GROUNDWATER LEVEL AND STORAGE CHANGES – REGIONS OF NEW MEXICO

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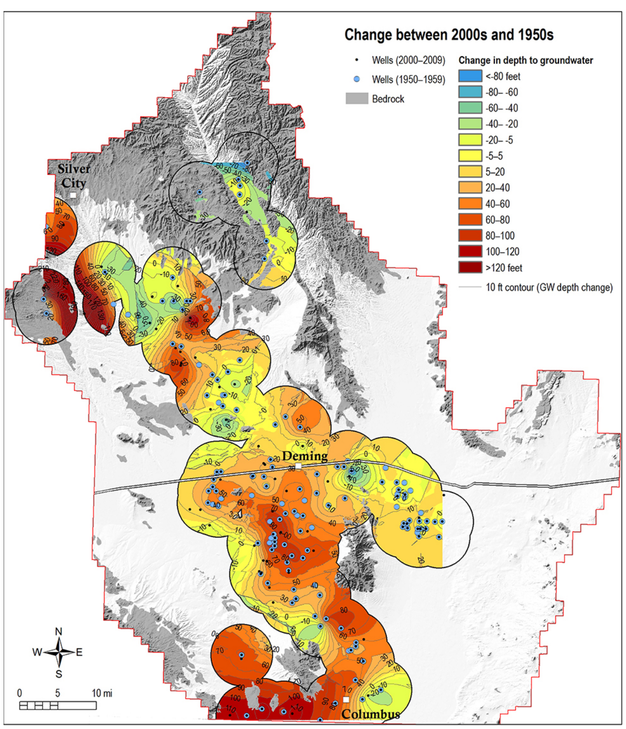

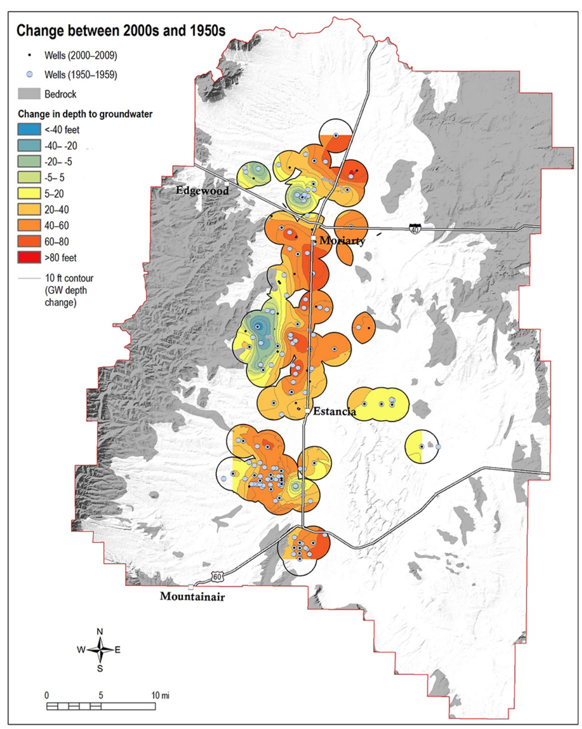

DISCLAIMER

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ABSTRACT

In a semi-arid state, where we have variable surface water availability, extended periods of drought, and limited recharge to groundwater, it is essential that we strive to quantify the available groundwater resources that New Mexico depends on. In an effort toward addressing a component of regional groundwater availability, we have developed a method of reviewing regional groundwater level changes and subsequent groundwater storage changes that have occurred recently and historically. Here, we describe the compilation of statewide groundwater level data into a single database and analysis at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), including data from the U.S. Geological Survey (USGS), New Mexico Office of the State Engineer (NMOSE), Bernalillo County, and NMBGMR. Changes in groundwater levels in the Mimbres and Estancia basins were interpreted using kriging and inverse distance weighting (IDW) interpolations. Aquifer properties used for total storage change calculations were derived from the literature. Estimates using either total difference in groundwater levels from pre-development times or a moving difference of water levels lead to comparable overall volume changes as well. We found that the patterns of the total differences in water levels accentuate areas of greater overall loss. The patterns seen in moving differences emphasize the timing of new withdrawals, or the lack thereof. We found that the different interpolations lead to slightly different (but still comparable) groundwater storage change patterns and amounts.

Keywords: groundwater level data compilation, groundwater interpolation comparison, groundwater storage change, Mimbres basin, Estancia basin, alluvial aquifer.

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1. JUSTIFICATION OF WORK PERFORMED

During extended droughts in semi-arid New Mexico, freshwater aquifers are a vital source of supplemental water for irrigation, commercial, industrial and domestic use. In some regions of New Mexico, groundwater is the primary supply, with no surface water resources available. However, aquifers in New Mexico are finite in volume, at best slow to recover from depletions, and, at times, closely coupled with surface waters so that dropping groundwater levels lead can lead to increased stream losses. At all times in semi-arid regions and especially during drought, understanding the historical changes in groundwater storage is vital to better management. In New Mexico, alluvial aquifers are especially critical as they underlie most of the state's largest agricultural areas and population centers. Before trends in basin-wide groundwater storage change and locations of groundwater depletion can be understood, consistent collection, compilation and analysis of water level data is required.

In this work, we discuss (a) the compilation of groundwater level well data collected by multiple agencies throughout New Mexico, and (b) a method to systematically estimate the change in groundwater storage for alluvial aquifers. Groundwater level data compilation requires careful quality control of data from different sources, from different measurement methods, and from changing well networks as sampling needs change or wells leave service. This requires decisions to be consistently made about storage formats, which well information is pertinent, and which water level data are reliable, all in a geographically-oriented data base that is maintained at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR).

After compilation is completed, the analysis must reliably estimate the changes in water levels through time as well networks expand and contract, and then use appropriate specific yields to convert the change in water level to a change in water volume. The first step, the interpolation of groundwater levels from well level data, needs to be robust to changes in aquifer structure, including differing depositional environment, geologic structure, and aquifer compartmentalization. The second step requires either the use of existing reliable hydrogeologic data, or the interpretation of pump test data. In this study, we have restricted ourselves to basins with relatively well-understood hydrogeologic parameters.

Because this effort is part of a continuing statewide water assessment, most of the emphasis has been placed on describing statewide data compilation and the method of groundwater level and storage change estimation. To test the method, we apply it in the Mimbres basin of southwest New Mexico, and Estancia basin of central New Mexico. These are both closed basins with mostly alluvial aquifers and some fractured bedrock aquifers. Both basin are relied on by major water users (irrigation and municipalities), and have water level records from pre-1950 (pre-development) through at least 2010.

We begin by summarizing in Sections 2.1 and 2.2 the compilations of groundwater level data into the AMP database. Then, we summarize our method for semi-automatically generating depth-to-water grids (Section 2.3). The method for estimating groundwater storage change from the differences in depth-to-water grids follows (Section 2.4). In Section 3, we examine the efficacy of the method in the context of the Estancia and Mimbres Basins. Section 4 summarizes our method and results, and provides some recommendations for future work.

In this study, we found that the combination of engineering judgement and statistical analysis successfully provides a robust way of estimating groundwater storage changes through time in basins dominated by alluvial aquifers.

2. METHODOLOGY

2.1 Statewide Groundwater Level Data Compilation and Database

Groundwater levels are measured in wells around the state by multiple agencies and groups, at various intervals and over various sampling periods and at various sampling frequencies. Figure 1 shows locations of wells with multiple water level measurements in the context of major aquifers of New Mexico. The most comprehensive, long-term groundwater level monitoring network, the NM Groundwater Data Program, is maintained in cooperation with the NM Office of the State Engineer and the U.S. Geological Survey (USGS) New Mexico Water Science Center. Historical records of

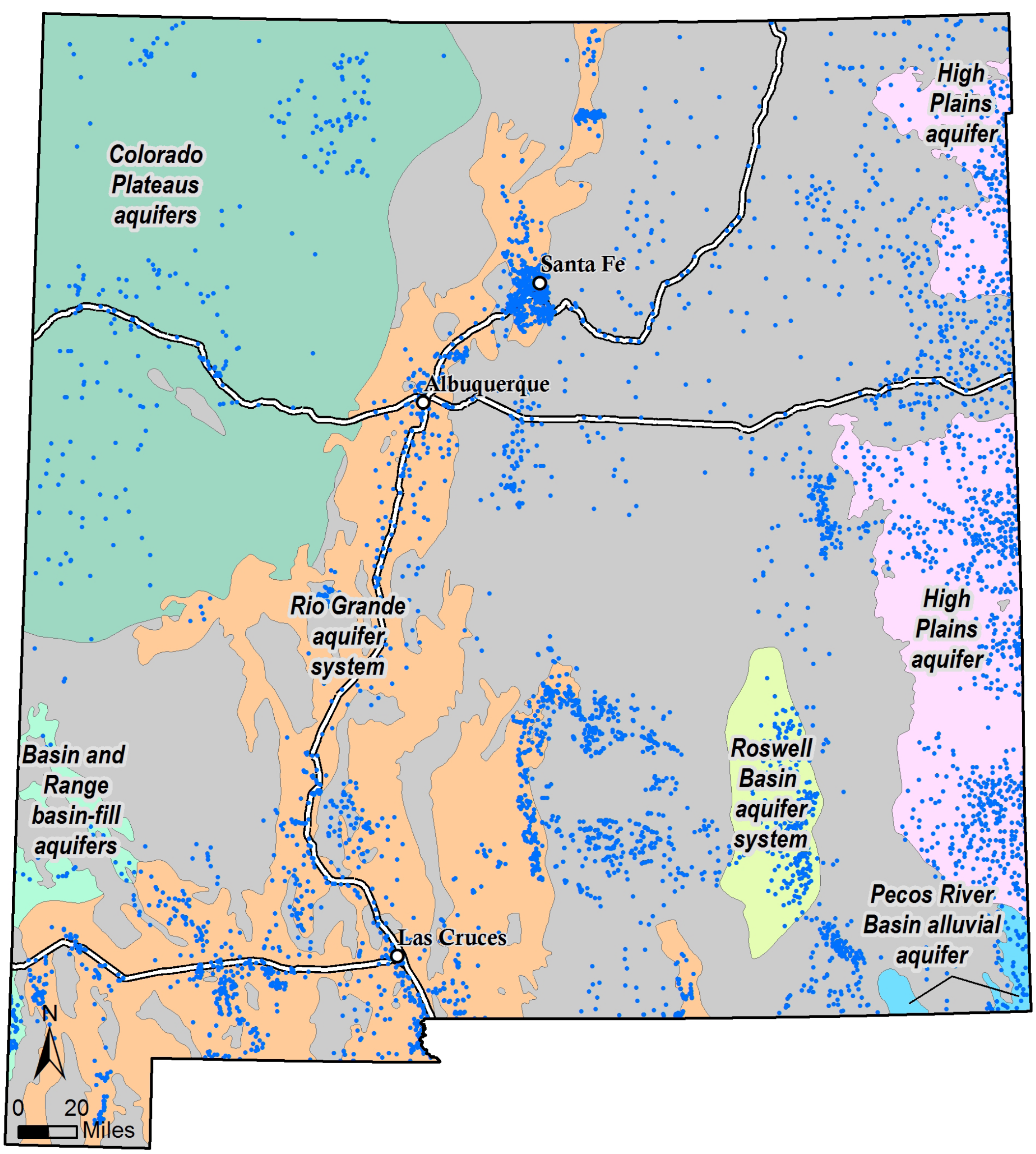

Figure 1. Shows locations of wells with multiple water level measurements in the context of major aquifers of New Mexico.

water level measurements beginning in the early 1900s, measured by the USGS, provide a valuable long-term record of water level changes.

The monitoring networks in New Mexico are primarily composed of wells used for other purposes, and they are not designated monitoring or observation wells. Water levels can be measured in many types of wells including domestic, irrigation, or public supply wells, for example. Data quality can be variable considering the other uses of the well. For instance, if a well is pumping or has been pumped just before measurements, the water level may not be representative of the true static water level. Data are maintained to describe the uses and construction of the wells, as well as the possible effects on a water level measurement at the time when it was measured. These data have been included in this deliverable and the efforts of compiling data are described below.

2.2 The Aquifer Mapping Database

Since 2007, New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has been developing and maintaining a relational database of water information that includes water levels, well information, aquifer hydraulic properties, and water chemistry among other things. This comprehensive, MS Access database, called the Aquifer Mapping Database (AMD), incorporates data from recent hydrogeology studies of the NMBGMR, including well and subsurface geologic data. Building upon the existing AMD for this WRRI statewide water level assessment, we have incorporated datasets from multiple agencies including the USGS, NMOSE, and other regional water level monitoring networks.

For this project, we incorporated three data retrievals from the USGS National Water Information System (NWIS) database, which has historic water level measurements across NM, and the recent NM Groundwater Data Program measurements. These retrievals were in the format of MS Excel worksheets with tabs separating well site locations, well information, and water level measurements. All records were cross-referenced by the USGS Site ID number. The first retrieval included all well points that are currently (2014) within the monitoring network. Beginning in 2006 the current monitoring network has been reconfigured to optimize use of OSE and USGS resources and provide better coverage over the state. The second dataset included the wells that had historical measurements prior to the start of network reconfiguration in 2006. The USGS filtered these data to include only wells that had measurements for at least three rounds of measurement, at a frequency of annually and/or every 5 years. The third data retrieval included all sites with any water level measurements, even if it was measured only once.

Groundwater level measurements were also contributed from Bernalillo County Public Works monitoring network which began in 2010. These data were also delivered in MS Excel worksheets.

2.2.1 USGS NWIS Data Processing by NMBGMR

To begin processing the data for input into the AMD, we first checked within the USGS datasets for duplicates in site locations and removed those. We then performed ArcGIS and site ID location checks to prevent duplication of sites within the AMD. Also, USGS site locations were provided in latitude/longitude decimal degree coordinates, which we converted to UTM coordinates in Zone 13. For those sites where the location is actually in UTM Zone 12, we projected the coordinates into Zone 13 for the database.

The first data retrieval from the USGS provided 1,952 site records. There were 1,731 records imported into the AMD after duplicates from within the dataset (177) and existing in the AMD database (104) were removed. There were 31,940 associated water level measurements from this dataset, which we imported into the AMD.

The second data retrieval included 2,388 site locations, of which 345 were duplicates within the dataset and 88 that matched existing locations in our database, leaving 1,955 records imported into the

AMD. There were 65,456 associated water level measurements from this dataset, which we imported into the AMD.

The third data retrieval from the USGS included 23,492 site locations, of which 390 matched existing locations in our database leaving 23,102 records imported into the AMD. There were 196,605 associated water level measurements for these sites, which we imported into the AMD.

2.2.2 Bernalillo County Data Processing by NMBGMR

The MS Excel spreadsheet delivered from Bernalillo County included worksheets of well locations and water levels. There were 194 locations in the dataset and 1,432 water level records. Two locations within the dataset did not have corresponding water levels. Coordinates for the Bernalillo County data were in NAD83 HARN State Plane in feet. These coordinates were converted to NAD83 UTMs Zone 13 for consistency within the AMD.

Of the 1,432 water level measurements, 62 were removed as they detailed events where the well was visited, but not measured due to various complications such as equipment failure, locked gates, etc. A total of 1,370 water level measurements were added to the AMD.

We added a data quality field to the Bernalillo County dataset. Where an acoustic sounder was used to determine the depth to water, we designated a data quality level of "2," which indicates that the data are considered "fair" quality, and that the measurement is repeatable (approximately within one-foot of previous measurements). The imported airline measurements, readings from pressure transducers, steel tapes and electronic tape were designated a data quality level of "1," which suggests a "good" quality water level measurement that is repeatable (within 1/10th of a foot). Essentially, these data quality fields were added to distinguish the lower data quality of acoustic sounder measurements.

2.2.3 Statewide Water Level Database

All data from the AMD were compiled with the USGS and Bernalillo County datasets. Once these data were reviewed, filtered and added to the database (as described above), a smaller, more streamlined database called the "Statewide Water Level Database (SWLD) was developed to share these data, as per this WRRI contract deliverable.

All well site locations and basic well construction information, including well depth and the water producing geologic formation (if interpreted), are compiled in a "Location" table. There are a total of 5,412 location records in this current database. In order for the MS Access database to function properly, the time-series water level data for all well locations are stored in a separate table and linked to the location table in a one-to-many relationship. This requires a 'primary key' field in the location table with a unique identifier assigned to each location. This field can have no duplicates and no blanks, and in the SWLD has been named "Point ID."

The "PointID" field includes NMBGMR inventoried well sites from various local hydrogeology projects. The two-letter prefixes on these PointIDs specify a particular project, as listed in the table called "Projects." All sites associated with the USGS dataset have a USGS ID field, and have "NM" as the two-letter prefix for the "PointID" field. All locations are in UTM NAD83 coordinates. To eliminate some confusion in projected location due to 2 projection zones (12 and 13) in New Mexico, we projected all locations in NAD83 UTM Zone 13 ("EastZn13"; "NorthZn13"). This enables ArcGIS to plot all locations at once, rather than having two batches of data in different zones. Also within the Location table are the site elevations in feet (column heading "altitude"), interpreted from various sources such as DEMs and topo maps. If it was available, the drill hole ("HoleDpthFtBGS") and well depth ("WellDpthFtBGS") was included, in feet below ground surface. The geologic formation of water production (interpreted) was also included in the “Formation” column. The codes associated with this field are described in the lookup table “LU_Formations.”

