

Dynamics of Rare and Sensitive Waters in Saguaro National Park

**A Final Report for the
2014 George Wright Society, U.S. Geological Survey, and National
Park Service Park Break Program**



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**Prepared by: Jennifer Aldred, Sylvana Bendana, Alexandra Bijak, Jesper Devantier,
Megan Haserodt, Heather Lancaster, Gregory Luna Golya, Derek Schook, Daniel Winkler,
Don E. Swann, Colleen Filippone, and Joshua Conver**

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ABSTRACT

Stream pools, known locally as *tinajas*, are a critical source of water for unique vegetation and wildlife in Saguaro National Park. The presence/absence of water in these pools has been monitored since 1996, but little is understood regarding the hydrogeology of these systems. To elucidate the dynamics of these rare and sensitive waters, we conducted a preliminary study of the relationship between the hydrologic and geologic features that may be controlling where tinajas occur, and temporal changes in water level. In the field, we collected strike, dip and number of joint sets at 1m² and 10m² scales in the Chimenea and Loma Verde drainage basins to understand structural geologic influences on the development of tinajas. We examined existing precipitation and pool survey data and created a classification scheme. We used ArcGIS to evaluate the relationships between tinajas and watershed contributing area, size, wash slope, as well as Lidar and orthophotography to identify geologic features. We created a water table map based on tinaja elevations in combination with field observations and existing water data to develop conceptual models. Additionally, we documented a new group of approximately 10 tinajas in the newly named Park Break Canyon. Together, these data suggest that the tinajas which have formed in fractured crystalline bedrock in Saguaro National Park are hydrologically connected via these fracture pathways and the presence of water in the tinajas can be attributed to: 1) equivalent porous media approach 2) local surficial geologic controls 3) confined aquifer conditions.

I. INTRODUCTION

IA. PARK BREAK INTRODUCTION AND PROGRAM GOALS

The George Wright Society 2014 Park Break program addressed the general question, "What drives the dynamics of rare and sensitive waters in Saguaro National Park?" The program took place March 10-14th, 2014 in the Rincon Mountain District of Saguaro National Park. The graduate students participating in Park Break reviewed Rincon Mountain geologic literature and selected papers related to this assignment, conducted field and geospatial imagery data collection, analyzed water quantity and quality monitoring data, and developed conceptual models for the park's waters on the basis of integration of results of these activities that were reported back to the park.

The program's specific goals included the development of one or more qualitative conceptual models, based on geological, geochemical and monitoring data that describe likely hydrologic processes within selected watersheds in the park, focusing especially on groundwater. Ultimately, these models will allow the park to better understand possible pathways of water supplying spring-fed rock pools (known locally as *tinajas*) and other springs. The conceptual models will provide a basis for refining monitoring programs, enabling the development of possible scenarios under different precipitation regimes, and aid in planning for protection of vulnerable aquatic and upland species for which these water sources make the difference between survival and extirpation.

The program began with the aim to address the following specific questions:

1. How is the regional geologic structure expressed at the local and intermediate scales in each of the drainages visited (Loma Verde and Chimenea)?
2. Are there relationships between local geologic features and presence of perennial/intermittent/or ephemeral pools?
 - a. At a range of scales, does there appear to be a relationship between geologic features and water?
 - b. At a range of scales, how do surface characteristics appear to influence water movement?
3. What does analysis of remote sensing data tell us about geologic structure, surface characteristics, and potential hydrologic processes in the Rincon Mountains as a whole and in the specific drainages we are studying?
4. What are the possible/likely processes and pathways by which higher-elevation precipitation travels to the valley basin?
5. What do precipitation (high and low elevation) and water level data indicate about potential water pathways on the mountainside (timing, intensity, and duration).
6. How do isotope and other water quality data affect the conceptual models?
7. Is there a correlation between watershed size or elevation and persistence of water present in tinajas?

IB. BACKGROUND TO THE RINCON MOUNTAIN DISTRICT OF SAGUARO NATIONAL PARK

IIB1. TINAJAS OF SAGUARO NATIONAL PARK, THEIR VALUE, AND POTENTIAL IMPACTS

Tinaja means “little cup” in Spanish, and is a local word used to describe bedrock pools in streams in the desert Southwest. Tinajas are of huge value to wildlife in the RMD and constitute the major source of water in Saguaro National Park during dry seasons (MacLeod et al. 2003). Long-term monitoring of leopard frogs and other aquatic species at the park (Wallace et al. 2010, Zylstra et al. 2013) has revealed their dependence on tinajas for reproduction and survival. They are undoubtedly essential for many non-aquatic species as well, as a large number of mammals and birds are regularly observed to visit them, especially during dry periods (Swann et al 2008, 2009). Because of the importance of tinajas for wildlife, the park has been gathering information and monitoring their water dynamics for more than a decade. Nevertheless we have little knowledge of how the tinaja systems of the Rincon Mountains function, which is why this is the subject of the 2014 Park Break.

Typical tinajas occur in streams throughout the Rincon Mountains, usually (but not always) in clusters associated with outcrops of hard metamorphic bedrock (as in Fig. 1). The park regularly monitors approximately 240 tinajas associated with leopard frog habitat, but there are many others (especially at high elevations) that are not regularly monitored. MacLeod et al. estimated capacity for more than 64 tinajas in RMD, and found that they ranged from close to 0 cubic meters to more than 44.1 cubic meters.



Figure 1: *Madrona Pools (tinajas) in Chimenea Creek at Madrona Ranger Station. Water levels in Pool 1D (in background) have been monitored since 2004. The pool has not been observed to go dry since regular observations began in 1996.*

Although it may seem plausible that tinajas are filled by stream flow during periods of high flow due to enhanced precipitation (typically during Jan-March, then during July-August) and retain this water as it gradually evaporates during subsequent dry months, various lines of evidence suggest that many tinajas are actually spring-fed. Experiments by park staff (Don Swann, personal communication) indicate that when water is excavated from small tinajas, they will subsequently re-fill. Data from data loggers (Fig. 2) also show that pool levels decline during the day when evapotranspiration is expected to occur and rise during the night. Interestingly, tinajas typically occur in areas where two sets of fractures meet (Fig. 3). It is not known how tinajas are formed, but evidence suggests it is by erosive stream activity on bedrock along fractures that are also associated with groundwater.



Figure 2: Detailed daily water levels of Pool 1D during a 3-day period in June. Y-axis is pool level; x-axis is number of 15-minute intervals. Pool levels rise slightly at night, then decline during the day, presumably due to evapotranspiration.



Figure 3: Photo of a “typical” tinaja located in Wildhorse Canyon. Red arrows indicate directions of prominent bedrock fracture.

While Saguaro National Park has been gathering data on tinajas since 1996, much of these data, especially that collected prior to 2004, is bimodal and only includes whether tinajas were wet or dry when visited during leopard frog surveys. In 2004, park staff began collecting pool surface water elevation on selected tinajas in the “Madrona Pools,” located at low elevation within the Chimenea watershed. Beginning in 2010, the park installed Level Troll dataloggers in several tinajas in the Madrona Pools and Loma Verde Creek. In addition, in 2010 staff began regular monthly surveys of water presence/absence in Loma Verde Creek that included taking pool level data on selected tinajas. In January 2013, this monitoring was extended to 4 other streams. Currently, on the first Thursday of each month staff visit these 5 streams, record where water is present and where it is not, and also record water levels (from a vertical datum above the pool) for a number of selected tinajas. Results of these activities are shown in Figures 4 and 5. Figure 4 is a plot of water levels taken every two weeks in two tinajas in Chimenea Canyon during 2004-2013. Pool 1D has not gone dry during this period; Pool 1L has gone dry twice.

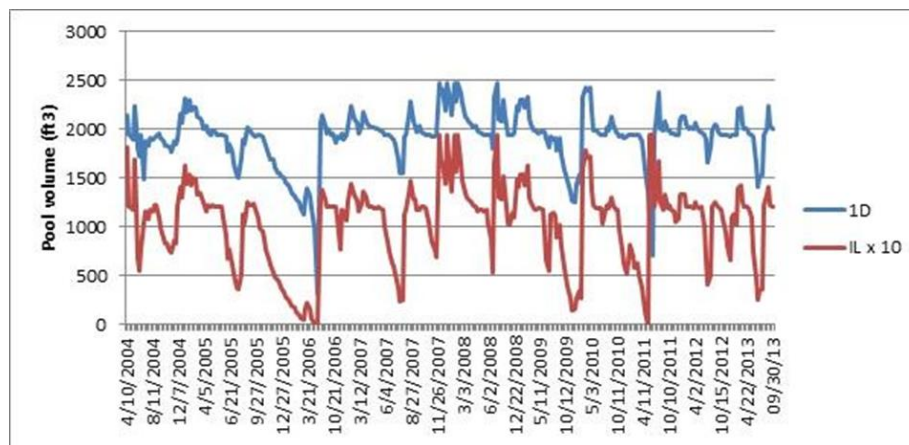


Figure 4: Pool volume of two tinajas in Chimenea Creek, 2004-2013. Measurements by hand prior to 2010, by data logger since 2010. Volume of pool 1L is much less than 1D, so it is multiplied by 10 in this figure.

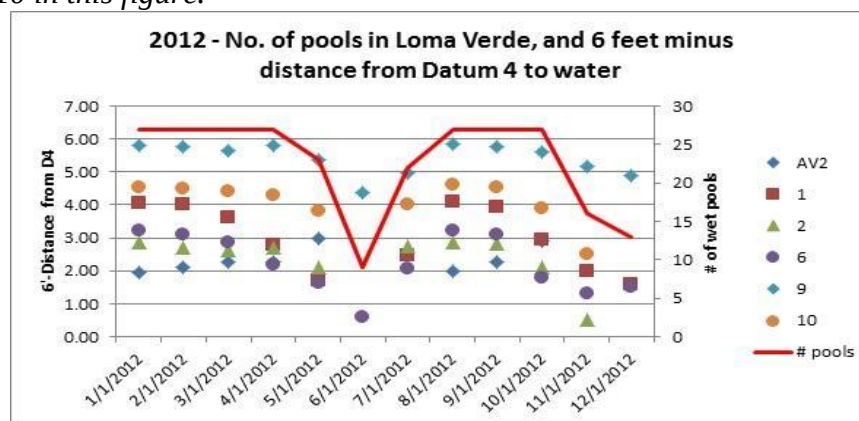


Figure 5: Relative tinaja water levels in 6 tinajas in Loma Verde Canyon and during monthly surveys 2012. Red line is the number of tinajas in the canyon (out of 27 total) containing water on that date. Pool levels are measured as distance from a vertical datum above the pool to the water surface. In general pool levels (and number containing water) are highest in January-April, decline May-August, increase after summer rains, then decline October-December.

A large number of tinajas in the park have never been observed to go dry since leopard frog monitoring began in 1996. Frog monitoring typically takes place in June-July and October-November, often the driest months of the year. Of pools that have been surveyed more than 20 times since 1996, 30 tinajas have never been observed as dry (Swann et al. 2013). These “perennial” tinajas represent extremely valuable habitat for wildlife. Khamsi et al. (2013) looked into universal patterns of tinaja volume in the RMD. They compared the number of tinajas that were wet or dry on survey dates and with surface water elevation in a single large tinajas (Pool 1D in Chimenea Creek, shown in Fig. 3) measured at the same time. They found a strong correlation not only within Chimenea Creek, but throughout the park. Figure 6 is a graph of the raw wet-dry tinaja data (represented as the percentage of tinajas containing water surveyed on that date) with elevation of the surface water in Pool 1D. When pool 1D is full, close to 100% of the park’s tinajas contain water. When the elevation is less than 3418 feet above sea level, less than 40% of the park’s tinajas contain water. Noise on this graph can probably be attributed to summer rains temporarily filling tinajas, which should be dry, based on the groundwater table. Erin Zylstra, UA PhD student (unpublished data), is expanding Khamsi et al.’s analysis and her preliminary work shows a strong statistical relationship between water in all tinajas in the park and Pool 1d water surface elevations.

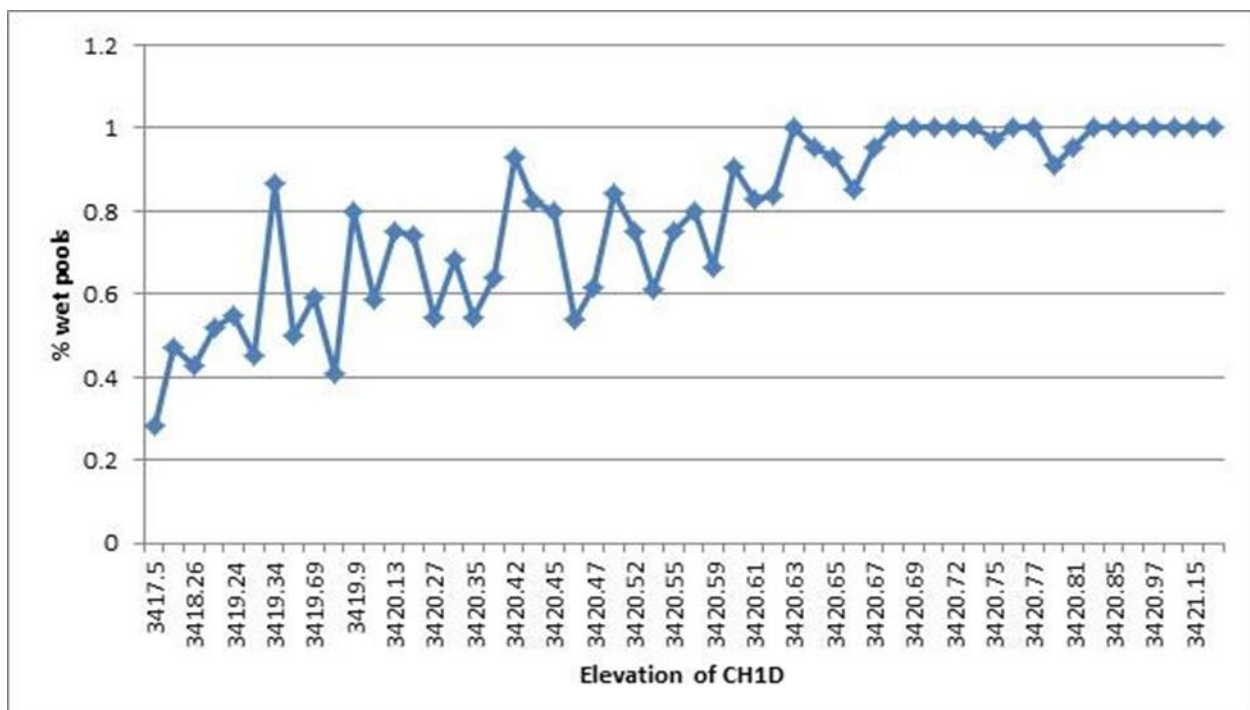


Figure 6: Number of tinajas in RMD that contain water compared to simultaneous measure of surface water elevation in Chimenea Pool 1D, a large perennial tinaja. When pool 1D is full, 100% of the tinajas contain water. When the elevation is less than 3418 feet above sea level, less than 40% of the park’s tinajas contain water.

Tinajas can fill rapidly as a result of flow in the creeks due to major precipitation events, including both local events and large events that occur through the Rincon Mountains. However, they can also fill somewhat rapidly in response to precipitation events that occurred weeks before

higher up on the mountains, (Don Swann, Eric Stitt, Erin Zylstra, pers. observations). Joshua Conver (unpublished data) analyzed response of tinajas in Chimenea Creek to specific rain events in the Rincon Mountains as measured at 8000' at Manning Camp.

After tinajas are filled and flow occurs in streams in the rocky foothills of the park, there may be a lag time between when flow occurs in the middle reach of Rincon Creek and other low-gradient reaches. Perger (2014b) has looked at a number of specific events where flow was observed in the Madrona Pools area of Chimenea Creek before it was observed 1.5 miles downstream in Rincon Creek. Figure 7 is an illustration of one event where the tinajas filled and discharge occurred at the Madrona Pools for more than one month before it was recorded in the monitoring wells and stream gage on Rincon Creek.

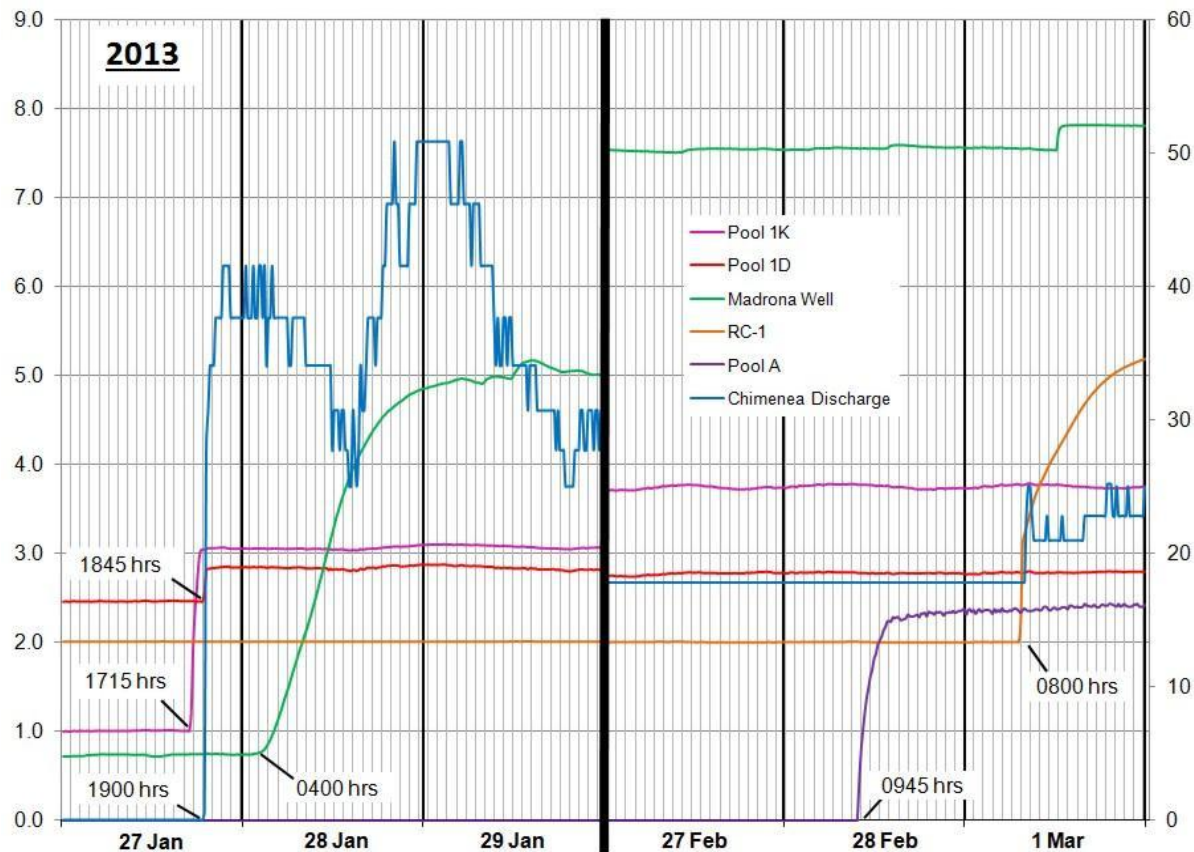


Figure 7: Diagram based on data logger data showing temporal response to a precipitation event high on the mountain in January 2013. Values on y-axis are relative, but show timing of response by the Chimenea Pool 1k (upstream tinaja), Chimenea Pool 1d (downstream tinaja), Madrona well (approx. 300 m downstream of 1d), estimated discharge at pool 1d, well RC-1 in Rincon Creek (located about 1.5 miles downstream of pool 1d), and elevation of surface water in Rincon Creek at Pool A (adjacent to well RC-1). Discharge in the major tributary of Rincon Creek (Chimenea) did not lead to flow in Rincon Creek until more than one month had passed, suggesting that it may take some time to fill the alluvial aquifer when it is dry.

