deciduous riparian forests and woodlands.

Carbonate aquifers exist in the vicinity and it is not known if these may contribute or abstract from the surface discharges. Though not shown, the Pantano Formation, traversed by Cienega Creek and Agua Verde Creek, is a leaky, partially confined aquifer that also contributes flow to the streams[19].

The Lower Cienega Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is minimal. A number of homes in the Agua Verde Hills rely on importing water via trucks for household use because well yields are low.

Mescal Basin

This area is defined based on geophysical modeling by Bill Ellett that indicates a structural trough up to 600 feet deep and bedrock outcrops that separate it from the Lower Cienega Basin. This basin may or may not receive inflows from Upper Cienega Basin. The basin boundary with the Upper San Pedro is based on changes in the inferred direction of flow, most recently studied by Geosystems Analysis for Pima County. Based on their work, the Mescal Basin is thought to be tributary to the Lower Cienega Basin[20]. One new well in the area encountered bedrock at a depth consistent with the model[21].

There are a number of springs discharging groundwater in this basin. Groundwater also supports riparian evapotranspiration.

Discharges from this basin may occur at Wakefield Spring at the southwestern boundary of the basin where it connects to the Lower Cienega Basin. It is possible that there may be microbasins within the basin with different directions of groundwater flow.

The Mescal Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is limited to existing wells, mostly associated with dry lots. Empirita Water Company is proposing to move water from its wells in this basin across the County line, but within the basin.

Upper San Pedro Basin

The Upper San Pedro Basin is an isolated basin, primarily located in Cochise County. Its western boundary is defined based on changes in the direction of flow between the Mescal area and areas to the east, most recently reviewed in detail by Geosystems Analysis for the Mescal Basin. The area in Pima County contains several areas of carbonate-rock aquifer in the western portion of the basin. An area of pediment in the extreme southeastern corner of Pima County, south of the Whetstone Mountains, drains toward the Upper San Pedro Basin based on ADWR well data[22]. This area might be considered tributary to the Babocomari subbasin of the Upper San Pedro.

The Upper Santa Pedro Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is limited to existing wells.

Middle San Pedro Basin

The Middle San Pedro Basin is differentiated from the Upper San Pedro Basin based on bedrock outcrops in Cochise County at the Narrows. The Middle San Pedro basin receives groundwater from the Upper San Pedro Basin in Cochise County. The direction of groundwater underflow from the Middle San Pedro is toward the north.

[19] Chong-Diaz, D. 1995. Modeling of stream aquifer interaction in lower Cienega Creek Basin using a finite element technique, Masters Thesis, University of Arizona Department of Hydrology, Tucson, Arizona.

[20] Geosystems Analysis, Inc., 2003. *Hydrologic Data Compilation for the Cienega Creek/Mescal Road Area*.

[21] Dickens, C. M., 2006. Hydrogeologic Report in support of designation modification. Empirita Water Company, Cochise County, Arizona. Prepared for Empirita Water Company. Accessed at images.edocket.azcc.gov/docket.pdf/0000056791.pdf.

[22] Kennard, M., A. E. Johnson, T. W. Perry, 1988. Preliminary Report on the Hydrology of Cienega Creek Groundwater Basin. Arizona Department of Water Resources, Division of Hydrology, Special Studies; and more recently see. http://www.sahra.arizona.edu/wells/

Groundwater supports springs, streams and riparian evapotranspiration. There is a discharge of groundwater from bedrock into the Middle San Pedro Basin at Edgar Canyon. There is an intermittent discharge of groundwater along the San Pedro River in the Middle San Pedro Basin, as well as at Bingham Cienega. Isotopic evidence indicates that at least part of the discharges to the Cienega is derived from San Pedro groundwater underflow. Tributaries also provide recharge to the San Pedro River and there is evidence for a confined aquifer along the San Pedro River as well[23].

The Middle San Pedro Basin can be differentiated into two parts based on depths to bedrock. Direction of groundwater movement in structural trough adjacent to the Catalina Mountains is unknown. Carbonate-rock aquifers occur upgradient in the Catalina Mountains.

