MAPPING FRESH AND BRACKISH GROUNDWATER TO INFORM BETTER MANAGEMENT OF DECREASING GROUNDWATER LEVELS IN THE WILLCOX BASIN, SE ARIZONA

By

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Abstract

Adoption of the recent Lower-Colorado River Basin Drought Contingency Plan will make Arizona more dependent on groundwater to meet water resource demands (Colorado River Drought Contingency Plan Authorization Act 2019). Knowing the extent and distribution of fresh and brackish groundwater in relation to existing wells and water table elevations would enable water managers and users to better quantify how much water is available. This study focuses on the Willcox Basin in southeastern Arizona, where groundwater levels have experienced and continue to experience significant declines, yet there is increasingly high demand for groundwater for irrigated agriculture. The current water table is approaching the terminal depths of numerous wells in some locations. Based on the lithology and data obtained from local wells, the saturated thickness of fresh groundwater averages 280 ft across the basin. Near the Willcox Playa, the saturated thickness of brackish water averages 100 ft; no other brackish groundwater was found with depth from wells in other parts of the basin. It is still unknown how much deeper the fresh water extends, or if water becomes brackish with depth, because the data are limited by a lack of deep wells in the basin, and a similar lack of geophysical surveys.

Introduction:

Increasing demands for freshwater are becoming ever more common, causing water managers around the world to search for new and sustainable water resources (e.g., Vorosmarty et al., 2000, Milly et al. 2005, Ferguson and Gleeson, 2012). One already-existing and very important resource is groundwater; however, groundwater can be easily depleted if it is not managed wisely. Groundwater depletion is defined as the decrease in volume of stored groundwater. Groundwater depletion is a threat to the sustainability of water resources and can increase pumping costs, reduce well yields, and cause land subsidence among other problems (e.g. Konikow, 2015). In "Long-Term Groundwater Depletion in the United States" Leonard F. Konikow puts the speed of groundwater depletion into perspective, indicating "that the cumulative depletion volume during the 20th century was about 800 km^3 (≈ $6.5x10^8$ acre-feet). The total depletion increased to almost 1000 km^3 (≈ $8.1x10^8$ acre-feet) by the end of 2008—a 25% increase in just 8 years." Konikow also states that Arizona as a whole has reversed their depletion in comparison to the rest of the country as shown in Figure 1. This is attributable to the changes in water management that were implemented by the Groundwater Management Act of 1980, and the increased use of Colorado River water made possible via the Central Arizona Project.

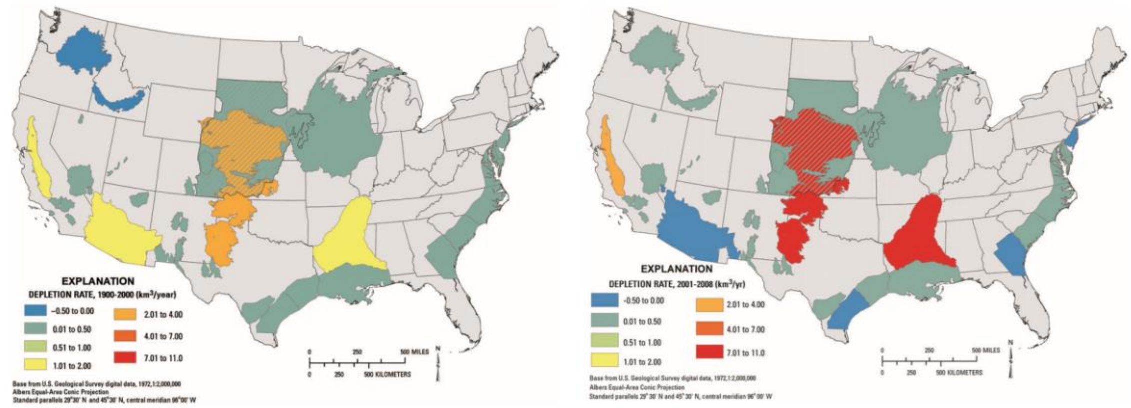

Figure 1. Average groundwater depletion rates from 1990-2000 (left) and 2001-2008 (right) (Konikow, 2015).

The Groundwater Management Act (GMA) of 1980 (for a summary, see: ADWR 2019) led to the creation of five Active Management Areas: Prescott, Phoenix, Pinal, Tucson, and Santa Cruz. These areas were chosen because of their critically low groundwater levels in need of regulation at the time. Looking at the groundwater levels now, it is evident that the GMA served its purpose; however, most of the state is not governed by the GMA. In fact, most of the state has no groundwater regulations at all, especially in rural Arizona like the Gila Bend Basin and Willcox Basin where groundwater use for agriculture is increasing (Scanlon et al., 2016).

The Willcox Basin in southeast Arizona recently made headlines because homeowners' wells in the area were running out of water (e.g. Gallagher Shannon, 2018). The Willcox Basin has had declining groundwater levels since they were first recorded in the 1940s, mostly because the basin is a hotspot for agriculture because of the lack of groundwater regulations and rural low-population density communities. Figure 2 depicts the magnitude of drawdown in a representative well in the Willcox Basin, and shows a star where the well is located, in addition to other well locations within the basin denoted by the blue dots. The plot exhibits the magnitude and severity of drawdown in some areas in the Willcox Basin. The well described in Figure 2 has seen almost

400 ft of drawdown since it was first constructed in 1953. Since the early 2000s, the water level in this well has been decreasing at a rate of approximately 14 ft per year.

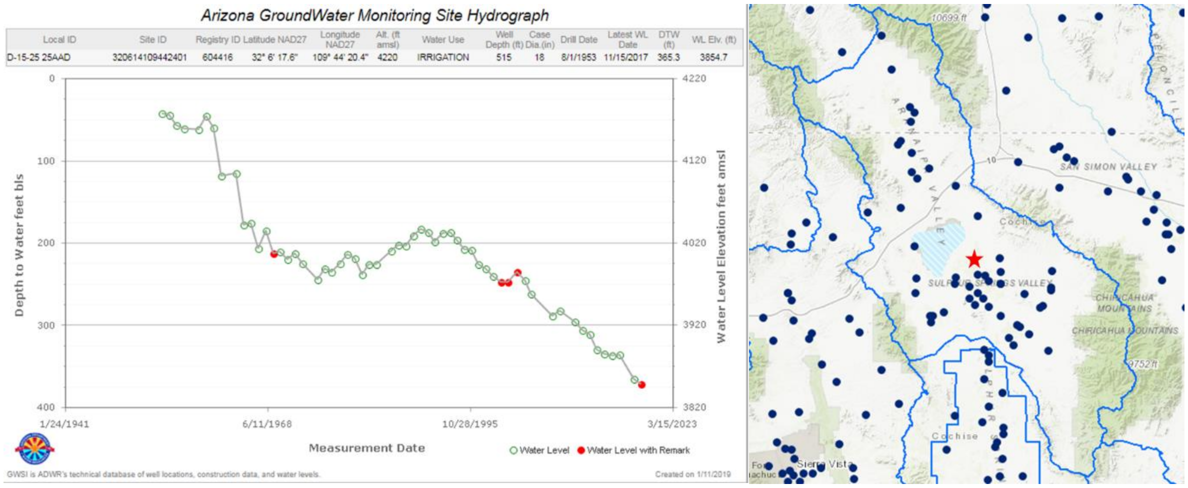

Figure 2. Plot of decreasing water levels in a well in the Willcox Basin with corresponding location (denoted by the red star) within the basin.