All water level measurements (current total 131,233 records) are within the “WaterLevels” table, which is related to the Location table by the PointID field. Included in this table are the dates of water level measurements and the depth to water, in feet below ground surface (“DepthtoWater_bgs”). The “LevelStatus” field includes a code that describes any possible effects on the water level measurement. These are described in the associated table called “LU_Level Status.” The “MeasurementMethod” field indicates the technique used to measure the water level, and is described in the “LU_Measurement-Method” table. The “DataQuality” field is not always populated, but is intended to provide a level of confidence in the measurement, as described in the table called “LU_DataQuality.” The “DataSource” codes are explained in the “LU_Depth/CompletionSource” table, and the “MeasureAgency” column attempts to further refine the source of the dataset, as described in “LU_MeasuringAgency.” All USGS measurements provided in the data retrieval are indicated in the MeasureAgency field as “USGS,” and Bernalillo County as “Bernalillo Cty.”

We have included two functional queries to help assess data. One is listed under queries called "MaxWLDateDTW" and it provides all points with their most recent water level measurement only. The second is shown by a form, which was built to run a query to get water levels from a beginning time and an end time, to calculate the change and compare water levels. When you open the database, this form immediately opens comes up. These two queries are built upon other multiple queries. Changing the existing queries could adversely affect these two functional queries.

One final note on the function of this database is that in order for this database to continue to operate as an “.mdb” file, and work with ArcGIS, it is important to set options under “File/Options/General” for “Default file format for Blank Database” to “Access 2002-2003.”

In summary, this SWLD is a subset of data included in the AMD, and for further information on these measurements or other available data, please contact Stacy Timmons at NMBGMR, or Nathan Myers at USGS, using contact information provide above.

2.3. Water level contouring

2.3.1. Basins of Interest

In order to develop the methodology of evaluation of groundwater level and storage change calculations, we chose to work with the Mimbres Basin of southwest New Mexico, and Estancia Basin of central New Mexico (Figure 2). These are both closed basins with mostly alluvial aquifers and some fractured bedrock aquifers, major water users (irrigation and municipalities), and water level data from pre-1950 (pre-development) through at least 2010.

The Mimbres Basin includes the population centers of Silver City and Deming, and covers portions of Luna, Grant, Doña Ana and Sierra counties (Figure 3). The basin boundary that we worked with is constrained by the surface topographic divides. There is only one perennial flowing stream, the Mimbres River. The Mimbres River is only perennial in its upper reaches within a constrained valley. Once it flows out into the Mimbres basin, the river is ephemeral with flows reaching its terminus approximately 15 miles east of Deming only during flood events. Other ephemeral drainages include arroyos, washes, and draws. Land use in the Mimbres Basin includes forest, irrigated farmland, rangeland, and mining. Groundwater provides approximately 75% of the water used, with 25% sourced from surface water (Hawley et al., 2000).

This region is composed of multiple structural basins, which were formed during Basin and Range extension creating roughly north-south oriented faulting and smaller sub-basins within the Mimbres

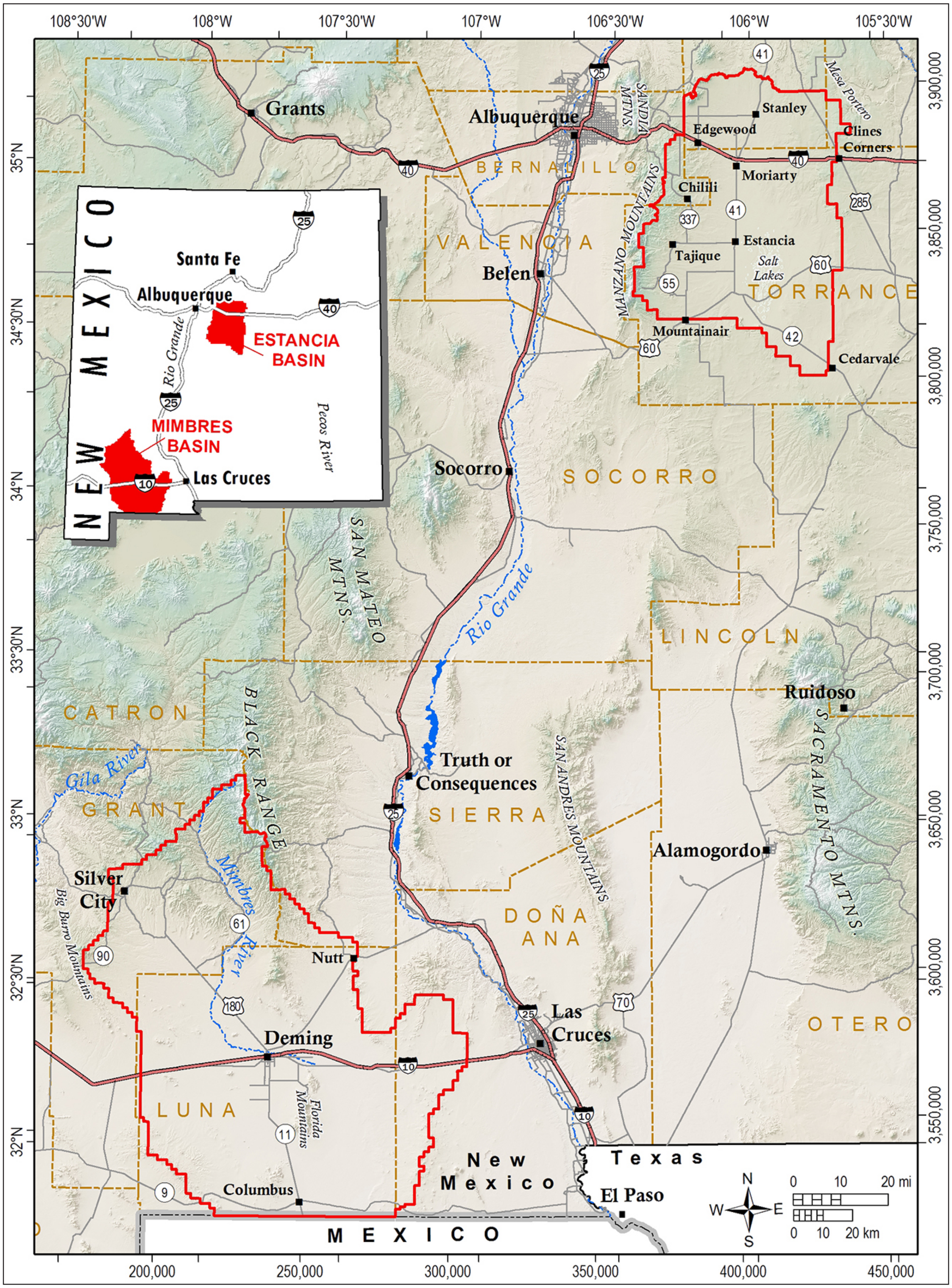

Figure 2. Locations of Mimbres and Estancia basins within New Mexico, with major geographic and political features shown.

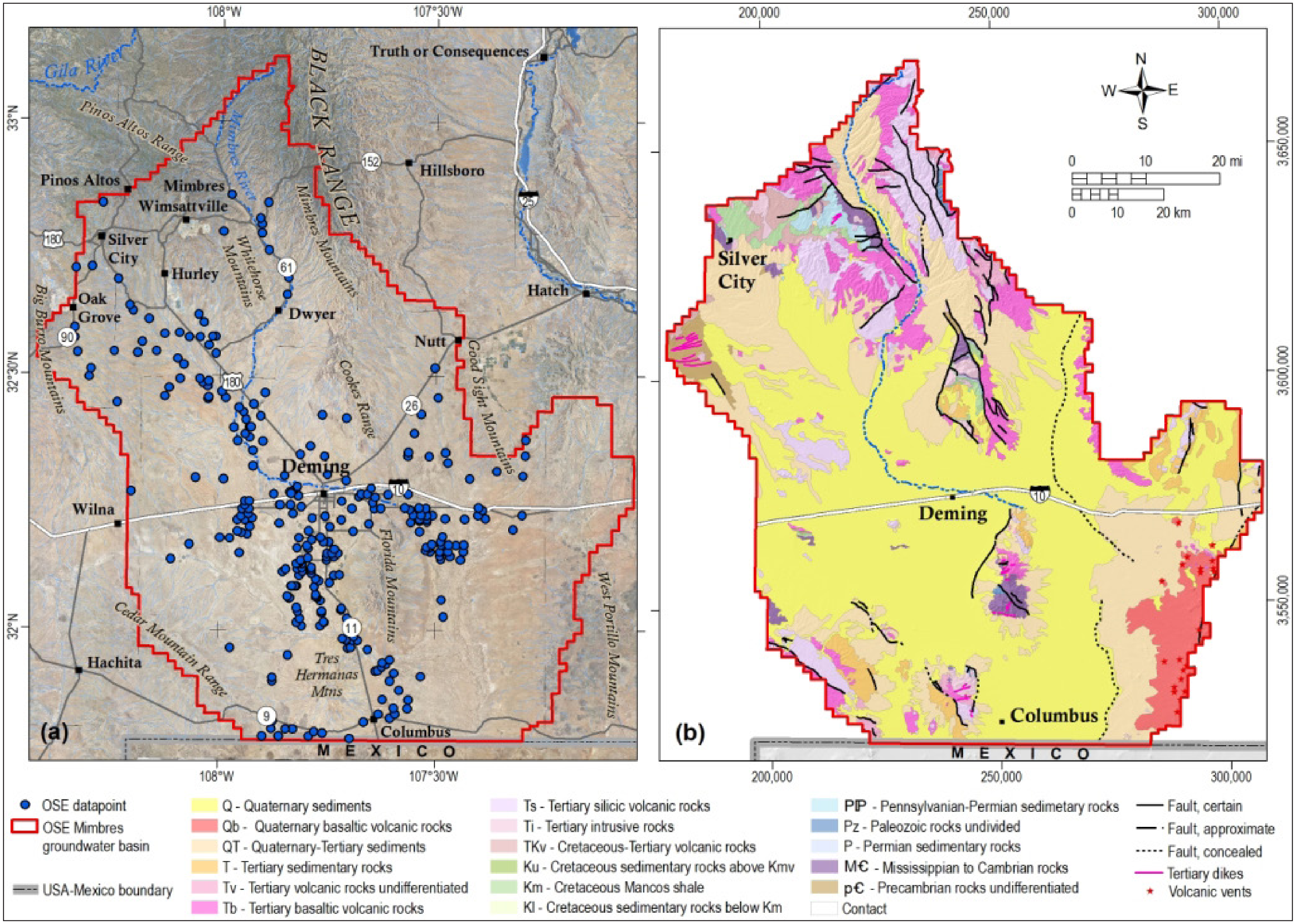

Figure 3. Overview of Mimbres basin, with (a) satellite image overlain with well locations, basin boundary, and major geographic, hydrographic and political features; and (b) clipped geologic map from 1:500,000 map (Geologic Map of New Mexico, 2003). The yellow units on this map indicate locations of the basin fill and Quaternary valley fill materials, which are the dominant aquifer units in the Mimbres Basin.

Basin. These sub-basins are generally characterized by water-bearing, unconsolidated to consolidated basin-fill material (Santa Fe Group and Gila Group) which ranges from a few tens of meters to more than 1000 meters in thickness (Hawley et al., 2000, fig. 4–2b). The sub-basins, which are variably interconnected, are surrounded by bedrock material including Tertiary volcanic materials, and older (Cambrian to Cretaceous) sedimentary bedrock units (Figure 3). Overlying the basin-fill material is thin (several tens of meters) Quaternary valley fill primarily associated with surface water drainages. The basin fill and Quaternary valley fill are the primary sources for groundwater in the Mimbres basin, and the focus of evaluation for groundwater storage changes with this study.

The Estancia basin located in central New Mexico (Figure 2) includes the population centers of Edgewood, Moriarty and Estancia and covers portions of Torrance, Santa Fe, Bernalillo, San Miguel, and Lincoln counties. Similar to the Mimbres basin, we constrained the basin study area by the surface topographic divides, which in this basin are the surrounding structural uplifts (Figure 4). Several ephemeral arroyos, draws and washes drain toward the center of the basin where groundwater discharges into salt lakes (Figure 4). Land use in the Estancia Basin includes forest on the basin margins, broad rangeland and irrigated farmland in the center of the basin. Water use in this region is nearly entirely groundwater.

White (1993) provides a review of various geologic units and their water-yielding characteristics in the Estancia basin, however the data availability in the Estancia basin historical well network are largely located in the basin-fill alluvium and lake deposits. This alluvial material (Santa Fe Group, and younger Quaternary alluvium) is composed of sand, gravel, silt and clay reaching thicknesses upwards of ~120 m in the center of the basin, and thinning toward the basin margins (Shafike and Flanigan, 1999) (Figure 4). Some wells in the Estancia basin are completed in older bedrock units, including the Madera Formation, but the storativity of this carbonate bedrock is far less than the alluvial material (Titus, 1973; and White, 1993), and therefore of minor importance in this analysis.

In both the Mimbres and Estancia basins, the majority of the wells with long-term groundwater level measurements were constructed within the mapped regions of alluvial, basin-fill materials (Figures 3–5). Additionally, in order to address groundwater storage changes in a region within the timeline and constraints of this study, we needed to apply a single specific yield value the study area. Working with the alluvium as the geologic constraint, we were able to remove wells that were located on bedrock, or non-alluvial materials as simplified and shown in Figure 5. This is discussed more below in Section 2.3.2.

In this study, we examine the statistical interpolations of snapshots of depth to water measurements through the record, rather than the dynamics of groundwater movement. Because of this, we do not require the full suite of aquifer properties. Assuming unconfined aquifers, we only require the average specific yields of the alluvial aquifers in the Mimbres and Estancia basins. In their integrative study of the Mimbres basin hydrogeologic framework, Hawley et al. (2000) found a reasonable specific yield to be 0.1, with the caveat that portions of the basin behave in a semi-confined manner. Given that we are examining groundwater elevation changes on decadal time scales, the use of this value is justified as the overlying aquifer units will equilibrate reasonably quickly with the more permeable units. In their study of the hydrogeologic framework and initial groundwater flow modeling, Shafike and Flanigan (1999) used a specific yield of 0.1 in the alluvial aquifers of Estancia basin as well. In our study, we assume a specific yield of 0.1 for the alluvial aquifers in both the Mimbres basin and the Estancia basin.

2.3.2. Approach

The ultimate goal of this project is to provide storage change estimates in alluvial basins throughout New Mexico. We developed a workflow and test it in the Mimbres and Estancia basins, both closed alluvial basins with some agricultural development. To achieve this, a semi-automatic workflow is necessary to find the changing water levels throughout the basin, summarized in Figure 6. The method needed to

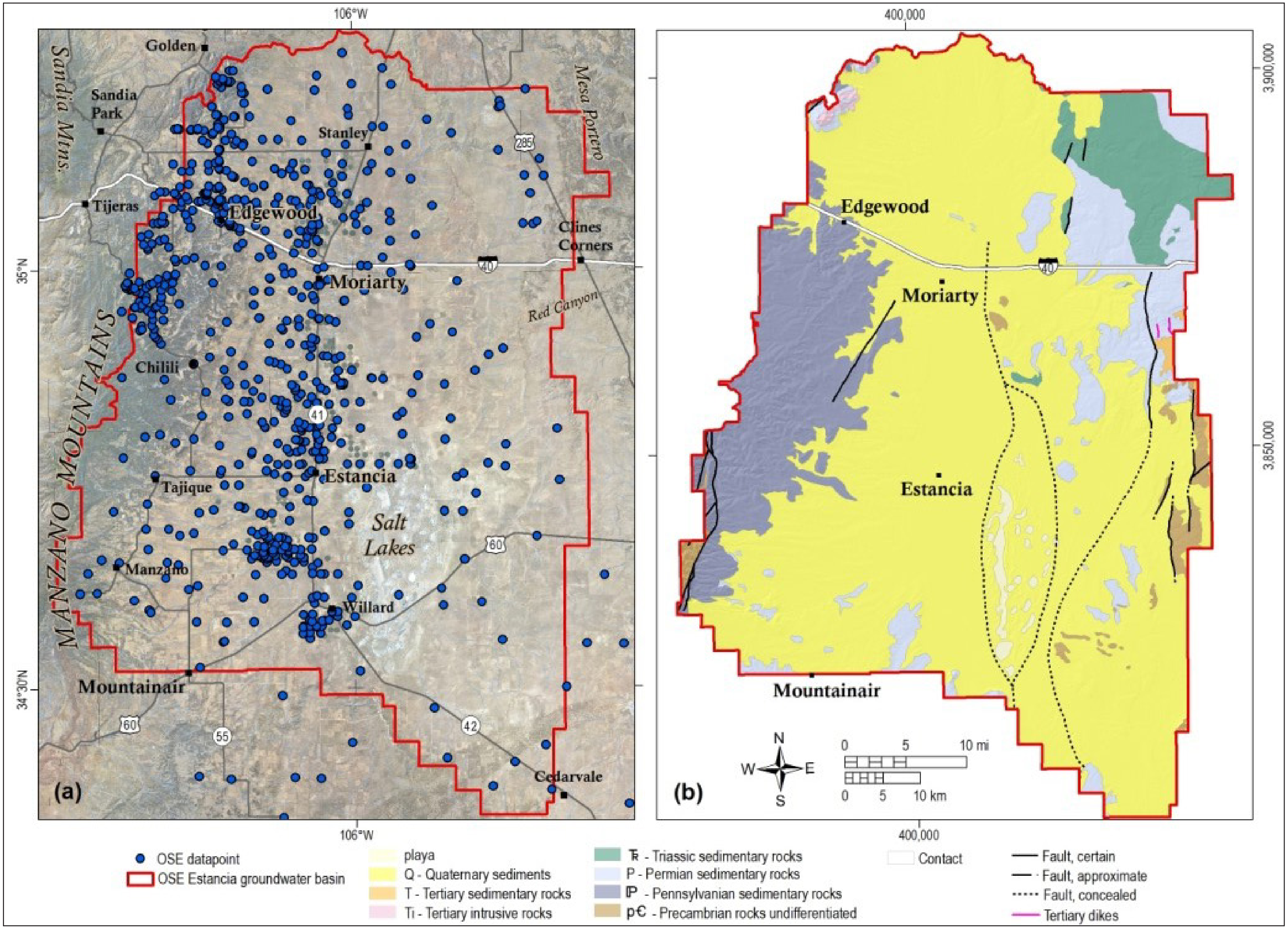

Figure 4. Overview of Estancia basin, with (a) satellite image overlain with well locations, basin boundary, and major geographic, hydrographic and political features; and (b) clipped geologic map from the New Mexico statewide 1:500,000 map (Geologic Map of New Mexico, 2003). The yellow units in this map represent the basin fill alluvium and lake deposits.

