

Article

A Spatiotemporal Characterization of Water Resource Conditions and Demands as Influenced by the Hydrogeologic Framework of the Willcox Groundwater Basin, Southeastern Arizona, USA

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Abstract: In the Willcox Groundwater Basin (WGB), increasing rates of agricultural groundwater withdrawal have led to significant regional groundwater level decline, threatening the basin's long-term water resource security. Updated characterization of the basin's water resource conditions and agricultural water demand is critically important for informing groundwater resource management efforts. We developed the hydrogeologic framework of the WGB and linked groundwater level data with land cover classification data to provide a spatiotemporal assessment of water resource conditions and agricultural development in the WGB. A correlation analysis evaluated the degree of association between the basin's mean annual depth-to-groundwater and agricultural land cover extent. Results of this study indicate that between 2008 and 2021, agricultural land cover in the WGB increased by 29%. The average rate of groundwater level change in the basin's measured wells was calculated at -13.8 m between 2006 and 2021. We found a strong correlation between the basin's mean annual measured depth-to-groundwater and the annual agricultural land cover extent, further reinforcing the understanding of agricultural water use in the basin as a principal driver of groundwater level decline. The methodological framework employed proved a simple and effective way to assess groundwater resources as influenced by geology and land use. The outcomes of this study provide critical information toward improved water resources management by providing an integrated understanding of local hydrogeology, groundwater level variability, and changes in agricultural land cover in arid inland basins such as those found in Arizona, USA.

Keywords: water resources; groundwater; hydrology; hydrogeology; land cover classification; land use-groundwater interactions; southeastern Arizona



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1. Introduction

Changes in land cover and land use practices can have meaningful implications for groundwater resource availability, both by physically altering groundwater systems and by increasing associated water resource demands [1]. In particular, agricultural land use and its associated water requirements can significantly impact groundwater resource systems. In the United States, agricultural irrigation accounts for 70% of groundwater withdrawal [2]. Where agricultural demand results in groundwater withdrawal rates in excess of groundwater recharge, it can lead to complications including groundwater level decline and land subsidence. In many areas, previous case studies have documented increasing agricultural land use and irrigation as principal factors in declining groundwater conditions [3,4]. Such

circumstances can present significant water resource security concerns, especially within communities highly dependent on groundwater resource availability.

Despite growing understanding of the connection between land use practices and groundwater resource systems, this knowledge has not been widely integrated within existing water management frameworks [5]. This is evident in much of rural Arizona, where groundwater regulation outside the state's designated Active Management Areas and Irrigation Non-Expansion Areas has enabled the rapid expansion of large-scale agriculture and subsequent groundwater resource development [6]. In the Willcox Groundwater Basin (WGB) in southeastern Arizona, ongoing agricultural development and increasing irrigation demands have led to a significant increase in groundwater withdrawal and subsequent decline in groundwater levels [7]. This has raised concerns about the regional water resource conditions in the WGB, prompting renewed deliberation about whether additional groundwater management measures are warranted [8]. Most recently, these concerns culminated in the November 2022 election, in which a citizen-initiated ballot measure aimed to establish the WGB as an Active Management Area. Although the particular ballot measure was unsuccessful, growing awareness exists of the implications of agricultural land use and associated irrigation demand for groundwater resources in the WGB and throughout rural Arizona. Because areas outside of Active Management Areas have limited observational data to directly link agricultural use with groundwater, it is difficult to make informed policy decisions. This is a critical gap in the WGB and other Arizona basins.

We used a spatiotemporal approach to develop a comprehensive understanding of groundwater and groundwater utilization by agricultural uses in the WGB. Following [9], we analyzed spatiotemporal changes in precipitation, groundwater level, and agricultural land cover throughout the WGB through 2021. We used available geology and hydrology information to generate the hydrogeologic framework and potentiometric surface maps for the WGB. To further understand how changes in agricultural land use and associated water demand in the WGB influence regional groundwater resource conditions, we examined the degree of correlation between basin-wide rates of agricultural development and observed rates of groundwater level decline [9].

2. Study Area

2.1. Study Area Extent and Physical Setting

Located in southeastern Arizona, the WGB encompasses approximately 4950 km² of rural Cochise and Graham counties. The basin is located between UTM coordinates 12 S 590902 E 3623286 N and 12 S 651863 E 3492055 N (Figure 1). The basin is elongated in a northwest-to-southeast orientation, with an approximate maximum length of 145 km and approximate maximum width of 75 km. The WGB is bordered by the Aravaipa Groundwater Basin to the north, the Safford Groundwater Basin to the east, the Upper San Pedro Groundwater Basin to the west, and the Douglas Groundwater Basin and San Bernardino Valley Groundwater Basin to the south. The City of Willcox, situated near the basin's center, is the basin's largest community and had an estimated population of 3500 residents in 2019 [10].

The physical setting of the WGB is typical of the southwestern United States' Basin and Range Physiographic Province, which is broadly characterized as consisting of expansive alluvial basins bounded by faulted mountain blocks [11]. On a more regional scale, the WGB constitutes the northernmost expression of the Sulphur Springs Valley, a large northwest-to-southeast trending structural depression also encompassing the Douglas Basin to the south [8]. Numerous mountain ranges surround the WGB, including the Dagoon and Winchester Mountains to the west, the Pinaleno Mountains to the northeast, and the Chiricahua Mountains to the southeast. Surface drainage divides, existing near the Aravaipa Creek headwaters in the northern extent of the basin and along the prominent hills bordering the Douglas Basin to the south, further delineate the basin's extent [12]. Elevation within the WGB ranges from an approximate high of 3270 m in the Pinaleno

Mountain Range, to an approximate low of 1260 m at the Willcox Playa, a small alkali flat near the basin's center [13]. With the exception of some areas along the southernmost margins of the basin, surface drainage within the WGB is understood to flow internally towards the Willcox Playa [13].