Upper Cienega Basin

The Upper Cienega Basin is an isolated basin which does not receive inflows from other groundwater basins. It is defined based on depth to bedrock contours, augmented by the geophysical work of Bill Ellett and bedrock mapping. The basin is demonstrably tributary to the Lower Cienega basin via discharge from Cienega Creek and water chemistry[24]. The basin may also be possibly tributary to the Mescal area via a structural trough inferred from Ellet's work. The overall direction of underflow is northwest. The Upper Cienega basin is partly bounded by a carbonate-rock aquifer area at the northeast corner of the basin. The carbonates contribute to discharges of Wakefield Canyon and Nogales Spring. There are a number of other springs and streams discharging groundwater in the basin.

At the northwestern margin near the Rosemont area is an area that appears to contribute underflow along the axes of the Davidson Canyon as well as the Oak Tree Canyon. Future hydrogeologic study might redefine the basin boundary between Upper and Lower Cienega.

The Upper Cienega basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is minimal.

Sasabe Basin

The Sasabe Basin is an isolated basin. The basin boundary is defined based on the work of Anning and Konieczki and follows the watershed boundary. Staff's review of extant water level information supports the interpretation that the direction of groundwater movement is toward Arroyo del Sasabe, which flows south toward Mexico.

The Sasabe Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is restricted to the existing agricultural development.

Aguirre Basin

The Aguirre Basin is an isolated basin with boundaries based upon Anning and Konieczki's work[25]. Depth to bedrock appears to be substantial in places (data provided by Steve Richards). Groundwater in the Aguirre Basin flows north-northwest from Pima County toward Pinal County but review of driller's logs indicated shallow bedrock may constrain some movement[26].

There are no surface discharges from this aquifer but there are extensive mesquite bosques, presumably dependent upon flood flows.

The Aguirre Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is restricted to the existing agricultural development.

[23] Robertson, F. N. 1992. Radiocarbon dating of groundwater in a confined aquifer in southeast Arizona. Radiocarbon 34: 664-676.

[24] Grahn, Howard, 1995. *A Hydrogeochemical Evaluation of the Lower Cienega Creek Sub-basin, Pima County, Arizona*. Thesis, University of Arizona, Department of Hydrology and Water Resources

[25] Anning, D.W., and Konieczki, A.D., 2005. ibid.

[26] Errol Montgomery and Associates., 2007. Technical memorandum from S. Schorr to J. Fonseca, regarding hydrogeologic investigation of Aguirre Valley Subbasin, Pima County, Arizona.

Eloy Basin

The Eloy Basin in Pima County is a shallow, isolated basin defined based on depths to bedrock. Groundwater flows north across a pediment from Pima County to a much deeper basin in Pinal County. There are no surface discharges from this aquifer.

The Eloy Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is limited.

Valley of the Ajo

This basin is located in western Pima County and underlies most of the Why-Ajo area. The boundary is based upon Anning and Konieczki's work[27]. This basin does not receive inflows from adjacent hydrogeologic areas. Outflow is generally northwest along the axis of Tenmile Wash. Depths of basin fill at Ajo are tens of feet, compared to hundreds of feet at Why. Maximum basin depths may be thousands of feet. There are no surface discharges but there are locally high groundwater levels (possibly perched) in parts of the town of Ajo and other locations at the edge of the pediment[28].

Because it is outside the AMA, there is little information about groundwater pumping. The Ajo Basin has no alternative supplies of water. Infrastructure to move and deliver groundwater is restricted primarily to old investments made by Phelps Dodge.

[27] Anning, D.W., and Konieczki, A.D., 2005. ibid.

[28] Schorr, S., Hydrogeologic Investigation of the Ajo-Why Area, Valley of the Ajo, Pima County, Arizona. 2007. Technical memorandum prepared for Pima County Regional Flood Control District by E. L. Montgomery and Associates.

Appendix B. Evaluation Of Some Important Riparian Areas In Pima County For Groundwater Monitoring

Appendix B presents a new summary of the ecological significance of potential streams for groundwater level monitoring and priorities for inclusion in EMP narrative formats.