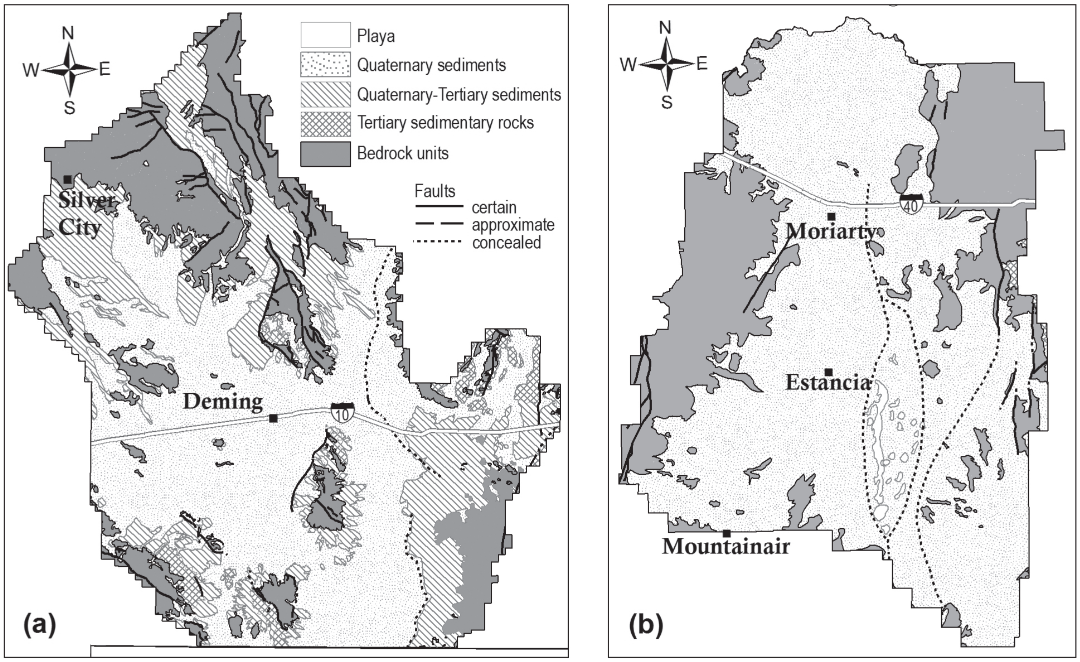

Figure 5. Bedrock units derived from 1:500,000 scale geologic map (Geologic Map of New Mexico, 2003) in (a) Mimbres basin, and (b) Estancia basin, assuming only alluvium and shallow basin fill make up the primary basin aquifers (Titus, 1969; White, 1993; and Kennedy et al., 2000). The playa deposits are located in the "center" of the basin where surface water and groundwater flow toward, and where groundwater discharges into salt lakes.

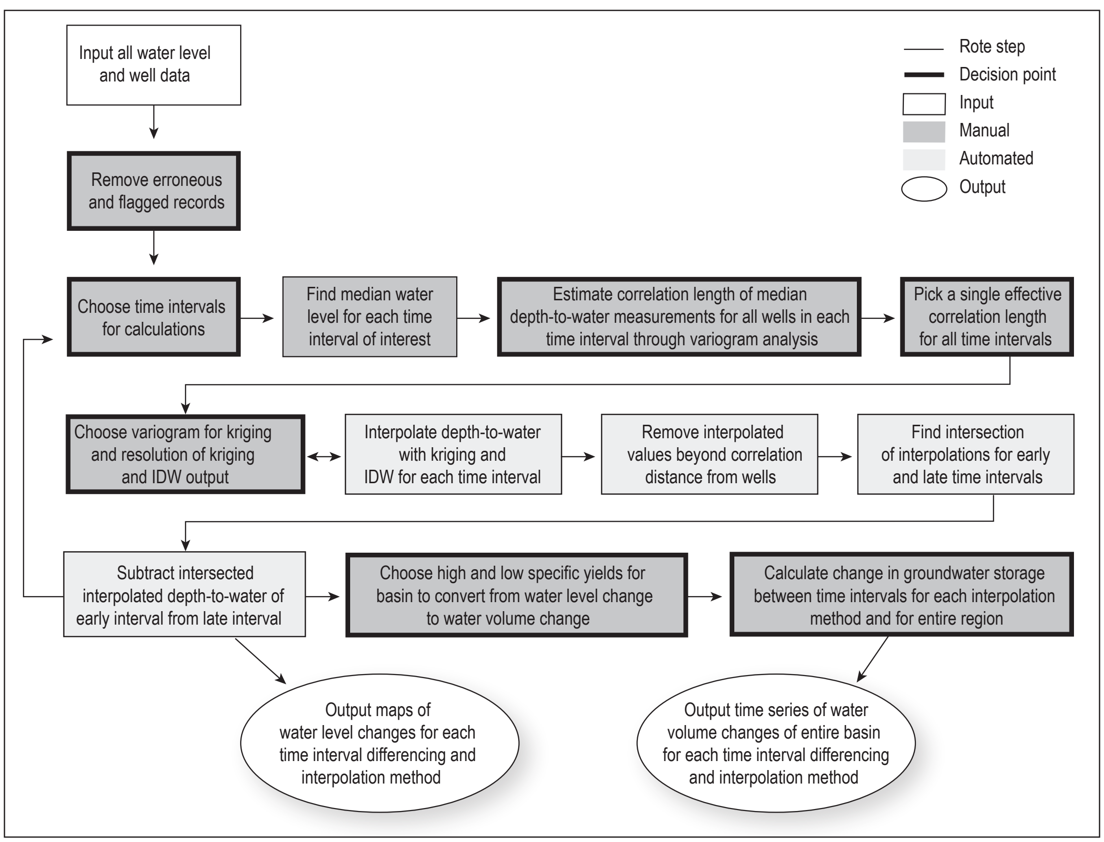

Figure 6. Workflow illustrating steps from inputted well water level data to output maps and time series of storage change. Input shown in white box, manual processing steps in solid gray boxes, automated processing steps in graded gray boxes, and outputs in outlined ellipses. Steps requiring parameter definition or other user decision to be made are shown by a heavy outline.

be repeatable, robust in different alluvial aquifers, statistically-based to avoid the need for forward modeling, and capable of efficiently utilizing large quantities of data.

A few studies have examined approaches for estimating groundwater storage change. These range from application-specific studies of regional aquifers, such as McGuire's (2013) study of the Southern High Plains aquifers, to comparisons of different types of kriging and other interpolations (Kumar 2007; Ahmadi, S.H.; and Sedghamiz, A., 2008; and Chung, J.W.; and Rogers, J.D., 2012). Other studies focus on interpolating the groundwater elevation or depth to water or? water tables in local to regional groundwater studies (e.g., Snyder, 2008).

After input of the water well locations and elevations, IDs, and water level records in a basin of interest, the data are reviewed using a user interface to remove outliers, flagged records, and records from the active irrigation season that is assumed to be between March 1 and October 31 of each year. Samples are flagged during measurement if there appears to be an inconsistency, such as the well being pumped, having been pumped recently, or a nearby well being pumped in the same aquifers. We then choose a time span (e.g., 10 year intervals) to find basin-wide median depth-to-water (DTW) levels, and find the median water levels from the beginning of measurements to the end of measurements. The data review and median calculations are performed with custom-built Matlab© functions (Figure 7).

For each interval (e.g., 1960 to 1969), we find the spatial scale to which the data are correlated. In each basin, we choose an effective spatial correlation length that is valid over the entire measurement period. This is done by visual examination of the semi-variogram of median depth. The following

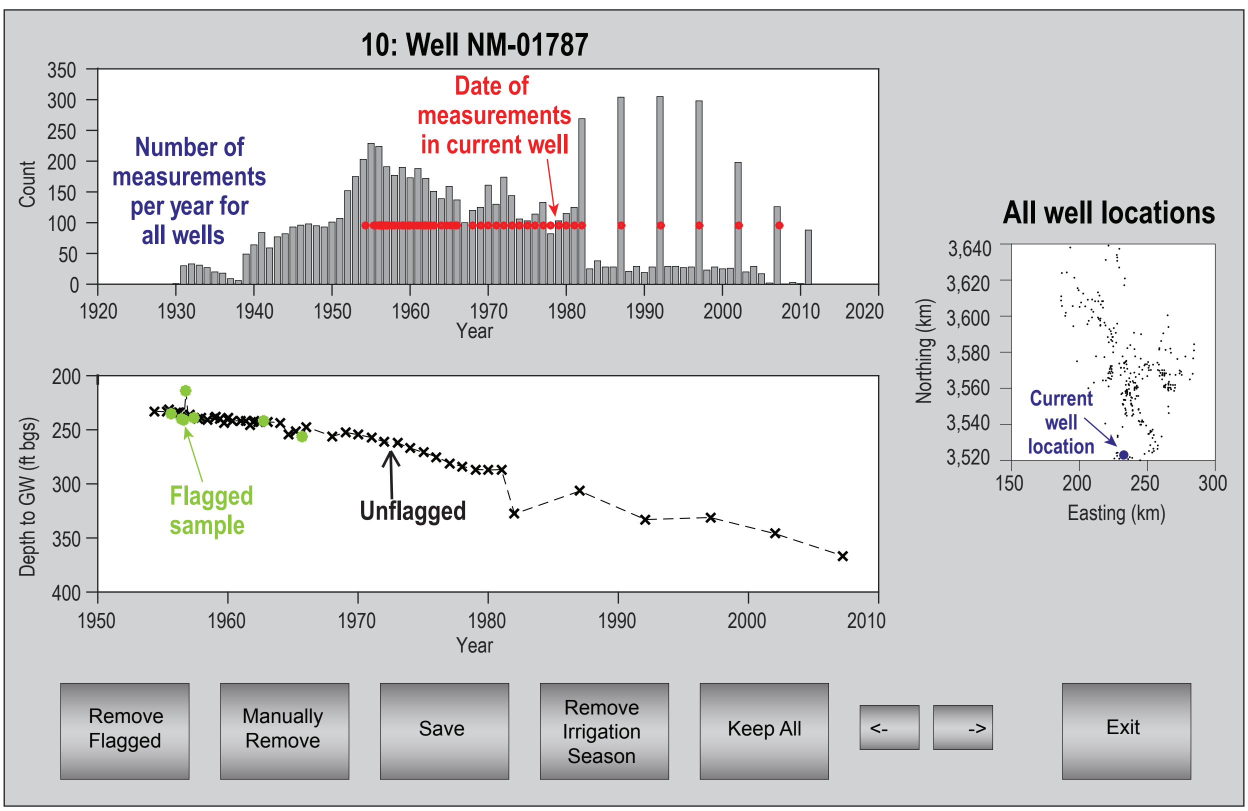

Figure 7. Image of interface used for data review. The top panel shows the number of measurements performed through time for the entire basin (bars) and the time of measurements for the current well (dots). The bottom panel is the hydrograph of DTW for the well, with flagged samples (red dots) and unflagged samples (crosses). The right panel shows the locations of all wells in the basin (black dots) and the location of the current well (larger blue dot). Buttons shown along bottom boundary allow the user to remove erroneous data, to navigate between hydrographs, and to save the hydrograph for the current well.

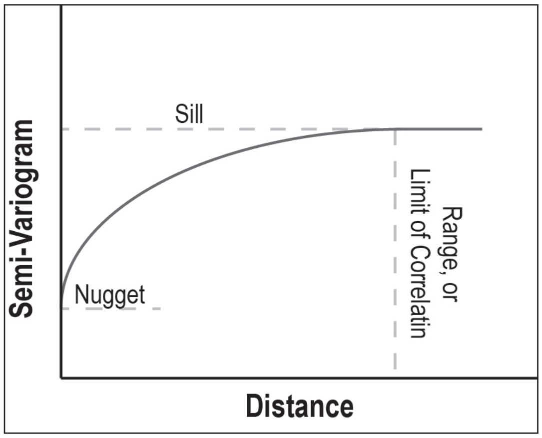

Figure 8. Conceptual diagram of a semi-variogram, showing the kernel, sill, and range or maximum distance of correlation.

description of semi-variogram analysis is summarized in Cressie and Wikle (2011). The semi-variogram of the median DTW measurements of a time interval of interest is found by calculating the one-half of the variance of the difference between measurements as a function of distance between measurement locations. Figure 8 conceptually illustrates the different parts of a (semi-) variogram. These consist of the nugget, the range and the sill. The nugget is is the variance at zero distance (i.e., at h=0). The range is the distance between h=0 and where the variogram begins to asymptote. The sill is the y-intercept of the asymptote of the variogram. This is the distance at which measurements are no longer correlated but are still randomly distributed. Commonly, beyond some larger distance past the onset of the sill, non-random variations can cause deviations from the sill. We visually chose the point at which the sill is reached. The variogram analysis is performed in Matlab©, using a combination of custom built functions and internal functions.

At this point, the data and parameters are inputted into an automated workflow in ArcGIS. To ensure that the results are robust, we use both kriging and inverse distance weighting (IDW) schemes for interpolation. Before commencing, an output resolution (e.g., 100-m gridded data), and fitting variogram for the kriging interpolation are found by trial and error. Both IDW and kriging are used to examine uncertainty from interpolation. Interpolating depth to water measurements rather than groundwater elevation was necessitated by (a) the higher uncertainty and variability of land surface elevation and the lower uncertainty and variability of DTW measurements at each point, and (b) the limitations of ordinary kriging.

Ordinary kriging assumes that the overall field has a mean value and that the variogram function can be reasonably fit. In many of the basins in New Mexico when using groundwater elevation, these assumptions are strongly violated. The assumptions are more closely followed in DTW measurements, because of both the limited variation in DTW and the lack of a second covariant (the surface elevation). Universal kriging performs a rough detrending of the data using a user-defined spatial basis function, and then statistically interpolates the remaining variation using a fitted variogram. We found that detrending with the ArcGIS universal kriging package did not accurately depict groundwater elevations or DTW. Ordinary kriging of groundwater elevations led to large, non-physical variations in interpolated groundwater elevations. We found it efficacious to simply interpolate median DTW groundwater measurements with both IDW and ordinary kriging.

Valid regions for interpolation and differencing are found by a combination of removing areas that are outside the distance of correlation in both time intervals of interest, and removing regions that are outside of the alluvial aquifer. After interpolating the median depth-to-water measurements in each time interval with both IDW and ordinary kriging, regions outside of the distance of correlation in each time interval and are removed from the interpolation. Then, the intersection of the clipped interpolated surfaces is found; this is assumed to be the region of statistically valid interpolation. Figure 9 illustrates the process of going from the raw interpolated grids to the separate statistically valid region for each time interval, to the intersection of the valid interpolations.

Geologically valid regions in which an alluvial aquifer is found are identified from units in the 1:500,000 scale state-wide geologic map (Geologic Map of New Mexico, 2003) after examining the existing literature on the hydrogeologic framework of the region. The regions outside of the alluvial aquifers are discarded after the statistically valid regions are found, as illustrated in Figure 10. The remaining interpolated surfaces for each interpolation are what we use to calculate changes in DTW through time.

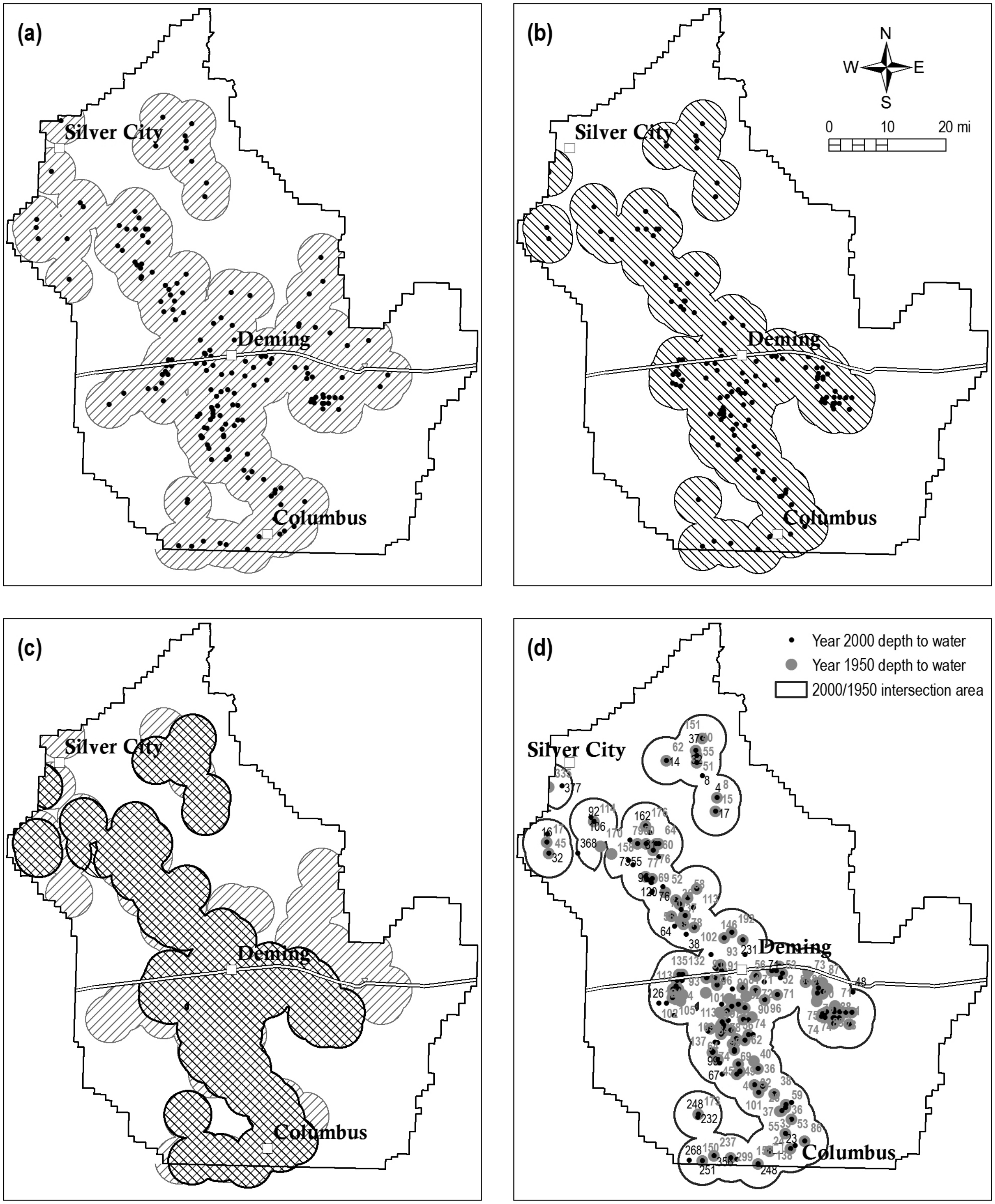

Figure 9. Example of removing interpolation outside of statistically valid region from Mimbres basin. (a) Valid region from median DTW measurements from 1950 to 1959, assuming a 6 km (3.7 mi) correlation range showing measured wells (dots); (b) Valid region in 2000 to 2009 for median DTW measurements, assuming 6 km (3.7 mi) range showing measured wells (dots); (c) both ranges (1950s right-hatch, 2000s left hatch) and their intersection (x-hatched); and (d) assumed valid region (outlined) with 1950s measured wells (large grey dots) and measured wells from the 2000s (small black dots).