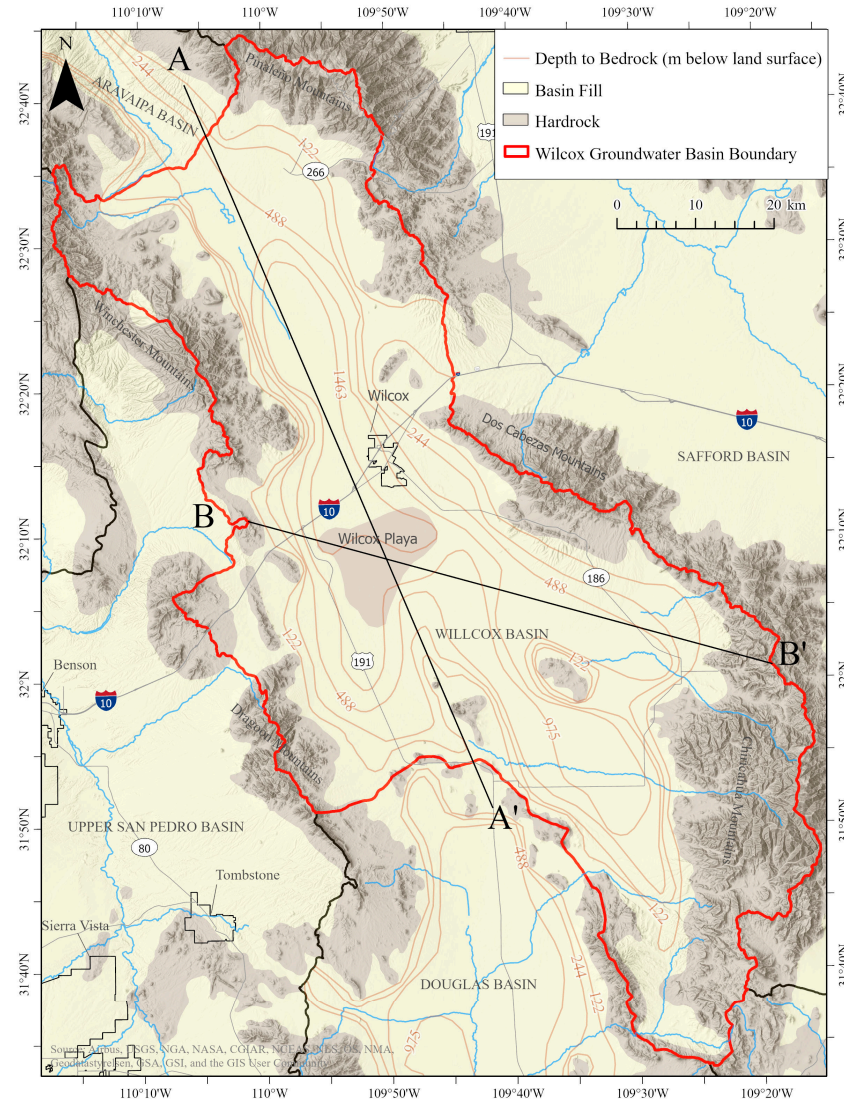


Figure 1. Surface geology, estimated depth-to-bedrock, location of geological cross-sections A-A' and B-B', and principal landscape features of the Wilcox Groundwater Basin (WGB).

2.2. Groundwater Resource Supply and Demand

Given the lack of surface water resources and the absence of water conveyance infrastructure to import water supplies into the basin, groundwater constitutes the predominant water resource within the WGB. Estimates approximate the WGB's total volume of groundwater in storage to range between 51.8 and 72.8 km³ [14]. Comprehensive data on annual basin-wide groundwater withdrawals are not readily available for the WGB, mainly due to a lack of reporting requirements for water use outside of designated areas in the state [15]. To compensate for the lack of groundwater withdrawal data, periodic groundwater withdrawal estimates for the basin have been compiled by the United States Geological Survey. Such estimates indicate a 56% rise in agricultural groundwater withdrawal between 2000 and 2020, increasing from approximately 0.17 to 0.26 km³ [16,17].

Agriculture is the primary driver of groundwater withdrawal throughout the WGB. The Arizona Department of Water Resources estimates that 90% of groundwater withdrawal in the basin is appropriated to agricultural irrigation [14]. An inventory of irrigated

agricultural land in the WGB in 2020 found that four crop types (corn, alfalfa, small grains, and orchards) accounted for over 85% of the basin's total irrigation demand [17]. The approximated consumptive use requirements, total irrigation withdrawal, and percentage of total irrigation demand for primary crops grown in the WGB in 2020 are summarized in Table 1. High-efficiency sprinkler irrigation is the predominant irrigation mechanism in the WGB, with an average irrigation efficiency of 88% [17].

Table 1. Generalized consumptive use requirements (m per growing season), total irrigation withdrawal (km^3), and the percent of total irrigation demand of primary crop types growing the WGB during 2020 [17].

Crop Type	Consumptive Use	Irrigation Withdrawal	Percent Basin's Total Irrigation Demand
Corn	0.6–0.7	0.090	34.5%
Alfalfa	1.2–1.3	0.054	20.8%
Small Grains	0.4	0.051	19.9%
Orchards	0.6–0.8	0.026	9.9%
Legumes	0.3–0.4	0.013	5.2%

Increasing rates of groundwater development throughout the WGB are also clearly observed in well registration data from the Arizona Department of Water Resources (Figure 2). Analysis of the well registration data from the Arizona Department of Water Resources [18] showed that the total number of wells registered within the basin increased by 20.9% between 2006 and 2021, increasing from a count of 3937 to 4759 wells. The average well depth increased by 18.0% over the same timeframe, increasing from an average depth of 105.9 to 125.0 m [18]. The noted increase in the basin's total number of registered wells and average well depth is consistent with the documented increases in the basin's annual groundwater withdrawal and further demonstrates the extent of ongoing regional groundwater development.

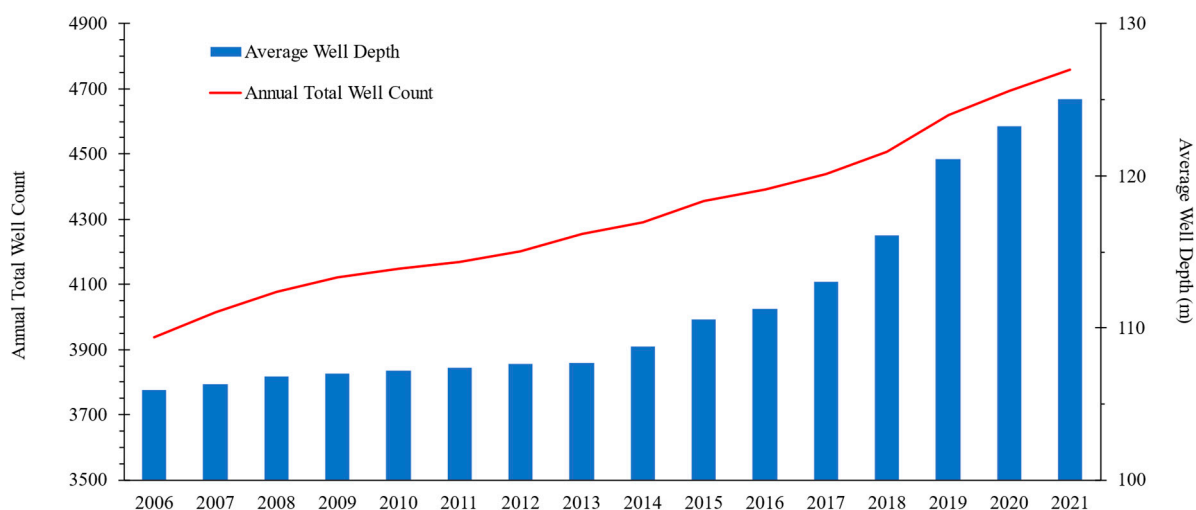


Figure 2. Annual increase in well count and average well depth between 2006 and 2021 for the Willcox Groundwater Basin (WGB).

2.3. Hydrogeologic Framework

Groundwater in the WGB is stored within the regional basin-fill aquifer system. The basin-fill aquifer consists of alluvial deposits of varying thickness, becoming deeper towards the basin's center, with a maximum thickness of approximately 1800 m [19]. Contours detailing the depth-to-bedrock throughout the WGB (Figure 1) provide the best available representation of the thickness of basin fill throughout the WGB. Underlying and bounding the basin fill is relatively impermeable hard rock of varying age and composition [20].

The basin fill is further delineated into older consolidated alluvium and younger unconsolidated alluvium. The consolidated alluvium underlies the unconsolidated alluvium and consists of silt, clay, sand, gravel, conglomerate, sandstone, and mudstone [21]. The unconsolidated alluvium consists of interbedded lake-bed deposits of silt and clay and stream deposits of sand and gravel [21]. The stream deposits within the unconsolidated alluvium generally have high permeability and make the unconsolidated alluvium the most productive sequence in the basin fill aquifer system [20]. Contrastingly, the fine-grained lake-bed deposits are highly impermeable and cause locally confined aquifer conditions where it overlays the stream deposits and perched groundwater where it underlies the stream deposits [22]. Near the Willcox Playa, where extensive lake-bed deposits exist, these conditions create an area of shallow groundwater relative to the rest of the regional basin-fill aquifer system [13]. While the generalized stratigraphic sequence in the WGB is well established, the specific extent and depth of its hydrogeologic units is not well understood across much of the basin, owing to insufficient availability and quality of subsurface data [19]. Table 2 provides a generalized stratigraphic overview of the hydrogeologic units present within the WGB.

Table 2. Lithology, permeability, and hydrologic properties of stratigraphic units in WGB as described in [20,23].