Streams below are grouped geographically by hydrogeologic basin. A larger set of 72 streams was reviewed initially, including those listed in a previous stream prioritization effort (Scalero and Fonseca, 2000) and all streams with perennial or intermittent flow reaches (PAG, 2001). Selected springs are also evaluated in the narrative in Appendix B, based largely on Fonseca et al. (2000).

Recommendations are in ***bold italic*** for top priority streams, and in *italic* for second priority streams.

Cienega-Mescal Basins

Agua Verde Wash: Some adjacent private land is affected by County land-use decisions and the County has acquired Poteet. This is one of the longer intermittent streams in the area but no perennial reaches are known and the riparian forest is not well developed. Little information is available regarding faunal significance. Very little recent water level information is available from ADWR. Groundwater monitoring for the EMP is a low priority at this time, but inventory should be supported. *Priority for groundwater monitoring should be re-evaluated in the future, especially if additional acquisitions are made*.

Colossal Cave Complex, including Posta Quemada Wash: There are wet caves known in the area of the County park as well as one private land. There are also intermittent springs and some riparian resources. Water supports the growth of cave formations. Humidity levels may have an effect upon bats. Ecology of the Arkenstone Pseudoscorpion does not rely upon groundwater (Pape, 2008). Hydrology in the area is complex and poorly understood. Monitoring of temperature and humidity conditions might be a more appropriate monitoring for the EMP than groundwater.

Cienega Creek (lower): Much of the riparian area is in County jurisdiction, and the management plan has identified persistence of streamflow as an objective. PCRFCD possesses a certificate of in-stream flow rights. Some adjacent private land is affected by County land use decisions. This stream possesses many ecological resources, including federally listed species (Table 1), and as such has been a focus of groundwater research and monitoring since 1987, including the ephemeral reach at the Empirita Ranch headquarters. The PCRFCD recently installed two deep monitoring wells, and PAG has installed several hand-driven piezometers near a headcut. ***Communication of reported data collected by PAG as part of the EMP is a top priority***.

Davidson Canyon: Davidson Canyon provides an important source of water for Cienega Creek and has riparian and aquatic ecosystems of its own. Much of this area is affected by County land use decisions. Recently, the County acquired additional land and water rights along the stream itself. At present, PAG monitors groundwater within the portion located in the Cienega Creek Natural Preserve at Interstate 10, where a stream gauge is also present. Upstream developments may affect groundwater resources and water quality (Myers, 2007). *Expansion of monitoring for the EMP is a moderate priority*.

Upper Cienega Creek: Due to the presence of federally listed aquatic plants and animals, this is the most ecologically significant stream reach in Pima County. Most of the contributing area is in federal jurisdiction and is not likely to be greatly affected by Pima County land use decisions with respect to groundwater use. However, conditions in upper Cienega could be affected by either mining in Pima County (Myers, 2007) or by groundwater pumping in Santa Cruz County. Upper Cienega is significant to County-managed lands as a source of groundwater inflow for the lower reach, and it has been a source population for aquatic species in the County's Cienega Creek Natural Preserve. BLM has begun wet-dry mapping and one stream gage is present. "The BLM and partners have recognized the need to develop a more detailed groundwater monitoring program for Cienega Creek and its tributaries Empire Gulch and Mattie Canyon (BLM 2003, Bodner et al. 2007)." ***Coordination of water resource reporting with BLM in the EMP is top priority***.

Wakefield Spring/Little Nogales Spring: This area has valued riparian and aquatic resources managed by the State, Forest Service and BLM. Some adjacent private land is affected by County land use decisions. County is actively seeking acquisitions in the area through Congressional action. The proposal would allow a certain amount of pumping on acquired land near Wakefield as a condition of relinquishing privately-held water rights to Cienega Creek. *If the land is acquired by Pima County, I recommend reporting of groundwater pumping, water levels in wells, and spring flow by the water company as a condition of the Congressional action*.