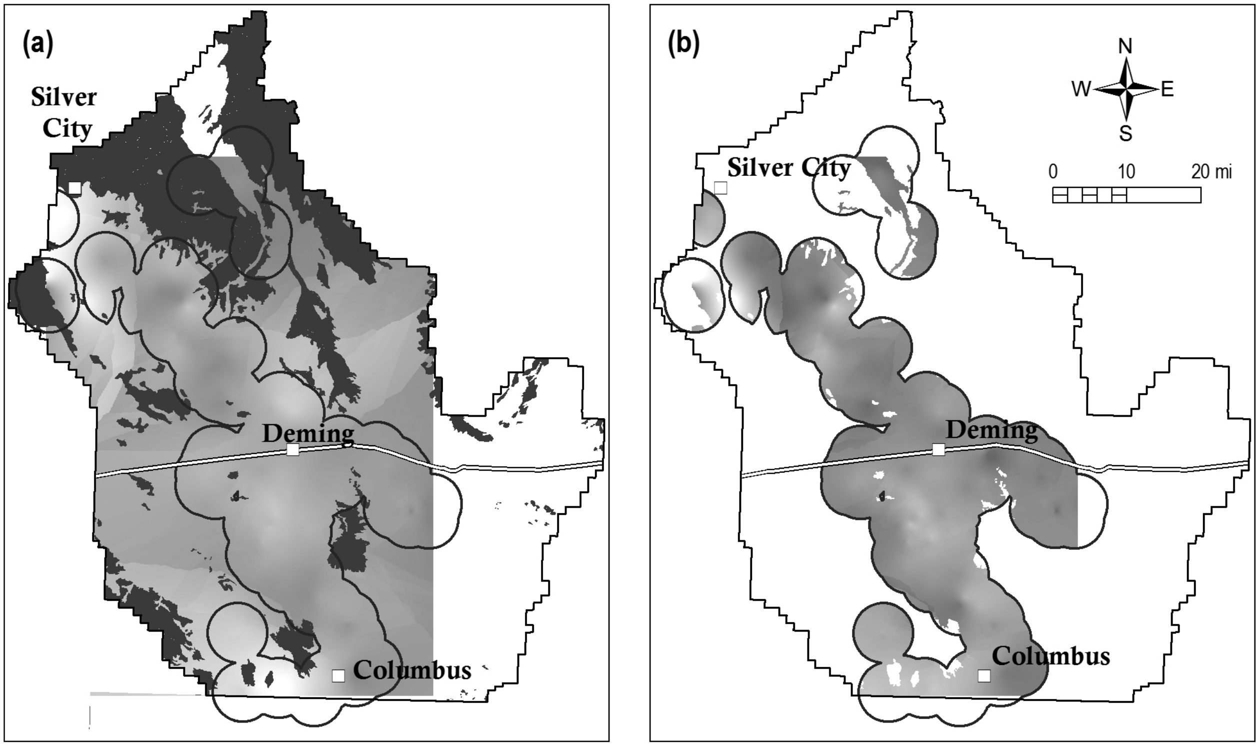

Figure 10. Schematic of clipping of interpolated DTW change estimation (light grey) to valid interpolation region (outline) and valid geologic region (dark grey). (a) The combined bedrock, buffering and differences interpolated layers, and (b) the clipped differenced interpolation.

Two separate approaches to differencing through time are used. The first approach defines an early time comparison period (e.g., pre-development), and subtracts this initial period interpolation from later time periods. For example, the interpolation of median DTW measurements from 1950 to 1959 would be subtracted from all later interpolations. The second approach is to find the moving difference between adjacent time periods. In other words, the difference in interpolated median DTW measurements from 1950 to 1959 would be subtracted from the median DTW measurements of 1960 to 1969, and then the interpolated median DTW measurements between 1960 and 1969 are subtracted from those of 1970 to 1979, and so on. The two approaches are applied both to ordinary kriging interpolations and IDW interpolations. Because well networks have expanded and shrunk through time, it is necessary to use both approaches. The comparison to a base period allows a comparison without noise introduced by repeated differencing that is restricted to a smaller but consistent region. The latter approach (moving differencing) may exacerbate sharp edged artifacts from the interpolations, but honors the changing, generally expanding well networks sampled.

The above process of interpolation, clipping out the buffer of valid regions, and finding the difference in DTW measurements has been streamlined in ArcGIS-Model Builder©. This platform allows the user to program a workflow using a flowchart schema, shown in Figure 11, resulting in an easily repeated process with the user only needing to input well locations, and the median DTW values for each well for two time intervals of interest. Finding the total differences and the moving differences is affected by inputting median DTW estimates for the appropriate time intervals. At the end of the analysis, maps of the differences and a text file of the gridded differences are output for visualization and storage change analysis.

After finding the differences in the interpolated median DTW measurements, the total change in groundwater storage can be estimated. To do this, an average specific yield is chosen for the alluvial aquifer by reviewing previous studies. Most of the alluvial aquifers in New Mexico have reliable existing analysis of aquifer properties, because of their societal importance through the last 50+ years. The specific

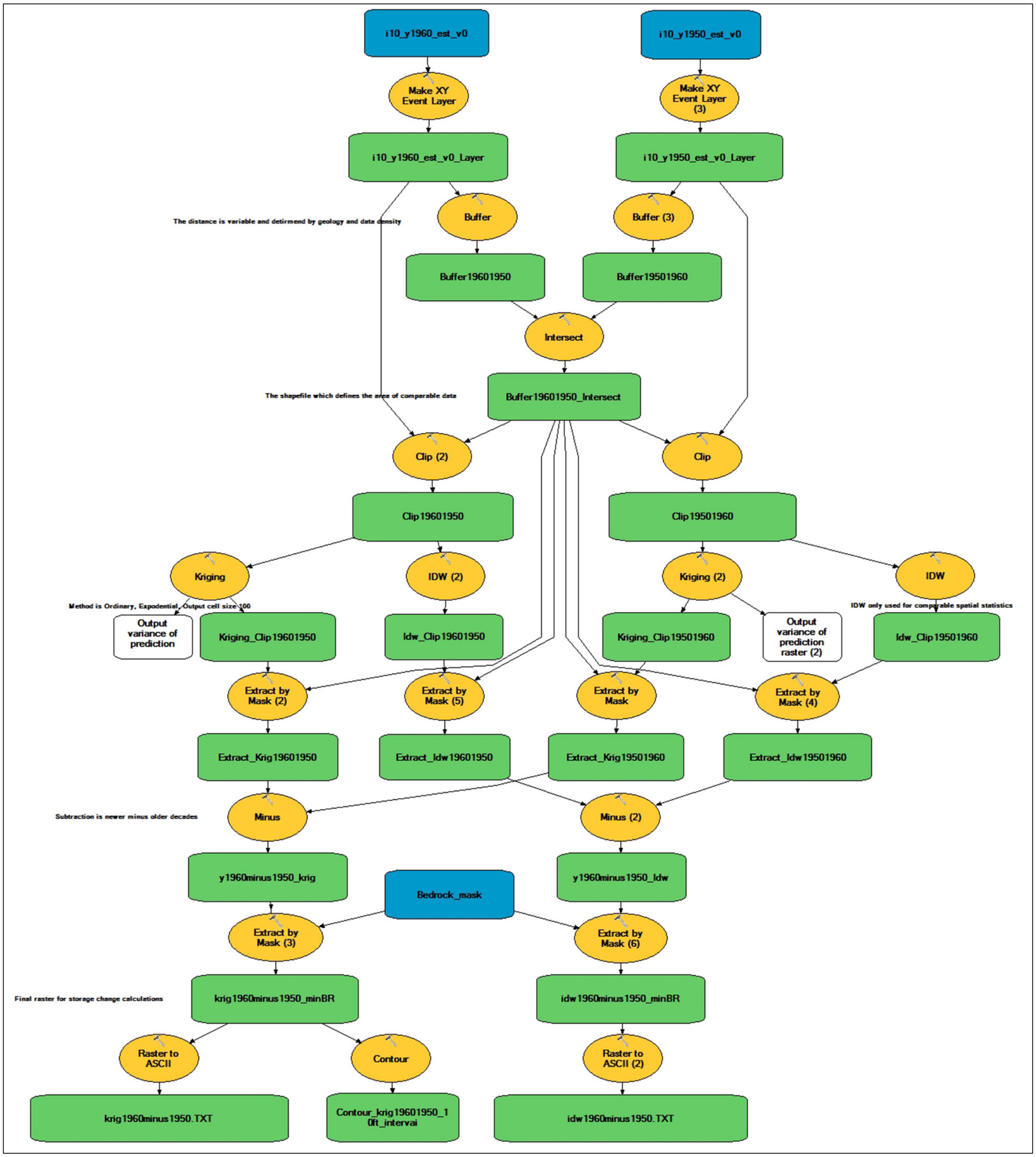

Figure 11. Image of implemented ArcGIS-Model Builder© workflow.

yield is defined as the water volume removed per unit change in depth-to-groundwater. Because aquifers exist in porous media, these values are generally close to the porosity of the aquifer, but are slightly lower because of water retention in the unsaturated zone. After choosing a set of basin-wide specific yield values, each pixel of change in interpolated median DTW measurement for all the different interpolations and differencing is multiplied by the set of specific yields. Thus, the volume of groundwater removed or added can be calculated using both kriging and IDW results, and using both total difference and moving difference estimates of change.

3. RESULTS AND DISCUSSION

3.1 Groundwater level changes

The analysis in Mimbres and Estancia basin had some consistent features. First, we found little sensitivity to the form of the variogram used in ordinary kriging within ArcGIS©. We chose to use the exponential variogram, using a minimum of the 12 nearest measurement points as interpolants. The outputted grid resolution from the interpolation, however, needed to be refined enough to capture the variability between points, but coarse enough not to introduce interpolation artifacts. We found for all interpolations in the Mimbres and Estancia basin that 300 ft (100 m) grid resolution was a reasonable compromise.

The use of both IDW and ordinary kriging provides distinct interpolations. Figure 12 shows an example in total change in groundwater elevations between the 1950s and the 2000s in the Mimbres basin using ordinary kriging (Figure 12a) and IDW (Figure 12b) interpolations. The ordinary kriging interpolation slopes toward zero-change away from the wells, likely similar to the pattern observed in nature. When using the IDW interpolation, however, the difference remains similar to those found in the nearest wells with the greatest change in DTW. This leads to non-zero change away from the well points. This non-zero change, however, provides a perspective on the hypothesis that the groundwater levels away from the wells are dropping at a similar rate to those in the well field.

3.1.1. Measurement History and Hydrographs

Both the Mimbres and Estancia basins show similar patterns in basin-wide sampling frequency and in patterns within their hydrographs (i.e., DTW time series). Figure 13 shows the number of unflagged

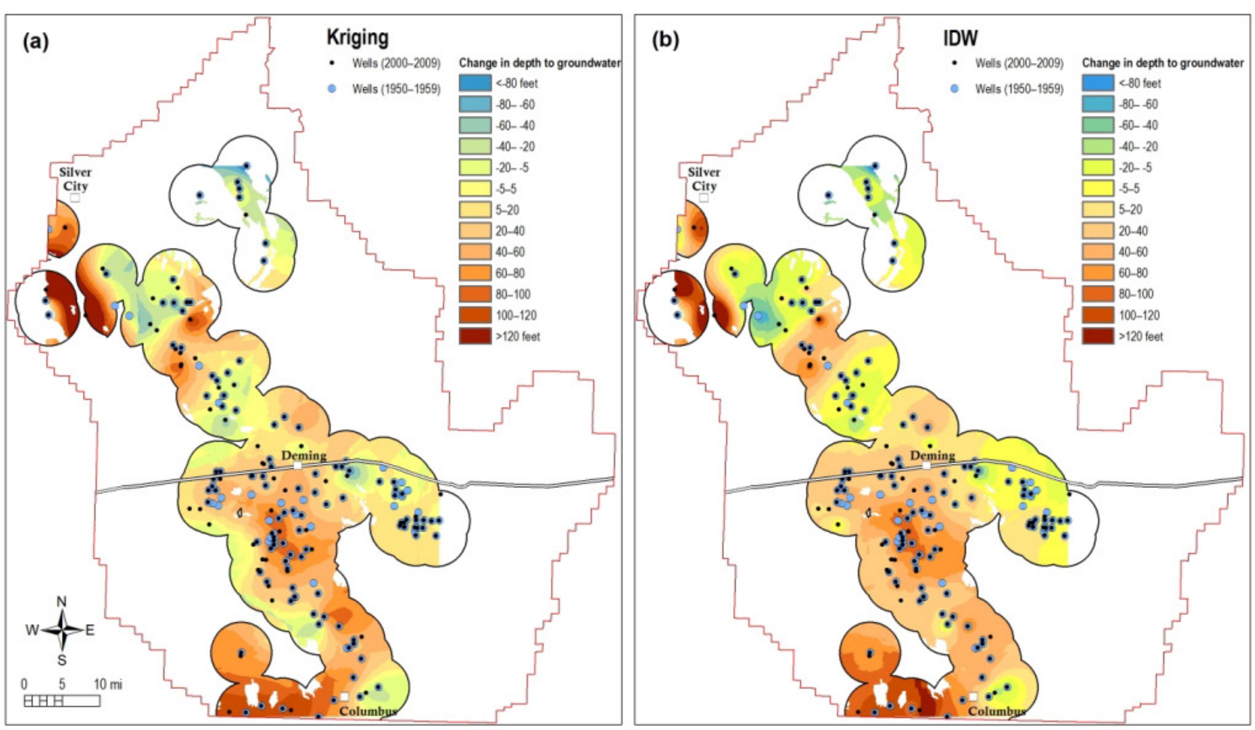

Figure 12. Difference in (a) kriging and (b) IDW interpolations for changes in median DTW between 1950-1959 and 2000-2009.

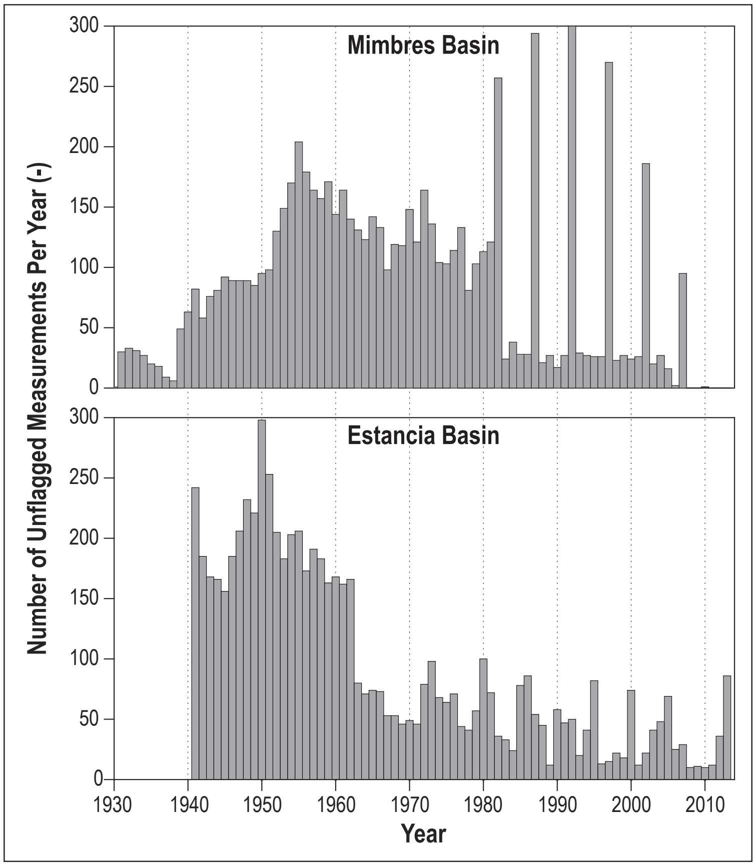

Figure 13. Number of valid DTW measurements made per year from the beginning of sampling (a) in the Mimbres basin, and (b) in the Estancia basin

(i.e., done with no complications from well activity) winter DTW measurements for both the Mimbres (Figure 13a) and Estancia basins (Figure 13b). Intensive sampling in the Mimbres basin began in the 1930s, with a peak of sampling in the middle 1950s. From the 1950s to the early 1980s, there was a sustained sampling effort (Figure 13a). Beginning in the early 1980s, the USGS began primarily sampling the Mimbres every five years, with some (less than 30) annual measurements in the intervening times (Figure 13a).