Furthermore, the article mentioned above (Gallagher Shannon, 2018) pointed out that areas in California are also beginning to regulate groundwater in the agricultural sector, which is causing farmers to look for new farmland with unregulated groundwater. These industrial farmers are looking for areas, such as the Willcox Basin, because of their lack of groundwater regulations. Additionally, the recent adoption of the Lower Colorado River Drought Contingency Plan will make Arizona much more dependent on groundwater (Colorado River Drought Contingency Plan Authorization Act 2019). This could potentially bring even more industrial farmers from regulated areas in Arizona (i.e. Active Management Areas) to the Willcox Basin or other basins with similarly unregulated groundwater resources. This is because Colorado River allocations to Arizona farmers are cut first so they will have to rely on groundwater once again. Thus, these farmers might be interested in relocating to an unregulated area where they can pump groundwater more freely.

Little is known about the volume of the aquifer in the Willcox Basin, because of the lack of deep wells or geophysical surveys. Therefore, it is unknown how the specific quality of the groundwater changes with depth. However, it is known that a layer of shallow brackish groundwater exists under the Willcox Playa (Towne & Freark, 2001). Generally, in most geologic settings, groundwater tends to become saltier with depth, usually going from freshwater to brackish to saline (Ferguson et al.,2018). Groundwater is considered brackish if it falls within 1,000 to 10,000 mg/L total dissolved solids (TDS). Simply put, brackish water is more saline than fresh water, but less saline than seawater. Developing brackish groundwaters into a beneficial source can magnify the water portfolios of many water managers around the world. This is especially true in Arizona where brackish water is more than abundant. A study completed by Montgomery and Associates (McGavock, 2008) found that there are approximately 600 million acre-feet (af) of brackish groundwater available in the state of Arizona alone. Figure 3 is the map McGavock (2008) developed to illustrate their results. Notice that there are almost 20 million af of brackish water available to use in the Willcox area. Brackish groundwater is not widely used in the Willcox Basin; however, its great quantity could be a partial solution for groundwater users in the area.

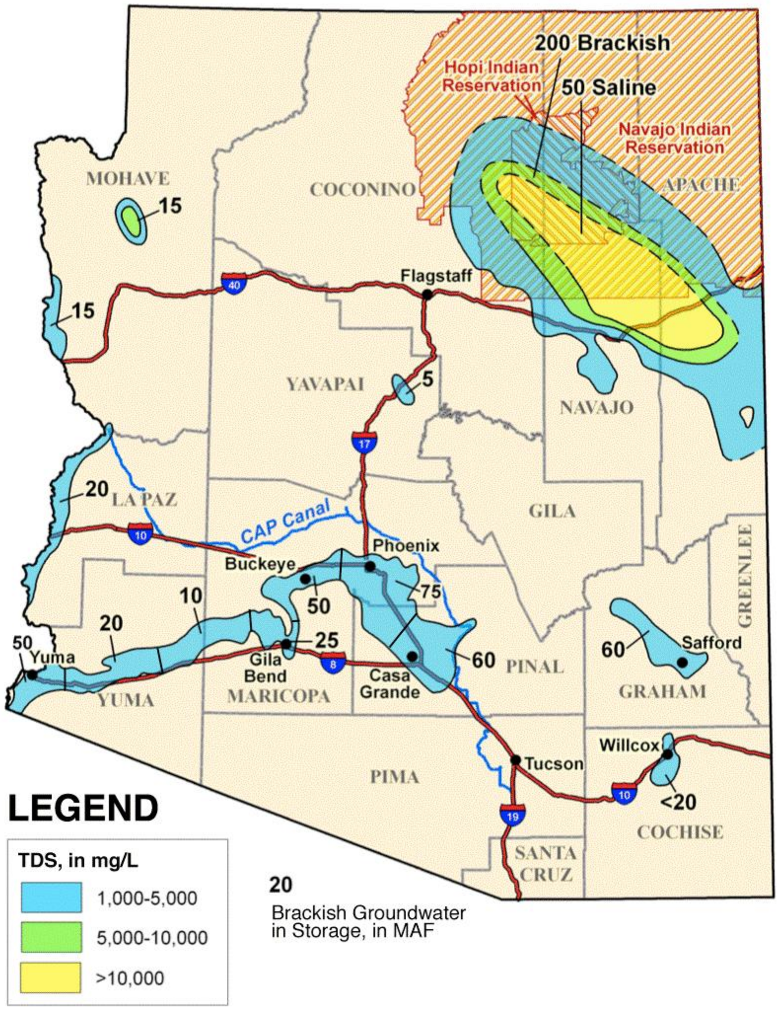

Figure 3. Locations and quantities of brackish water volumes and locations (McGavock, 2008).

There is a race for groundwater, both fresh and brackish, particularly in areas where groundwater is not being regulated (Ferguson et al., 2018). Ultimately, it is a question of who can get to that water first, and then it is an issue of sustainability. However, if groundwater depletion persists in aquifers, there will come a point in time when the ability of the aquifer to supply water will be adversely affected. In fact, areas where groundwater depletion has continued for decades have seen incredible decreases in well yields that have adversely affected agricultural production because farmers must reduce their irrigated acreage, reduce the seasonal irrigation volumes, or cease irrigation altogether (Scanlon et al., 2012). The goal of this project is to map the spatial distribution and extent of fresh and brackish groundwater in relation to the existing water wells, and assess the saturated thickness of fresh and brackish groundwater that is available to pump and use in the Willcox Basin. The quality of groundwater with depth will also be analyzed, including salinity and other elements that can affect irrigated agriculture in this area. Those elements include: arsenic, boron, beryllium, cadmium, chlorine, cobalt, copper, fluorine, iron, lithium, manganese, molybdenum, sodium, nickel, lead, selenium, vanadium, and zinc (Kang et al., 2019).

Literature Review:

Groundwater overuse is a worldwide problem that many scientists have studied (e.g., Vorosmarty et al., 2000, Milly et al., 2005, Ferguson and Gleeson, 2012). Kang and Jackson (2016) and Ferguson et al. (2018) conducted research on the increasing interest on brackish groundwater and how brackish groundwater might become one of the many solutions needed for solving water resource problems. This project will evaluate if brackish groundwater could be a potential resource for the Willcox Basin in southeastern Arizona.