Hydrogeologic Unit.	Geologic Unit	Hydrologic Properties
Unconsolidated Alluvium	Lake-Bed Deposits Stream Deposits	Non-water bearing, creates confining conditions Sand and gravel lenses are highly permeable
Consolidated Alluvium	Poorly Consolidated Alluvium Moderately Consolidated Alluvium	Low to moderate permeability Very low to moderate permeability
Hardrock	Igneous, metamorphic, and sedimentary hardrock consistent with the lithology of surrounding mountains	Variable based on lithology and degree of fracture

The WGB is a closed basin, where groundwater flows inward toward the basin's center. Recharge in the basin largely results from runoff and seepage along the adjoining mountain fronts, with estimates of naturally occurring recharge ranging between 0.02 and 0.06 km³ annually [14]. Additional recharge occurs due to agricultural irrigation in the basin. It was approximated at 0.08 km³ in 2015 by the Arizona Department of Water Resources in 2018 [7]. In the northern and southern extents of the basin, saturated alluvial material extends into the Aravaipa and Douglas Groundwater Basins. However, groundwater flow is limited in each case by a groundwater divide, limiting interbasin flow [7]. The regional groundwater flow system is also impacted by multiple large groundwater depressions, associated with the basin's agricultural pumping wells [13]. Groundwater pumpage in these areas accounts for most of the groundwater discharge throughout the basin and has resulted in a northward shift of the groundwater divide along the Aravaipa and Willcox Groundwater Basins [7].

3. Materials and Methods

3.1. Precipitation Analysis

Data from the Oregon State University PRISM Climate Group were utilized to assess spatial and temporal trends in precipitation throughout the WGB. The datasets developed by the PRISM Climate Group are the most widely utilized spatial climate datasets covering the United States [24]. They are publicly accessible through the online PRISM Data Portal: <https://prism.oregonstate.edu/> (accessed on 7 February 2023). Raster data containing 30-year average precipitation estimates for the WGB were used to derive a contour map,

illustrating the spatial distribution of average annual precipitation in the WGB between 1991 and 2020. The 30-year annual precipitation record between 1991 and 2020 was also compiled from PRISM for three specified locations within the WGB. The three selected locations included the Willcox Playa, the Pinaleno Mountains, and the Chiricahua Mountains. These locations were selected because precipitation in the WGB strongly depends on elevation and precipitation rates are historically known to be highest along the higher-elevation mountains spanning the basin's eastern margins [23]. Therefore, these sample points were selected to account for variability in precipitation patterns arising from spatial distribution and elevation. A Mann–Kendall Trend Test was conducted using the time-series data obtained for the three locations in order to assess for the presence of any long-term climatic trends. The Mann–Kendall Trend Test is well suited for assessing hydrologic time-series data for monotonic trends. It accommodates non-normal data distributions and is less sensitive to the influence of outlier data points, typical qualities of hydrology data [25]. Subsequently, in instances where a trend was identified, Sen's Slope Estimation Method was used to evaluate the corresponding rates of change.

3.2. Analysis of Water Year 2021 Groundwater Conditions

Groundwater level data used in this research were derived from the Arizona Department of Water Resources' Groundwater Site Inventory Database. The Groundwater Site Inventory Database is Arizona's primary data repository for groundwater monitoring data collected throughout the state [26] and is readily accessible through the online Groundwater Site Inventory data portal: <https://azwatermaps.azwater.gov/gwsi> (accessed on 1 December 2022).

During Water Year 2021, the Arizona Department of Water Resources conducted an intensive data collection project in the WGB [27]. A water year (WY) begins on 01 October and ends on 30 September of the following year, with the water year being designated by the year it ends. The data collected during this project provided an updated assessment of the basin's groundwater conditions. Initial processing of the groundwater level data involved a systematic assessment of each measurement, a review of the associated measurement remarks and comments, a review of the full record of groundwater level data available for the site, and a spatial assessment of the data. Any sites that indicated the potential presence of non-static groundwater conditions at the time of measurement or presented high levels of uncertainty were removed from the finalized datasets. In addition, the data were constrained to include only measurements taken between October and February, to account for potential variability associated with seasonal patterns in groundwater recharge and withdrawal. Following data review and processing, the finalized groundwater level dataset for Water Year 2021 consisted of 206 measurements.

A groundwater elevation contour map was developed to characterize the current groundwater resource conditions throughout the WGB. Due to the sparse distribution of data points for parts of the WGB, supplemental depth-to-groundwater data for an additional 47 well sites within the Aravaipa and Douglas Groundwater Basins were also included to develop the groundwater elevation contour map. These additional sites provided valuable reference data along the northern and southern margins of the basin, where saturated alluvium is understood to extend into the Aravaipa and Douglas Groundwater Basins.

To validate well site altitude and derived groundwater elevation, each well site altitude was cross-referenced against a 10 m resolution digital elevation model of the land surface. In each instance, the listed well site altitude was within five meters of the value specified by the digital elevation model. This confirmed the accuracy of the well site altitude and the derived groundwater elevations. We also cross-referenced the spatial locations of wells with the basin's mapped geology and eliminated any wells outside the regional basin-fill aquifer system.

We developed a groundwater contour map from groundwater elevation data using a blend of expert interpretation and automated spatial interpolation. First, we applied

inverse distance interpolation to groundwater elevation point data to generate an initial estimate of groundwater elevation; we then converted the resultant raster to a contour map. Because groundwater elevation data were unevenly distributed through the basin and were particularly sparse along basin margins; this approach resulted in considerable uncertainty in regions of the basin with little data. Therefore, we additionally used expert interpretation to hand digitize contours, drawing heavily from past hydrologic maps of the area, historical groundwater data, and a conceptual understanding of the regional groundwater flow system.

To further illustrate the regional groundwater system in the WGB, two conceptual cross-sections were created for selected transects (A-A' and B-B') in the basin (Figure 1). Various datasets were used to inform the development of the cross-section diagrams, including basin-wide depth-to-bedrock data, a limited number of well logs, a regional geologic map, and a digital elevation model. Using the groundwater elevation contour map as a reference, an approximated representation of the regional groundwater elevation was also plotted on each cross-section.

3.3. Groundwater Level Change Analysis between Water Years 2006 and 2021

Groundwater level fluctuations between WY 2006 and WY 2021 were also assessed using datasets compiled from the Groundwater Site Inventory database. For any well site with a groundwater level measurement taken in both WY 2006 and WY 2021, a groundwater level change value was calculated by subtracting the WY 2006 depth-to-groundwater measurement from the WY 2021 depth-to-groundwater measurement. The derived negative groundwater level change values indicate declining groundwater level conditions, and the positive values indicate rising groundwater level conditions. In total, 149 water level change values were calculated over the 15-year timeframe of interest. The calculated groundwater level change data were plotted as a map to illustrate the spatial distribution of observed groundwater level changes throughout the WGB.

Groundwater level change was also assessed at a higher frequency by analyzing the water level records for the 52 annually monitored wells within the WGB. As these sites generally have water level measurements taken each year, they provide a more consistent record of water level change over the timeframe of interest. Using the available depth-to-groundwater data for each of the annually measured wells, a mean depth-to-groundwater was calculated for each year between 2008 and 2021. Annual change in the mean depth-to-groundwater was then calculated by subtracting each year's mean depth-to-groundwater value from the subsequent year's mean depth-to-groundwater value. These mean annual depth-to-groundwater values served as a valuable reference for considering the year-to-year change in basin-wide groundwater conditions. Additionally, the annual mean depth-to-groundwater values functioned as an ideal metric for comparison against the basin's estimated annual agricultural land cover extent.