In the Estancia basin (Figure 13b), sampling began in the early 1940s, and reached a peak in the early 1950s. From then until the early 1970s, there was a steady decline until the mid-1970s. At this time, a roughly five year sampling interval was established, but with a more even distribution of annual sampling in the intermediate times than in the Mimbres basin (Figure 13b).

Hydrographs in the Mimbres basin show a range of typical hydrographs of measured DTW, as seen in Figure 14. The primary pattern is either of steady declines withdrawals (Figure14a) with declines up to 150 ft (45 m), or of an initial 10 to 20 yrs of declines of up to 150 ft (45 m), followed by a period of steady levels (within 10 ft or 3 m) (Figure 14b). These make up at least 80% of the records. Rarely, hydrographs show steady DTW levels (Figure 14c) or even rebounding levels after initial declines (Figure 14d). Increases in levels are very rarely more than 30 ft (9 m).

As seen in Figure 15, typical hydrographs in the Estancia basin are similar to those in the Mimbres (Figure 14). Once again, the most prevalent patterns are those of either steady decline (Figure 15a) or of an initial drop followed by steady water levels (Figure 15b). Water level declines are generally between 50 ft (15 m) and a little over 100 ft (30 m). In less than 15% of the wells, water levels have remained steady (Figure 15c) or have recovered after initial declines (Figure 15d).

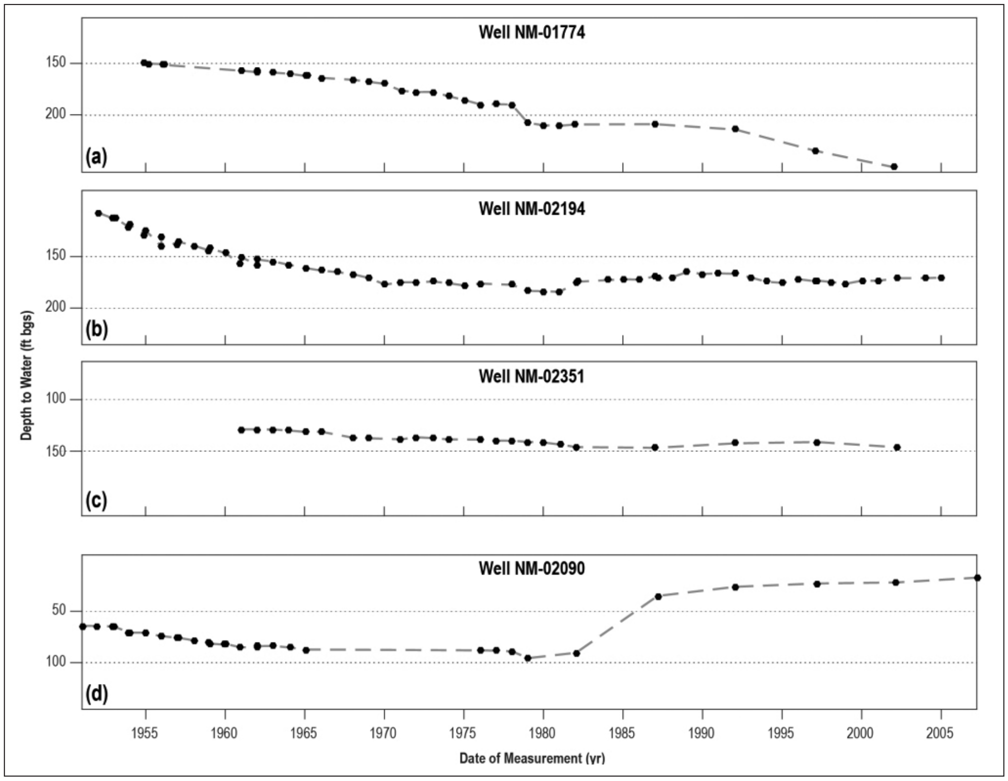

Figure 14. Hydrograph examples from the Mimbres basin, with (a) steady declines, (b) initial declines followed by steady levels, (c) steady levels throughout the record, and (d) initial decline followed by a rebound in levels. Depth to water is shown in feet below ground surface (ft bgs) and date in years (yr).

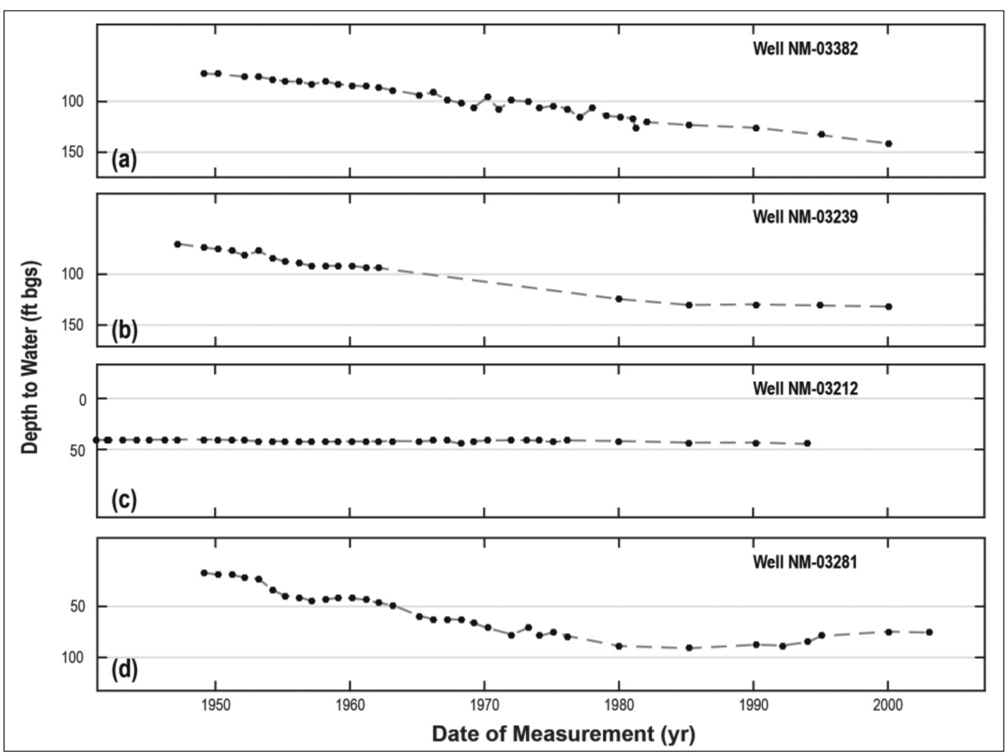

Figure 15. Examples of hydrograph from the Estancia basin, with (a) steady declines, (b) initial declines followed by steady levels, (c) steady levels throughout the record, and (d) initial decline followed by a rebound in levels. Depth to water is shown in feet below ground surface (ft bgs) and date in years (yr).

3.1.2. Mimbres Basin Groundwater Level Changes

The analysis of groundwater level changes in our method begins with a manual examination of variograms depicting the range for depth-to-water correlations, followed by four estimates of the spatial pattern of groundwater storage change. Refer to Figure 3 for Mimbres basin locations referenced in following text.

For the Mimbres basin, Figure 16 shows the fitted estimates of the variogram with both raw (Figure 16a) and binned (Figure 16b) estimates. The raw estimates are the correlation between each two median water levels for each well between 2000 and 2009. The binned estimates lump the variability into 0.5 km wide bins. From these binned estimates, the mean value of the semi-variogram is found. This is a monotonically increasing function, neglecting the outliers at 2.25 km and 5.25 km until 6.00 km. Between 6.0 km and 6.75 km, the sill is reached. The sill shows a statistical variability of roughly 30 ft below ground surface (bgs). After 7 km the data begin to oscillate. This is likely due to non-statistical correlations. All decades showed a sill being reached between 6 km and 7 km. As a compromise, we chose 6.5 km as our sill. This value was used to clip the later interpolations. We have excluded all wells not in the alluvium or Quaternary-aged basin fill from our analyses. The majority of these wells are in low porosity aquifers or in fractured aquifers, both of which have low storativity.

We attempted to perform interpolations with 10-year and 5-year intervals in the Mimbres basin. It was found that the well networks were not consistent or dense enough through time using 5-year intervals. This caused large artifacts to be introduced in the interpolation. The primary cause of this is that the

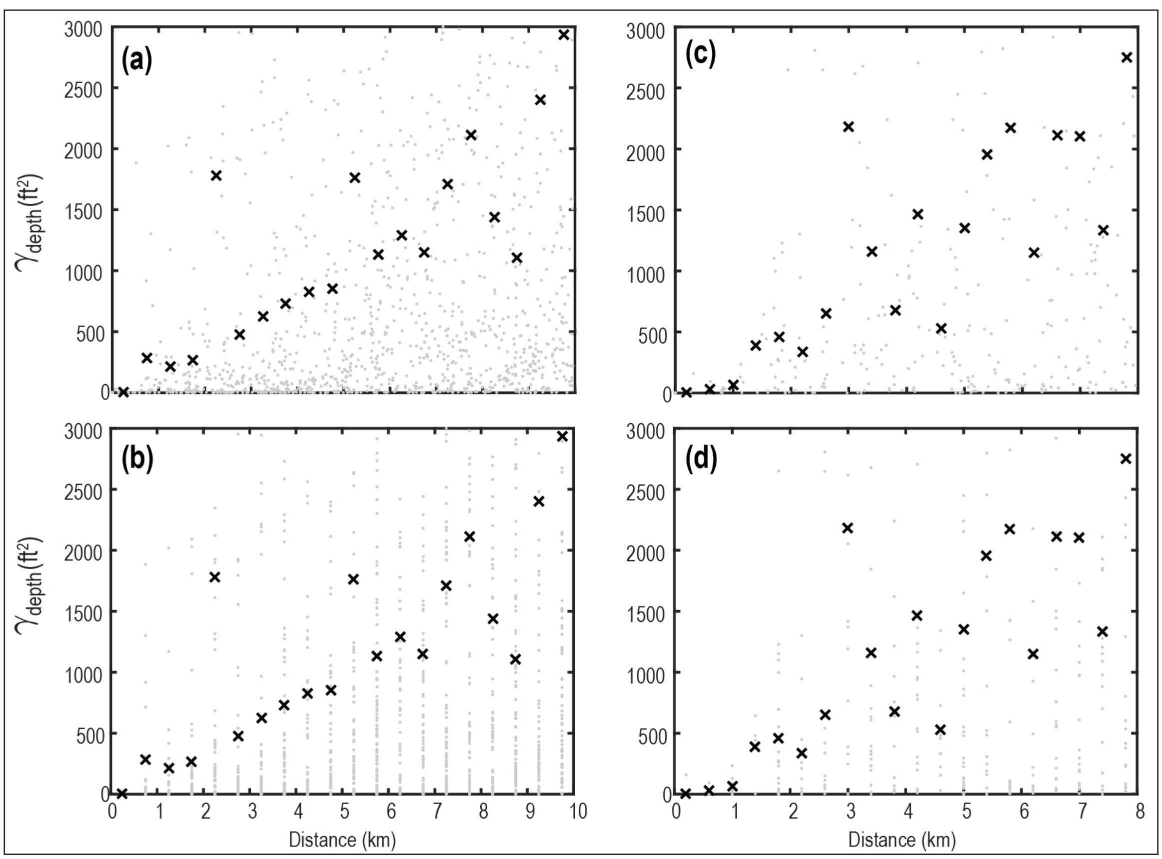

Figure 16. Examples of variogram analysis for median DTW measurements in the (a,b) Mimbres and (c,d) Estancia basins between 2000 and 2009; showing fitted variogram (x) estimates overlying (a) raw covariance estimates (dots) for Mimbres basin, (b) binned covariance estimates (dots) for Mimbres basin, (c) raw covariance estimates (dots) for Estancia basin, and (d) binned covariance estimates (dots) for Estancia basin.

well networks did not have a similar distribution in space between 5-year intervals. The 10-year intervals allowed a greater chance that similarly spatially distributed networks would be used in all regions during the interpolation.

As discussed in the methods, there are second order differences between kriging and IDW interpolations, with IDW showing persistent decreases away from the well fields. However, the magnitudes of change are not significantly different. In the discussion below, we only show the kriging interpolations.

The differences in kriging-interpolated median DTW measurements between 1950-1959 and 1960-1969 (Figure 17), 1950-1959 and 1970-1979 (Figure 18), 1950-1959 and 1980-1989 (Figure 19), 1950-1959 and 1990-1999 (Figure 20), and 1950-1959 and 2000-2009 (Figure 21) are shown. Measurements in the pre-1950 well fields were too spatially restricted to find a reasonable estimate for the storage change to modern time. Because the measurements are depth-to-water, the negative changes in DTW imply rising groundwater levels and positive changes in DTW imply declining groundwater levels.

Figure 17 shows that between the 1950s and the 1960s there were overall mild declines in groundwater levels throughout the Mimbres basin, with some local zones of strong declines in the north-central and the southern portion of the basin. North of the Florida Mountains in the central portion of the basin east-southeast of Deming, there is a zone of substantial increases. Other zones of significant increases may be artifacts of ordinary kriging and of changing well networks.

Beginning in the 1970s, the magnitude of declining water levels from the 1950s is more pronounced (Figure 18). The largest declines are west and southwest of Deming, and surrounding Columbus. These declines are real; the well network remained relatively constant between the two intervals. To the north, at and southeast of Silver City, large declines are also seen. In this time interval, it is less clear if these are real as new wells were added to the network from the 1950s to the 1970s. To the north of the Florida mountains, some rising water levels are persistent, if lower in magnitude, from the previous decade. Water level declines east of the Florida Mountains are modest (<20 ft) compared to much of the rest of the basin. Overall, the well network remains relatively constant and most of the differences in interpolated values are likely valid.

The difference between the 1950s and 1980s (Figure 19) show an increase in the area of declining water levels. The areas around Columbus, Deming and Silver City continue to show increasing groundwater level declines. Some modest rises are seen east and south north of Silver City. The rises and declines north and east of the Florida Mountains remain relatively constant from their first change in the 1960s. Figure 20 shows the change between the 1950s and the 1990s. Similar to the change seen in the 1980s, the magnitude of declines increases and the area of those declines increases. Modest increases from the 1980s changes are seen north and east of Florida Mountains. At this point, much of the Mimbres basin has experienced water level declines of around 40 feet, with some significant zones with declines between 70 and 110 ft. The difference between the 1950s and 2000s interpolation is more contrasting (Figure 21). The area south and southeast of Silver City shows large, greater than 120 ft declines, which are likely dominated by a single set of measurements in bedrock. South of Deming and west of Columbus, nearly the entire regions shows greater than 50 ft water level declines. The area north and east of the Florida Mountains show a slight rebound from previous decades. Beginning in the 1980s and continuing through the 2000s, the Mimbres valley shows a zone of significant recharge, with water level rising around 30 ft. This is only locally significant.

Figures 17, 22, 23, 24, 25 show the moving differences of the kriging interpolations of median DTW for the differences of 1950-1959 to 1960-1969 (Figure 17), of 1960-1969 to 1970-1979 (Figure 22), of 1970-1979 to 1980-1989 (Figure 23), of 1980-1989 to 1990-1999 (Figure 24), and of 1990-1999 to 2000-2009 (Figure 25).

The difference in interpolations between the 1960s and the 1950s was discussed above. Between the 1970s and the 1960s, there is little change in much of the basin, with an erroneous zone of water level rise in the center portion of the basin caused by the introduction of new wells which may not be real

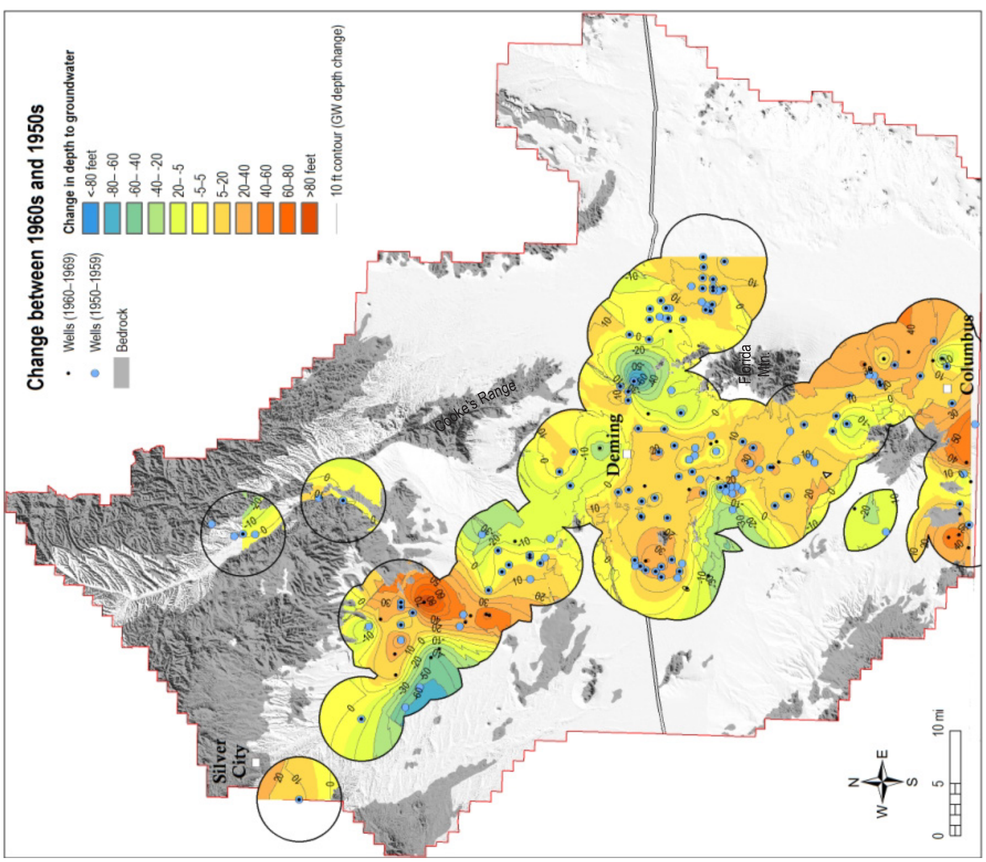

Figure 17. Difference between 1950-1959 and 1960-1969 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1960-1969 well field (small black dots), and the edge of the statistically valid zone (black line).