Tinajas are formed by erosion and are often clustered in the flowline of streams. They depend on groundwater and/or runoff surface water. Springs and tinaja ecosystems are of high wildlife value, supporting a variety of endemic species and providing a source of drinking water

for the park's many animal species. These ecosystems also function as important stops for long-distance migratory neo-tropical bird species, as well as functioning as corridors of dispersal for both plant and animal taxa (Baird et al. 2000).

The lowland leopard frog (*Rana yavapaiensis*) is dependent on the waters of perennial tinajas, and is actively being monitored by Saguaro National Park. Springs and tinajas have the ability to serve as paleoreugia: stable, confined environments where evolutionary processes over time result in large numbers of specialized and endemic species. North America's highest densities of endemic species occur in and around xeric spring ecosystems, such as Montezuma Well, Arizona, Ash Meadows, Nevada, and Cuatro Cienegas, northern Mexico. (Stevens and Meretsky 2008). As such, springs are viewed as keystone ecosystems; confined habitats exerting a disproportionately large influence on the biodiversity and processes of the surrounding landscapes (Perla and Stevens 2008).

The distribution and density of springs vary greatly across North America. Topographically diverse regions, such as the Rocky Mountain have proved to hold the highest concentration of springs, as opposed to the Great Plains which holds the lowest. In numbers, Nebraska and Kansas have 0.0001 springs per square kilometer, whereas Arizona has the second highest density of springs with 0.017 per square kilometer. These numbers are subject to some uncertainty, since no state-level inventory of springs has been conducted. Inventories of springs, in cliff-dominated habitats, appear to induce an even higher level of uncertainty. Estimates suggest that less than 25% of springs, in the Grand Canyon and rocky parts of the southern Colorado Plateau, have been mapped (Stevens and Meretsky 2008).

It is estimated that anywhere between 40 and 90 % of riparian ecosystems and springs habitats in the American Southwest have been lost as a result of anthropogenic activities. Studies at several large land management units in Arizona, found that 80 – 93 % of remaining, springs have had their ecological integrity severely impacted, again, the cause of this is anthropogenic activities (Perla and Lawrence 2008). Disappearances of desert springs and their biota have accelerated in the recent past and this, almost exclusively due to humans.

Agricultural irrigation and dropping groundwater tables are the primary causes of depletions of springs. Overgrazing is a pervasive threat, that directly changes community composition, increases erosion and decreases the infiltration capacities of the entire wetland area. Climate changes are also likely to affect springs of the Southwest in a negative direction. Models predict increasing summer temperatures, decreasing annual rainfall and prolonged periods of drought, changes which presumably will affect the groundwater table, and thus, the springs of the region (Overpeck et al. 2013).

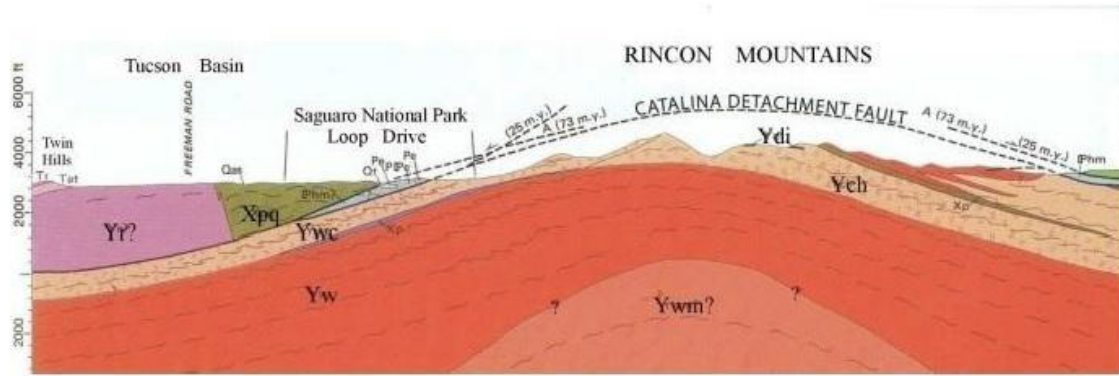
IB2. RELEVANT PHYSICAL PROPERTIES

The Rincon Mountains are one of southern Arizona's Sky Island Mountain ranges, which rise up out of the desert into woodlands and forests at high elevations and connect the Rocky Mountains to the north with the Sierra Madre Mountains to the south (Fig. 8). The Rincons also lie at the interface of the Sonoran and Chihuahuan deserts. In addition, because they range in elevation from 2,680 to 8,666 feet, the Rincons encompass six structurally distinct biotic communities, from Sonoran Desert shrub to mixed-conifer forest, that contain an incredible diversity of life.

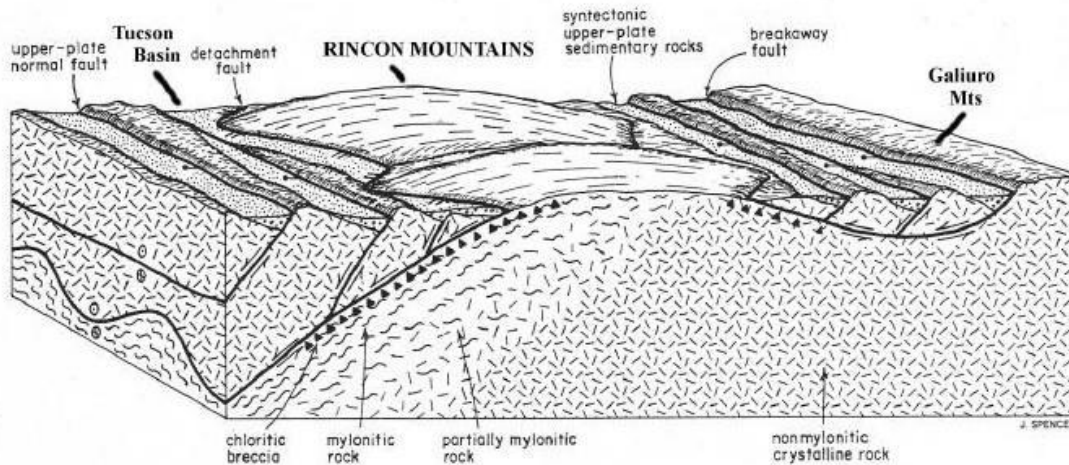


Figure 8: Rincon Mountain District within the Sky Island Region of Arizona, New Mexico, and Sonora, Mexico. The park lies on the eastern edge of the Sonoran Desert; the western edge of the Chihuahuan Desert; the southern-most portion of the Rocky Mountains; and the northern extension of the sub-tropical Sierra Madres. The Santa Cruz River flows on the west side of the Rincons, and the San Pedro River flows on the east side.

The Rincon Mountains have long been the subject of extensive geologic study and mapping, and Saguaro National Park has an official Geological Inventory Report (Graham 2010; http://www.nature.nps.gov/geology/inventory/publications/reports/sagu_gri_rpt_view.pdf). Although this report is not perfect, it is the most comprehensive guide available to the geology of the park and provides many references to specific geologic features. Drewes (1976) is a dated, but excellent geologic map of the Rincon Mountain District, and Richard et al. (2005) is a more recent map of the Rincon Valley. In addition, there is a somewhat recent book, A Guide to the Geology of Saguaro National Park (Bezy 2005). What follows is a brief description of the geology of the Rincon Mountains largely taken from the inventory report.



A) Cross section view



B) Block diagram

Figure 9: Cross sectional view (A) and block diagram (B) of the metamorphic core complex in the western Rincon Mountains (Graham 2010), showing Catalina Detachment Fault and the rock units above and below the fault. For more information see Davis (2013).

The regional landscape of the park evolved as part of the Basin-and-Range province, a tectonic terrain developed during extensional (“pull-apart”) faulting about 15 million years ago. The Rincon Mountains are part of a large three-humped metamorphic core complex. Unique to the mountainous North American Cordillera, metamorphic core complexes consist of metamorphosed basement rocks overlain by unmetamorphosed rock units. These two structures are separated by the shallowly-dipping Santa Catalina detachment fault (called a “décollement”), which displaces the overlying units up to several kilometers. Outcrops along Cactus Forest Drive are considered to be the “showpiece” of diagnostic features of metamorphic core complexes, and the geology of the RMD served as the basis for distinguishing and classifying the fundamental structural characteristics of metamorphic core complexes (Davis and Coney 1979; Davis 1980, 1987, 2013; Dickinson 1991).

In general, the metamorphic core complex of the Rincon Mountains consists of a dome-

shaped granite pluton overlain by severely stretched and micro-fractured granitic, sedimentary, and volcanic rocks. The low-angle Santa Catalina detachment fault separates the underlying metamorphic rocks (gneiss) from a variety of rock types including highly faulted, brittle layers of Paleozoic rocks (Fig. 9). The convex-up fold (“antiform”) in the Tanque Verde Ridge is shaped like a mountain-sized turtle shell, which plunges southwesterly toward the park headquarters (Davis 1987; Bezy 2005). Rock layers that once covered the crest of the Rincon Mountains have been eroded by downward cutting streams. Continued erosion by running water along joints and faults have cut canyons into the hard gneiss. Beveled rock platforms, called pediments, formed from erosion of granite at the foot of the mountain.

Because of the region’s semi-arid climate, soils are not well developed in southern Arizona. The ground surface of most of the Rincon Mountains consists of bedrock or regolith. A thin veneer of alluvium covers pediment surfaces along the margins of the range. This alluvial fill thickens to tens of feet along larger drainages, such as Rincon Creek, and has been cut into terraces by stream entrenchment in places. Aridisols with calcium carbonate (caliche) concentrations have developed on this deeper alluvium. Aridisols are soils that are typically saline or alkaline with very little organic matter and are found in arid regions. At the highest elevations, where the natural vegetation is coniferous forest, thin soils with distinctive soil horizons have developed.

IB3. RELEVANT CLIMATOLOGICAL PROPERTIES

Temperatures in the lower elevations of the park often exceed 100°F about 70 days (20%) per year, and freezing temperatures occur about 6 nights per year. Temperatures average 20 to 30 degrees F cooler at higher elevations in the Rincons (Mott 1997). Sunshine is abundant, humidity is low, and snowfall can be heavy in the high country in winter.

Annual precipitation in the Tucson Basin averages 28 cm (11 in), but at Mica Mountain (elev. 8,666 ft) it can exceed 76 cm (30 in.). Most precipitation occurs during two rainy seasons: July through September, and January through March (Fig. 10). Intense thunderstorms take place from July through September, derived from moisture picked over the Gulf of Mexico, and account for about half the total precipitation. More gentle rains and snow, derived from the Pacific Ocean fall during January to March (Mott 1997). Although the region receives more rain than most deserts, it is a very arid environment due to average potential evaporation of 229 cm (90 in).

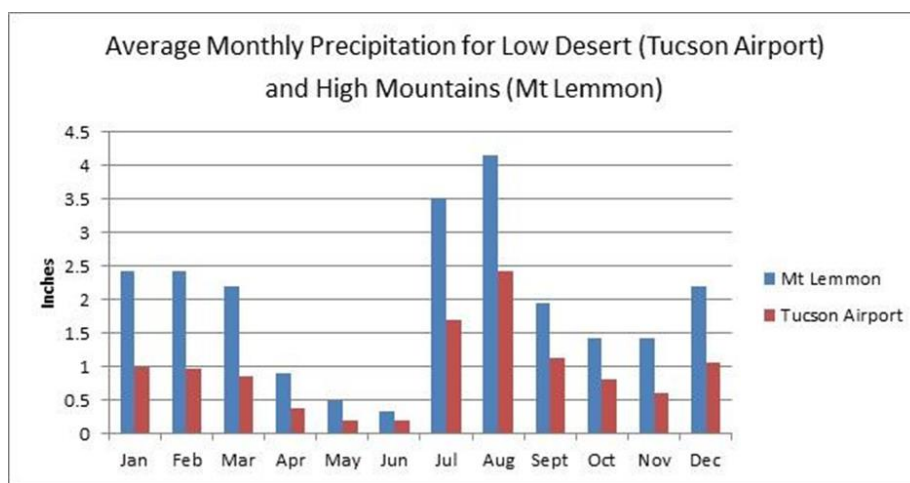


Figure 10. Average monthly precipitation for desert and mountains near Saguaro National Park.

IB4. RELEVANT HYDROLOGIC PROPERTIES

The hydrology of the Rincon Mountain District has been summarized in several technical reports, including Mott (1997), Baird et al. (2000), and MacLeod (2003). The Mott and Baird reports highlighted what was known and not known about water in the park, and raised a number of important long-term conservation issues that the authors felt that the park needed to address. They led directly to the Rincon Creek water rights case.

Most of the precipitation that falls in the Rincon Mountains drains to the west into the Santa Cruz River (see Fig. 8). Tanque Verde Creek (on the north) and Rincon Creek (on the south) drain 85% of the park's surface area into the Santa Cruz (MacLeod et al. 2003). Of the remaining 15%, 2% drains from Box Canyon directly into Pantano Wash (and then to the Santa Cruz), and 13% drains through Paige Creek on the east side of the Rincon Mountains into the San Pedro River.

Located just outside the northern boundary of the park, Tanque Verde Creek flows due west and also drains portions of the Santa Catalina Mountains. The total watershed of this creek is about 567 km², with about 91 km² within RMD. This watershed is approximately 33% of the total land area of RMD and includes major canyons on the west side of the range such as Wildhorse and Loma Verde, which drain into Monument Wash (and then into Tanque Verde Creek), as well as canyons on the north side of the range, such as Joaquin and Del Pino and the creek's main stem, which flow north directly into Tanque Verde Creek. Within the RMD, the elevation range within the watershed is from about 815 to 2650 m (2675-8660 feet) (MacLeod 2003).

The Rincon Creek watershed drains 52% of the total RMD area. Major subwatersheds include Chimenea, Madrona, and "Rincon North" creeks, as well as the main stem of Rincon Creek below Rincon Peak. There are many minor tributaries. Chimenea Creek drains 29% and Madrona Creek drains 16% of the Rincon Creek watershed that is within the park. Within the RMD, the Rincon Creek watershed ranges from about 900 to 2,740 m (2950-8660 feet), with the highest point being Mica Mountain in the northwest part of the park. The "middle reach" of Rincon Creek runs along the south boundary of the park. The park has an important water rights case in the creek, which will be described in a separate chapter.

Stream reaches in the RMD can be conveniently separated into one of two physical categories (Baird et al. 2000). The first category is comprised of high-gradient (>25 m/km) reaches (hereafter, "upper reaches") characterized by alternating outcrops of bedrock channel with alluvial floored stretches. These alluvial pockets occur upstream from geologic structures that create small, shallow basin that are filled with sediment. These pockets presumably have only a small alluvial water storage capacity compared to valley bottom capacity, although it may be locally significant for the park's wildlife.

The second category (Baird et al. 2000) is comprised of low-gradient reaches with slopes less than 25 m/km and characterized by continuous alluvial floodplain. These low-gradient reaches, sometimes called middle or lower basin areas, have relatively shallow alluvial sediments and occasional bedrock outcrops, which form sub-surface dams that force groundwater to the stream surface. Typical low-gradient "middle reaches" include Rincon Creek above and below the confluence of Chimenea Creek and Monument Wash, a tributary of Tanque Verde Creek in the northwest portion of the RMD (Baird et al. 2000).

The geologic framework of Tanque Verde Ridge and Rincon Valley, including the major Pantano and Catalina faults, exerts a strong control on the hydrology of the riparian systems within the park (Baird et al. 2000). These faults constitute a line of hydrogeologic separation

between the occurrence and utilization of groundwater in Rincon Valley and the main Tucson Basin, and thus has the effect of isolating groundwater in the lower basin of Rincon Creek from the effects of pumping in the Tucson Basin.

In average years, snowmelt in winter and spring leads to most of the annual surface flow. In summer, surface flow occurs exclusively after large storms. Streams are perennially interrupted, intermittent, or ephemeral, but pools of water often remain year round. Several springs and seeps occur throughout the upper elevations. Water sources that contain water during drought periods (generally a few tinajas within larger drainages, but also some short reaches of Chimenea and Rincon creeks) are crucial to wildlife, and in some cases are essential to the persistence of a species in an area. Loss of these resources can be caused by nearby groundwater pumping, erosion from wildfires, or invasion of exotic species such as tamarisk and buffelgrass.

MacLeod et al. (2003) prepared a preliminary water budget for the RMD. They estimated that the Tanque Verde watershed within the district had a unit area discharge of $0.044 \text{ mm}^3/\text{km}^2/\text{year}$, yielding an estimated annual discharge of $4.0 \text{ Mm}^3/\text{year}$. For the Rincon Creek watershed unit area discharge was $0.067 \text{ Mm}^3/\text{km}^2/\text{year}$ and estimated annual discharge was $9.40 \text{ mm}^3/\text{year}$.

Groundwater decline is a major issue in the Tucson area. From 1947 to 1985, the majority of the area experienced groundwater declines ranging from 40 to 80 feet (Mott 1997). As aquifers are dewatered, the basin experiences land subsidence and surface fissures.

Estoe (2012) studied the origin of waters in the Rincon Mountains and vicinity using hydrogen, oxygen, and tritium isotopes. Among other things, Estoe (2012) found that shallow groundwater originating as Rincon Creek runoff contains isotopes consistent with winter precipitation as the dominant source, with minimal evaporation prior to infiltration in flood-plain sediment, while shallow groundwater originating from Tanque Verde Creek has undergone greater evaporation prior to infiltration, and may include summer as well as winter runoff. The author suggests that the difference in degree of evaporation corresponds with the steepness of the creeks, with Rincon Creek being much steeper and shorter than Tanque Verde Creek. In most cases with water in the Rincons, the range of isotope compositions from spring to spring, and the presence of measurable tritium, suggests the presence of short (recent) flow paths. However, groundwater residence times are much longer in a few locations such as Douglas Spring and “the Grotto”, a large pool in Rincon Creek.