Several sources of data on brackish groundwater quantity, concentration, and location were used for this project. Gootee et al. (2012) mapped the locations of wells with high salinities in Arizona, and focused in particular on areas with salinities higher than 10,000 mg/L. This is useful to pinpoint the locations of wells that have salinity concentrations higher than brackish water - one of which falls within the Willcox basin. Stanton et al. (2017) compiled data on groundwater resources in the United States and created a summary of the distribution of brackish groundwater along with its chemical and physical characteristics and use. This project narrows the scope to the Willcox basin, using some of the data used for Stanton et al.’s study. The University of Arizona’s *Arroyo* (Eden et al., 2011) provides a map created by Montgomery and Associates that identifies the locations and concentration of brackish groundwater in the state, as well as the quantity of groundwater associated with the concentrations. This map helped determine the basin of interest for this capstone project, and insured that the basins selected for this capstone study had a sufficient amount of brackish groundwater and non-brackish groundwater (i.e. salinity concentrations less than 1,000 to 10,000 mg/L).

Thiros et al. (2015) provide detailed descriptions of how basin-fill aquifers function, and they also provide a description of the anthropogenic and natural causes of brackish groundwater conditions. They also discussed the fact that aquifers in the Southwest tend to be heavily influenced by irrigation of agricultural lands. Agriculture affects groundwater in Arizona; in turn, water availability affects agriculture in the state. In AMAs, agricultural stakeholders are the first to have their water allotment withheld if a shortage is declared on the Colorado River. Therefore, now more than ever it is important for agriculture to find alternate resources such as brackish groundwater for irrigation. Stanton and Dennehy (2017) state that using brackish groundwater for irrigation could positively impact fresh groundwater use and magnify water portfolios in the Southwest.

Tahtouh et al. (2019) evaluate the effect of brackish groundwater and treated wastewater, which both tend to have higher salinity levels, on clayey soils in west Texas. They found that the soils did not result in any major changes to the soils; thus, provided the salinity does not adversely affect the crop, both these types of "non-traditional" irrigation water could replace freshwater irrigation in arid areas. Tahtouh et al. did not study the effects of increased salinity on crops. Ozturk (2018) completed a comparative study of two types of halophyte (salt-tolerant) plants irrigated with brackish groundwater (BGW) and brine produced by the desalination of BGW through reverse osmosis. The study was motivated by the increasing use of BGW irrigation in arid areas where water is more prone to shortage. Buono et al. (2016) also discuss examples that underscores the idea that not all brackish groundwater uses require desalination. They also highlight the challenges posed by desalination of brackish groundwater use.

The Arizona Department of Water Resources Groundwater Flow Model of the Willcox Basin (ADWR 2018) provides a detailed analysis of the previous, present, and future possible conditions of the Willcox water supply. Their modeled scenarios predict approximately 400 ft of additional drawdown in 100 years, which would dramatically decrease the volume of groundwater available for use. This could perhaps motivate residents to use the brackish groundwater in the area, and if so, it would be wise to start planning for the use of BGW now rather than to wait until groundwater is too scarce. The other option being drilling deeper wells.

Site Description:

Only wells that fall within the boundaries of the Willcox Basin, shown in Figure 4, were used in this study. The Willcox basin was chosen for both its water quantity and quality. The Willcox Basin is a hotspot for agriculture, which has dramatically affected the groundwater supplies. In the past, agriculture in this area consisted of smaller farming families. Currently, the lack of rural groundwater regulations has attracted large industrial agriculture companies to expand into the Willcox Basin, which has amplified the depletion of the aquifer (Gallagher Shannon, 2018). Additionally, the Willcox Basin has a unique distribution of salinity. Generally, salinity in groundwater tends to increase with depth; however, this basin has a layer of brackish water sitting on top of the fresh water. This brackish water is attributed to the Willcox Playa, which has high evaporation rates that have increased the concentration of evaporites, which in turn increases the salinity of the water below it.

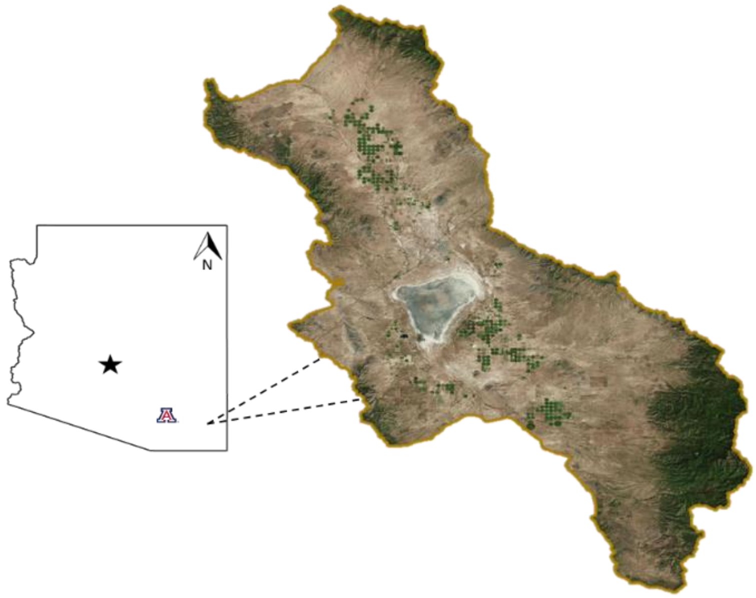

Figure 4. Location of the Willcox Basin in relation to the rest of the state of Arizona.

Methods:

Data were obtained from the U.S. Geological Survey (USGS) and the Arizona Department of Water Resources (ADWR). This project used total dissolved solids (TDS) and raw chemistry provided in the Brackish Water Database (Qi and Harris, 2017), and the National Uranium Resources Evaluation (Smith, 1997). Additionally, water level and well data collected for ADWR's Groundwater Site Inventory was used. The TDS and raw chemistry data were not uniquely tied to the Willcox Basin since they were organized by county; thus, data pertaining to the Willcox Basin were filtered using ArcMap. The data were then mapped in several ways. ADWR's data on well use in the Willcox Basin were used to make a pie chart of groundwater use in the basin (Figure 5). It is clear from the pie chart that 53% of water used in the Willcox Basin is dedicated to irrigated agriculture, and 21% is for stock needs. This means 74% of groundwater is pumped by farmers, and 23% is pumped for domestic use. It was important to find the proportions of groundwater use in the Willcox Basin to get a better understanding of the reasons behind decreasing water levels in the area.