Arivaca Basin

Arivaca Creek, Arivaca Cienega: This area has an extensive sacaton bottomland and other valued wetland and riparian resources. County has supported groundwater studies in the area and is actively seeking acquisitions in the area. Some adjacent private land is affected by County land use decisions. Arivaca Water Education Taskforce (AWET) has monitored various wells at various times. AWET currently monitors 30 wells on a monthly schedule. Five wells are National Wildlife Refuge wells, the rest are private. Seven of the wells are equipped with transducers and manually downloaded periodically. ADWR has installed transducers and transmitters on three wells in the Refuge. The ADWR data is displayed online in real-time. (AWET coordinator Richard Conway, personal communication, 2008). AWET would like guidance on how best to report and analyze data. ***Coordination of reporting with AWET (and by extension, ADWR and USFWS) for the EMP is highly recommended***.

San Pedro Basins

Geesaman Canyon: A portion of the stream is owned by Pima County, but riparian resources are limited and no hydrological information is known. Inclusion in the EMP is not recommended at this time, but should be re-evaluated at a later date.

Espiritu, Edgar, and Youtcy: All of these streams are located in bedrock areas within County managed A7 Ranch. All three streams include valued riparian resources and the potential for future native fish or frog establishment. Management goals include protecting and enhancing riparian areas, developing a monitoring program for the riparian areas, and minimizing use of natural surface waters for livestock operation. Wells on the ranch are actively monitored for water quality. *Inclusion in the EMP is a moderate priority*. Streamflow extent monitoring during June might be adequate, possibly supplemented with water levels in inactive wells.

Buehman/Bullock: This watershed is ecologically important, as documented in the SDCP by Harris (2001) and by the fact that this stream is considered an Outstanding Water by the State of Arizona, conferring a high degree of water quality protection. At present, however, most of the valued riparian and aquatic resources are under management of other entities. ***In the event that Pima County acquires the area, inclusion in the EMP is recommended as a top priority***.

San Pedro/Bingham Cienega: Pima County and PCRFCD own land and water rights in the valley. TNC manages the land and conducts groundwater and surface water monitoring at Bingham as a contractual obligation. In addition, TNC has assisted in wet/dry mapping along the entire length of the San Pedro. Because of the size of the system, and valued wetland flora and fauna, ***reporting of TNC data in the EMP is a top priority***.

Sopori Basin

Sopori/Papalote Wash: There are riparian woodlands on Sopori and sacaton grassland on Papalote. There are both surface water diversions and groundwater pumping, and the potential for significant future exurban development. Currently County land holdings are limited, however there is the possibility of additional acquisitions. Inclusion of groundwater monitoring in the EMP is low priority but should be evaluated if further acquisitions occur.

Tucson Basin

Tanque Verde Creek/lower Agua Verde Creek: Upstream of Houghton, much of this area is in County jurisdiction, and a few parcels are owned by Pima County. The lower reach possesses a mesquite bosque and cottonwood-willow forest in declining condition due to groundwater depletion and drought. The upper reach is more stable. This area is one of the few nodes of riparian evapotranspiration in the AMA aquifer model and water budget for the Tucson Basin. A groundwater monitoring program is in place for the regional aquifer by Tucson Water and Metropolitan Water and could be supplemented with local private wells. ***Monitoring of ecosystem conditions is high priority for the EMP, but might be accomplished in other ways than groundwater monitoring***. Access to private wells would require citizen support, and there is no clear constituency for it. With citizen involvement, the site could be useful in promoting drought awareness.

Lemmon/Sabino/Bear Creek: The upper reach is in Forest Service management but County land and water activities at Summerhaven influence the water budget indirectly. The FS has an in-stream flow application for the stream. Much of the downstream area is in the County's land use jurisdiction. Pima County owns a small tract of land along lower Bear Canyon. Audubon holds surface diversion rights and the Forest Service has filed for in-stream flow water rights. This stream possesses valued aquatic and riparian resources which are being affected by variety of stresses. Municipal groundwater monitoring is unlikely to represent conditions in the Recreational Area but may influence trends in the lower reaches (PAG 2008). Audubon has an existing well at the Madden property, but it is not monitored. *Monitoring of ecosystem conditions is moderate to high priority for the EMP, but might be accomplished in other ways than groundwater monitoring*. If opportunities to communicate information in conjunction with the Forest Service's monitoring efforts can provide an outstanding opportunity to promote drought awareness in the local community, the priority could be revised.