II. METHODS

IIA. EXISTING DATASETS ON THE TINAJAS OF SAGUARO NATIONAL PARK

Preliminary searches through existing datasets were carried out to help formulate hypotheses as well as to guide field data collection and analyses. Datasets including climatological, monitoring, spatial and satellite imagery data were mined to help answer questions being addressed by the Park Break participants. All previously collected data is cited in the instances and analyses it was used.

IIB. FIELD METHODS

To elucidate structural geologic influences on the presence of tinajas we measured joint density and the strike and dip of joint sets in the Chimenea (Madrona pools M1A-M) and Loma Verde (AV2-3, LV0B-1 and one potential tinaja location) drainages basins. We chose these two basins because of the pre-existing hydrologic data for these basins, the apparent difference of tinajas size, distribution and presence of water in tinajas, differences in contributing area as well

as logistical considerations. We took measurements at two scales, 1m² and 10m² to capture local and basin scale trends. We also took qualitative data regarding the surficial geology and vegetation at the Madrona pools in the Chimenea basin. For the 1m² plots strike and dip were measured for each joint in a set. Degree range for individual joint sets was set at 5°. For the 10m² plots the number of joint sets was counted and strike was taken to determine consistency, but not all joints in a set were measured for strike. Dip was taken where it was possible to determine the 3rd dimension. Degree range for individual joint sets was set at 20. Joint sets that did not fall into the degree range set were distinguished as a new joint set. To be considered a joint set, at least 3 joints had to be present. All measurements were taken using the right hand rule convention with azimuth Brunton compasses.

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IIC. TINAJA CLASSIFICATION

Tinaja water levels are determined by local hydrologic driving forces. During the past decade of monitoring, dozens of visits to a tinajas have documented that some tinajas are perennially pooled. However, other tinajas experience both wet and dry periods, but their rates and patterns of drying vary. Our multiple working hypotheses recognize that different physical processes may be supporting the tinajas. Anecdotal evidence also supports this idea that multiple types of tinajas occur within Saguaro NP.

We used monthly visits to a subset of SAGU tinajas to classify them based on the timing of water presence or absent at each. Two subsets of data were used: 1) Monthly visits to 95 tinajas across 5 drainages (Loma-Verde, Steel Tank, Wildhorse, Madrona Creek, and Chimenea), from February 2013 to February 2014, and 2) Monthly visits to Loma-Verde Wash from 2011 to 2014. Tinajas were classified through cluster analyses using Euclidean Distance and Ward's group linkage method. The 5-drainage classification was pared at five classes, and the Loma-Verde classification pared at 4 classes.

IID. WATER TABLE MAP

Recognizing that a basic water surface map was not previously constructed, a water table map was made using the tinaja elevations. Elevations were found by using the 10m resolution digital elevation model (DEM) at the tinaja point. There are obvious errors using such a coarse DEM in a sloped environment. The elevations were plotted on a map with 25m land surface

contours. The map was constructed assuming that the tinajas reflect an outcropping of the water table, that water table contours should honor areas where no tinajas were present and where tinajas were present, and that the hydrogeology of all the tinajas is connected. These data produced a reasonably smoothed interpretation. Where a water table contour exceeded the equivalent land elevation contour, groundwater should outcrop on the surface. This map should not be interpreted as an exact representation of the water table. Future maps could be drastically improved by having an actual elevation of the tinaja water surface.

IIE. DISCHARGE POINTS

Groundwater discharge points are critical to the function and long-term preservation of tinajas in Saguaro NP. Groundwater discharge is a spatially variable process, and identifying where discharge occurs facilitates hypothesis testing. Documenting known discharge tinajas allows these sites to be considered as a unique subset among all tinajas. Using monthly visits to tinajas in 4 drainages (Steel Tank, Wildhorse, Madrona Creek, and Chimenea), we identified tinajas that were recorded to have surface outflow but no surface water inflow.

III. RESULTS AND DISCUSSION

IIIA. INFLUENCE OF PRECIPITATION

In this region, most of the annual rainfall occurs during high-intensity or long-duration storm events in summer and winter. There appears to be a lag between major precipitation events and rises in pool elevation, as well as between dry periods and declines in pool elevation for the Madrona pools in the Rincon Creek watershed (Figs. 11 and 12). Cumulative rainfall observed over 3-, 7-, and 30-day periods visually suggests that the rate of change in pool elevation may be closely related to upstream groundwater recharge (Fig. 11). There is also a lag between precipitation and pool discharge, which is logical because flow only occurs when pools fill to maximum levels (Fig. 12). This only serves as anecdotal evidence that groundwater recharge from throughout the contributing watershed area is the predominant source of water to tinajas during dry periods. Stable isotope analysis has revealed that winter precipitation is the dominant water source to the Rincon Creek shallow groundwater flow (Estoe 2012). Lag times ranging from days to months, and perhaps even years, and long residence times are indicative of complex groundwater flow pathways. Furthermore, the synchronized changes in pool elevation seem to suggest strong regional connectivity in groundwater sources of tinajas, while the prevalence of tinajas is more likely controlled by local topography and geology.

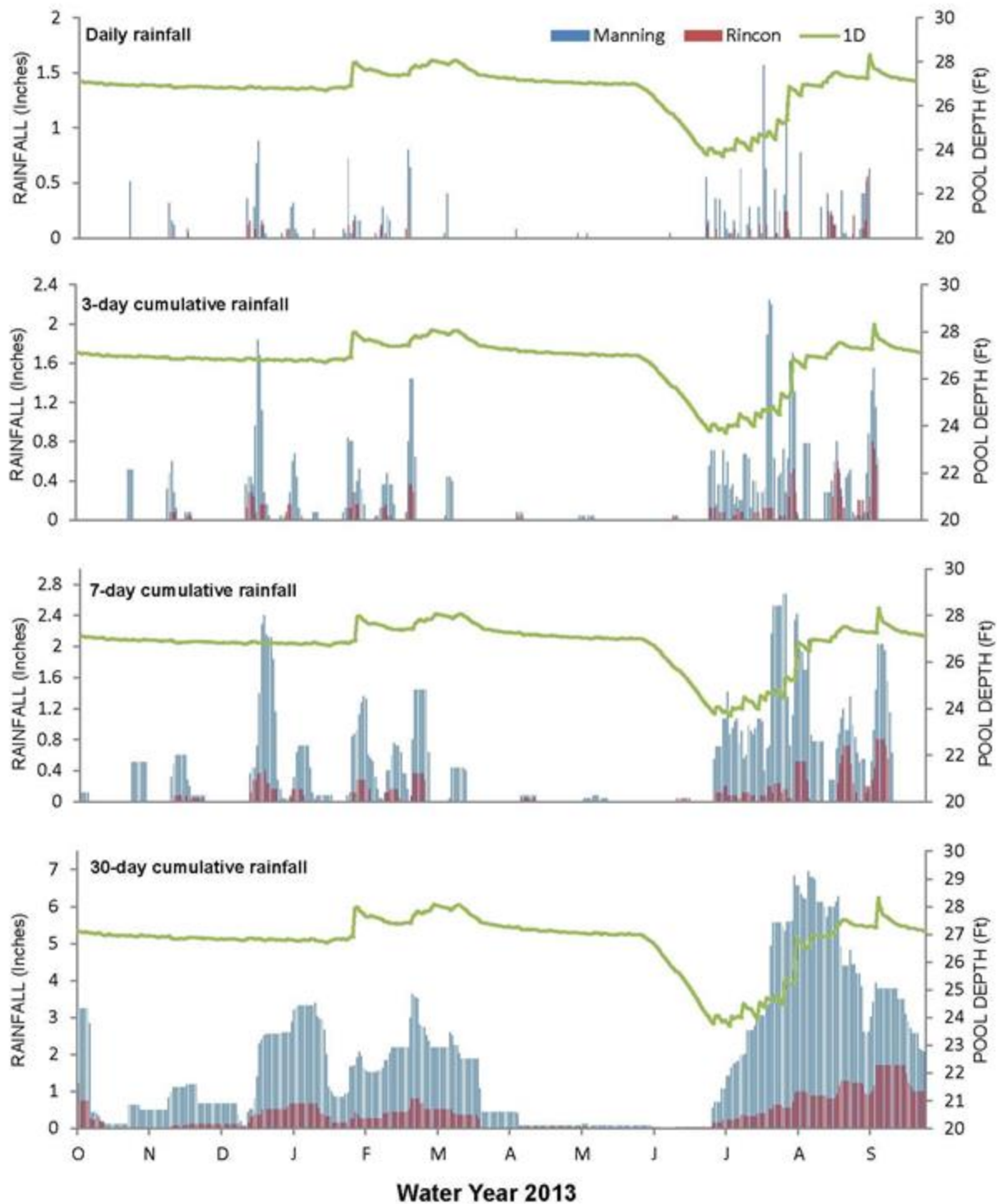


Figure 11: Daily rainfall measurements (top) taken from tipping-bucket gages at Manning Camp Station (high elevation) and Rincon Creek Station (low elevation) and 3-, 7-, and 30-day cumulative rainfall (below), with daily pool 1D depth (adjusted from original data logger measurements) [Data provided by Saguaro National Park].

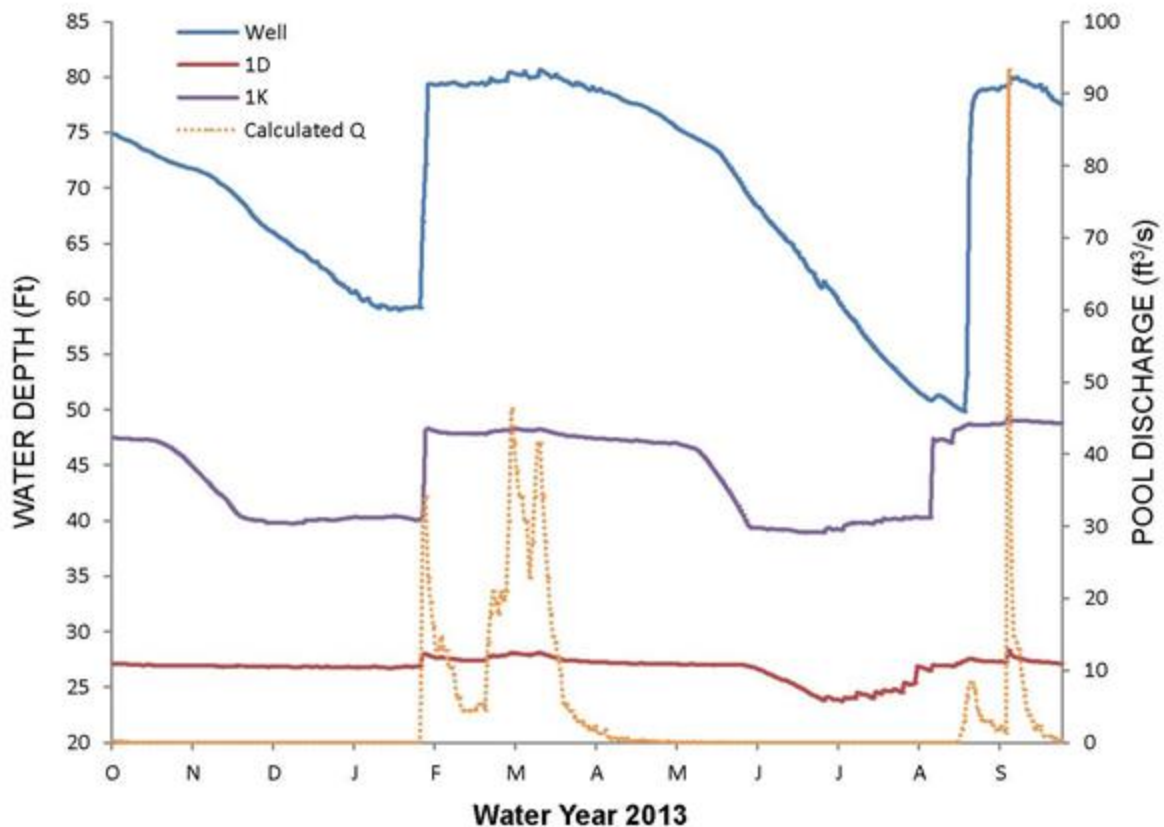


Figure 12: Water level in Madrona Pools (1D, 1K) and Madrona Well, with discharge for Pool 1D (adjusted from original data logger measurements) [Data provided by Saguaro National Park].

Future research on the factors controlling tinaja depth should include investigation into groundwater recharge rates. Cross correlation analysis on existing precipitation and well level data may be used to quantify lag time (See methods: Lee et al. 2006; Lee and Lee 2000). In addition to ongoing conductivity measurement collection, solute mass balance analysis can be used to estimate groundwater recharge rates by measuring solute concentration, such as chloride, in rainwater and well/pool water (McCoy and Blanchard 2008). The avenue(s) by which precipitation recharges regional and local aquifers is also of particular interest. High-intensity storms in desert watersheds will likely produce surface runoff due to the limited infiltration capacity of arid, compacted soils, while perhaps longer duration events will infiltrate and disproportionately contribute to groundwater recharge. Studying infiltration and groundwater flow paths will improve our understanding of seasonal patterns in the persistence and drying of tinajas.

IIIB. ANALYSIS OF TINAJAS AND THE PHYSIO-HYDROLOGICAL LANDSCAPE

In addition to intensive field collection of geological data associated with tinajas of the Loma Verde and Chimenea stream beds and washes, geospatial analyses of park datasets including high resolution (6-inch pixels) orthophotos, a Lidar DEM (2-foot pixels), and digital 1:24,000 geological maps provided a broad scale perspective of the park's tinaja landscape. Numerous raster based products were generated from the parks 2008 and 2011 Lidar DEM datasets allowing more accurate modeling of watershed delineation and hydrological processes. Watershed basins were generated in ArcMap for the East Saguaro park boundary. A total of 653 complete and partial basins, many truncated by the park boundary, were created using a Lidar DEM-based flow direction raster. Of the 326 previously recorded tinajas, 324 tinajas (96.4%) were located in the five largest basins - the only basins exceeding 1,000 hectares in size (Fig. 13). The Park Break crew recorded 8 new small tinajas in a small basin reducing the percentages of park tinajas located in the 5 largest basins to 94.2%. The documentation of previously unrecorded tinajas during the Park Break study indicates that there are many tinajas remaining to be discovered in the park.

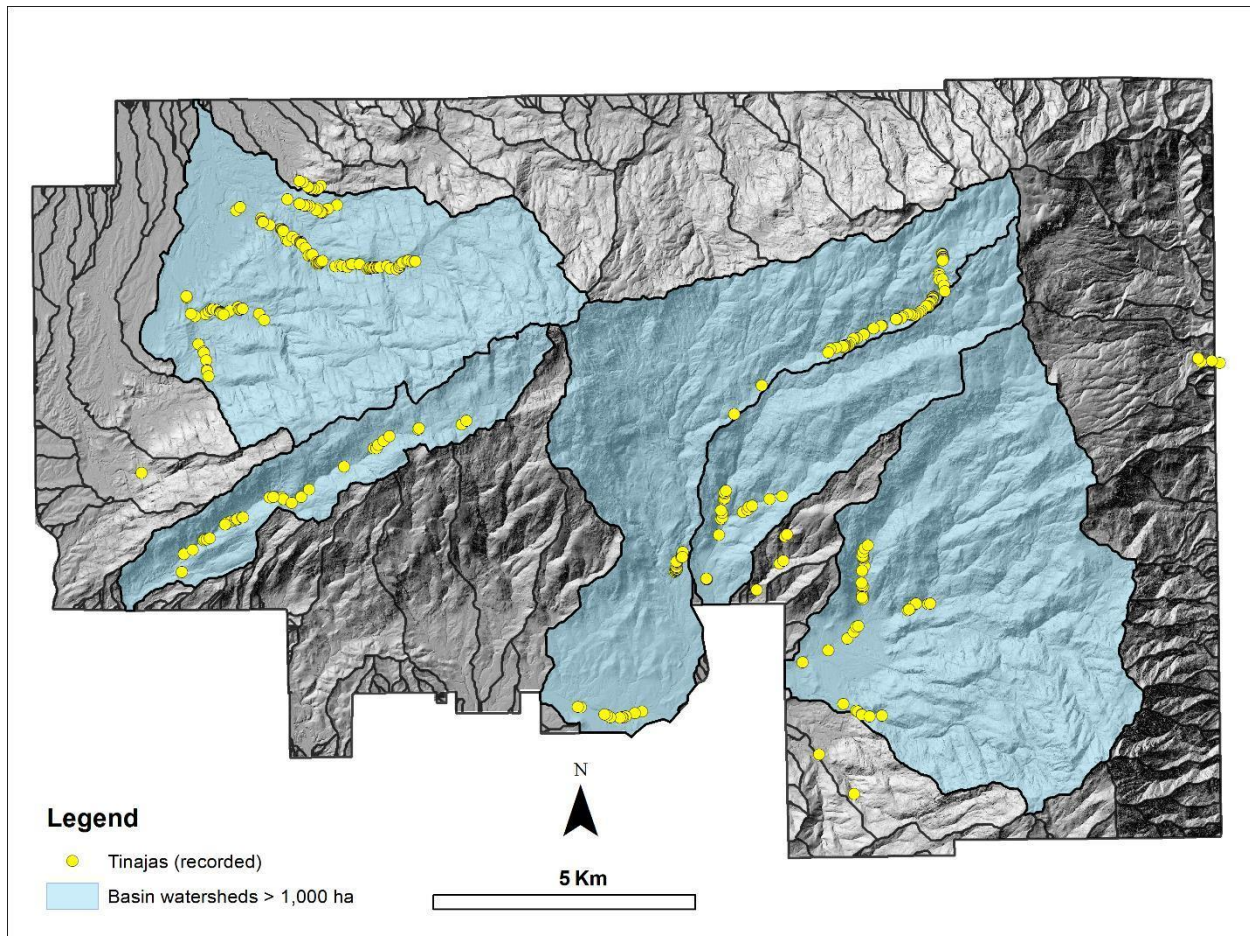


Figure 13: Five largest watershed basins in Saguaro East contain 94.2% of the currently documented tinajas.

Clearly, stream beds and washes located in the largest watersheds are more likely to contain tinajas. Moreover, examination of the contributing watershed areas for the uppermost tinajas of Loma Verde South, Loma Verde, Wildhorse, Steel Tank, and Park Break washes had relatively large contributing areas (Fig. 14). The upper most contributing watershed areas encompassed between 46.3 and 543.4 hectares (Table 1). These data are consistent with a model where tinaja formation requires a relatively large contributing watershed. In other words, they do not form on the uppermost elevations of a watershed.