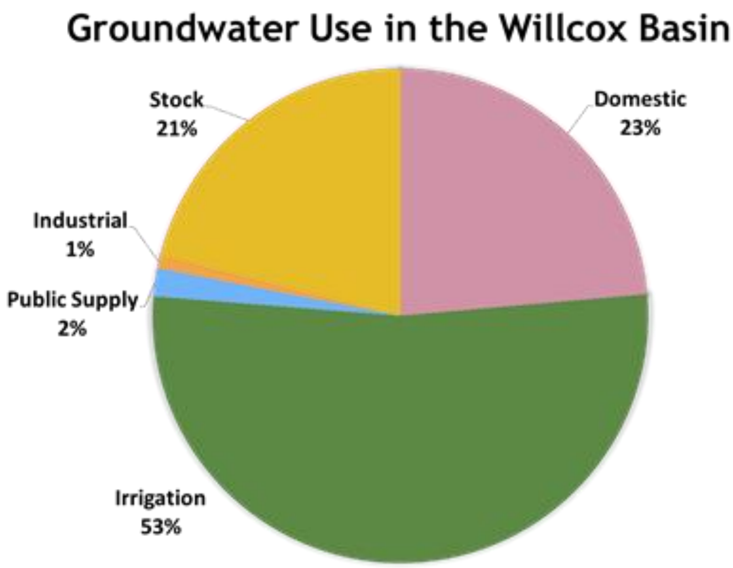

Figure 5. Groundwater use in the Willcox Basin.

Well depths that were also provided by ADWR were used to average well depth by the three dominant users in the Willcox Basin (Figure 6). Figure 6 gives insight as to who is able to tap into deeper groundwater resources. For instance, people that use the groundwater for irrigation seem to be able drill deeper wells compared to domestic users. Livestock wells are usually not very deep which is reflected in Figure 6. Using ADWR's water level data from 2014 to 2018, depth to water in the basin was also mapped in Figure 7. This map helps identify the areas that have had the most drawdown in the basin. The most drawdown occurs in the two main areas of agriculture, one to the north of the Willcox Playa and one southeast of it. The distribution of brackish water within the basin was mapped in Figure 8. Since brackish groundwater is being considered as a potential resource for the Willcox Basin in this study, it is important to know where it is located spatially. Yellow to orange gradations indicate fresh groundwater. The pink to purple gradations indicate brackish groundwater, which appears to be concentrated mostly below Willcox Playa. The only brackish groundwater in the Willcox Basin appears to be concentrated mostly below Willcox Playa. The areas to the northeast of the playa, near the edge of the watershed were poorly interpolated and are not indicative of a location of brackish groundwater.

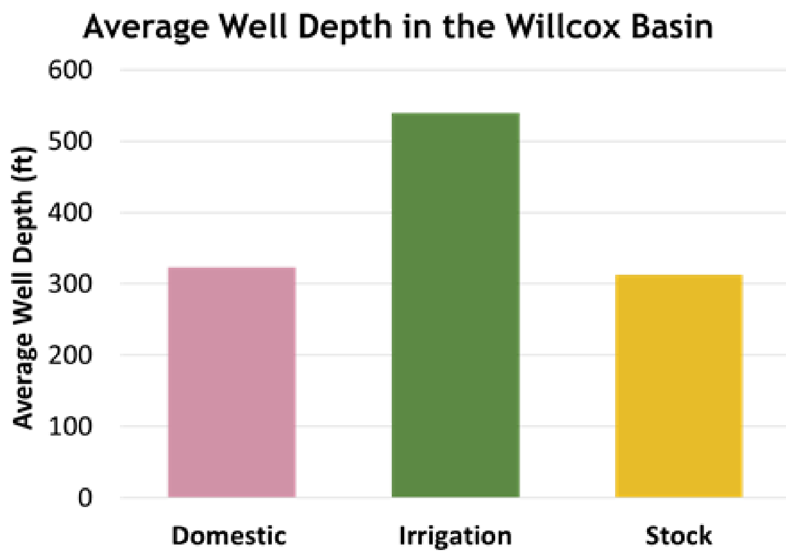

Figure 6. Average well depth of the three predominant groundwater users in the Willcox Basin.

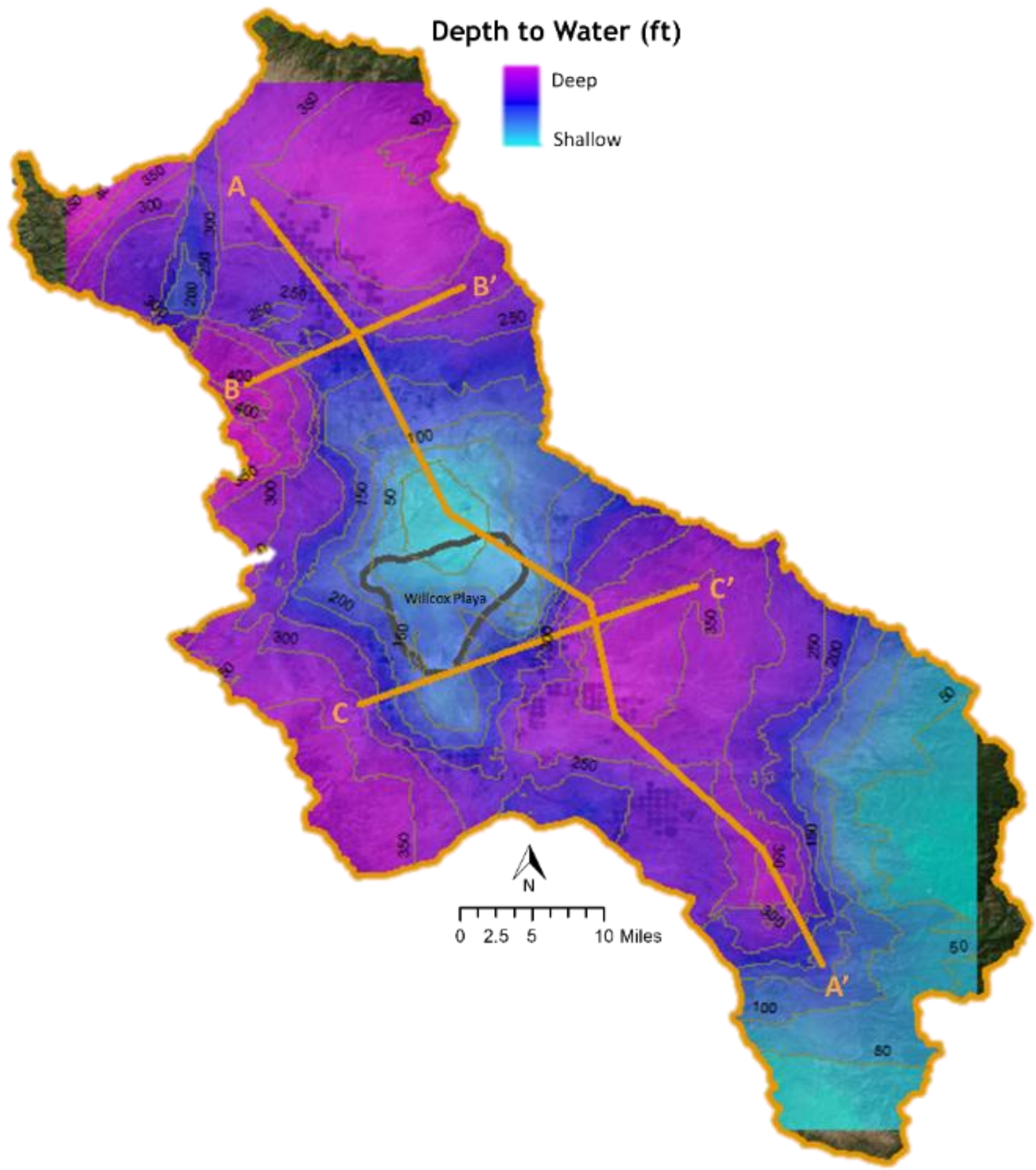

Figure 7. Map of depth-to-water in the Willcox Basin, where purple is deep and light blue is shallow. Two main cones of depression, indicated by the purple areas, are visible: one is northwest of the Willcox Playa and one is southeast of it.