3.4. Agricultural Land Cover Change Analysis

Due to limitations in available groundwater withdrawal data for the WGB over the last two decades, directly quantifying the basin's record of agricultural consumptive water use is challenging. Consequently, we inferred agricultural use by evaluating changes in the extent and distribution of agricultural land cover in the WGB. Agricultural land cover change in the WGB was assessed through the use of the National Agricultural Statistics Service's (NASS) Cropland Data Layer (CDL). The CDL is the only available data source that provides comprehensive spatial data on nationwide agricultural and non-agricultural land cover on an annual basis [28]. The CDL incorporates satellite-based remote sensing data, ground truth observations, and other supplemental data, to develop a 30 m resolution, raster-formatted, thematic land cover classification map [29]. Due to its markedly high spatial and temporal coverage, the CDL has been increasingly applied in research involving land cover change estimations [30]. The Cropland Data Layer is an

open-access resource accessible through the NASS online CropScape Data Portal: <https://nassgeodata.gmu.edu/CropScape/> (accessed on 22 January 2023).

CDLs covering the WGB are available for each year between 2008 and 2021. As this research was strictly concerned with the generalized agricultural and non-agricultural land cover extent throughout the WGB, the CDLs were reclassified into more broadly defined cropland and non-cropland land cover classes. Aggregating the highly specific land cover classes into more generalized cropland and non-cropland classes has been demonstrated to improve the overall classification accuracy of the CDL, as it eliminates error resulting from misclassification between different crop types [31].

Formal accuracy assessments are conducted for each year's CDL on a state level by NASS and are published online as confusion matrices. Accuracy assessment of the reclassified CDLs was conducted using these published statewide error matrices, reformatting each year's error matrix to reflect the applied reclassification scheme. The revised error matrices indicated that the overall average accuracy of the reclassified CDLs ranged between 97.3% and 99.2%. Although the published error matrices pertain to classification accuracies across the entire state of Arizona, the diversity in landscape within the WGB is far less than the diversity of landscape across all of Arizona, suggesting that state-wide errors would be a conservative estimate of those in the more homogenous WGB. Moreover, the Cropland Data Layer has been documented as having higher accuracy in more arid landscapes, such as the WGB, where greater contrast exists between cropland and the surrounding landscape [31]. Given these presumptions, we expect that the true classification accuracies for the WGB to be better than those presented in the statewide composite error matrices.

Area estimates of agricultural land cover were then derived for each CDL using a pixel counting methodology. This approach involved summing the number of classified pixels for the aggregated cropland class and multiplying the total by a factor of 900 m², corresponding to the area within each of the 30 m resolution raster cells. The total area in m² was then converted to hectares (ha). Pixel counting is often subject to considerable uncertainty due to the possibility of misclassification between thematic classes. Therefore, pixel counting should only be utilized to estimate area when the accuracy of the image classification is found to be at an acceptable level [32]. This was determined to be the case, as the revised accuracy assessments demonstrated.

Using the annual area estimates of agricultural land cover derived from the reclassified Cropland Data Layers, the annual change in agricultural land cover was calculated by subtracting each year's total acreage from the subsequent year's total area. Total agricultural land cover change between 2021 and 2008 was calculated by subtracting the 2008 area estimate from the 2021 area estimate. A raster overlay analysis was conducted to produce a map illustrating the spatial extent of agricultural land cover change in the WGB between 2008 and 2021.

3.5. Correlation Analysis

A bivariate correlation analysis was conducted to test the level of association between the mean annual depth-to-groundwater measured in the basin's annually measured wells and the estimated basin-wide agricultural land cover extent between 2008 and 2021. Based on the characteristics of the data, a Spearman Rank Order Correlation Analysis was selected to assess the level of correlation between the variables. The Spearman Rank Order Correlation Analysis is a nonparametric statistical test used to assess the level of correlation between two variables of interest. The benefits of using the Spearman Rank Order Correlation Analysis include that it is uninfluenced by data distribution and is resilient to outlier values [33]. The Spearman's Rank Order Correlation Analysis culminates in the Spearman Rank Order Correlation Coefficient (ρ), which ranges in value between -1 and 1 , with values further from zero indicating a greater level of correlation [34]. The statistical significance of the derived correlation coefficients is further evaluated through the calculation of a " t -statistic," which is then compared to a table of critical " t -statistics" and used to determine the statistical " p -value" [33]. In addition, the compiled time-series data was

utilized to derive projected estimates of the WGB's mean annual depth-to-groundwater and estimated agricultural land cover extent through the year 2031.

4. Results

4.1. Precipitation Analysis Results

4.1.1. Precipitation Distribution Map

The developed precipitation contour map illustrates the distribution of 30-year average precipitation throughout the WGB (Figure 3). Average precipitation is greatest along the basin's high-elevation mountain ranges, with some areas in the Chiricahua and Pinaleno Mountains averaging over 950 mm of precipitation annually. Lesser annual precipitation totals exist across the basin's lower elevation areas, with much of the basin interior averaging less than 350 mm of precipitation annually. The observed spatial distribution of precipitation appears consistent with past representations and descriptions of regional precipitation patterns.

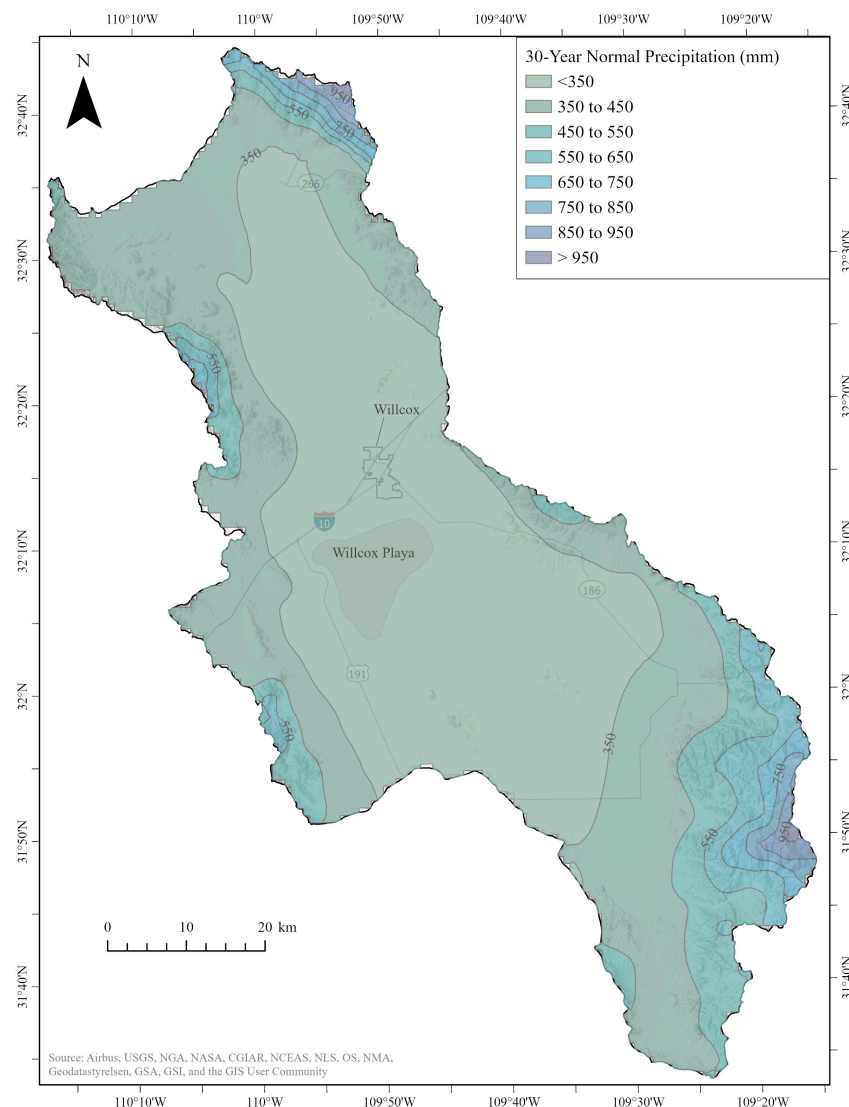


Figure 3. The 30-year average precipitation distribution for the Willcox Groundwater Basin (WGB).