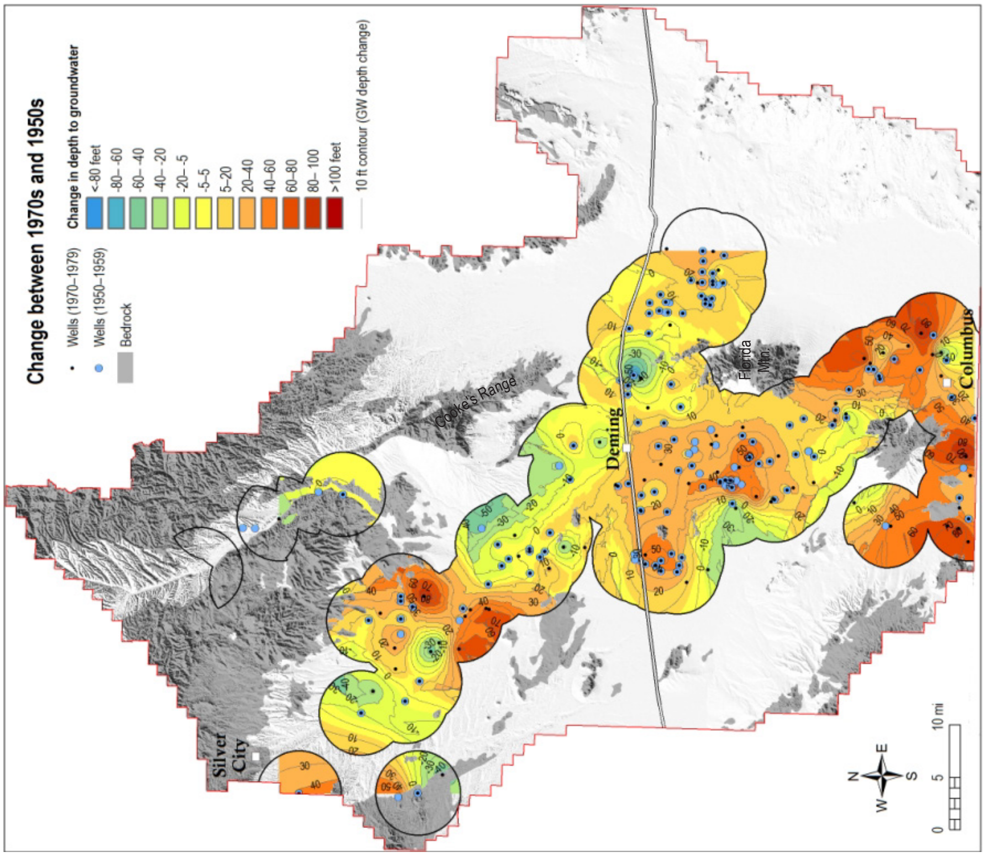

Figure 18. Difference between 1950-1959 and 1970-1979 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1970-1979 well field (small black dots), and the edge of the statistically valid zone (black line).

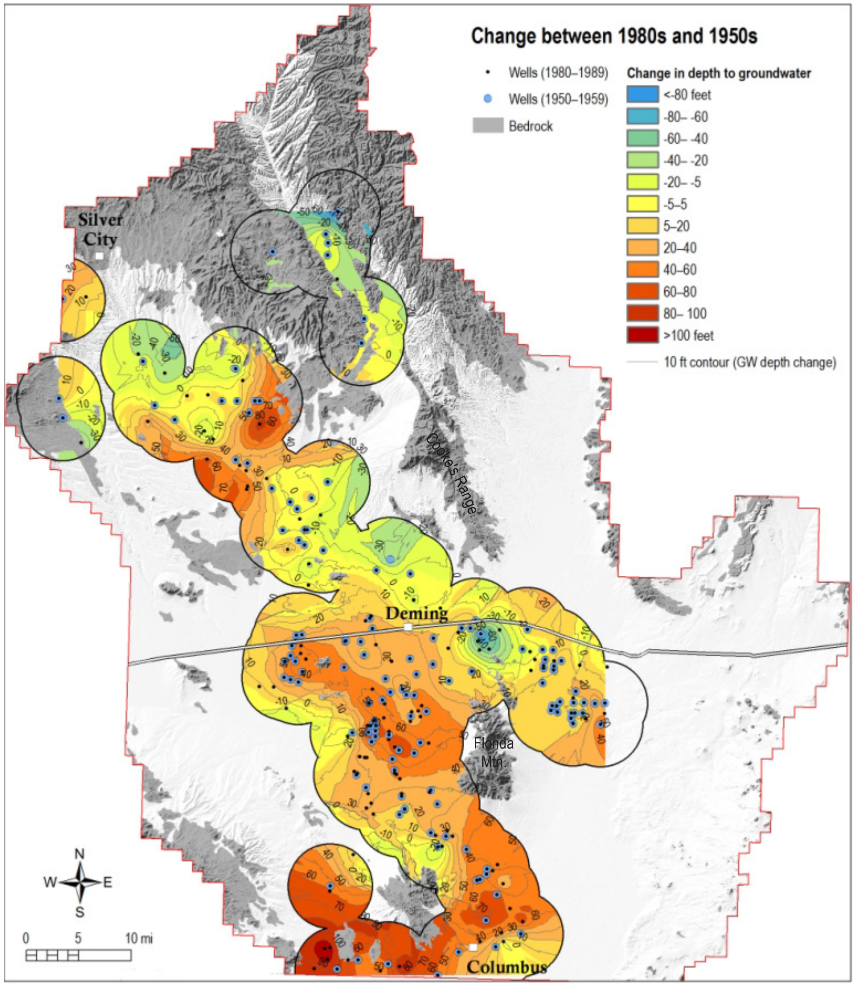

Figure 19. Difference between 1950-1959 and 1980-1989 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1980-1989 well field (small black dots), and the edge of the statistically valid zone (black line).

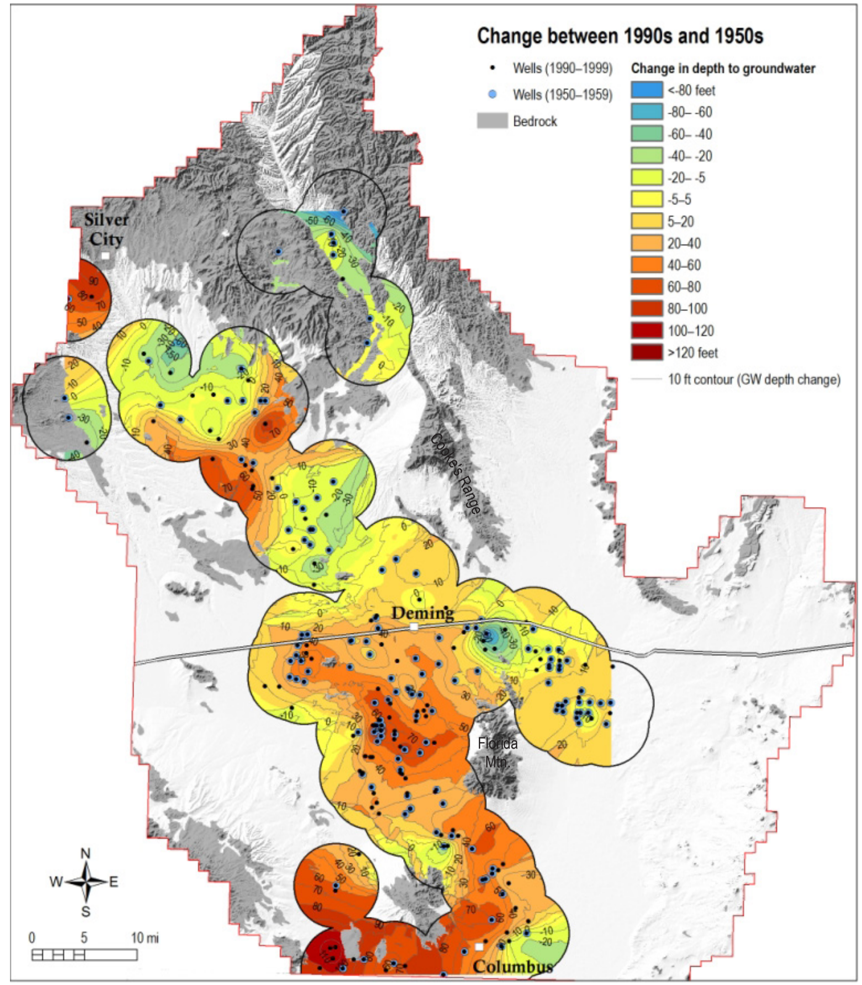

Figure 20. Difference between 1950-1959 and 1990-1999 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1990-1999 well field (small black dots), and the edge of the statistically valid zone (black line).

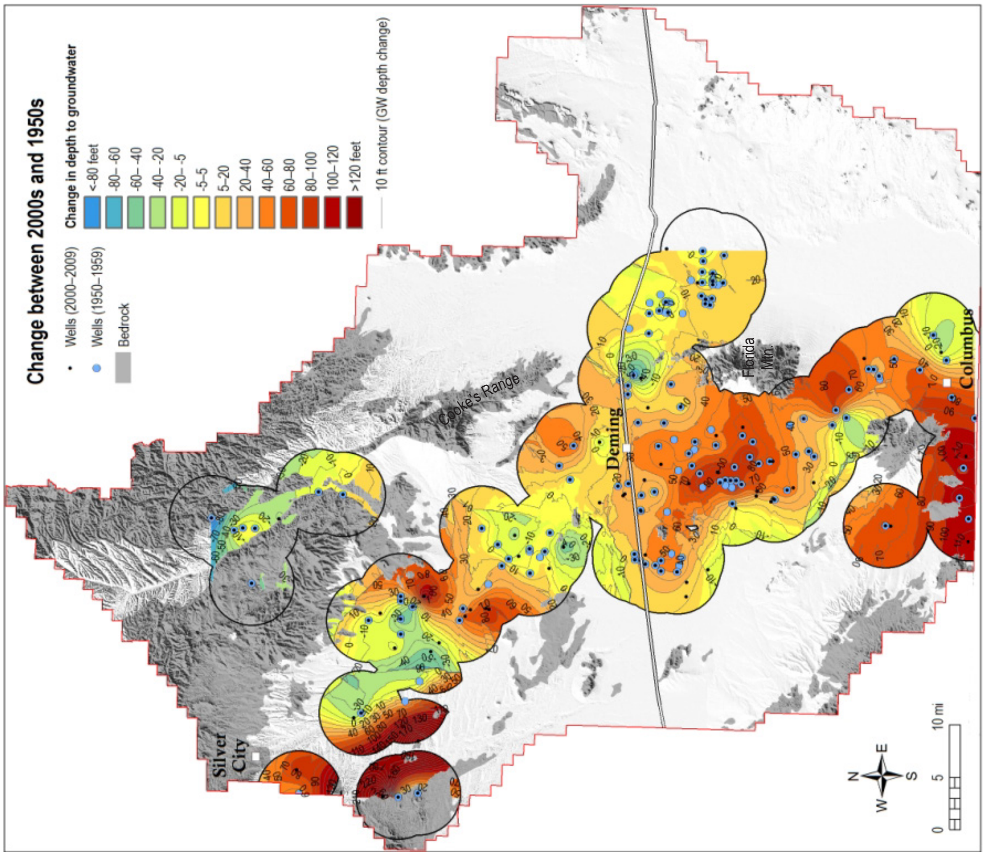

Figure 21. Difference between 1950-1959 and 2000-2009 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 2000-2009 well field (small black dots), and the edge of the statistically valid zone (black line).

(Figure 22). West of Deming, there are small (5 to 20 ft) declines. Around Columbus, however, there is a broad swath of declines of as much as 40 ft. Between the 1970s and the 1980s, our results show declines of around 10 ft for much of the basin (Figure 23). Once again, near Columbus, there is a region of declines of up to 70 ft, mostly greater than 20 ft. There are small regions northeast of the Florida Mountains of modest rise (roughly 10 ft). South of Silver City, there exist small regions of larger rises (up to 60 ft).

Between the 1980s and the 1990s, the overall trend is groundwater declines (Figure 24). Once again, much of these declines are found between Deming and Columbus. North of Deming, there are two large zones of decline (as much as 60 ft). West of Deming, there exists another zone with large groundwater level declines. Just south of Silver City, the declines noted earlier as possibly being an artifact are, in fact, verified as real with declines of greater than 80 ft. Small zones of groundwater level rises exist north of Deming, just east Columbus, east of the Florida Mountains, and intermittently between Deming and Silver City. The well network between the 1980s and the 1990s remains relatively constant with the majority of wells sampled in both decades. This increases the confidence in these measurements.

The difference in groundwater level interpolations between the 1990s and the 2000s is more ambiguous, though showing a continued trend of declines between 10 ft to 30 ft per decade (Figure 25). In fact, the overall groundwater levels in the basin begin declining more sharply in this decade. The area immediately next to the U.S.-Mexico border south of Columbus shows large declines. Between Columbus and Deming, except for an isolated zone of rising groundwater levels, declines are prevalent. Surrounding Deming in all directions, groundwater levels are declining. East of Cooke's Range, a zone of groundwater level rise exists, but the lack of coverage in previous decades and in the total groundwater level

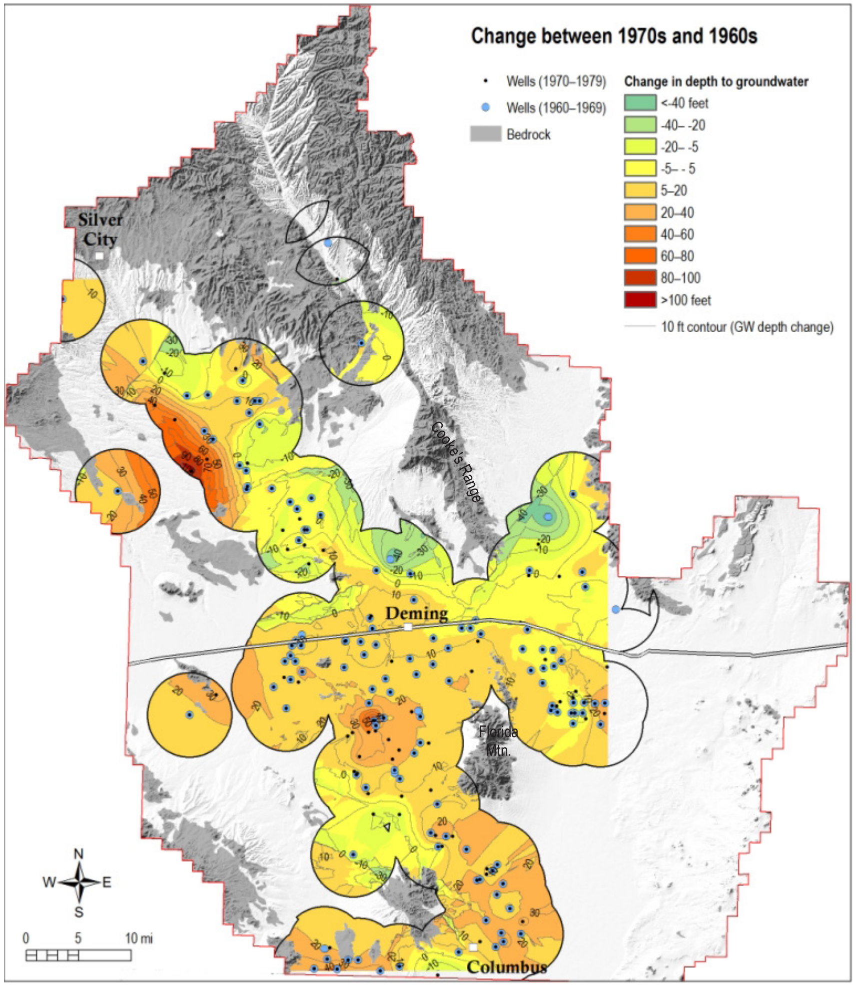

Figure 22. Difference between 1960-1969 and 1970-1979 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1960-1969 well field (large blue dots), the 1970-1979 well field (small black dots), and the edge of the statistically valid zone (black line).