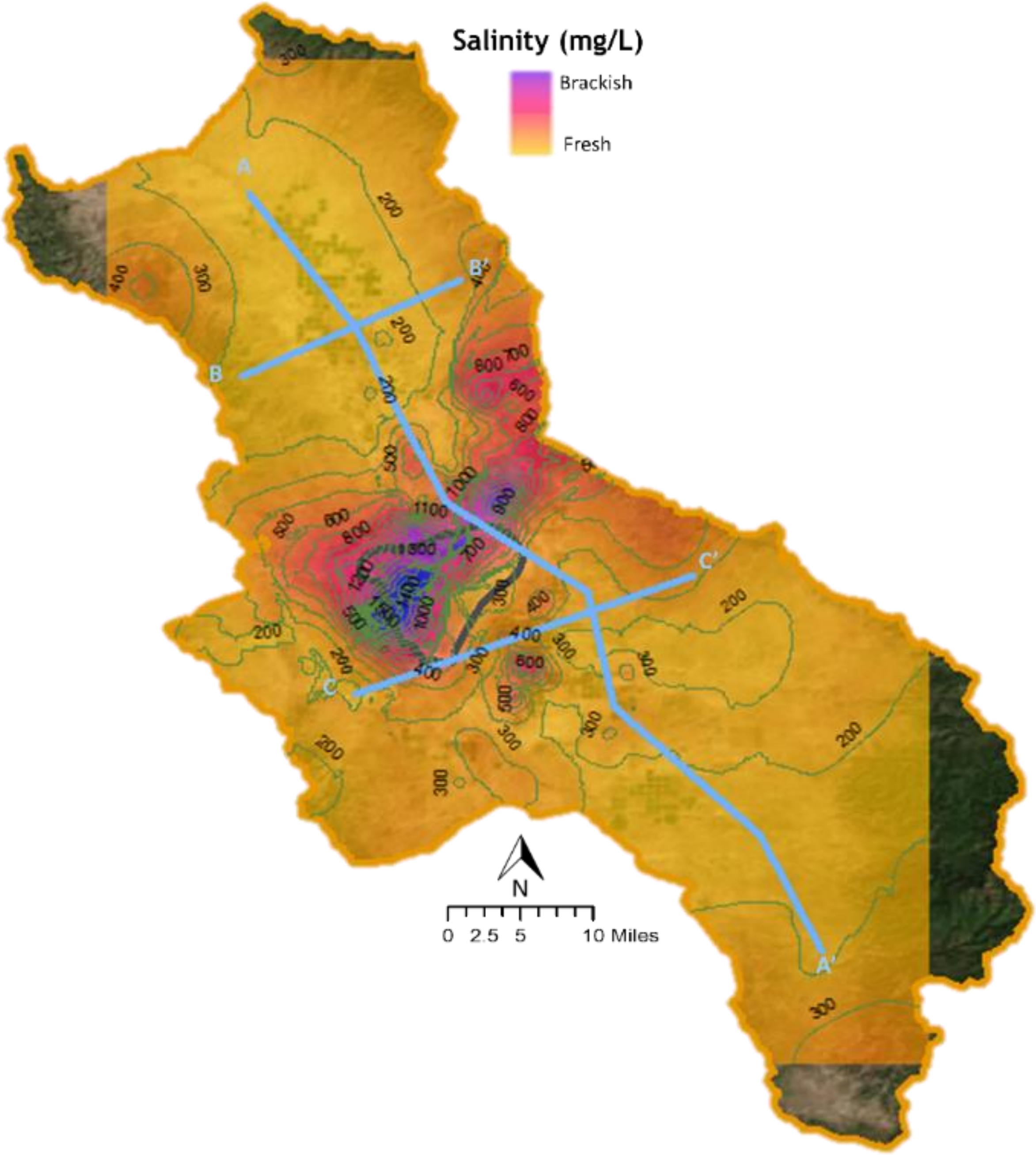

Figure 8. Map of salinity distribution in the Willcox Basin; where yellow to orange gradations indicate fresh groundwater and pink to purple gradations indicate brackish groundwater.

Geological cross-sections created by the Arizona Geological Survey were used to gain insight into the geologic characteristics of the basin (Gootee, 2012). These same cross sections were used to visualize the extent of fresh and brackish groundwater with depth and in relation to the area's water wells, Figures 9-11. The details of these figures will be discussed in the Results section below.

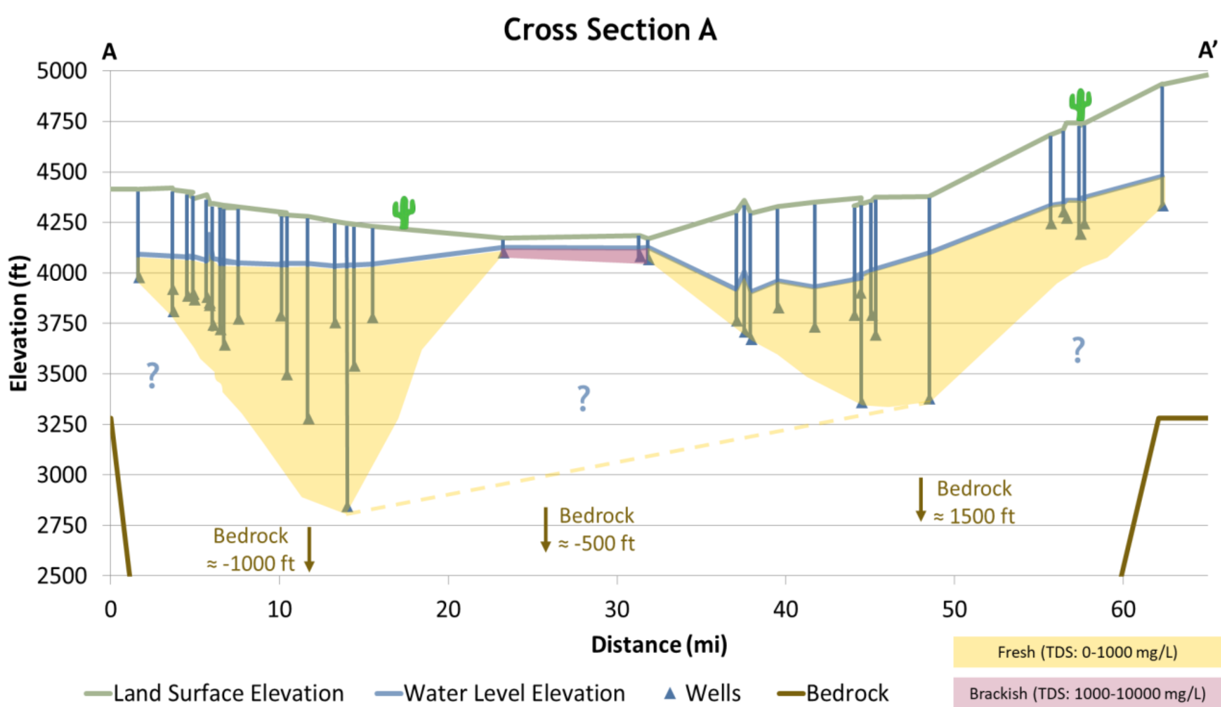

Figure 9. Cross-section A intersects from the northwest to southeast of the Willcox Basin. The lowest plateau on the land surface elevation line is where the cross-section intersects the Willcox Playa.