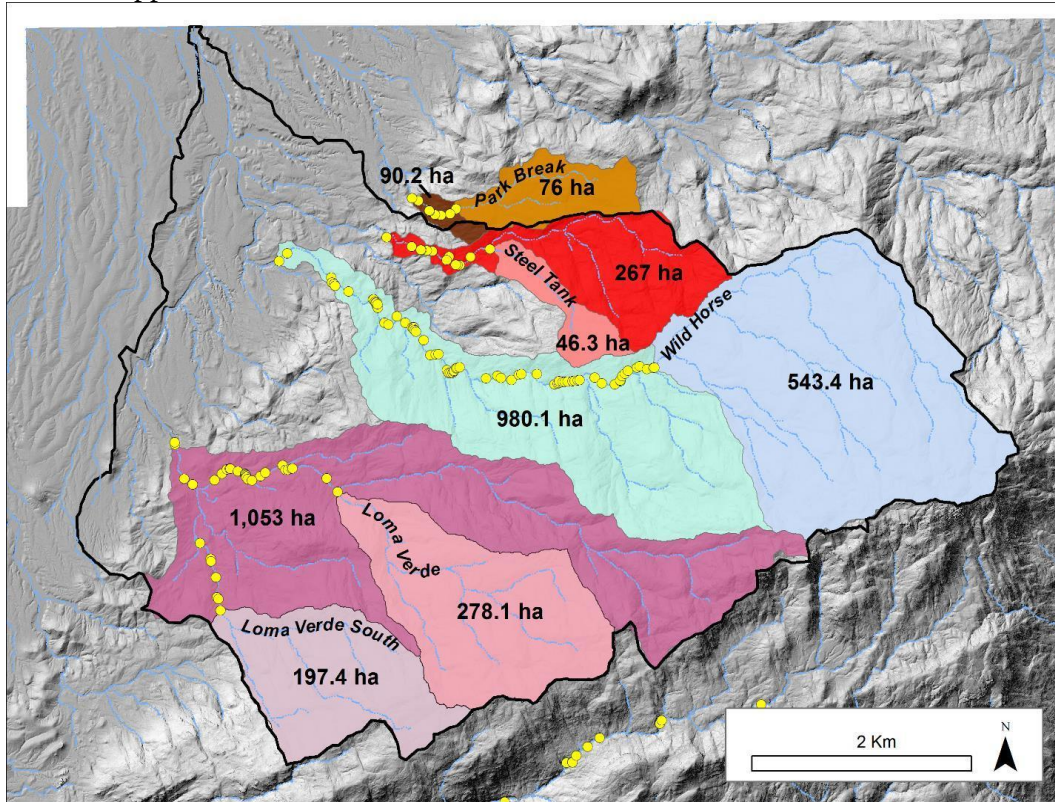


Figure 14: Contributing watershed areas for upper and lower most tinajas in Loma Verde South, Loma Verde, Wildhorse, Steel Tank and Park Break washes.

Wash	Upper tinaja contributing area (ha)	Lower tinaja contributing area (ha)
Park Break	76	90.2
Steel Tank	46.3	267
Wildhorse	534.4	980.1
Loma Verde	278.1	1,053
Loma Verde South	197.4	1,053

Table 1. Contributing watershed areas for uppermost tinajas and lowermost tinajas.

Tinajas overlaid on 1:24,000 geological maps do not readily identify strong correlations between broad scale lithographic units and tinaja presence (Figs. 15 and 16). Severity of incising and size of contributing watershed are co-related and cut across broad scale geological zones mapped by the USGS. Accordingly, it was fundamental to the success of the Park Break project to examine fine scale geological structures and patterns in the field.

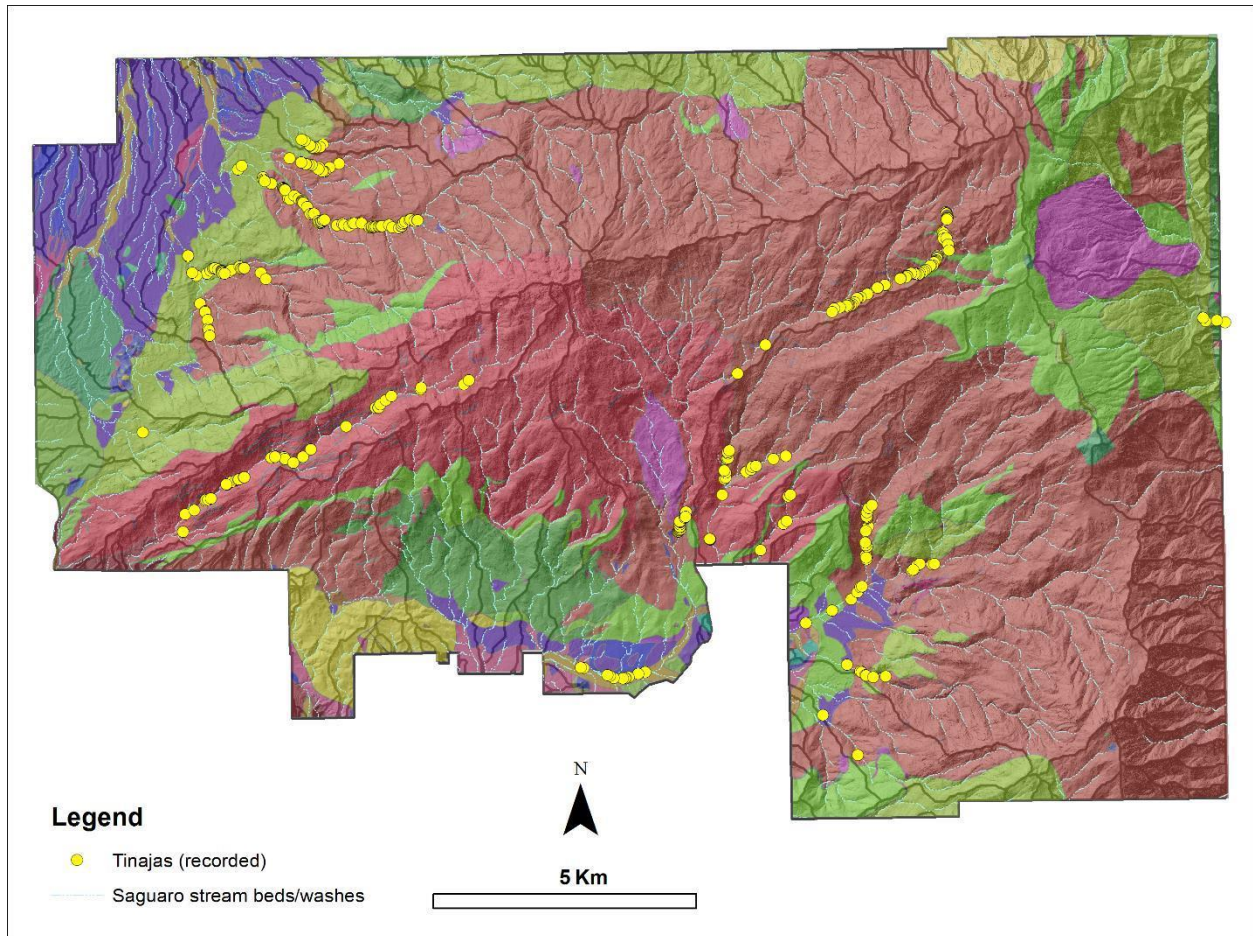


Figure 15: 1:24,000 geological map and 344 park tinajas.

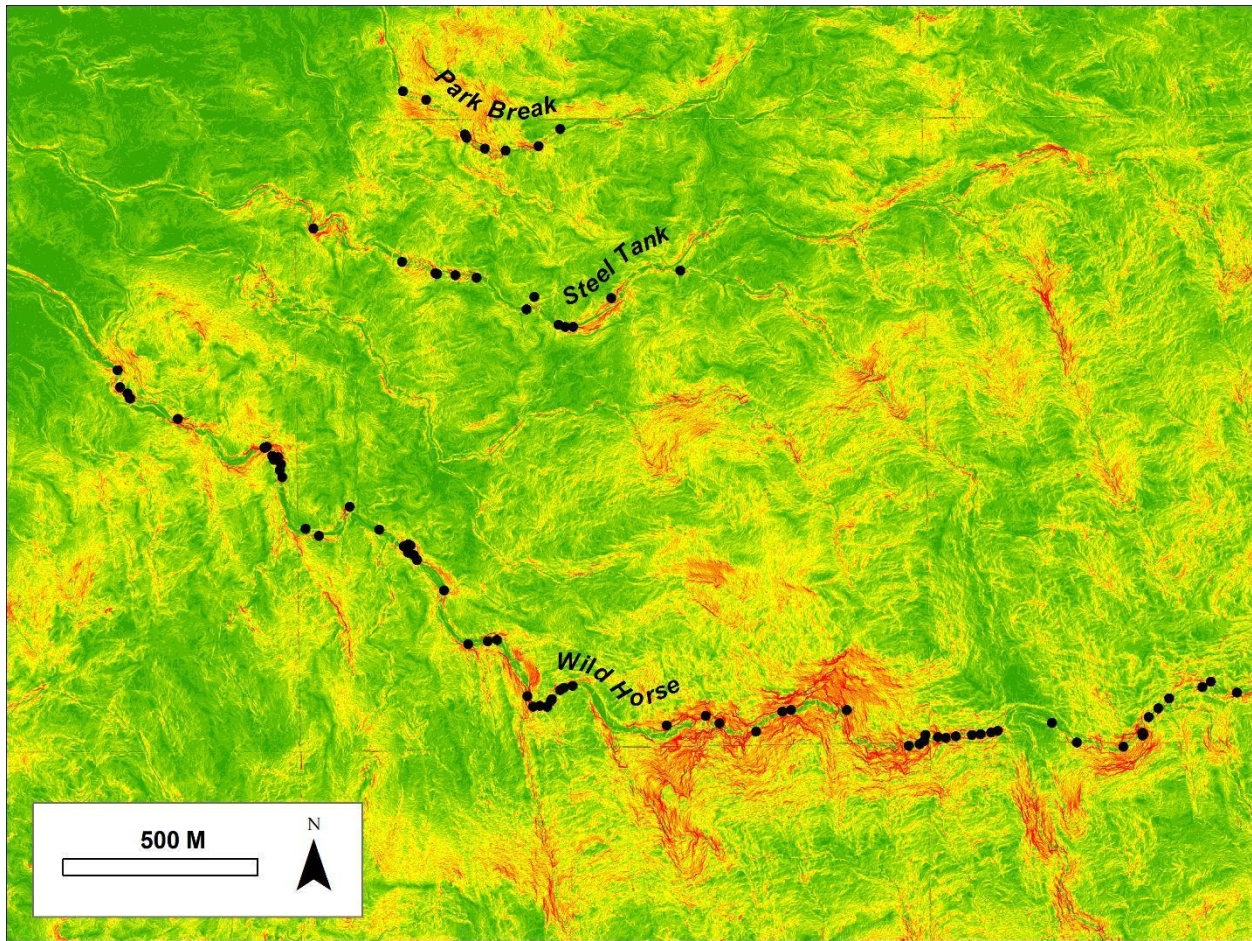


Figure 17: High resolution slope map identify incising along stream beds with tinajas. Other incised low order stream beds may lack sufficient contributing watersheds or other structural features to produce tinajas (red areas reflect steep slopes).

Additionally, the park's high resolution Lidar DEM and orthophotos should be analyzed for patterns of structural faulting and other features associated with tinaja presence. While junctions of stream beds and faults and confluences of stream branches are often associated with tinajas, many of the confluences and intersections are not associated with tinajas (Figs. 18 and 19). However, combining the visible structural features of the remotely sensed imagery and the collection of field data of structural geology and hydrology features can greatly enhance our ability to model the hydro-geological processes associated with tinaja presence and formation. The integration of multi-scale (remotely sense and field collected data) will enable model building and hypotheses testing aimed at understanding the geohydrological basis for tinaja manifestation within the park's streambeds and washes.

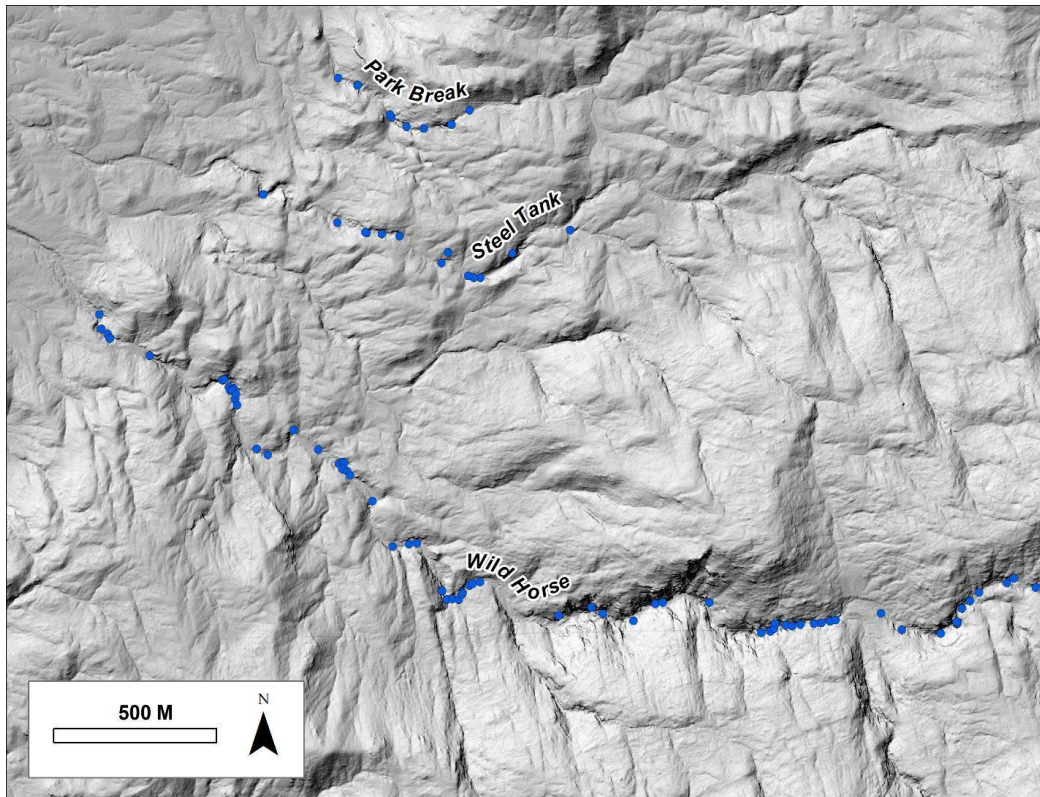


Figure 18: Lidar provides detailed topography and geological features along stream beds with tinajas.

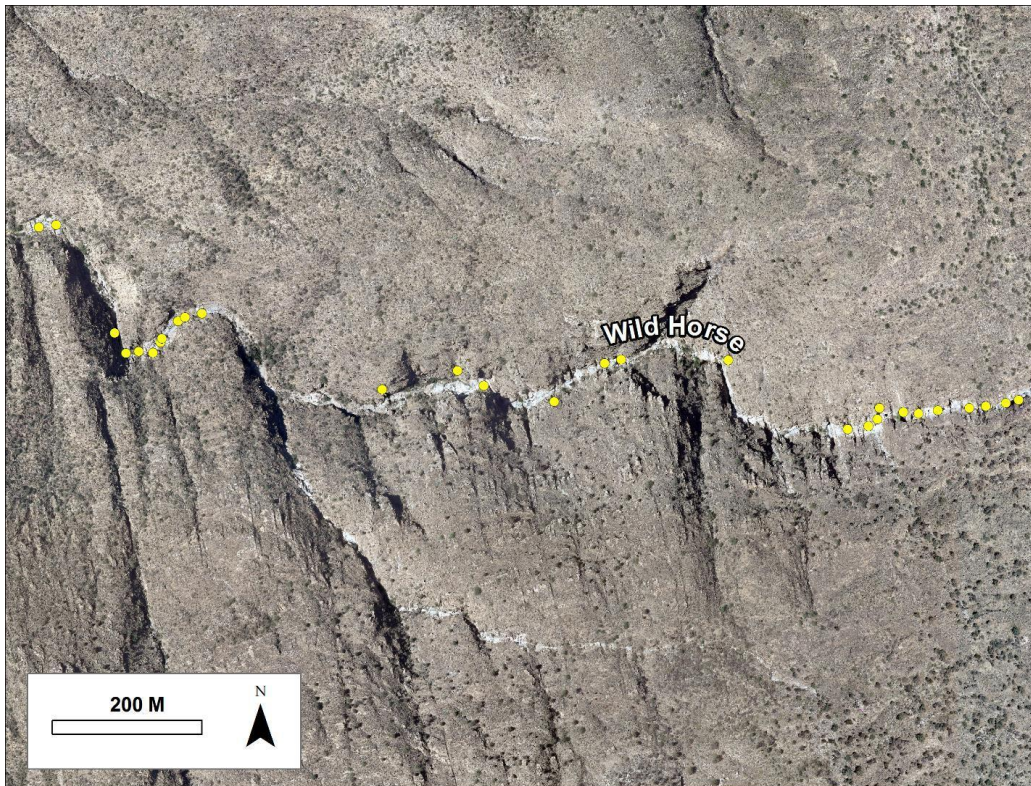


Figure 19: High resolution orthophotography for Wildhorse Canyon with high density tinaja presence. Geological fracturing and faulting perpendicular to the stream bed are visible.

IIIC. DISCHARGE POINTS

Each of the 4 drainages supported tinajas that were groundwater discharge points (Fig. 20). Some tinajas were identified as discharge points multiple times, while others received inflow but had no surface water outflow (Appendix A). These discharge tinajas are vital to the greater tinaja network, and discharge at one tinaja may support subsequent tinajas down valley. Tinajas supported by groundwater discharge are vital habitats for wildlife and wetland plants in Saguaro NP.

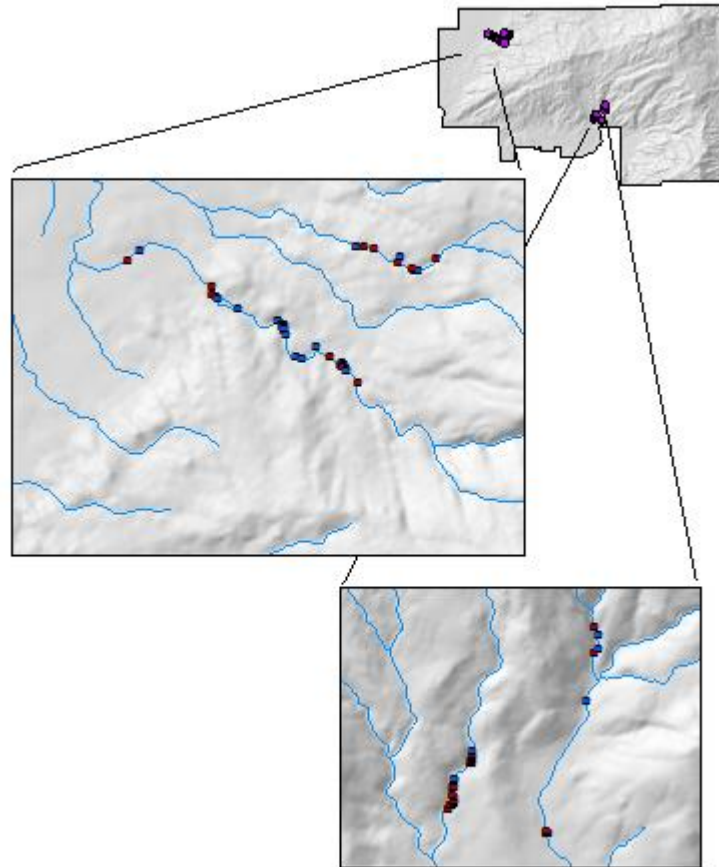


Figure 20: Map of the distribution of tinajas that at some point during Feb 2013- Feb 2014 were recorded to have surface water outflow but no surface water inflow, identifying them as groundwater discharge points. These discharge point tinajas (blue) are shown in relation to the non-discharge tinajas (red).