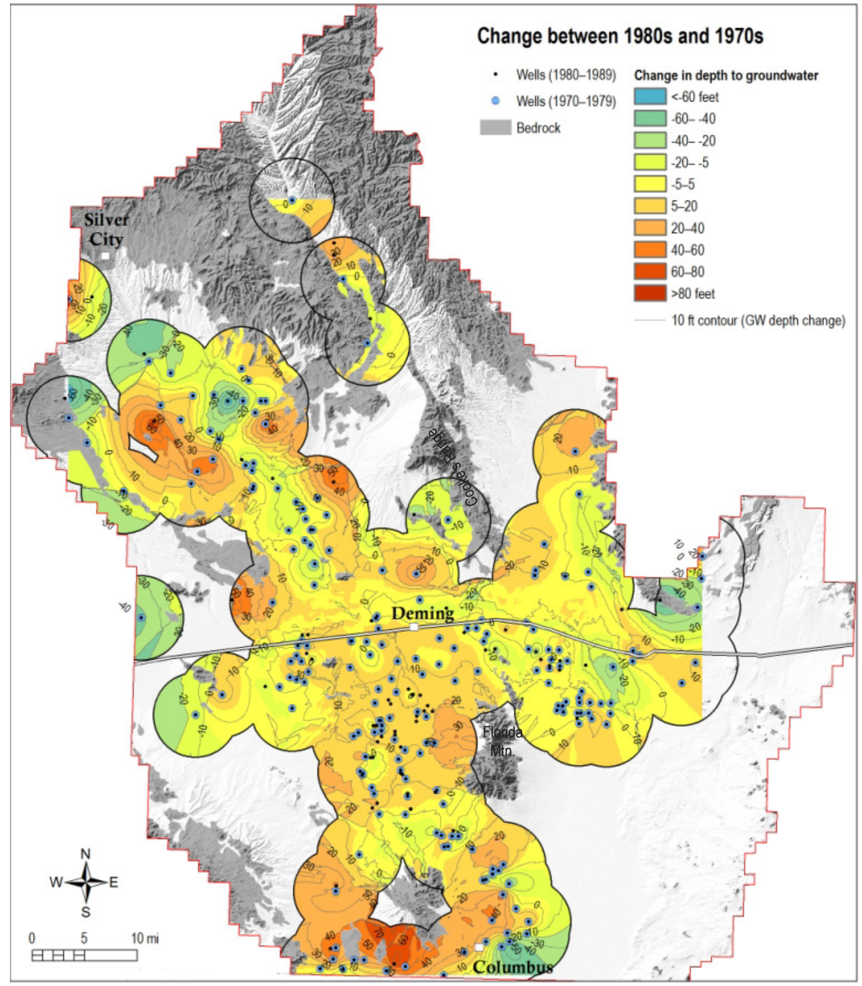

Figure 23. Difference between 1970-1979 and 1980-1989 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1970-1979 well field (large blue dots), the 1980-1989 well field (small black dots), and the edge of the statistically valid zone (black line).

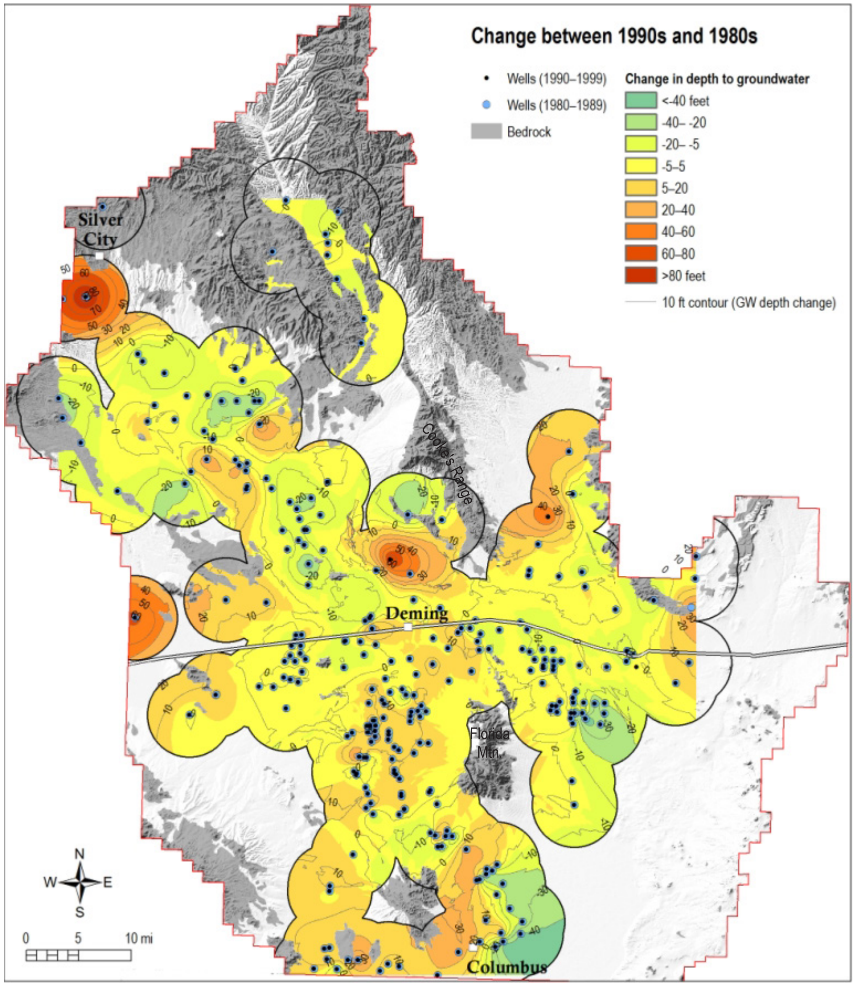

Figure 24. Difference between 1980-1989 and 1990-1999 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1980-1989 well field (large blue dots), the 1990-1999 well field (small black dots), and the edge of the statistically valid zone (black line).

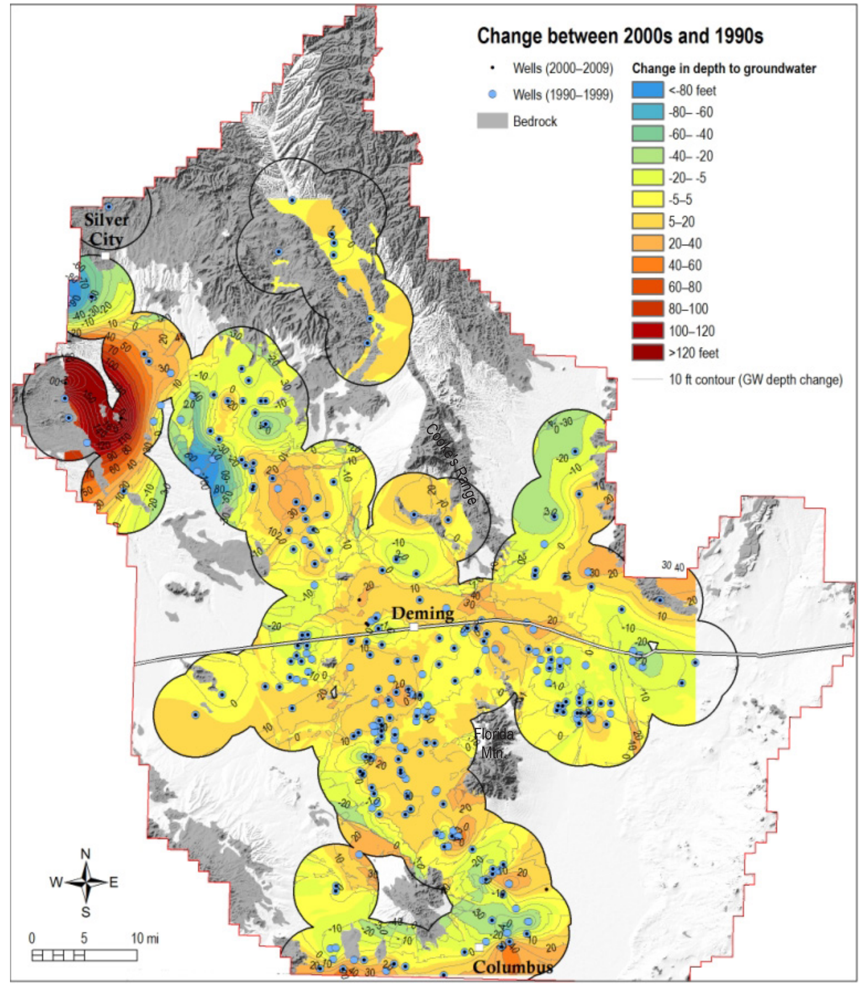

Figure 25. Difference between 1990-1999 and 2000-2009 median DTW kriging interpolations in the Mimbres basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1990-1999 well field (large blue dots), the 2000-2009 well field (small black dots), and the edge of the statistically valid zone (black line).

change figures (Figures 16- 21) disallows much discussion. South of Silver City, a small zone of large rises in groundwater levels (as much as 80 ft) is followed to the south by a large zone of declines (greater than 160 ft).

Overall, the spatial patterns of both the total groundwater level changes (Figures 16-21) and the moving differences in the groundwater level changes (Figure 16, 22-25) are consistent. There are overall declines between Deming and Columbus, local small increases east of the Florida Mountains and Cooke's Range, and a swath of overall declines between Deming and Silver City with a large zone of declines south of Silver City. Detailing the causes of rises is beyond the scope of this project. But, in general, increased pumping in agricultural areas, drainage of open pit mines, and changing annual temperature and precipitation patterns may contribute to groundwater declines.

The ultimate goal of this study is to understand the integrated and spatial patterns of groundwater withdrawals in a consistent framework. The fact that, even with changing well networks between the total difference and the moving difference calculations, that the spatial patterns and magnitudes of change are similar is promising. It indicates that the method is relatively robust for internal comparisons between interpolations and differencing methods.

3.1.3. Estancia Basin Groundwater Level Changes

Before performing any calculations on groundwater level interpolations in the Estancia Basin, it was necessary to first define the zone of statistical relevancy through examination of the variograms. Figure 16c and 16d show the raw, binned and mean covariance structure with distance (i.e., the semi-variogram) for the Estancia basin for median DTW measurements between 2000 and 2009. The zone of good correlation is smaller here than in the Mimbres basin, though the sample size for each semi-variogram estimate is smaller (compare Figures 16b and 16c) for Estancia basin than for the Mimbres basin. Nonetheless, in all of the estimates in the Estancia basin between 1950 and 2010, the rough location of a sill between 1.5 km and 3.0 km is consistent. We have chosen to take the range of the variogram, and the clipping distance in our workflow, to be 2.5 km for all the analyses that follow. We have assumed that anything that is not either Santa Fe Group-aged or younger does not have large amounts of storage in the Estancia basin. There are some well fields completed in the Madera Formation, a Pennsylvanian limestone, but these fields have been found to be low-storativity fracture aquifers (Titus 1973; and White 1993). Refer to Figure 4 for locations referenced in following text.

Figures 26 through 30 show the differences in median DTW measurements between 1950 and 1959 and the median DTW measurements of 1960-1969 (Figure 26), 1970-1979 (Figure 27), 1980-1989 (Figure 28), 1990-1999 (Figure 29) and 2000-2009 (Figure 30). Once again, the figures show changes in DTW in both contours and by color. The older well network is shown and underlies the more modern well network. Between the 1950s and the 1960s, groundwater declines occurred down the central axis of the basin with declines of greater than 30 ft (Figure 26). Small zones of upward-moving groundwater exist along the eastern mountain block. In the next decade, groundwater levels decline in the central axis of the basin with changes of greater than 30 feet (Figure 27). Only a single zone of rising water levels exists on the northern edge of the basin (Figure 27). Rather thanrising, the western edge of the basin shows only small changes (rising or declining by less than 5 feet). The well network locations remained relatively constant in the areas of largest change.

Between the 1950s and the 1980s, large changes occurred, once again, primarily along the central axis of the basin (Figure 28). Groundwater depths declined by more than 60 feet in many locations, and declines between 30 and 50 ft are common. However, groundwater levels once again rose relative to the 1950s measurements along the western edge of the basin (Figure 28). The well network locations changed slightly, but the new measurements generally were located near the historical measurements. These placements limited the impacts of changing sampling on the interpolation.

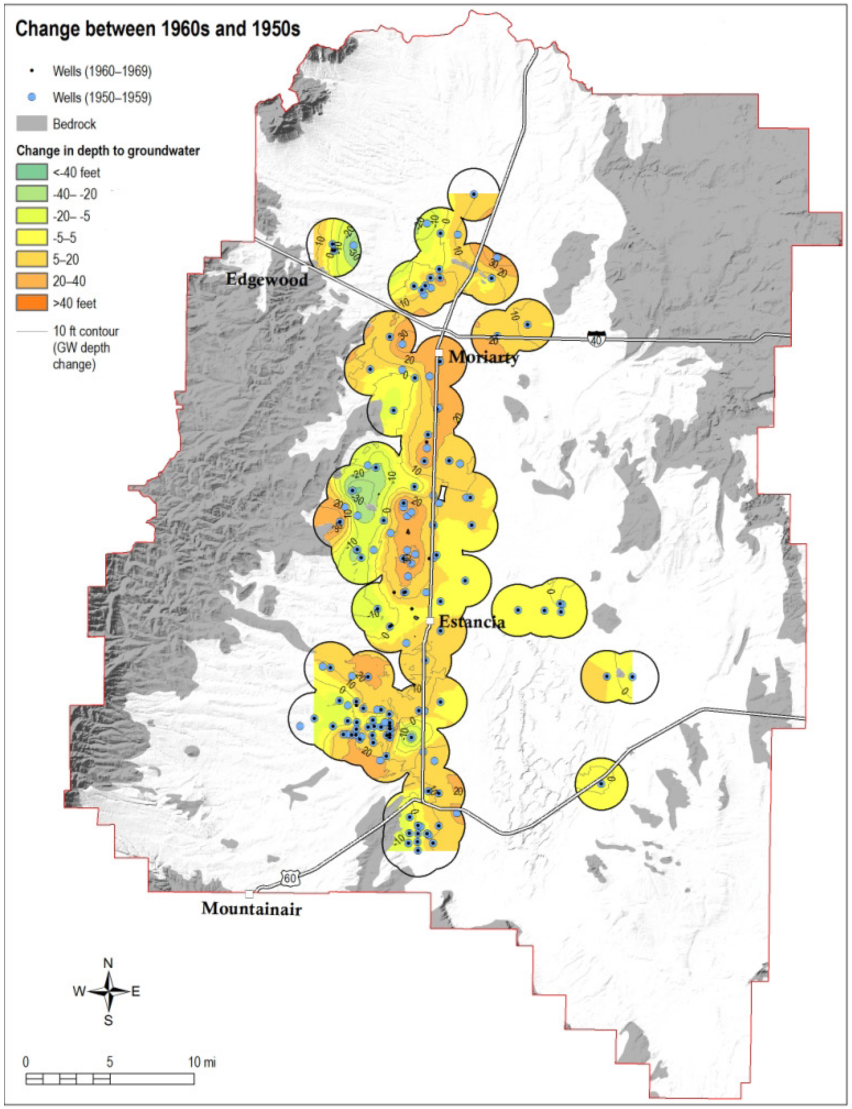

Figure 26. Difference between 1950-1959 and 1960-1969 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1960-1969 well field (small black dots), and the edge of the statistically valid zone (black line).

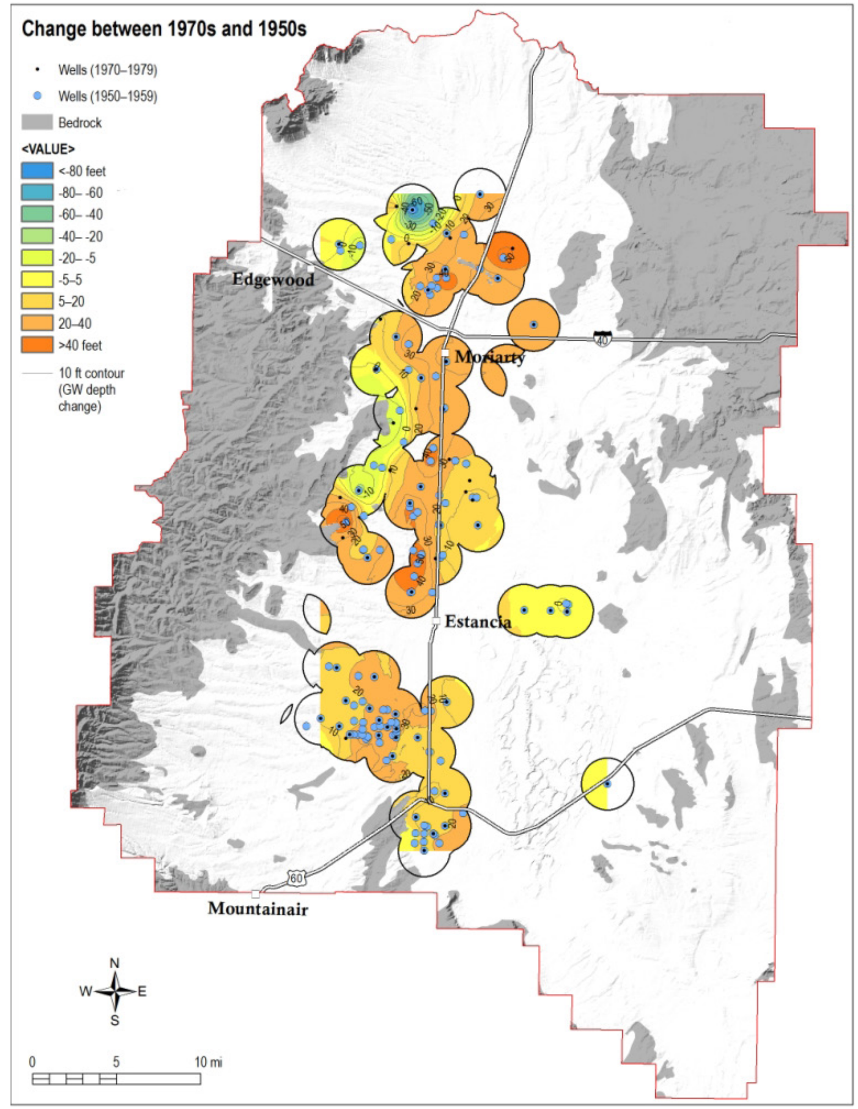

Figure 27. Difference between 1950-1959 and 1970-1979 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1970-1979 well field (small black dots), and the edge of the statistically valid zone (black line).