Agua Caliente Wash, Agua Caliente Spring: The wetland fauna and flora is largely decimated, but the shallow water table supports valued riparian habitat along the wash. Pima County Natural Resources, Parks and Recreation (PCNRPR) monitors discharge of the spring and pumps a nearby well for pond management purposes. Inclusion of existing data is a low priority for the EMP but could be very useful in promoting drought awareness in the community.

La Cebadilla Spring: The wetland fauna and flora is largely intact and the shallow water table supports valued riparian habitat. Pima County owns land next to the spring and conservation easements are held by Rincon Institute. La Cebadilla Homeowners contract for spring flow monitoring, which seems to vary independently of trends at Agua Caliente Spring. Priority for EMP aquifer monitoring is low; however, reporting of spring discharge by the Homeowners Association to PCNRPR could be used to help understand whether this system varies synchronously with discharge in Tanque Verde Creek recharge.

Madera/ Florida Canyons: The most ecologically significant portions are in Forest Service lands and outside Pima County jurisdiction or influence. A lower, intermittent reach is in Pima County jurisdiction but its limited size and relative ecological importance warrants a low priority.

Rincon Creek: This area has valued wetland and riparian resources. County may seek acquisitions in the area. Some adjacent private land is affected by County land use decisions. National Park Service (NPS) has supported groundwater studies. Volunteers with NPS monitor seven shallow wells at the confluence of Chiminea Canyon and Rincon Creek (Don Swann, personal communication). There is no coordination of reporting of data from a broader network. Once the in-stream flow claim is substantiated, it is unclear whether the program will continue. Rincon Institute used to monitor groundwater on Rocking K lands downstream. *Inclusion in the EMP is recommended as a second priority*.

Canada del Oro Wash: PCNRPR has recorded water levels on acquired land along the lower CDO. They are too deep to support valued riparian resources. The reach in the National Forest is ecologically significant, but largely outside of County land use jurisdiction. Inclusion in the EMP is not recommended.

Sutherland Wash: This intermittent stream and bosque may be supported by shallow groundwater conditions, and its fate outside and upstream of Catalina State Park will, in part, be determined by State and County land use decisions. At present, Pima County has no land base to monitor here; therefore, inclusion in the EMP is not recommended. However, this should be reviewed again if a significant portion of the shallow groundwater area is acquired.

Upper Santa Cruz River: There is a mesquite bosque at the southern end of Canoa Ranch which may be dependent upon a shallow water table. There is much groundwater pumping at wells within Canoa Ranch for the mines but effects on shallow water levels at the southern end seem limited. There is the potential for restoring shallow aquifer conditions in concert with artificial recharge, improved infiltration of tributary surface flows, or acquisition of pumping rights but more study is needed. Inclusion of groundwater monitoring in the EMP is low priority, but continued monitoring for recharge and restoration is warranted.

Avra Basin

Lower Santa Cruz River: Pima County monitors groundwater levels in the area and has a great influence of the biotic integrity of this effluent-dominated reach. Groundwater levels are too deep to support valued riparian resources. Surface water discharge is meticulously monitored for recharge purposes, and constructed recharge activities are proposed. Because this area has one of the largest riparian forests in Pima County (Harris, 2000), inclusion in the EMP is recommended. However, reporting of groundwater level monitoring would not be an appropriate indicator of the health of the ecosystem.

Wild Burro: The stream has intermittent flow and County jurisdiction but no fish or leopard frogs are known to use the site. Not recommended for the EMP due to small size relative to other potential sites.

Cocio Wash/Spring: The riparian resources are so degraded, and the watershed so irreversibly altered by upstream mining that inclusion in the EMP is not recommended.

Cochie Spring: The status of the spring and wellhead need to be checked periodically for on-site management, but inclusion of data in the EMP is not recommended due to the small size of the system.

Other

Quitobaquito Spring, home to the Quitobaquito pupfish, is already monitored by the National Park Service in western Pima County. Pima County has little potential to affect the spring. Coordination of reporting with this entity and inclusion in the EMP is a low priority.

Figure 15. A fish biologist regards Cocio Spring, when it used to have year-round water. Native fish and frogs no longer inhabit the area. (BLM Photo, 1981)