IIID. POTENTIAL CONCEPTUAL MODELS FOR TINAJA SYSTEMS

A basic conceptual model of the groundwater flow system is critical for understanding why tinajas form and answering questions about vulnerability of this unique resource. While the Park Break week was brief and data collection limited to a few days, three plausible models were proposed based on prior data, qualitative field observations, and basic hydrogeologic knowledge. These models are not exclusive and it is likely that all of the tinajas do not fall into a single model.

Bedrock fracture flow can be difficult to model due to extreme heterogeneity where crystalline bedrock essentially acts as an aquitard with no pores providing primary porosity, as is

the case in a classic sandstone aquifer. All hydrogeologic function is derived from the secondary porosity due to fractures. Fractures can act as high hydraulic conductivity conduits and storage, which allows crystalline bedrock to behave as an aquifer. It should be noted that to recharge groundwater in fractured bedrock a permeable surface material must overlay the bedrock somewhere in the system. Due to the high potential evaporation of this region, any precipitation that does not quickly infiltrate into the ground would rapidly evaporate. Most precipitation that falls directly on bedrock will quickly become overland flow due to the impermeable crystalline matrix. Therefore, the presence of permeable unconsolidated material overlying the bedrock in the recharge zone is likely critical for getting groundwater recharge; such a material would capture precipitation and then allow for slow infiltration into underlying bedrock fractures. This study did not examine if such a material was present at high elevations in the Rincons and future groundwater studies in the area would benefit from assessing upland infiltration potential. For the purpose of the conceptual models, it was assumed that the fractured bedrock was receiving recharge.

The three conceptual models were 1) an equivalent porous media approach; 2) local surficial geology controls; and 3) confined conditions. The models were created from general field observations, where tinajas were located where they were absent, and from a water table map. It was observed that there were no high flow springs in the Rincons but, rather, relatively stagnant water surfaces with low to no visible flow. This indicates that the majority of tinajas are not connected to a pressurized confined aquifer which would allow for artesian conditions. Therefore, an unconfined model must also be considered. Water level dynamics in many of the tinajas were strongly correlated, indicating a strongly connected system. For most tinajas, if the water is removed during the dry season, they will re-equilibrate to the previous water level. This suggests a strong connection to a groundwater system and rules out persistence of overland flow left behind in low points of the streambed.

The water table map (Fig. 21) suggested that a plausible water table could be constructed using water level elevations across drainages. This supported a connected, unconfined groundwater system that extended beyond drainage watersheds. A confined system would likely not have such a steeply sloping potentiometric surface and adjacent tinajas would have similar water level elevations. This was not observed. Note, this map was constructed using a 10 m resolution DEM and could be drastically improved using a higher resolution DEM.

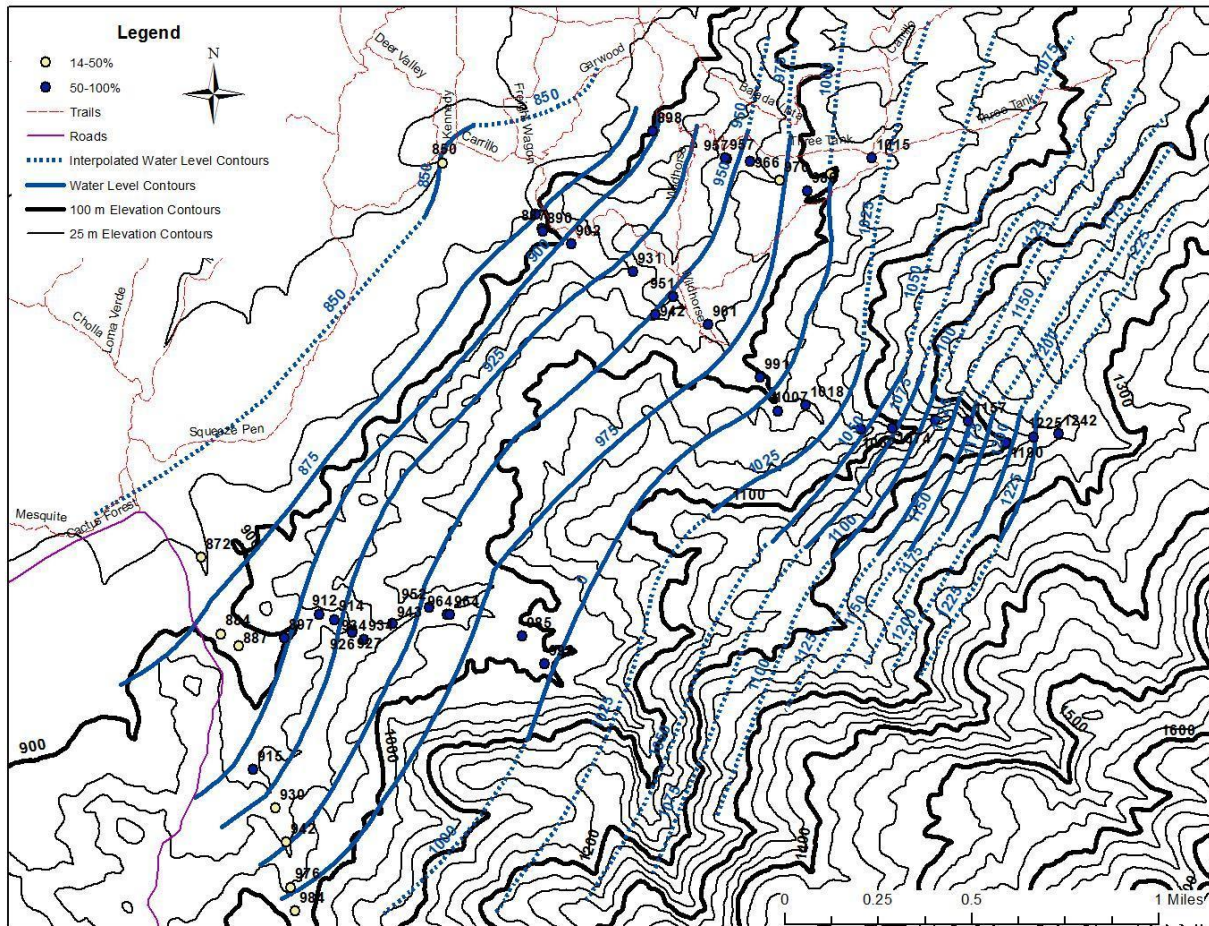


Figure 21: Water table map from tinaja elevations at Loma Verde, Wildhorse Canyon, and Steel Tank drainages.

Conceptual model 1 (Fig. 22) considers the fracture system as an equivalent porous media where the water table surface is manifest in the fractures. Fractures are common in the highly metamorphosed rocks of the Rincons. It is plausible that these fractures could form enough of a connected network to create an equilibrated aquifer system.

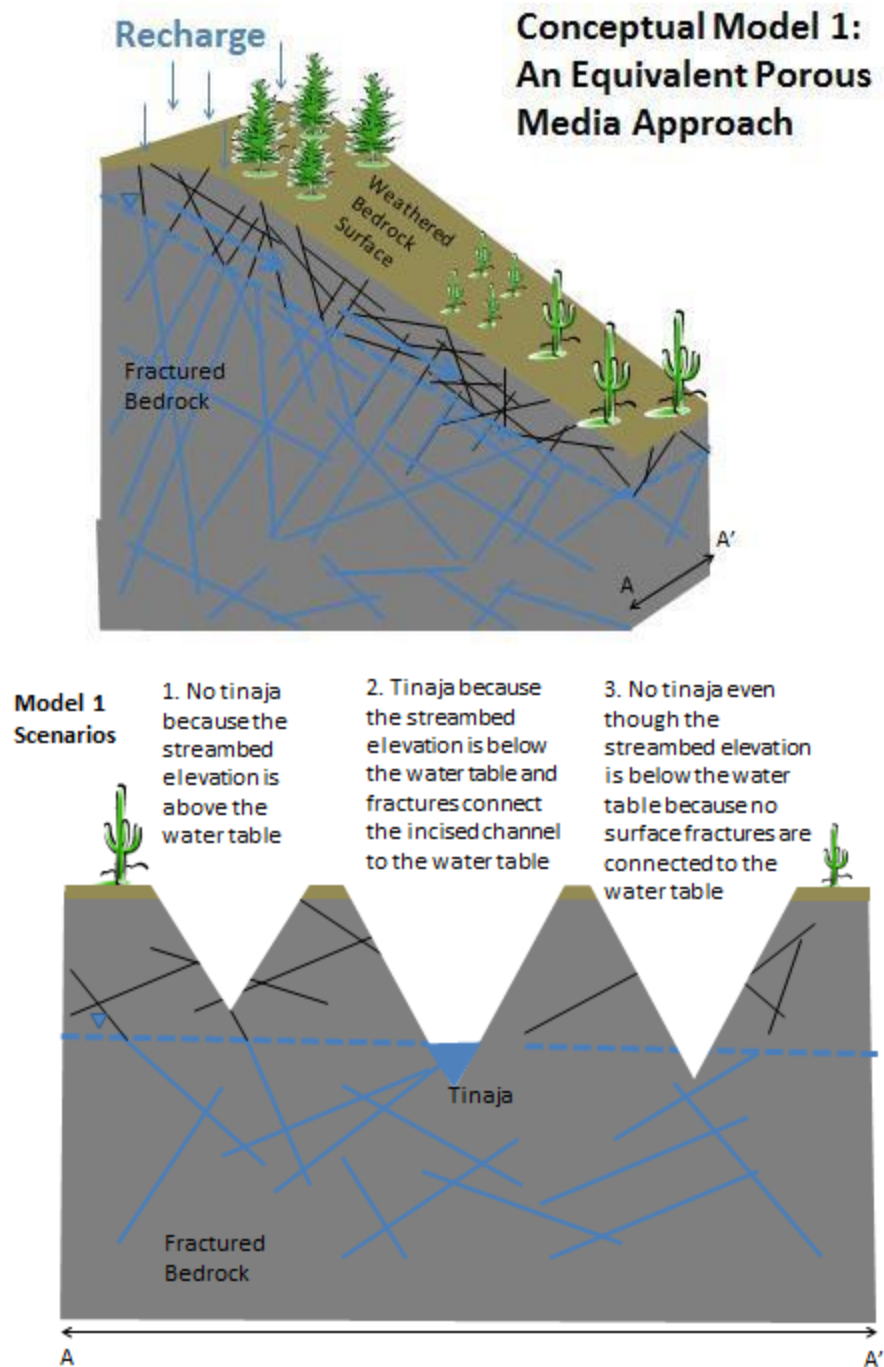


Figure 22: Conceptual model 1 viewed along slope and a cross-section with hypothetical drainages along transect from A to A'.

Under model 1, tinajas form where the water table exceeds the land elevation and the groundwater is expressed on the surface. The tinajas are where they are for three reasons: 1) the stream is incised down to where the land surface meets the water table, 2) fractures connect the pool to the groundwater system, and 3) rock pools have been cut into the bedrock by stream

action and can capture the water that is expressed. The level of water in the pool is in equilibration with the water table. The larger the watershed, the greater the number of tinajas because of greater incision in higher order streams. The bedrock locations where there are not tinajas are also where there are not suitable fractures or the water table is below the land surface. These three scenarios are summarized with the cross-section along slope, perpendicular to drainages.

To test conceptual model 1, a longitudinal profile along Wildhorse canyon (Fig. 23) was constructed using land surface elevation from a Lidar DEM with 2 ft resolution. Tinajas were graphed in orange. From this plot it is apparent that the tinajas occur entirely in the steepest section of the drainage. When streambed slope exceeds the water table slope it is more likely for tinajas to occur. It was difficult to see particular pools from this profile and a detailed field survey may be necessary to compare pool elevations and a water table surface.

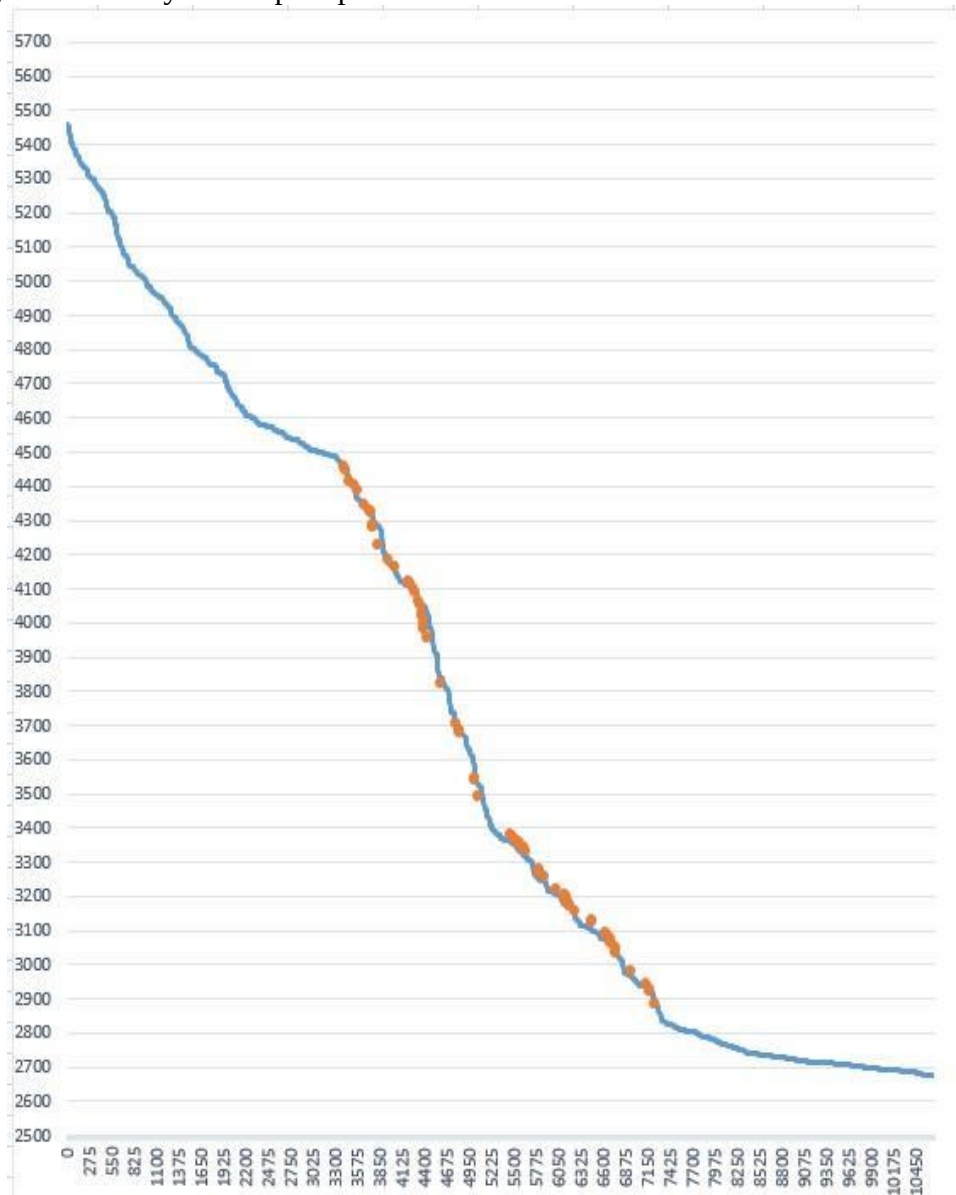


Figure 23: Longitudinal profile of Wildhorse Canyon with tinaja locations.

A hypothetical stream profile with pools was created to illustrate potential intermittent behavior of the pools under conceptual model 1 (Fig. 24).

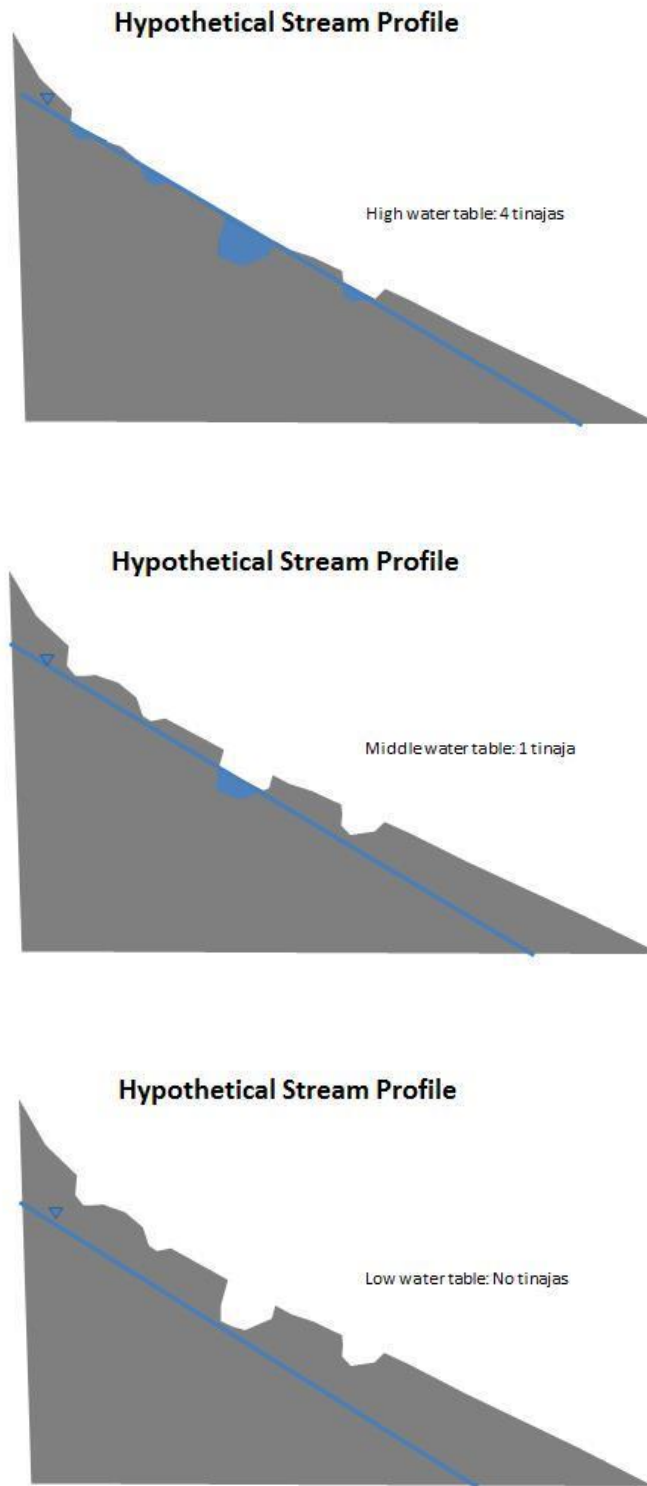


Figure 24: Hypothetical stream profile with three water table scenarios.