4.1.2. Mann–Kendall Trend Analysis

Figure 4 shows the time-series plots of estimated annual rainfall between 1991 and 2020 for the three selected locations within the Willcox Playa, Pinaleno Mountains, and Chiricahua Mountains. These long-term precipitation records further illustrate the influence of

elevation on annual precipitation totals, with the higher elevation locations in the Pinaleño Mountains and Chiricahua Mountains averaging 92.0% and 99.6% more precipitation than the Willcox Playa location between the years 1991 and 2020. Variation in annually received precipitation was greatest in the Chiricahua Mountains. Between 1991 and 2020, annual precipitation ranged from 388 to 1438 mm in the Chiricahua Mountains, from 442 to 1025 mm in the Pinaleño Mountains, and from 177 to 497 mm in the Willcox Playa location.

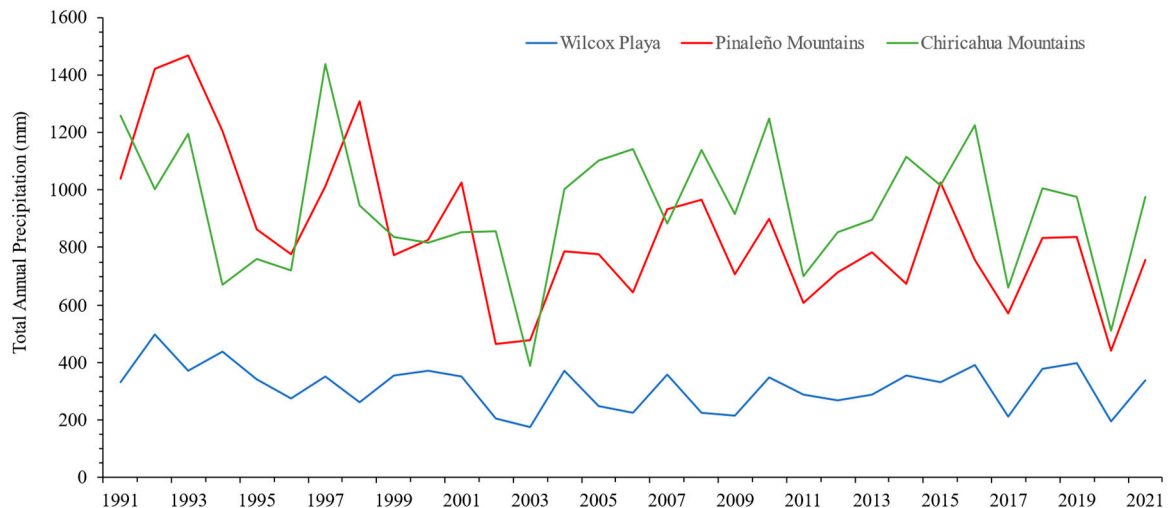


Figure 4. The 30-year average precipitation record for select locations in the Willcox Groundwater Basin (WGB).

Results of the Mann–Kendall Trend Test and Sen’s Slope Estimation Method, which were used to assess annual precipitation records at the select locations in the WGB for the presence of climatic trends, are summarized in Table 3. As the derived “ τ ” values indicated, no meaningful trends were observed for the Willcox Playa or Chiricahua Mountains locations. However, a moderate negative trend was identified for the location in the Pinaleño Mountains ($\tau = -0.35$, $p < 0.01$, $n = 30$). Subsequent application of the Sen’s Slope Estimation Method derived the annual rate of change in precipitation at the Pinaleño Mountains location to be -13.4 mm.

Table 3. Trend Test and Sen’s Slope Estimate Method for evaluating annual precipitation totals for select locations in the WGB.

	Willcox Playa (12 S 609086 E 3569500 N) Elevation = 1271 m	Chiricahua Mountains (12 S 661147 E 3527591 N) Elevation = 2614 m	Pinaleño Mountains (12 S 605170 E 3613985 N) Elevation = 2782 m
Tau (τ)	−0.11	0.00	−0.35
p -Value ($\alpha = 0.05$)	0.21	0.52	<0.01
Sen’s Slope Estimate (mm)	−1.50	−0.02	−13.40

4.2. Analysis of Water Year 2021 Groundwater Conditions

4.2.1. Groundwater Elevation Contour Map

The groundwater elevation contour map depicts the spatial distribution for groundwater elevation throughout the WGB in 2021 (Figure 5). The updated groundwater level conditions were consistent with previous hydrologic maps and area characterization. Nonetheless, it is recognized that the potential for considerable uncertainty exists within the developed groundwater elevation map. Accordingly, this map should be viewed as a generalized representation and not as a definitive portrayal of groundwater conditions in the WGB. Groundwater elevation ranges from a high of approximately 1500 m above sea level (masl) along the Chiricahua Mountains, to a low of less than 1175 masl south

of the Willcox Playa. As indicated by the groundwater elevation contour map, the generalized direction of groundwater flow in the WGB is away from the basin's margins and towards the basin's center. Groundwater depressions are observed throughout much of the basin's interior and correspond with areas of agricultural activity. A relatively shallow groundwater elevation area is noted in the basin's center, likely due to the locally confined aquifer conditions and area of perched groundwater associated with the lake-bed deposits in this area.

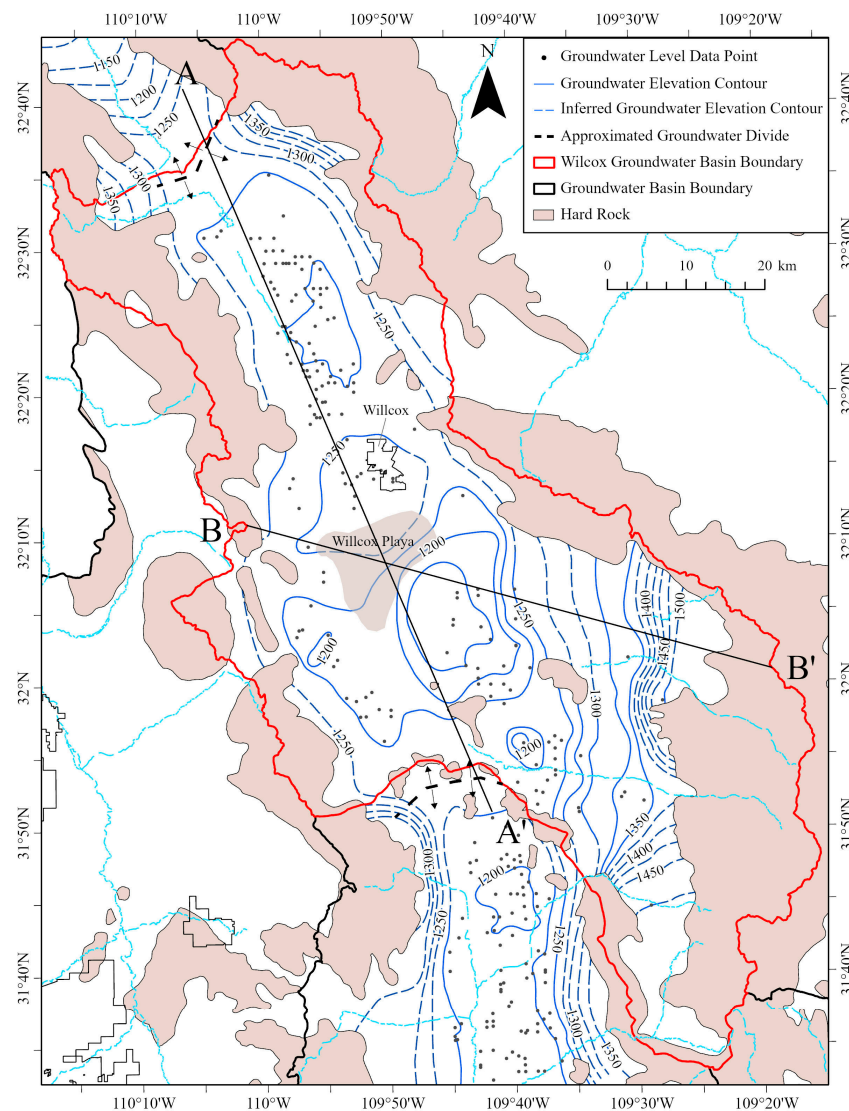


Figure 5. Potentiometric surface of the Willcox Groundwater Basin (WGB) and the surrounding region.