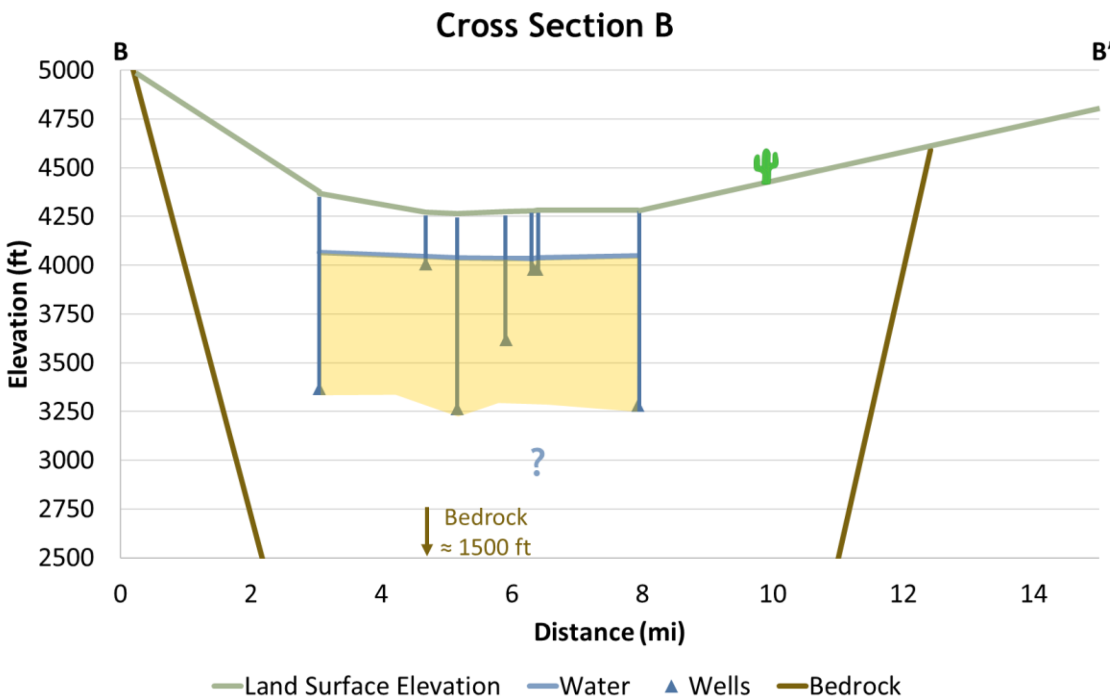

Figure 10. Cross-section B is located north of the Willcox Playa and intersects the northern cone of depression in the Willcox Basin.

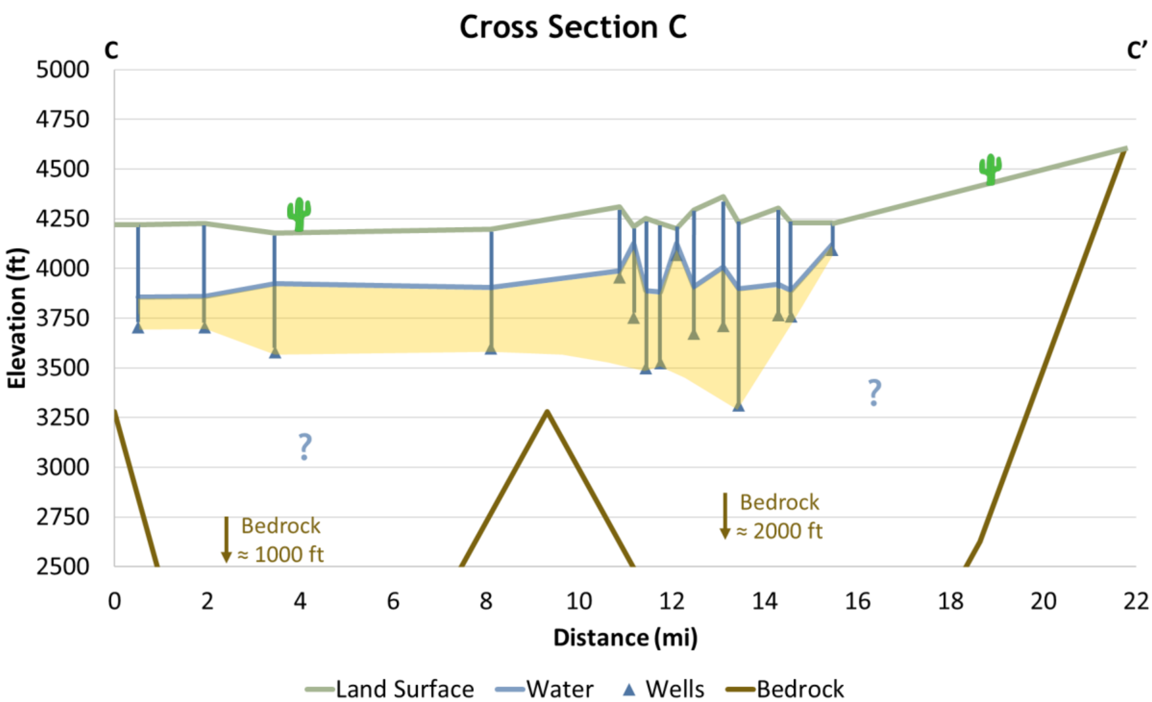

Figure 11. Cross-section C cuts across the southeastern cone of depression. The spike in the bedrock line is the Sulphur Springs high, which could have been caused by folding of the bedrock.

Further chemical evaluations of groundwater in the Willcox Basin were done similar to those conducted by Kang et al. (2019). They evaluated toxic trace elements (Al, As, B, Be, Cd, Cl, Co, Cr, Cu, F, Fe, Li, Mn, Mo, Na, Ni, Pb, Se, V, and Zn) in relation to irrigation. They divided the samples by deep and shallow groundwater, where deep groundwater is at least 500 ft. The distinction underscores the increasing importance of deep groundwater. The results of the current analysis for the Willcox Basin excluded aluminum and nickel because none of the samples contained either element.