Conceptual model 2 (Fig. 25), where local surficial geology controls tinaja presence, would not explain the majority of the park tinajas but could be important locally for select pools. Under this model a highly permeable alluvial unit, such as a debris flow, allows for infiltration and storage of precipitation. Water infiltrates down until it hits a harder bedrock contact, then flows laterally and is caught in a bedrock depression in the stream valley. Water in the alluvium may sometimes be focused into a local fracture.

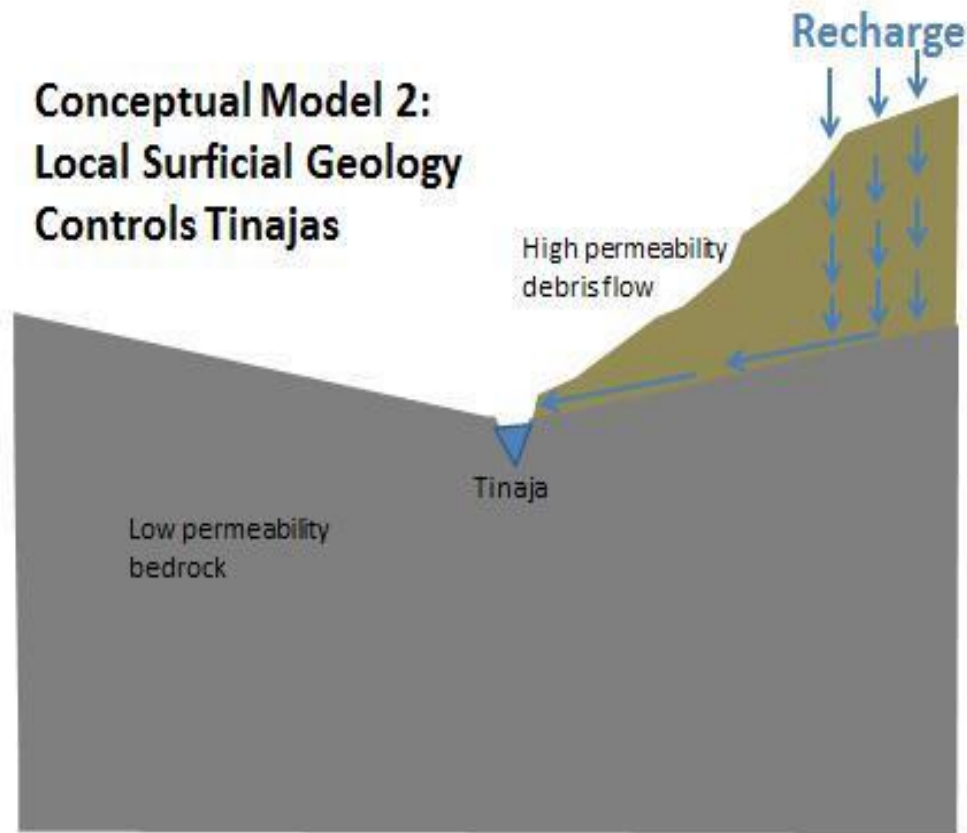


Figure 25: *Conceptual model 2 viewed in cross-section perpendicular to the drainage.*

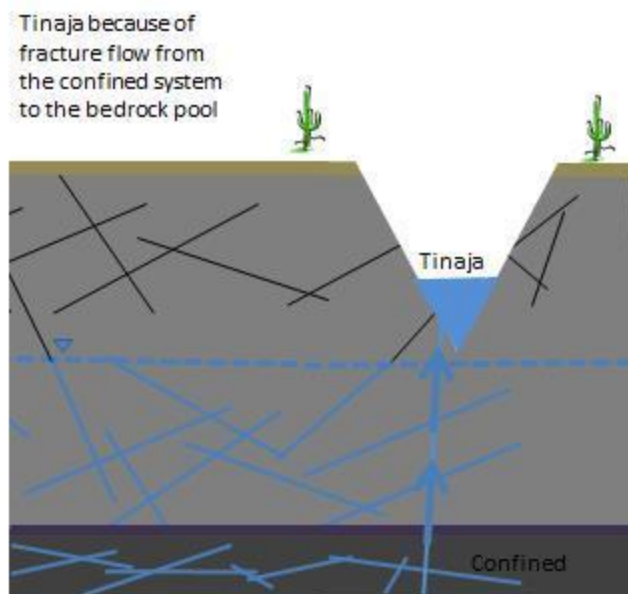
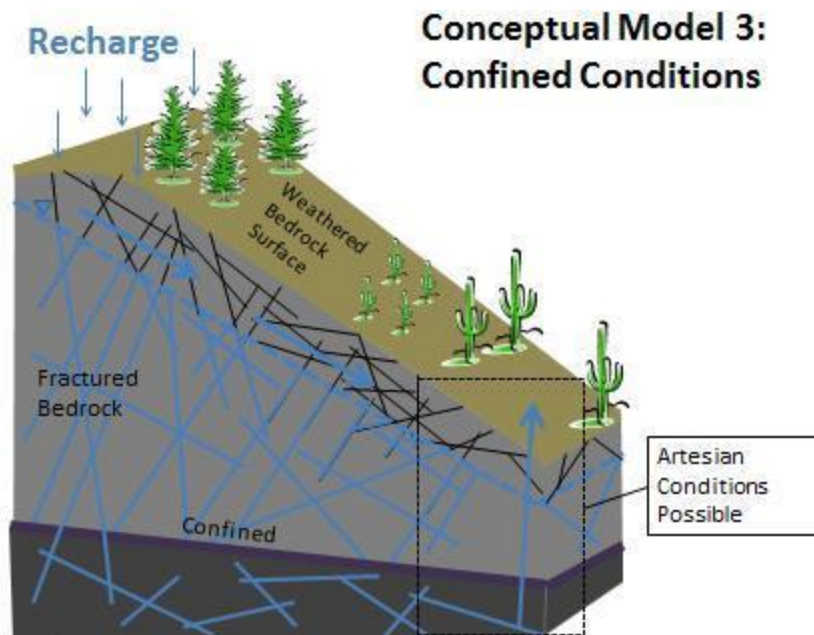


Figure 26: Conceptual model 3 viewed along slope and in cross-section perpendicular to the drainage.

Conceptual model 3 (Fig. 26) shows tinajas that may be fed by an artesian system, where water moves up a particular fracture from the confined system to the land surface. Support for this alternative is that some tinajas seem to stay full all of the time and there is water flowing from them even in dry months. In addition, the isotope work indicates that some of the tinajas

(Grotto, Douglas Spring, and some of the water in Rincon North 10) is older, pre-bomb testing that started in 1954, water. It seems possible that some tinajas that are artesian may also receive water through model 1.

To conclude, three conceptual models were constructed that could explain the presence of tinajas in the park. These three models are not exclusive and there may be multiple processes controlling the presence of tinajas in the park. These models are preliminary and additional data could be collected to refine them. Suggestions for future research are included at the end of the report.

IIIE. TINAJA CLASSIFICATION

Across five drainages, tinajas separated into 5 distinct classes based on timing of water presence (Appendix B). All drainages supported most tinaja types (Fig. 27), revealing that drainage identity alone does not dictate the pattern of water presence. Loma-Verde's dataset was longer, so a second classification for this wash produced 4 tinaja classes. The multi-year dataset used to create this classification means that this classification will likely be more robust than the 5-Drainage classification. Within drainages, multiple tinajas types occur, a major consideration when addressing monitoring, research, and management questions. Each drainage contains at least one tinaja that did not dry during the sampling period. These pools are the most important habitat refuges during dry periods. The different classes are influenced by different hydrologic processes, and classes may represent these different processes, such as pools that rely more on surface water inflow, local groundwater discharge, or larger-scale groundwater systems.

Each classification identified that the processes at play are more complex than a relatively simple continuum from wet to dry. For example, Table 2 identifies that all tinajas in Groups 2 and 3 contain water most of the time, but the May-August period shows a more complex situation. Group 3 dried before Group 2, but its water also returned sooner. In the Loma Verde classification, in October and November 2013 Group 2 is drier than expected if the four classes simply identify a continuum from wet to dry sites (Table 3). In each classification, the examples highlighted could represent that one of these groups is more connected to surface water and one to groundwater. Alternative explanations are that one is more driven by snow and the other by rain, or one by flashy processes and the other long-term processes. The mechanisms supporting the different classes should be assessed in the context of our working hypotheses.

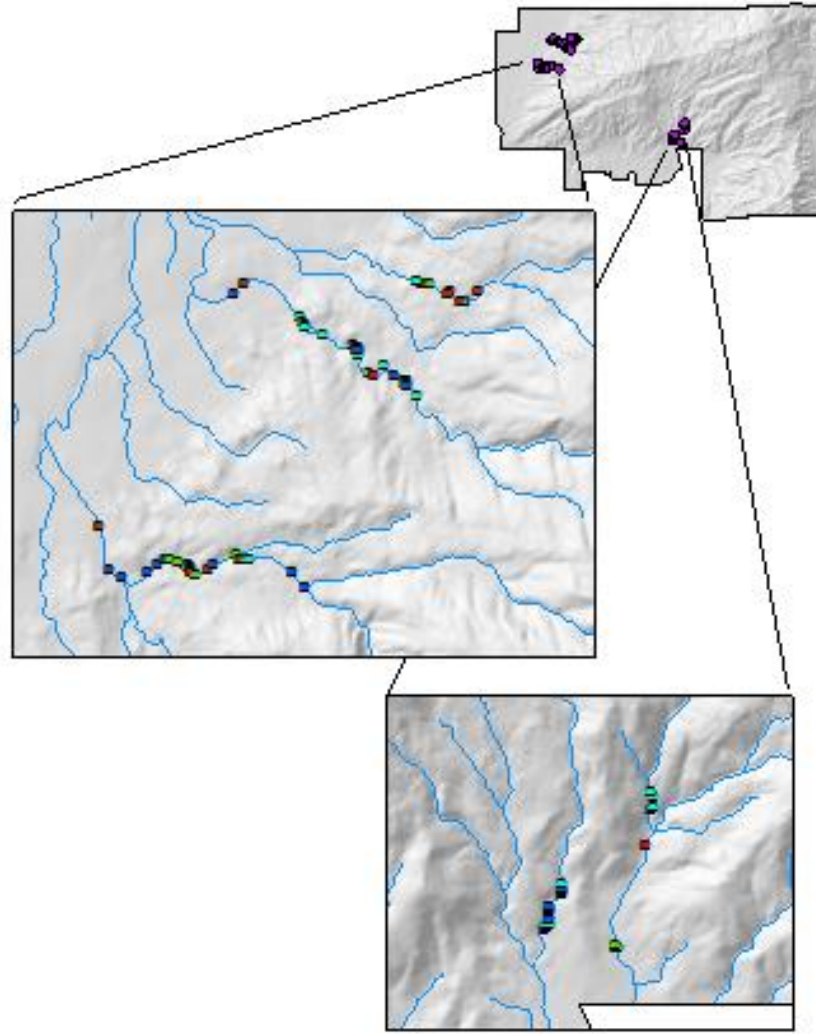


Figure 27: Spatial distribution of the color-coded 5 tinaja classes across the five drainages.

	2/7/2013	3/7/2013	4/4/2013	5/2/2013	6/6/2013	6/20/2013	7/3/2013	8/8/2013	9/5/2013	10/17/2013	11/7/2013	11/25/2013	12/6/2013	1/2/2014	2/5/2014
Group 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Group 2	1	1	1	1	0.9	0.4	0.8	0.8	1	1	0.6	1	1	1	1
Group 3	1	1	1	0.6	0.2	1	1	1	1	0.9	1	1	1	1	1
Group 4	1	1	1	0.6	0	0.1	0.7	0.6	1	0.9	0.5	0.9	1	0.9	0.9
Group 5	0.8	1	0.7	0	0	0	0.7	0.6	1	0.1	0.1	0.9	0.9	0.9	0.7

Table 2: Percentage of tinajas within each of the 5 groups that contained water at each visit. Group 1 has the wettest tinajas, while Group 5 identifies the driest sites. Note that Group 3 dries and wets sooner than Group 2 during May through August, indicating the difference in hydrologic processes supporting each group.

	1/4/2011	2/2/2011	3/2/2011	4/6/2011	5/3/2011	6/1/2011	7/3/2011	8/4/2011	9/7/2011	10/5/2011	11/3/2011	12/7/2011	1/4/2012	2/1/2012	3/5/2012	4/4/2012	5/2/2012	6/6/2012	7/5/2012	8/6/2012	9/6/2012	10/4/2012	11/9/2012	12/6/2012	1/3/2013	2/7/2013	3/7/2013	4/4/2013	5/2/2013	6/7/2013	6/20/2013	7/3/2013	8/8/2013	9/6/2013	10/17/2013	11/6/2013	11/25/2013	12/6/2013	1/2/2014	2/6/2014
Loma Group 1	0.8	0.7	0.5	0	0	0	0	1	1	1	0.7	0.8	1	1	1	1	0.3	0	0.7	1	1	1	0	0	0.8	0.7	1	0.7	0	0	0	0.7	0.7	1	0.7	0.5	1	1	1	1
Loma Group 2	1	1	1	1	0.3	0	0	1	1	1	0.7	1	1	1	1	1	1	0	0.9	1	1	1	0.4	0.1	1	1	1	1	0.4	0	0	0.4	0.9	1	0.4	0	1	1	1	1
Loma Group 3	1	1	1	1	0.8	0.6	0.6	1	1	0.8	0.8	1	1	1	1	1	1	0	1	1	1	1	0.8	1	1	1	1	1	0.6	0	0.6	1	1	1	1	1	1	1	1	1
Loma Group 4	1	1	1	1	1	1	0.6	1	1	1	1	1	1	1	1	1	1	0.8	1	1	1	1	0.8	1	1	1	1	1	1	0.7	0.8	1	1	1	1	1	1	1	1	1

Table 3: Percentage of tinajas within each of the 4 classes that contained water at each visit. Note that a unique hydrologic regime is indicated by the 11/6/2013 Group 2 data, where it was dry although usually this class was wetter than Group 1.

IIIF. JOINT DENSITY OF THE MADRONA POOLS AT CHIMENEA CREEK

Field Observation: Overall rock lithology at Madrona Pools was granitic Gneiss. As we move higher in the drainage system we noticed the banding became more noticeable and the feldspars increased in size becoming pegmatic. Garnets were also present commonly forming in bands with white mica and quartz (Figure 28).



Figure 28: View of some banding in the granitic gneiss at the lower Madrona pools at Chimenea creek. Garnets, white mica, feldspar and quartz can all be seen in the banding

The major joint set trending south became less noticeable after pool 1F. We noticed an assumed dike in this drainage that trended around 200 degrees (Fig. 29). This coincides with the major joint set, and is not cut by other joints trending this direction. However, it is cross-cut by the eastern trending joint set, thus the intrusion had to have occurred before the large scale

jointing.

Strike and Dip: Strike and dip data at the lower Madrona Pools in the Chimenea creek drainage show similarities between large scale and small scale features (Table 4).

Major scale joint sets show strikes that follow two trends, the first being an eastern trend commonly striking $104-111^{\circ}$ and the second being a southern trend striking around 200° . The eastern trend shifted to a strike range of $115-120^{\circ}$ as we move upstream. Dip angle increased initially as we moved upstream and then decreased.

Minor scale joint sets seem to reflect the large scale joint sets. Similarly two trends can be seen: the eastern trend with strike averaging $105-113^{\circ}$ and the southern showing a strike average around 192° . Similar to the major scale joint sets the dip angles decreased as we moved upstream.



Figure 29: A portion of the lower Madrona pools displaying the dike that follows the 200° strike.

Tinaja Number	Major Joint Strike	Major Joint Dip	Minor Joint Strike	Minor Joint Dip
1A	104 197	61	109 192 105	78 78 81
1B	104 200	73	109 192 105	78 78 81
1D	104 200	73	103	81
1E	111 200	70	113	72
1F	112 200	73	106 111	78
1G	111	67	112	57
1H			113 150*	54 7*
1I	119	56	108	54
1J	115	-----	93	64
1K	108	-----	95	60
1L	-----	-----	95	60
1M	-----	-----	107	46

Table 4: Table containing average strike and dip measurements for both the major and small scale joint sets for the Madrona pools and Chimenea creek. Asterisk (*) indicates strike and dip along foliation plane.

IIIG. JOINT DENSITY OF THE LOMA VERDE DRAINAGE

Field Observations: Major rock lithology at this site was chloritic breccias. At this location there were large amounts of sediment in the discharge channel. In comparison the tinajas at Loma Verde are more fractured and jointed than the Madrona Pools tinajas at Chimenea creek. The strike and dips are very cohesive in Madrona pools, however they are less so in Loma Verde (Table 5). This could be a result of different source events of the joints. Also the lithology would influence the ease of the material being fractured and jointed. Lithology varies between the locations. The dominant lithology in the lower Madrona pools was granitic gneiss while in Loma Verde it was more a chloritic breccia. Both locations show foliation indicating the area has experienced metamorphism.

Tinaja Number	Major Joint Strike	Major Joint Dip	Minor Joint Strike	Minor Joint Dip
AV3	260	40	89 201 191	21 85 88
AV2	-----	-----	149	71
PT	346 208	81 53	199 294 138	63 88 72
0B	195	56	192 186	57 63
Pool 1	114	56	160	76

Table 5: Table containing average strike and dip measurements for both the major and small scale joint sets for Loma Verde.

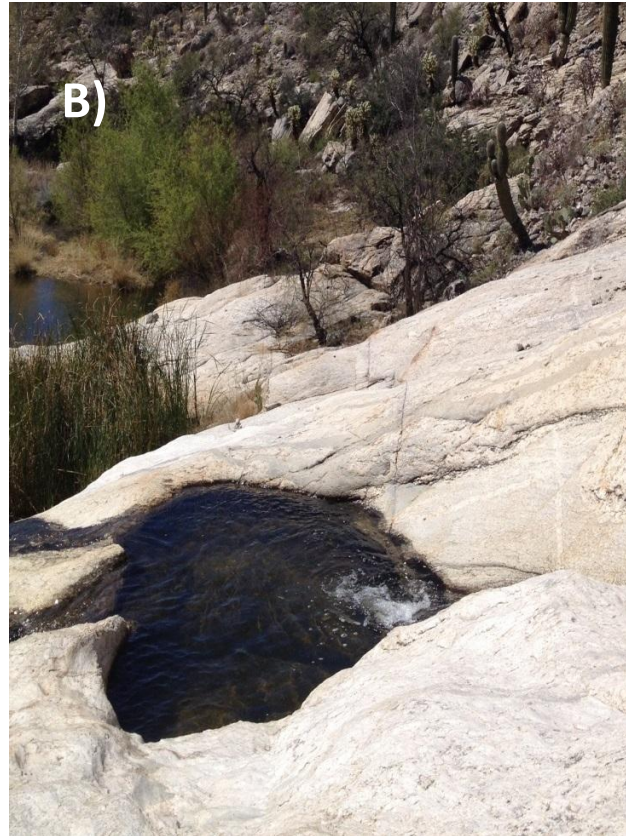


Figure 30: Images comparing the pools. A) Lower portion of Loma Verdes AV3 show discoloration of water and banding on rock wall. B) Portion of the lower Madrona pools showing clarity of the pools. C) Closer view of AV3.