4.2.2. Conceptual Cross-Sections

The conceptual cross-sections (A-A' and B-B') developed for the WGB depict several key characteristics of the regional groundwater system. Fine-grained lake-bed deposits observed in the center of the basin form both a perched groundwater zone and locally confining groundwater conditions. Precipitation and subsequent runoff along the basin's high-elevation mountain range recharges the aquifer along the basin's exterior margins. Groundwater predominantly flows towards the basin's interior, discharging at large groundwater depressions spatially associated with areas of high agricultural land cover (Figure 6).

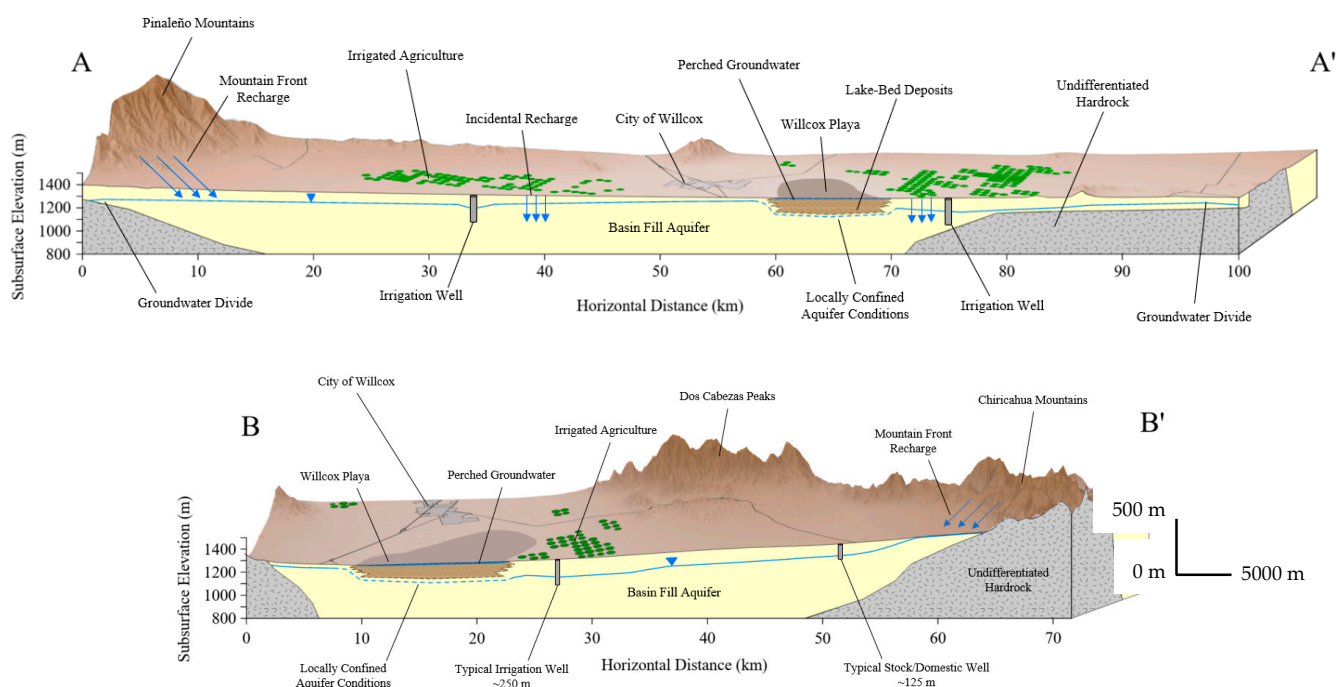


Figure 6. Conceptual cross-section (A–A' and B–B') diagrams of the Willcox Groundwater Basin (WGB).

4.3. Groundwater Level Change Analysis

Of the 149 groundwater level change values calculated for well sites within the WGB between WY 2006 and WY 2021, 93.2% had groundwater level declines of more than one m. Only 3.4% of the groundwater level change values presented water level rises of more than 1 m. Negligible rates of groundwater level change amounting to less than one meter were observed at 3.4% of sites. Groundwater level change values ranged from a water level rise of 4.1 m to a water level decline of −38.8 m. The mean and median water level change values were calculated at −13.1 and −13.8 m, respectively. Since rates of groundwater level change are variable throughout the basin, the mean and median water level change values serve as valuable metrics for considering basin-wide rates of groundwater level change. Table 4 summarizes the water level change values calculated between WY 2006 and 2021.

Table 4. Statistical summary table of the change in groundwater level (in meters) from WY 2006 and WY 2021.

Minimum Water Level Change	Maximum Water Level Change	Median Water Level Change	Mean Water Level Change	Standard Error
−38.8	4.1	−13.1	−13.8	0.7

Visual assessment of the water level change distribution shows groundwater level declines occurred throughout much of the basin (Figure 7). The most significant groundwater level declines are observed south of the Willcox Playa; however, groundwater level declines over 20 m are also present north of the City of Willcox. Smaller groundwater level declines and wells with negligible rates of change are concentrated in the vicinity of the City of Willcox and along the basin's southwestern margin. The only observed instances of water level rise throughout the basin occurred along the foothills of the Chiricahua Mountains in the southeastern extent of the basin.