Results:

As expected, most of the groundwater use in the Willcox Basin is for agriculture, either for irrigation or for livestock (Figure 5). Irrigation wells comprise over half of the wells in the basin and are the deepest wells on average (Figure 6), which gives insight as to who is able to tap into deep groundwater. Figure 6 is consistent with the New York Times article, "Water Wars of Arizona," that highlights a family's well running out of water despite that many acres of agricultural land were being irrigated all around them (Gallagher Shannon, 2018). Figures 5 and 6 help reiterate that agriculture is the dominant groundwater user in the Willcox Basin.

There are two main areas of drawdown in the Willcox Basin that coincide with the two areas of agriculture in the basin; these two areas (indicated by purple shading) are located northwest and southeast of the Willcox Playa. The two areas also represent the two main cones of depression that have occurred due to the two main agricultural areas. These areas are depicted in Figure 7, a map of depth-to-water in the basin. The purple areas to the west of the playa are mountain ranges, so the results pictured in Figure 7 are probably erroneous, caused by the type of interpolation used to create the map. The light blue color is where depth-to-water in the shallowest, which makes sense because the Willcox Basin is a closed basin. This means that water flows towards the center of the basin, where the playa is located. Additionally, surface water contributes to the shallow water table as runoff from agriculture flows to the playa (ADWR, 2018).

Most of the wells in the Willcox Basin draw fresh groundwater, as shown in Figure 8. Fresh water on that map ranges from yellow to orange and brackish water ranges from pink to purple. The wells near the Willcox Playa draw brackish water, which was already known because surface runoff drains toward the Willcox Playa. Much of the runoff carries fertilizers and pesticides that increase salinity of the water; additionally, evaporation at the playa makes the water even saltier, which creates brackish conditions (Towne & Freark, 2001). Given the current wells in the basin, the brackish groundwater around the playa was the only water that was found with brackish conditions.

The cross-sections below, Figures 9-11, help visualize the extent of fresh and brackish groundwater in the basin. Cross-section A (Figure 9) traverses through the middle of the Willcox Basin, from the northwest to southeast. On this plot, the extent of fresh water under the north and south areas of agriculture are visible, A to A', respectively. To be consistent with Figure 8, the yellow on the cross-section represents fresh water and the pink represents brackish water. To reiterate, the only brackish groundwater was found directly under the playa, and that layer extends about 100 ft from the water table and is shown in pink in Figure 9. Since it was already known that brackish water was found near the playa, not many wells were drilled around it, and the wells that are near it are fairly shallow. Thus, it is unclear how much deeper brackish groundwater extends or the extent of the mixing with nearby fresh water. It is also important to note that bedrock is the deepest in the northern side of the basin. Cross-section B (Figure 10) intersects the northern area of agriculture. Groundwater extends deeper in this area than it does in the south, which is supported by the visual provided by cross-section A. Brackish groundwater was not present in this area, nor in the southern area of agriculture that Cross-section C travels through (Figure 11). The most important thing to observe in Cross-section C is the spike in the bedrock that is known as the Sulphur Spring High. This geologic feature will limit the depth that wells can be drilled in that area.

On average, fresh water extends about 280 ft below the water table throughout the whole basin. Again, brackish water, which was found only underneath the playa, extends 100 ft from the water table. The extent of fresh water north of the playa averages about 100 ft deeper than the area south of the playa. Accordingly, cross-section A (Figure 9) is the only cross-section displaying brackish groundwater, since it is the only one that intersects the Willcox Playa.

These cross-sections give insight on the water quality of only the first 280 ft below the current water table. The map in Figure 12 (ADWR, 2016) displays contours of saturated thickness, and shows that saturated thickness varies slightly across the basin. It is the deepest at the center of the basin, ranging 2000 to 5000 ft. This underscores the magnitude of how much is still unknown about the quality and quantity of groundwater in the Willcox Basin.

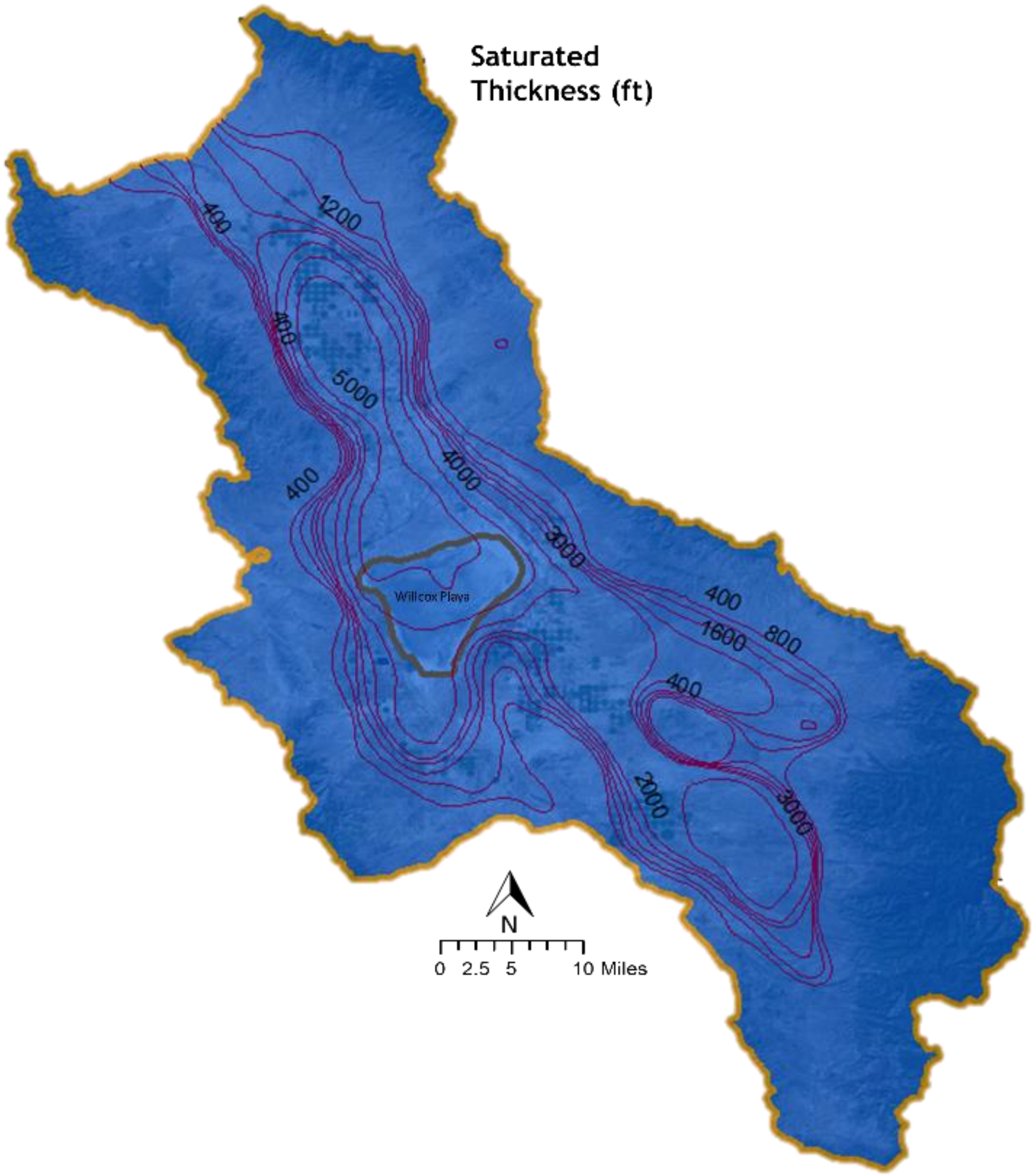

Figure 12. Map of saturated thickness contours in the Willcox Basin (ADWR 2016). The contours complement the cross sections regarding the extent of the basin that remains unknown.