In the Loma Verde drainage the channel contains more sediment than the channel in Chimenea. The pools located in or in close proximity to this sediment seem to be less defined than the pools located in solid bedrock. Another difference between pools is that the pools from Chimenea creek are clear while the pools from Loma Verde contain more algae and are dirtier. This also reflects the higher sediment value at Loma Verde (Fig. 30).

There is an intrusive feature at both locations, however it is less pronounced at Loma Verde than it is at Madrona pools. Throughout the lower pools of Madrona in Chimenea creek the strike of the dike remains constant. An accurate trend of the intrusion in Loma Verde could not be obtained. The intrusion appeared to extend laterally creating a lateral layer more than a dike.

IIIH. GEOLOGIC ORIENTATION OF JOINT SYSTEMS AT TINAJAS

Strike data collected at the Chimenea and Loma Verde basins were plotted using the program Oriana (<http://www.kovcomp.co.uk/index.html>) as rose diagrams (Figs. 31-36), which provide a means to visualize the frequency and distribution of circular data. The Madrona pools exhibit bi-modal data with a preferred orientation in a WNW-ESE direction (105-115°) that continues upstream in the Chimenea basin. Conversely, the Loma Verde pools exhibit both bi- and uni-modal data. There is not a consistent trend in the orientation of these data. AV3 exhibits bimodal data with a preferred orientation in an E-W direction whereas AV2 and LV1 have a preferred orientation in a NW-SE direction and LV10B has a preferred orientation in a NE-SW direction. We attribute this disparity to the difference in lithology in which these tinajas are forming. The lower pools in the Chimenea basin have formed in the Wilderness granite (Davis 2013, in press) that has a distinct mafic dike that intrudes through the granite in the middle of where the channel has incised. In contrast the lower Loma Verde pools have formed in the ultracataclasite/chlorite breccia (Davis 2013, in press) which due to the shear zone deformation is more highly fractured and jointed in comparison to the Wilderness Granite.

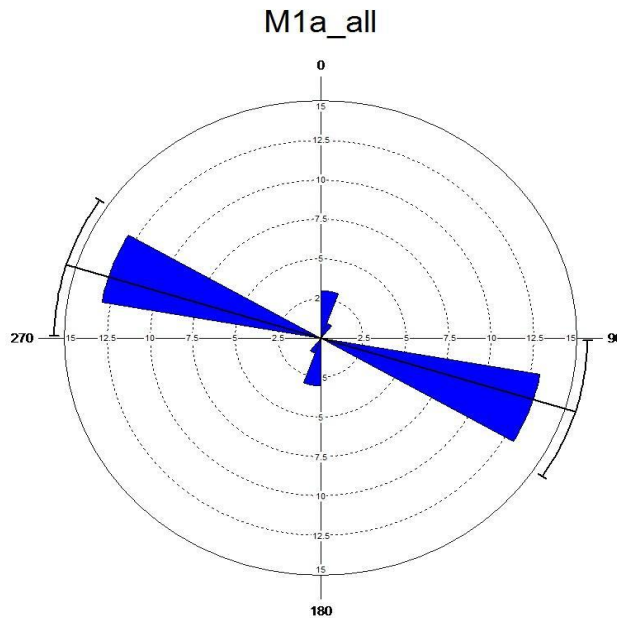


Figure 31: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Madrona pool 1a in the Chimenea basin: mean vector:107; circular standard deviation: 32.78.

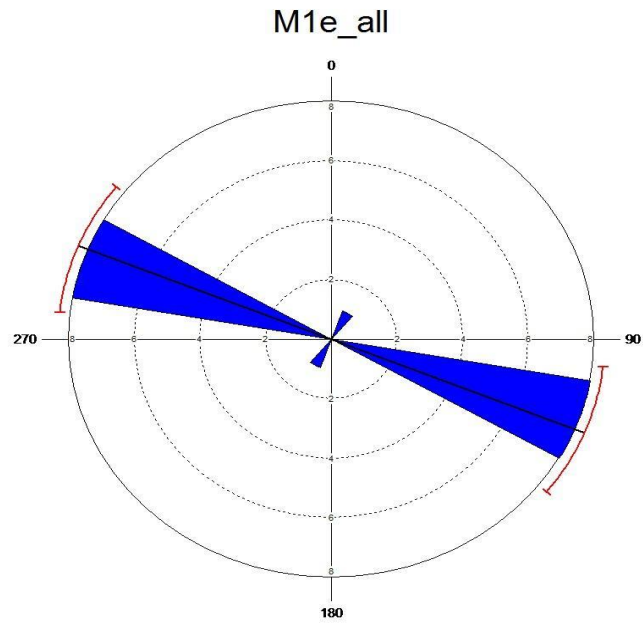


Figure 32: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Madrona pool 1e in the Chimenea basin: mean vector:112; circular standard deviation: 20.46.

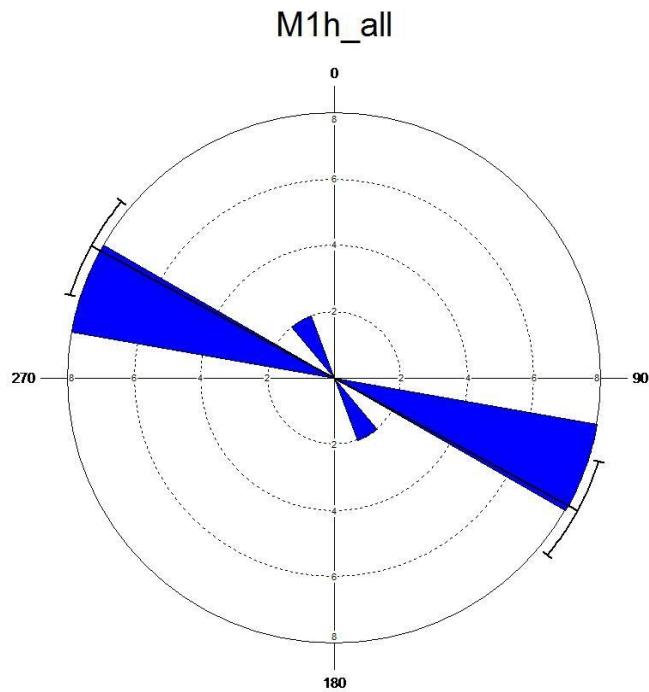


Figure 33: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Madrona pool 1h in the Chimenea basin: mean vector:118; circular standard deviation: 15.2.

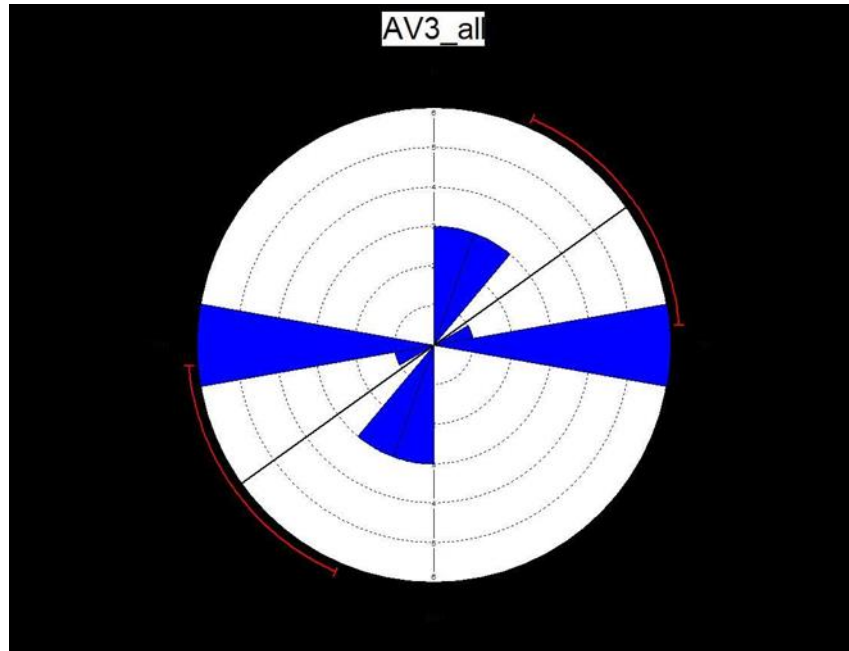


Figure 34: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Loma Verde pool AV3 in the Loma Verde basin: mean vector: 54; circular standard deviation: 39.4.

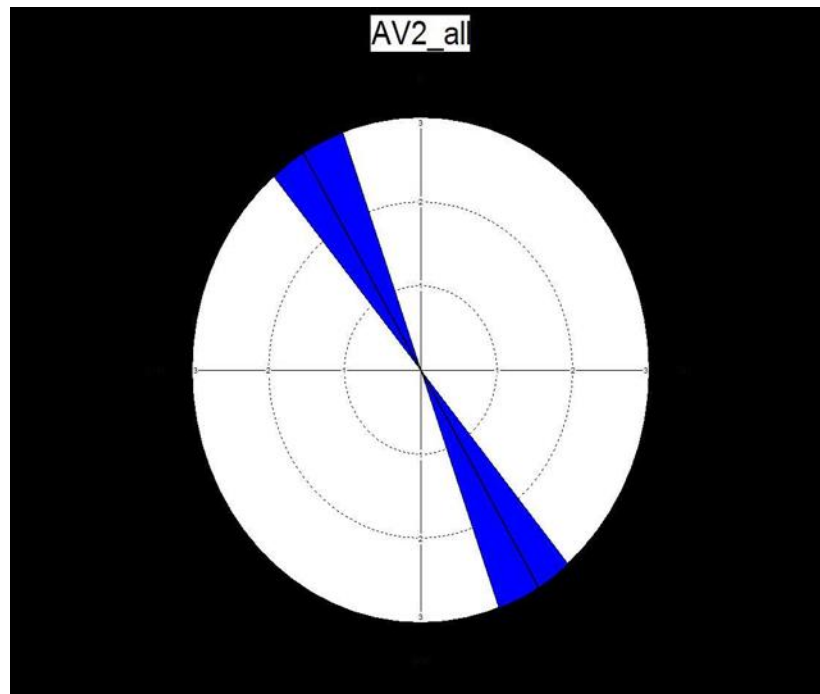


Figure 35: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Loma Verde pool AV2 in the Loma Verde basin: mean vector: 149; circular standard deviation: 1.14.

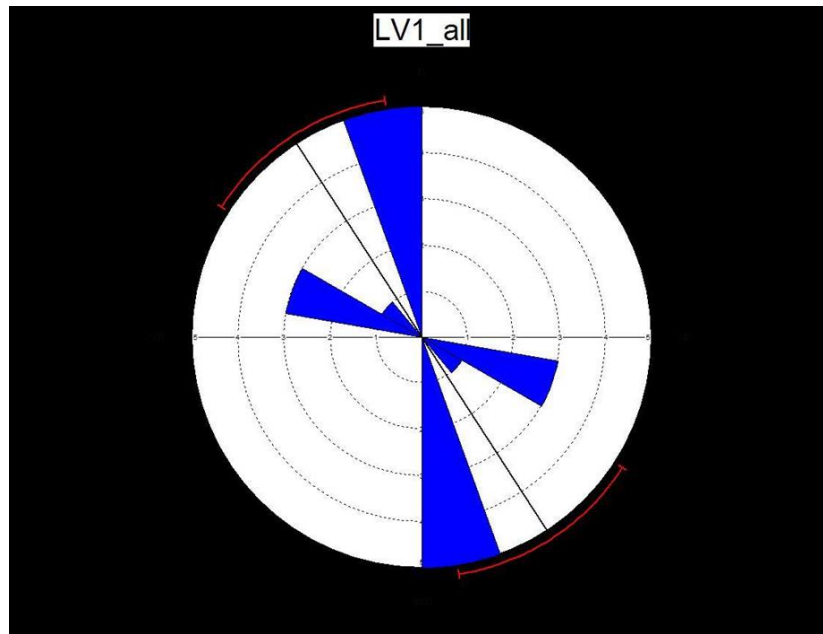


Figure 36: Rose diagram illustrating 1m2 and 10m2 strike data combined at the Loma Verde pool LV1 in the Loma Verde basin: mean vector: 147; circular standard deviation: 31.7.

III. “PARK BREAK CANYON” TINAJAS

During a reconnaissance trip to the Wildhorse Canyon and Steel Tank tinajas, Park Break participants visited neighboring drainages looking for potential geologic indicators that might explain why tinajas are found in some drainages but not others. The first drainage was located east of Wildhorse Canyon’s lower tinajas near the Wildhorse and Carrillo trails. The unnamed wash is located between the old gate posts at the end of the Wildhorse trail and Steel Tank. The Carrillo trail cuts across the wash before climbing a hill that drops down to Steel Tank. Park Break participants explored approximately 100m upstream from where the Carrillo trail crosses the wash. No tinajas were found during the brief search. It was clear that the wash was extremely different from Wildhorse Canyon; this wash was in more of an upland area with barely any exposed bedrock and had a narrow stream channel that was filled with sediments and perennial vegetation (including *Ambrosia sp.* and *Opuntia sp.*) growing within the wash.

After visiting Steel Tank and exploring the immediate vicinity near the tank, Park Break participants attempted to return to the trailhead via the Vista Trail while examining the associated drainage along the way. The Vista Trail is no longer operational and is in the process of being restored. The Park Break participants hiked down via the newly-named Park Break Canyon to examine the geologic structure of the canyon. Approximately 10 tinajas were found within Park Break Canyon. Additionally, several moist spots were found in soils near exposed bedrock (Fig. 37) and when soil was dug out, the moisture levels increased with depth. Several of the pools were associated or located at the base of dryfalls. One shallow (approximately .25m deep) pool located at the base of a steep, narrow dryfall was filled with red/orange discolored water (Fig. 38).



Figure 37: Photo of moist contact zone between exposed bedrock and sediment within the stream channel in Park Break Canyon. Sediment was dug out, revealing an increase in moisture with increasing depth.



Figure 38: A shallow tinaja at the base of a steep dryfall in Park Break Canyon. The water was heavily discolored a red/orange color. Wasps were observed drinking from the tinaja.

Several tinajas were in close proximity of one another (approximately 5-10m apart) and were connected via a dry, exposed bedrock channel. Additionally, one visited tinaja was densely vegetated with cattails (*Typha sp.*) and other lush green perennials growing in the tinaja and surrounding area. This likely indicates a perennial water source at the tinaja. Invasive plant species were also noted in Park Break Canyon. This included fountain grass (*Pennisetum setaceum*) which was common, and sometimes dense, within the canyon, as well as buffelgrass (*Pennisetum ciliare*) which was seen in 4-5 locations at lower elevations in the canyon.

Wasps were commonly seen at or near most of the tinajas in Park Break Canyon. A group of 3-4 white-tailed deer were seen in the lower part of the canyon. Other animals observed included unidentified hummingbirds, an owl, lizards, and honeybees.

IV. CONCLUSION

Understanding the hydrogeological and climatological factors that control the prevalence and water level of tinajas will be important in assessing the resilience of these systems to environmental changes. One relevant manifestation of climate change may be altered precipitation regimes, resulting in storms of greater intensity but lower frequency (MacCracken et al. 2003). Given that precipitation occurring over long durations may be the dominant water source for some tinajas, such altered regimes may result in the decline of these tinajas. The spread of invasive plant species such as buffelgrass will have implications for tinaja ecology, as they displace native vegetation communities which provide habitat for sensitive wildlife such as leopard frogs. Projected population growth in Tucson will likely stress an already declining groundwater supply. Further research is needed on the effects of downstream groundwater extraction on tinajas.

V. FUTURE DIRECTIONS AND RESEARCH SUGGESTIONS

Mapping the structural geology of Loma Verde Canyon: Dr. George Davis at the University of Arizona offered the possibility of having him map the structural geology of Loma Verde Canyon and the associations surrounding the Loma Verde tinajas. Dr. Davis said the entire mapping project would take approximately 3-4 days to complete and would be incredibly beneficial as it would provide a fine scale look at the structure of the tinaja-rich canyon.

Full Survey of Park Break Canyon and its tinajas: The reconnaissance trip through Park Break Canyon was brief and incomplete. Not all tinajas encountered were marked with GPS points and there were additional, smaller pockets of water in cracks and shallow bowls that were not noted. It is unclear if the tinajas in Park Break Canyon are perennial, intermittent, or ephemeral, or simply the result of the recent rain events that occurred in the area within the last two weeks. A complete survey of the canyon and its tinajas is required to gain accurate information about the number and possible seasonality of the tinajas in the canyon. Exotic control teams will also likely be needed to conduct a complete survey of the two invasive plant species observed: fountain grass (*Pennisetum setaceum*) and buffelgrass (*Pennisetum ciliare*).

Tinaja Classification: Continue the monthly data collect. After 2 years, another cluster analysis can be conducted to refine this first run. Consider the different tinaja classes when developing monitoring, research, and management plans. Assess which conceptual models align with which tinaja types. Some tinajas are simply filled from the uphill spill-over from a tinaja with a surplus water supply.

Future Monitoring Suggestions: A detailed groundwater study would involve drilling several monitoring wells into the fractured bedrock. Such a study would be cost-prohibitive and potentially detract from the park's natural aesthetics. Furthermore, the logistics of drilling wells off the road system can be complex. Several less costly approaches can be utilized to better understand this groundwater system.

To do items:

1. Create an accurate longitudinal profile by surveying the stream thalweg (deepest point in a stream cross-section) throughout the profile, pool bottom elevations, and the water level elevation of the tinajas. Surveying to a GPS point can allow for linking of survey data to the 2 ft resolution Lidar DEM to get actual elevations.
2. Accurate water elevations should be used to improve the water table map. As a start the 2 ft resolution Lidar DEM elevation at each tinaja point could be used instead of the 10m resolution DEM data.
3. Collect specific conductance measurements regularly in the tinajas as a proxy for groundwater flowpath length. Collecting an accurate "fresh" water sample will be challenging. These data can be used to group tinajas receiving similar water sources and potentially differentiate between the conceptual models or yield insight into other potential models.
4. Analyze the temperature data from the data loggers to assess differences in temperature responses between pools. This could indicate different water sources or relative amount of groundwater input.
5. Collect isotope samples both temporally within a single pool and spatially between pools.
6. Map all of the drainages in a certain area looking for where there is water/tinajas and where there is not.
7. Look at whether there is a strong relationship between watershed size and tinajas, not because the tinajas are associated with larger watersheds, but because larger watersheds will have streams that are more incised relative to the land elevation.