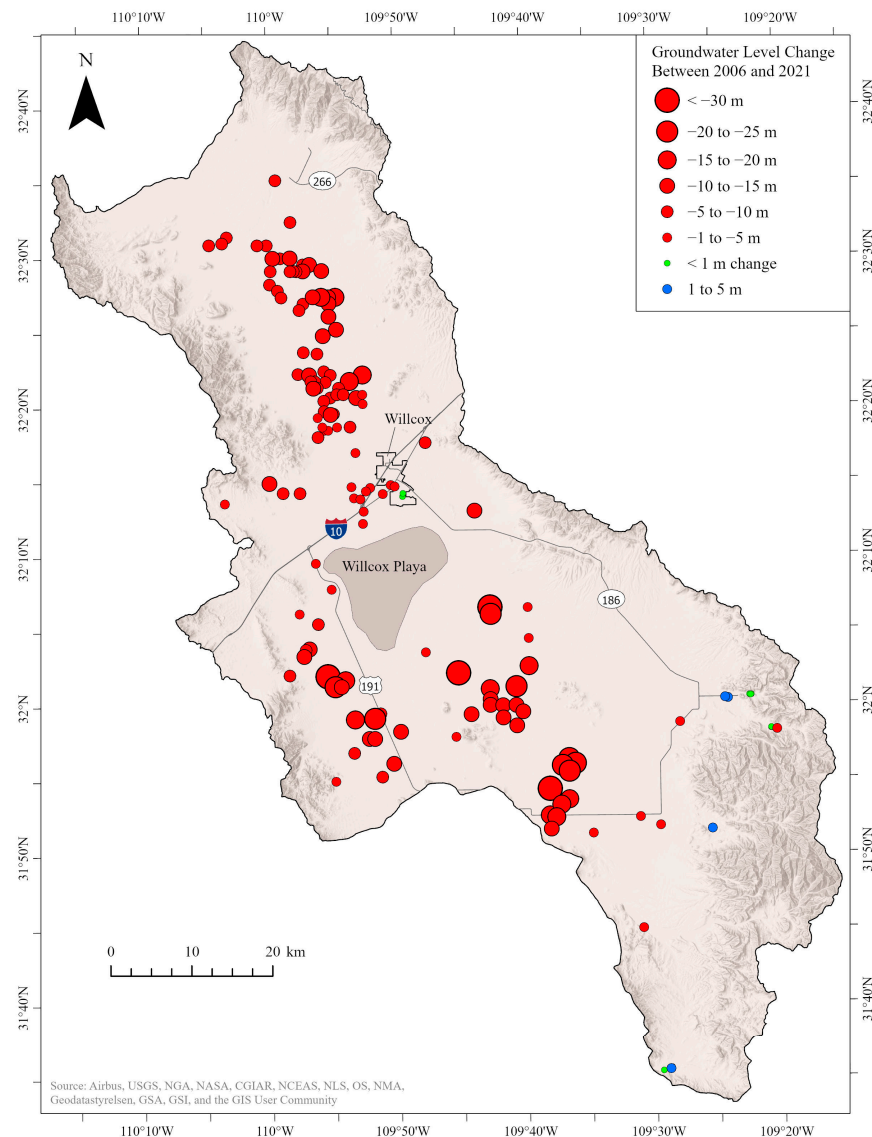


Figure 7. Spatial extent of groundwater level change in the WGB between WY 2006 and WY 2021.

Estimates of mean annual depth-to-groundwater, derived using data from the basin's 52 annually measured index wells, increased continuously between WY 2008 and WY 2021. Mean annual depth-to-groundwater ranged from a minimum depth of 56.4 m in WY 2008 to a maximum depth of 93.2 m in WY 2021. The notably larger mean water level change observed using these estimates is believed to be the consequence of the dataset's smaller sample size and the specific characteristics of the basin's index wells. The mean annual depth-to-groundwater values were applied in the correlation analysis with the annual extent of agricultural land cover.

Agricultural Land Cover Change Analysis

The agricultural land cover change analysis showed an approximately 29% increase in active agricultural land cover between 2008 and 2021, increasing from 18,326 to 23,652 ha. The updated estimate for 2021 appears valid compared to the most recent United States Department of Agriculture Census of Agriculture, which reported irrigated cropland throughout Cochise County at approximately 34,803 ha [35]. Agricultural land cover in the WGB is predominately distributed along the center axis of the basin, with significant concentrations to the north and south of the Willcox Playa (Figure 8). Areas of increasing

agricultural land cover are present throughout the entire basin; however, the greatest increase in agriculture appears to be in the southern extent of the basin.

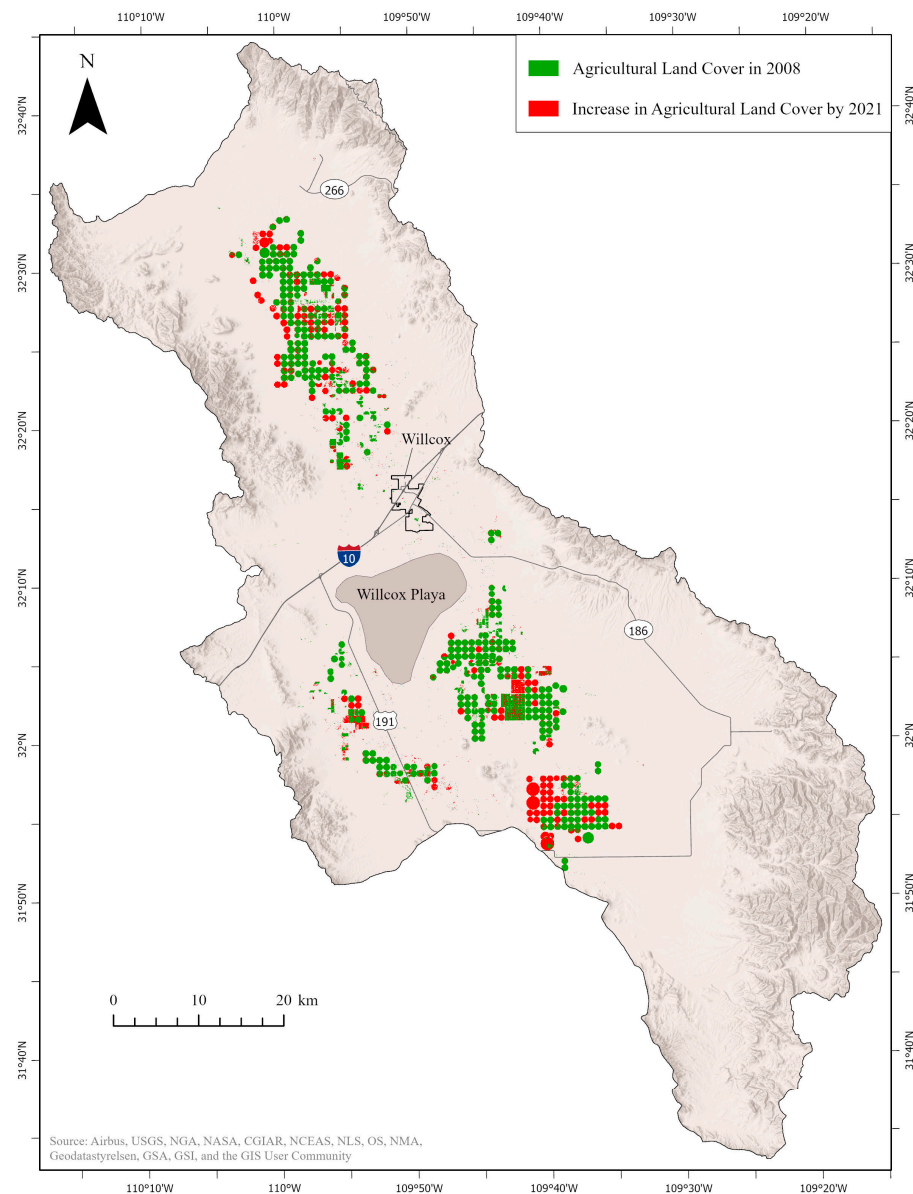


Figure 8. Agricultural land cover change in the Willcox Groundwater Basin (WBG) between 2008 and 2021.

4.4. Correlation Analysis

Agricultural land cover and annual depth-to-groundwater showed a strong, positive, linear association between the two variables (Figure 9). As the annual agricultural land cover extent within the Wilcox WGB has increased, there has been a corresponding increase in the mean annual depth-to-groundwater. A more definitive assessment of the level of correlation between the mean annual depth-to-groundwater and the annual agricultural land cover extent between 2008 and 2021 was achieved using a Spearman Ranked Order Correlation Analysis. Results of the Spearman Ranked Order Correlation Analysis found that a strong correlation ($\rho = 0.89$, $p < 0.001$, $n = 14$) exists between the mean annual depth-to-groundwater and the estimated annual agricultural land cover extent between 2008 and 2021. The demonstration of a strong correlation between these variables reinforces the conceptual understanding of agricultural development as a principal driver of groundwater level change throughout the WGB.