Agricultural irrigation is the predominant water user in the Willcox Basin. Water used for irrigation must comply with several water quality standards; toxic trace elements for irrigation are outlined by Kang et al. (2019), and include Al, As, B, Be, Cd, Cl, Co, Cr, Cu, F, Fe, Li, Mn, Mo, Na, Ni, Pb, Se, V, and Zn. A similar analysis of these elements was performed for the Willcox Basin (Figure 13); however, no data for aluminum (Al) or nickel (Ni) was available so those two elements were excluded from the study. Figure 13 represents the percentage of data for each of these elements whose concentration was greater than the recommended maximum for irrigation. The data were further categorized into two sections: one with well depths deeper than 500 ft and one with well depths less than 500 ft, because groundwater deeper than 500 ft is what is considered deep groundwater for this study. The majority of these elements fell under compliance for wells deeper than 500 ft, except fluoride and iron. Fluoride, chloride, sodium, and molybdenum have several exceedances for wells less than 500 ft deep. Most of the exceedances by far occurred with fluoride, which is something for which the Willcox basin is known (Towne & Freark, 2001). Vinson et al. highlights that such high levels of fluoride can be linked to exceedances in arsenic due to shallow volcanic rock in some areas of the Willcox Basin (2011). In this study exceedances in arsenic concentrations also occur in shallow groundwater as shown in Figure 13.

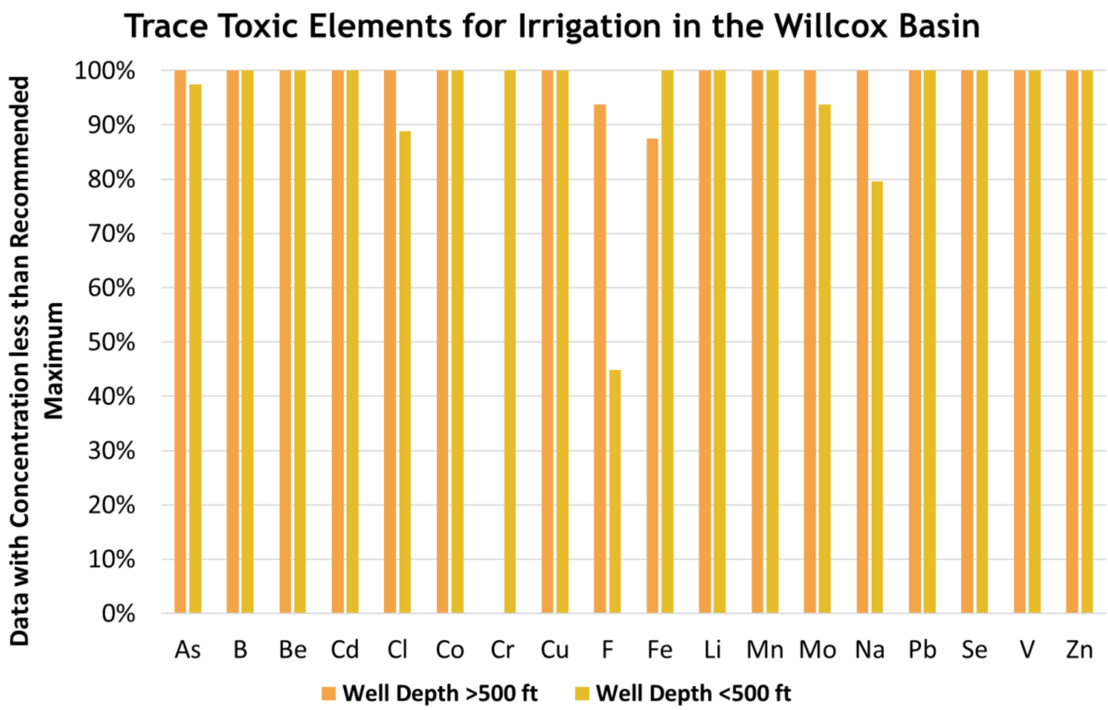

Figure 13. Percentage of data that indicate a low concentration of trace toxic elements, identified as those data that registered below the maximum concentration range. The plot excludes aluminum and nickel because of their absence in all samples.

Conclusions:

Groundwater in the Willcox Basin has been declining for decades and continues to decrease given the new wave of industrial agriculture in the area. The quality of the groundwater was determined by sampling the wells in this basin, from the current water table to an average of 280 ft below it (i.e. the deepest well). Southeast of the playa, depth-to-water is about 100 ft deeper than it is north of the playa. This means that water users in the southern part of the basin might eventually need to drill deeper wells. However, Figure 11 demonstrates yet another limitation south of the playa—the Sulphur Springs High. This geologic feature will limit the depth that wells can be drilled in that area. The area north of the playa has greater potential for drilling deeper wells. The saturated thickness in the basin can extend from 2000 to 5000 ft in the deepest parts of the basin, which means most of the aquifer's water quality is unknown. The basin might be very fortunate and have fresh water that extends to bedrock. Conversely, salinity could increase with depth, which is usually the case for basins such as the Willcox Basin (Ferguson et al., 2018).

If the groundwater depletion trend persists, it seems like water users in the Willcox Basin will continue to pump groundwater until their wells run dry. They will then be left with two potential solutions: drill deeper wells or pump shallow brackish water around the playa. Both options are likely to be costly; money would either be spent on drilling very deep wells that might or might not tap into more fresh water or on desalinating the shallow brackish groundwater around the playa. Brackish groundwater can be used directly for many purposes, but for this basin the most impactful use would be for livestock, which accounts for almost a quarter of groundwater use in the basin. It could also be used for irrigating crops; however, farmers would have to be wary of other salinity sources, like fertilizers, that could harm their crops.

Something must be done in the Willcox Basin. This groundwater system has been depleted. At this point water users still have options, but at the current rate of depletion they are likely to reach a point where pumping groundwater is no longer feasible. This study can be used by farmers and all other water users in the area as a map of what is known about their groundwater system. It also shows how much is still unknown about the Willcox Basin, and if groundwater levels continue to drop past well depths, they might have to venture into this unknown.

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