To test the conceptual model 1:

- a) Extract water from a bunch of tinajas; they should all return to equilibrium.
- b) Create a more accurate water table map.
- c) Do a longitudinal profile of a section of tinajas, and look at where there is water and where it is not. Draw in the water table. If pools lie below the water table they should have water in them unless suitable fractures are absent.
- d) Look at isotope and specific conductance chemistry.

To test the conceptual model 2:

- a) Look at isotope chemistry. The signatures could reflect recharge during that season. Assuming lower elevation debris flows receive no winter snowfall, the isotopes should look very different than snow recharge.
- b) You might expect a different delay time in these pools than in pools of model 1.

To test the conceptual model 3:

- a) Look at isotope chemistry.
- b) Develop a better water table map and determine if the pools fall within it; if pool agrees with the water table it is likely not confined.
- c) Assess temperature differences.
- d) Measure specific conductance.

Groundwater Discharge Points Data Collection and Analyses: The ongoing monthly tinaja monitoring program should continue. This analysis should be repeated in the future after the dataset has been extended. Analyses can be performed on the percentage of the time that a given tinaja has outflow but not inflow. Some sites may only have discharge during rare events, while others may the majority of the time. In the field and using remote sensing data, further investigation should be given into the tinajas that are documented as groundwater discharge points.

Structural Geology and Lithology: A better understanding of the structure and lithology of the two sites visited in this study and their interaction, especially the role of dikes, would be very beneficial to furthering the understanding of where the water in the tinajas comes from. One recommendation would be to do a detailed mineralogical and petrologic study on the bedrock and intrusive rocks of these sites. Such studies could show the interaction of the dike with the rock and relative/or possible actual dates. Another recommendation would be to look at the subsurface rocks. A better understanding of what is going on under the surface would lead to a better perspective of the dynamics between the tinajas, the precipitation and water, and the bedrock. Possible methods could include geophysical, such as seismic, to better understand this concept.

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APPENDIX A: Pool Discharge

Table A1. Surface water inflow and outflow were recorded at each tinaja during monthly visits from February 2013 to February 2014. If a tinaja had inflow but not outflow for a given visit, it received a score of -1. If it had outflow but not inflow, it received a score of +1. Scores were scored across all visits. The lowest values represent the most frequent groundwater recharge, while positive values represent frequency of groundwater discharge. Only tinajas with at least non-zero visit are reported.

Tinaja	Discharge Value
Chim1a	-5
Chim1k	-4
Chim1g	-3
Chim2a	-3
Chim2h	-3
SteelT5	-3
WildH5	-3
WildH11b	-2
WildH15c	-2
MadC12	-1
MadC13	-1
MadC2	-1
MadC6	-1
SteelT2	-1
SteelT8	-1
WildH10a	-1
WildH13a	-1
WildH8	-1
Chim1i	0
Chim1m	0
WildH15a	0
Chim1L	1
Chim2d	1
Chim2e	1
Chim2i	1
MadC14	1
MadC3	1
MadC5	1
MadC7	1
MadC8	1
SteelT0a	1
SteelT11	1
SteelT3	1
WildH10b	1
WildH10g	1
WildH11	1
WildH12	1
WildH15	1
WildH6	1
WildH9	1
Chim1j	2
SteelT0	2
SteelT4	2
SteelT6	2

WildH0b	2
WildH10f	2
WildH10x	2
WildH13	2
Chim2j	3
WildH4	3
Chim1h	5
WildH3a	5

APPENDIX B: Drainage Cluster Analysis

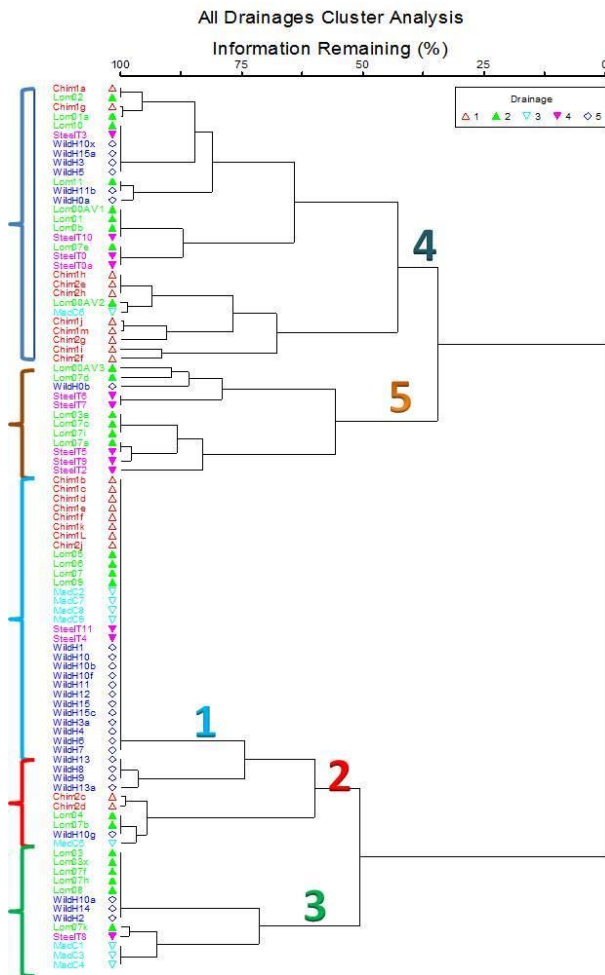


Figure A2a. Cluster Dendrogram for 95 tinajas across 5 drainages. Five groups were identified and are illustrated by the colored numbers. Note that Group 1 is a subset of Group 2, but it was given its own class because water was always present.

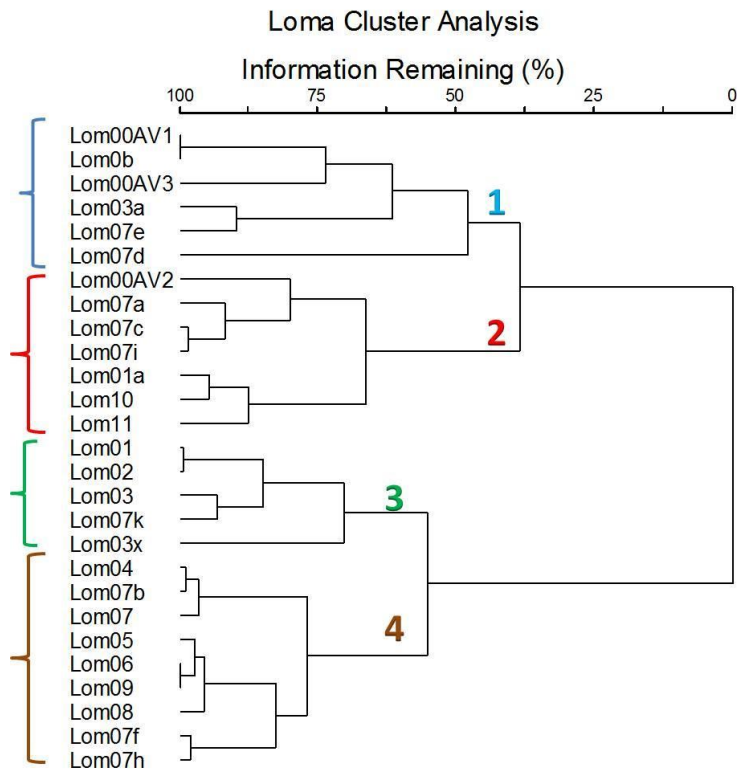


Figure A2b. Cluster Dendrogram for 27 tinajas at Loma-Verde Wash. Four groups were identified and are illustrated by the colored numbers.

APPENDIX C: Madrona Lower Pools Vegetation and Lithology

Pool 1A

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. There is also a dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures.

Pool 1B 2 meters deep

Percent Cover = 7%	Substrate Type
Tree = 3%	Bedrock = 90
Shrub= 2%	Boulder = 5
Forb = 1%	Cobble = 5
Grass =1%	Gravel = 0
	Sand = 0
	Silt = 0

This tinaja is full, water is flowing into it and out of it (2cfs). The area surrounding the tinaja is dominated by bedrock with a section on river right with a mix of boulder and cobble moving into the debris flow. The tinaja is 55% covered by cattails. Lots of benthic macro invertebrates.

Vegetation is very sparse around this tinaja. River right has a few mesquite trees and snags growing in a small rill on the alluvium leading in to the tinaja. Groundwater is scattered annual forbs. The rest of the plot holds scattered vegetation, all rooted in rills of the bedrock.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. There is also a dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures. The dike material looks to be the base bedrock for the tinaja formed here. Also there are fractures running through the dike.

Pool 1C

Percent Cover = 2%	Substrate Type
Tree = 0%	Bedrock = 100
Shrub= 0%	Boulder = 0
Forb = 1%	Cobble = 0
Grass =1%	Gravel = 0
	Sand = 0
	Silt = 0

This tinaja is a completely filled bathtub with 2cfs in and out. It is on a slope between 2 larger tinajas. The river right side eventually rises up to debris flow. Depth of the tinajas ~4ft. Some algae in the tinaja but otherwise it is free of vegetation.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. There is also a dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures. The dike material looks to be the base bedrock for the tinaja formed here. Also there are fractures running through the dike.

Pool 1D

Percent Cover = 2%	Substrate Type
Tree = 0	Bedrock = 100
Shrub= 1	Boulder = 0
Forb = 0	Cobble = 0
Grass =1	Gravel = 0
	Sand = 0
	Silt = 0

Tinaja is full with ~2cfs in and out. Cattails cover 20% of the water surface. Near the grasses are growing in the fractures, higher up some cacti shrubs are growing out of the fractures. River right is bedrock at an angle 60, moving into the debris flow. Everything else is bedrock. Frog eggs and tadpoles are located in the cattails. Depth >2m.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. There is also a dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures. The dike material looks to be the base bedrock for the tinaja formed here. Also there are fractures running through the dike.

Pool 1E

Percent Cover = <1%	Substrate Type
Tree = 0	Bedrock = 100
Shrub= 0	Boulder = 0
Forb = 0	Cobble = 0
Grass =1	Gravel = 0
	Sand = 0
	Silt = 0

The tinaja is full with a discharge of 2cfs in and out. Some algae. No other aquatic vegetation. Vegetation is minimal, just a few fractures that have grass growing out. Bedrock is located on the river right and river left for ~20m. Wasp nest under bedrock on upstream side. Depth is about 2m.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. There is also a dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures. The dike material looks to be the base bedrock for the tinaja formed here. Also there are fractures running through the dike.

Pool 1F

Percent Cover = 5%	Substrate Type
Tree = 0	Bedrock = 95
Shrub= 2	Boulder = 5
Forb = 2	Cobble = 0
Grass =1	Gravel = 0
	Sand = 0
	Silt = 0

This tinaja is full with flow in and out ~2cfs. It is located very close to 1E. The sides rise up initially at ~70' and then level out before sloping up again. No aquatic vegetation.

River right holds no vegetation, except a small cluster of grasses in gravel, on top of bedrock.

River left of shrub (desert cotton and mesquite) and forbs (*Artemisia ludovicina* dominating) grasses are scattered in between. This belt of vegetation is approximately 2.5 meters wide and ends in a transition to bedrock.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. Also in the bedrock there are garnet and mica bands. The bedrock also looks to be much more foliated and banded. The dark, finer-grained amphibolite dike that cuts through the bedrock and follows the trending direction of one of the general major fractures is getting thinner. The dike material looks to be the base bedrock for the tinaja formed here. Also there are fractures running through the dike.

Pool 1G

Percent Cover = 45%	Substrate Type
Tree = 013	Bedrock = 50
Shrub= 12	Boulder =30
Forb = 5	Cobble = 015
Grass =20	Gravel = 010
	Sand = 05
	Silt = 0

This tinaja is full and the surface area is much larger than normal based on the picture. There are cattails in 15% of the pool (they cover a larger portion when the water level is lower). A few different types of submerged plants cover 5% of the bottom of the tinaja. River right is dominated by bedrock. River Left is a mix of bedrock, boulder and cobble. Vegetation is primarily on the river left.

River right is dominated by shrubs, but also hosts different cacti (barrel cactus, saguaro and prickly pear) Vegetation is limited to upstream sections of this side.

River left is dominated by grasses 20% but has high tree cover (13%) provided by evenly aged willows standing 5 meters tall. Forbs and scattered between grasses, white shrubs (Desert cotton) are concentrated the furthest from the pool. Vegetation covers the stream of the tinaja, its growth limited by bedrock making up the river right bank.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. Also in the bedrock there are garnet and

mica bands. The bedrock also looks to be much more foliated and banded. Dike isn't present at the surface.

Pool 1H

Percent Cover = 36%	Substrate Type
Tree = 15	Bedrock = 40
Shrub= 4	Boulder =35
Forb = 1	Cobble = 010
Grass =16	Gravel = 010
	Sand = 05
	Silt = 0

This tinaja is a long thin tinaja. Some emergent vegetation <1% in pool (algae covers 40% of the bottom of the tinaja). River right is dominated by bedrock sloping up to the debris flow. River left is dominated by a mixture of boulders and cobble. River right is dominated by grasses growing out of fractures in the bedrock. Upland desert vegetation is present on the outskirts of the plot. River left is characterized by dominating grasses (20%) and high tree cover (15%- half of trees are snags) shrubs are young willows and desert cottons 4%.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. Also in the bedrock there are garnet and mica bands. The bedrock also looks to be much more foliated and banded. Dike isn't present at the surface.

Pool 1I

Percent Cover = 16%	Substrate Type
Tree = 08	Bedrock = 55
Shrub= 2	Boulder =30
Forb = 1	Cobble = 010
Grass =5	Gravel = 05
	Sand = 0
	Silt = 0

This is a shallow tinaja with a flow amount of 2cfs. There is a large patch of dead cattails in the tinaja. Algae are present. The river right side is dominated by bedrock. The river left side is dominated by large boulders. On the river right-side vegetation is sparse, only growing in the fractures.

River right is primarily grasses, growing in fractures in the bedrock. Some uplands desert vegetation is present. Further up slope, at the foot of the alluvium. River left is dominated by trees 8%, half of this is generated by a large velvet ash- *Fraxinus velutina*. Grass cover is 5% and is concentrated in the upstream section around the stream. The whole side is plastered with large boulders making up most of the ground cover.

Lithological description: Granitic Gneiss with large feldspathic, quartz, and garnet phenocrysts. Fractures both on the small and large scale present. Also in the bedrock there are garnet and mica bands. The bedrock also looks to be much more foliated and banded. Dike isn't present at the surface. There are light-colored veins of resistant (granitic material?). This material is not foliated.

Pool 1J

Percent Cover = 18%	Substrate Type
Tree = 05	Bedrock = 75
Shrub= 2	Boulder =10
Forb = 1	Cobble = 010
Grass =10	Gravel = 05
	Sand = 0
	Silt = 0

This is a shallow pool with a long running channel. The channel appears to frequently have water due to the amount of vegetation along it. There are species of emergent vegetation lequis, cattails etc. , covering ~30% of thee tinaja surface. There is a large amount of algae on the tinaja bottom.

River right holds little vegetation outside the stream. Grasses, forbs and small shrubs occur in and around fractures in the bedrock. Left side is dominated by trees and shrubs on the upstream section and grasses on the downstream section. Groundcover is primarily rock and boulder.

Lithological description: Granitic Gneiss with large feldspathic, quartz phenocrysts. Fractures both on the small and large scale present. Not really any large veins. Dike isn't present at the surface. There are light-colored veins of resistant (granitic material?). Fracture along the more apparent foliation planes.

Pool 1k

Percent Cover = 45%	Substrate Type
Tree = 025	Bedrock = 35
Shrub= 15	Boulder =35
Forb = 3	Cobble = 025
Grass =6	Gravel = 05
	Sand = 05
	Silt = 05

This is a large pool with a gravel/sandy bottom and a sand bar thing in on the downstream side. There are some algae, but no other aquatic vegetation. The upstream and river right side is dominated by bedrock. The river left side is a cobble gravel mixture, and downstream is boulder mixed with gravel. There are 3-4 springs on the river left side that are flowing. Discharge coming into the pool is 1-1.5 cfs.

River right side vegetation is sparse grass, growing in rock fractures and shrubby mesquite. River left is a tree dominated community with an understory of forbs and shrubs. Ground cover is rocks and boulders. Half of the trees are dead. Downstream side is a mix of shrubs and grasses rooted in gravelly sediment.

Lithological description: Granitic Gneiss with large feldspathic, quartz phenocrysts. More alluvium covering the bedrock around the tinajas. Fractures both on the small and large scale present. The bedrock also looks to be much more foliated and banded. Dike isn't present at the surface. There are light-colored veins of resistant (granitic material?). Fracture along the more apparent foliation planes.

Pool 1 L&M

Percent Cover = 5%	Substrate Type
Tree = 0	Bedrock = 90
Shrub= 3	Boulder =5
Forb = 0	Cobble = 05
Grass =2	Gravel = 00
	Sand = 0
	Silt = 0

These two connected tinajas are classic examples of the bowl in bedrock. There is no aquatic vegetation. The river right side is bedrock. River left is dominated by bedrock, but as you go further from the tinaja the substrate becomes more boulder with cobble.

River right side vegetation is very sparse-few grasses grow in fractures of the bedrock. River left is dominated by dense shrubbery on the boulders field furthest from the tinaja. Closer to the edge bedrock is the groundcover and grasses dominated.

Lithological description: Granitic Gneiss with large feldspathic, quartz phenocrysts. More alluvium covering the bedrock around the tinajas. Mainly small scale fractures present. The bedrock also looks to be much more foliated and banded. Dike isn't present at the surface. There are light-colored veins of resistant (granitic material?). Fracture along the more apparent foliation planes. The dark amphibolite dike reappears, but it's more pegmatic and lighter in color.

APPENDIX D: Loma Verde Lithology

Pool AV3

Lithological description: Heavily fractured chloritic breccia. In the channel below the tinaja gravel and sand alluvium has accumulated. Vegetation is primarily on the downstream side in alluvium or in fractures. We see some dark possible metamorphosed mafic material.

AV2

This tinaja was dry when we visited 3/13/2014.

Lithological description: Heavily fractured chloritic breccia. In the channel below the tinaja gravel and sand alluvium has accumulated. No large scale fractures to take note of around this area to take measurements from.

Possible Tinaja between AV2 and 0B

Location of small amount of water, but does not appear to be labeled a tinaja.

Lithological description: The rock is heavily fracture chlorite breccia. There is a bedrock slab in the middle of the channel, but upstream and downstream of it are cobble and gravel. Major and small fractures measured here.

OB

Lithological description: The rock is heavily fracture chlorite breccia with what looks like igneous intrusions/ igneous layer going underneath the tinaja. Many of the small scale fractures repeat the joint geometry but are not continuous Major and small fractures measured here.

Pool 1

Lithological description: The rock is heavily fracture chlorite breccia, with no sighting of igneous intrusions or layer at the surface. We see large (cm scale) feldspars.