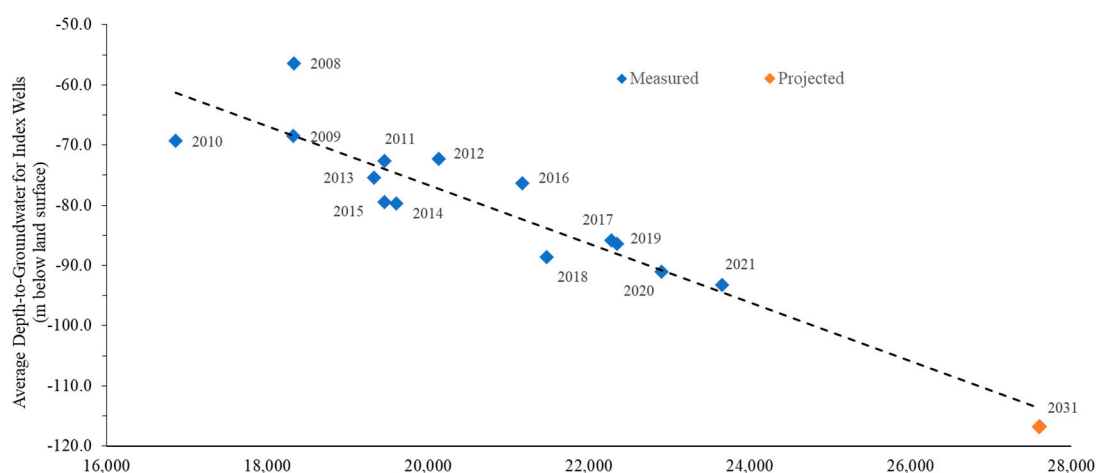


Figure 9. The relationship between mean annual depth-to-groundwater and estimated annual agricultural land cover between 2008 and 2021 and the projected values through 2031.

Projection of the mean annual depth-to-groundwater and agricultural land cover extent data in the WGB through 2031 anticipates sustained changes for both variables (Figure 9). Between 2021 and 2031, projections indicate a 25.3% decline in the basin's mean annual depth-to-groundwater, increasing from 93.2 to 116.8 m. Similarly, projections of the basin's agricultural land cover extent indicate a 16.7% increase between 2021 and 2031, increasing from 23,652 to 27,603 ha.

5. Discussion

5.1. Summary of Key Findings

Mapping of the 30-year normal annual precipitation estimates found the highest precipitation totals along the basin's adjoining high-altitude mountain ranges. Trend analysis of the 30-year annual precipitation record for select locations in the basin yielded evidence of declining precipitation rates along some of these mountains. Declining annual precipitation rates along the basin's mountain ranges, such as the Pinaleno Mountains, could have important implications for the basin's rate of naturally occurring recharge. Declining recharge rates would only exacerbate further the groundwater level decline rates throughout the basin.

Analysis of groundwater level change between WY 2006 and WY 2021 found significant rates of groundwater level decline throughout the WGB. Among the 149 measured well sites in the basin, 93% registered a groundwater level decline of one meter or greater during the fifteen-year comparison timeframe. The mean calculated groundwater level change at measured well sites over this timeframe was -13.8 m. The largest observed water level decline occurred south of the Willcox Playa and was calculated at -38.8 m. Groundwater level decline was widely distributed throughout the basin's interior; however, the most significant rates of groundwater level decline were observed to correspond to areas with high agricultural land cover. These findings were consistent with the developed groundwater elevation contour map, which depicts the presence of large groundwater depressions over the basin's agricultural pumping centers.

Basin-wide active agricultural land cover was found to have increased by nearly 30% between 2008 and 2021. Areas of increasing agricultural land cover were identified throughout the basin's various agricultural centers. However, the greatest increasing agricultural land cover concentration was observed south of the Willcox Playa. Correlation analysis between the basin's agricultural land cover extent and mean annual depth-to-groundwater for each year between 2008 and 2021 determined that these variables were strongly associated. The observed association further reinforces the understanding that expanding agricultural development and its increasing rates of groundwater withdrawal are significantly impacting the basin's groundwater resource system.

The findings presented in this study contribute towards an existing body of research surrounding water resources conditions and demands in the WGB. The availability of more recent data allowed for an updated evaluation of basin-wide precipitation patterns, groundwater conditions, and agricultural land use. In addition, this research provided further evidence of how agricultural development and irrigation in the basin are impacting regional groundwater conditions. Such updated information is expected to be of use in water resource management and planning efforts in the WGB.

The practical approach shown in this case study makes use of hydrogeology information and readily available spatiotemporal data pertaining to precipitation, groundwater, and land cover conditions. Through application of this methodological framework, we derived key insights surrounding the evolving water resource conditions and demands for the WGB. This applied approach has applicability for the evaluation of water resource conditions and demands in other localities, particularly where comparable data availability and environmental conditions exists. Moreover, the insights obtained through the development of our hydrogeologic and analytical frameworks could be of value for regions with similar geology and groundwater resource issues. Additionally, this research demonstrated the applicability of PRISM climate datasets and the NASS Cropland Data layer for analyzing patterns in basin-wide precipitation and agricultural land cover change.

5.2. Implications of Groundwater Level Decline

Ongoing groundwater decline in the WGB presents a clear challenge to the basin's long-term water resource security, especially considering the basin's reliance on its available groundwater supply [36]. Continued groundwater development and withdrawal will invariably reduce available groundwater in storage. The Arizona Department of Water Resources forecast suggests 29.6 km³ of groundwater may be removed from storage by 2115 [7].

Declining groundwater conditions also have more immediate implications for many of the basin's water users. Analysis of the basin's registered well data from the Arizona Department of Water Resources indicates that nearly 30% of registered wells in the basin reported a depth of 50 m or less [18]. For shallower wells such as these, the rates of groundwater level change determined in this research are significant. As groundwater levels throughout the WGB continue to decline, it is foreseeable that a growing number of wells will go dry. Dry wells are a serious concern for the livelihoods of the basin's water users, who may find the associated costs of deepening or drilling new wells prohibitive. Such expenses can be substantial, with the cost of drilling an irrigation well in the WGB to a depth of 365 m, estimated at \$420,000 in 2017 [36].

Land subsidence represents another issue arising from the declining groundwater conditions in the basin. As groundwater is extracted from the basin-fill aquifer system, the accompanying water pressure holding open pores in the alluvium is no longer present and the alluvium is compacted, resulting in land subsidence [37]. In the WGB, land subsidence rates have been measured as high as 0.15 m annually [38]. High rates of land subsidence can result in several serious repercussions. For example, compaction of fine-grained alluvial material is often irreversible and can lead to a permanent loss in aquifer storage capacity [37]. Additionally, high rates of land subsidence can lead to the formation of hazardous earth fissures. In the WGB, over 60 km of earth fissures have been documented, some of which have damaged infrastructure and pose a hazard to local communities [38].

5.3. Study Limitations

Some limitations associated with groundwater data availability should be recognized. Most notably, this research does not directly quantify rates of groundwater withdrawal, largely owing to the lack of a continuous record of groundwater withdrawal data for the WGB. Instead, increasing groundwater utilization in the WGB was characterized by evaluating changes in the basin's agricultural landscape. Such an approach was effective in the WGB, where agricultural water use is recognized to constitute the majority of groundwater

withdrawal. However, such an approach may not be applicable in settings where a greater diversity in groundwater uses exists. It is also important to recognize that such an approach overlooks considerations surrounding potential variability in groundwater withdrawal throughout the agricultural landscape, stemming from factors such as differences in crop type or cultivation practices.

While this research identifies a strong association between ongoing agricultural development and groundwater level decline in the WGB, it should be noted that the short record of available data constitutes another important consideration. Agricultural land cover data from the CDL is only available for the most recent 13-year timeframe. Although a strong positive trend was identified in the WGB's agricultural land cover change, the short timeframe of the analysis imparts some uncertainty with respect to more long-term land use trends within the WGB. Therefore, potential limitations surrounding data availability and timeframe of analysis should be taken into consideration if this methodological framework is to be applied towards the study of other localities.

6. Conclusions

Groundwater is fundamentally important to the WGB, as it constitutes the basin's only readily available water source. Nonetheless, extensive rates of groundwater development throughout the basin have led to adverse conditions for the basin's groundwater system, potentially jeopardizing the basin's long-term water resource security. The results of this study provide an updated assessment of water resource conditions throughout the WGB, including precipitation and groundwater. They also present new evidence regarding the influence of basin-wide agricultural pressures on the regional groundwater resource system. These updated insights are expected to be of value to assessing water security concerns within the WGB and inform considerations surrounding the basin's water resource management.

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