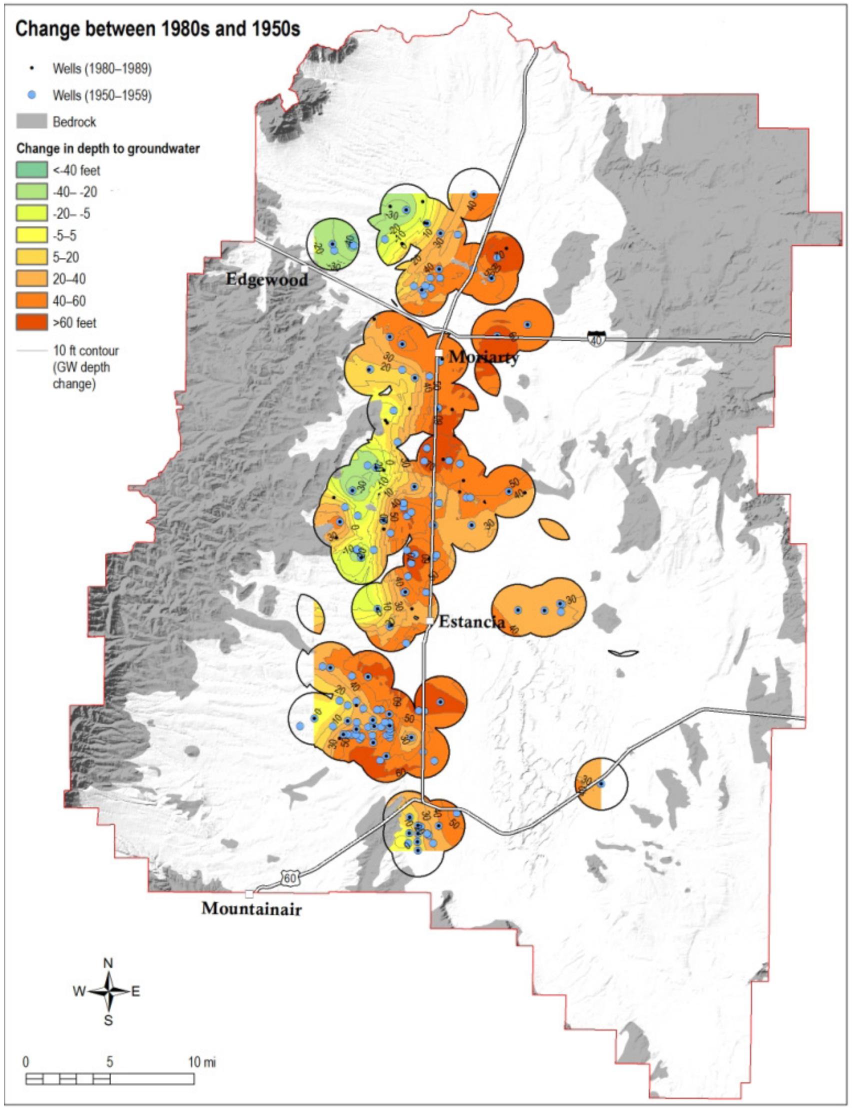

Figure 28. Difference between 1950-1959 and 1980-1989 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1980-1989 well field (small black dots), and the edge of the statistically valid zone (black line).

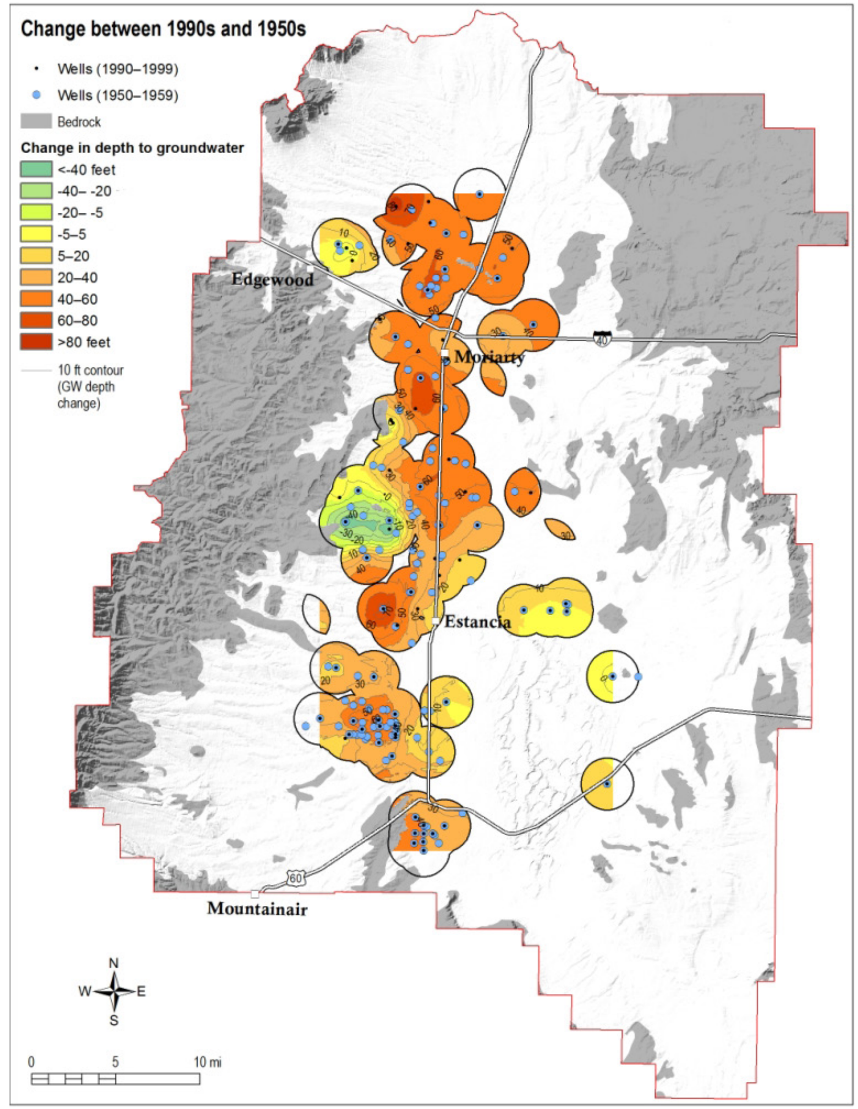

Figure 29. Difference between 1950-1959 and 1990-1999 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 1990-1999 well field (small black dots), and the edge of the statistically valid zone (black line).

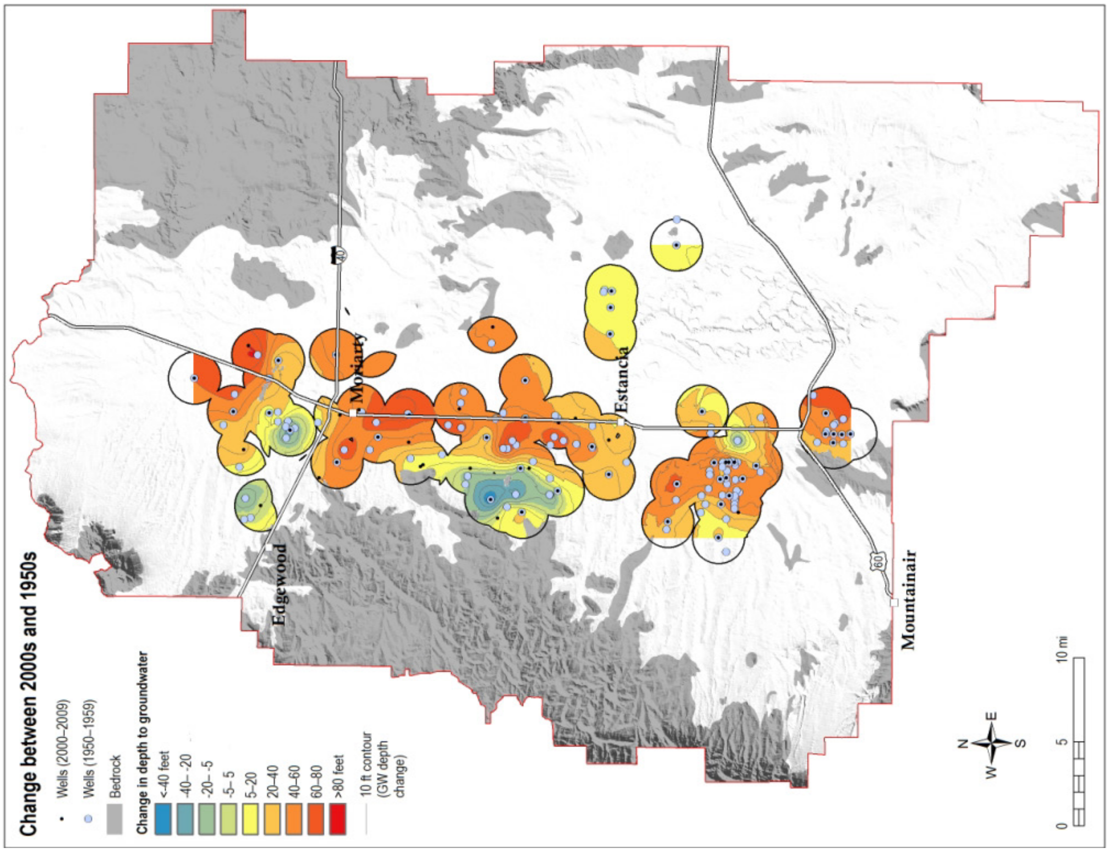

Figure 30. Difference between 1950-1959 and 2000-2009 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1950-1959 well field (large blue dots), the 2000-2009 well field (small black dots), and the edge of the statistically valid zone (black line)..

The pattern of declines changes for the difference between the 1950s and the 1990s groundwater interpolations (Figure 29). Once again, the declines fall along the central axis of the basin. However, now the largest declines (greater than 70 ft) occur north of Moriarty rather than between Moriarty and Estancia. The area north of Moriarty did show declines to the east, but the western zone generally showed small changes or even rises. Now, it shows large declines. The zone along the eastern edge of the basin between Moriarty and Estancia shows large rises, however, with water levels rising by more than 30 ft.

Groundwater levels between the 1950s and the 2000s show the zone of declines along the center-line of the basin, with local zones of groundwater level rises north of Moriarty and Edgewood, and along the eastern edge of the basin halfway between Moriarty and Estancia. Due north and south of Moriarty are the areas of the largest groundwater level declines (Figure 30). Loss of network wells to the north-east of Moriarty make it difficult to assess if the change in pattern in the 1990s has continued into the 2000s.

Through the entire series of maps (Figs. 26-30), increasing groundwater declines are observed in most of the basin. Rises are generally small and isolated to two small zones. The zone of greatest declines is along the centerline of the basin. This is likely due to groundwater pumping for irrigation.

Figures 26, and 31 through 34 show the differences in median DTW interpolations between 1960-1969 and 1950-1959 (Figure 26), between 1970-1979 and 1960-1969 (Figure 31), between 1980-1989 and 1970-1979 (Figure 32), between 1990-1999 and 1980-1989 (Figure 33), and between 2000-2009 and 1990-1999 (Figure 34). These moving differences have the advantage of more consistent well locations between time intervals and, at least for some decades, a larger sampling area. The groundwater level changes between the 1950s and the 1960s are discussed above. Between the 1960s and the 1970s, groundwater levels declined along the central portion of the basin by more than 30 ft. Common magni-tudes of declines were between 10 ft and 20 ft (Figure 31). Between the 1970s and the 1980s, the overall

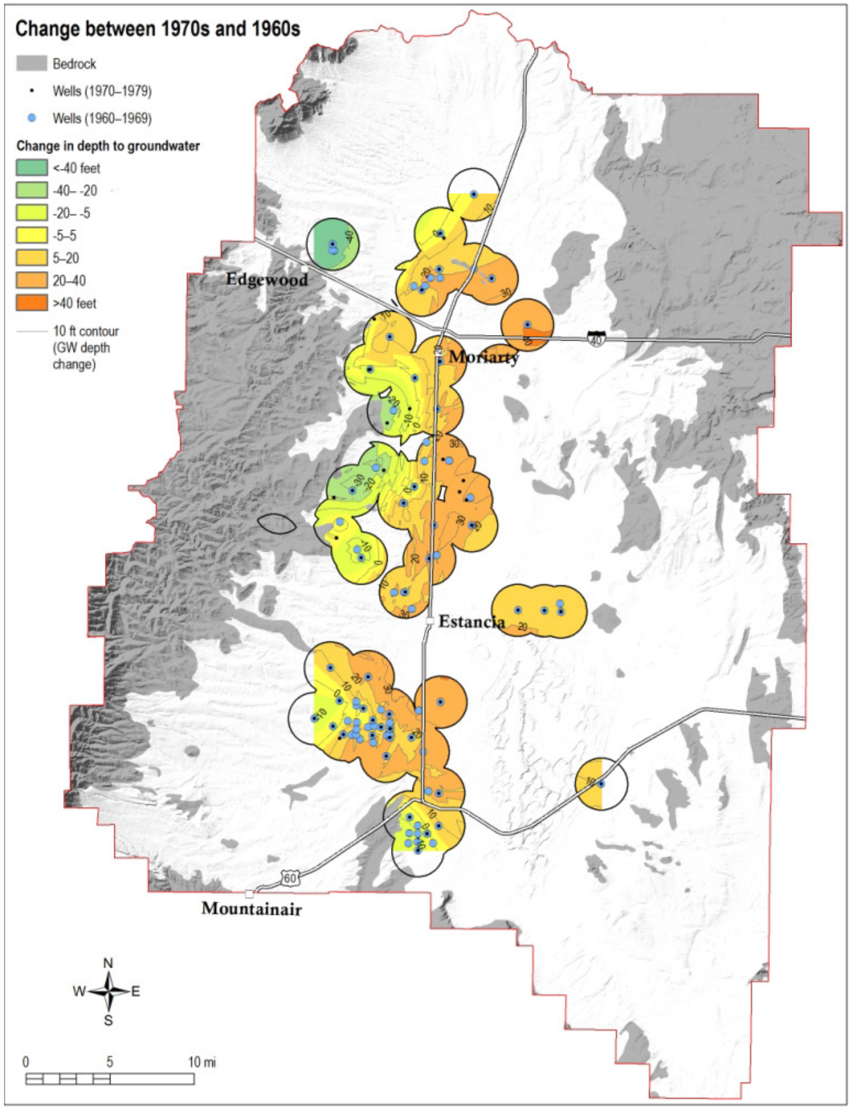

Figure 31. Difference between 1960-1969 and 1970-1979 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1960-1969 well field (large blue dots), the 1970-1979 well field (small black dots), and the edge of the statistically valid zone (black line).

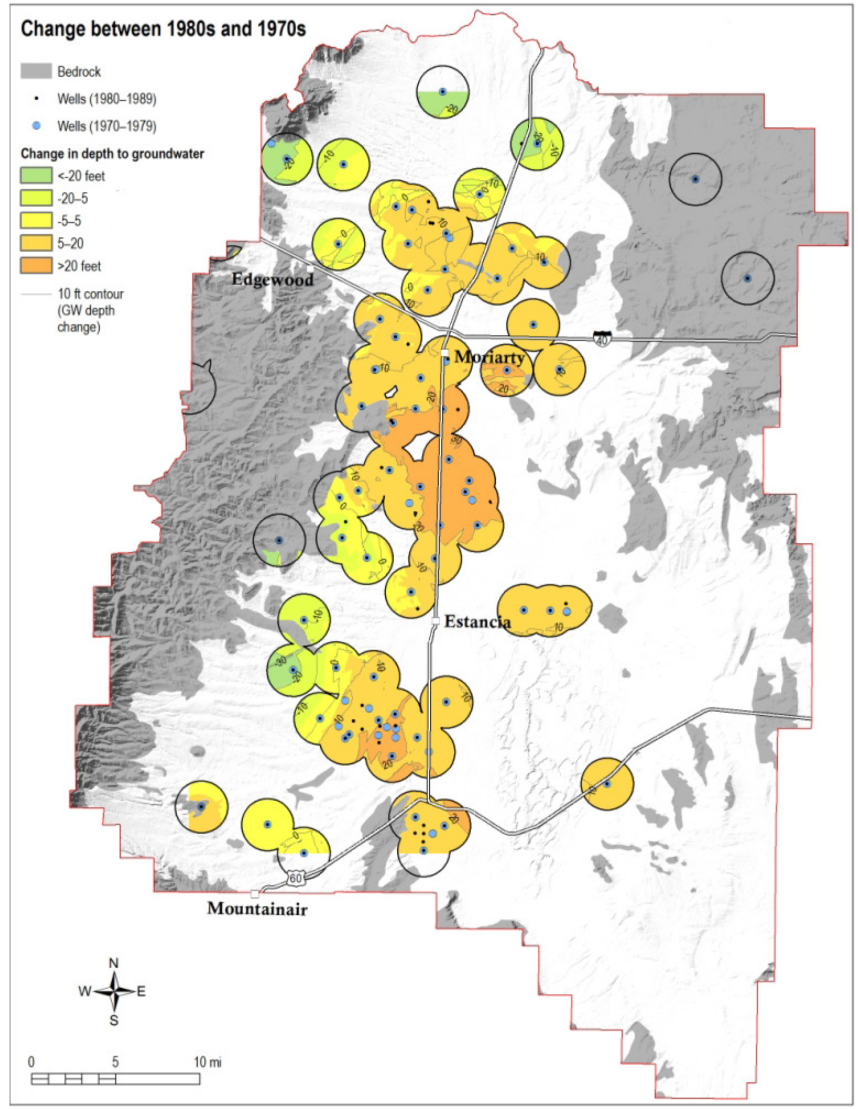

Figure 32. Difference between 1970-1979 and 1980-1989 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1970-1979 well field (large blue dots), the 1980-1989 well field (small black dots), and the edge of the statistically valid zone (black line).

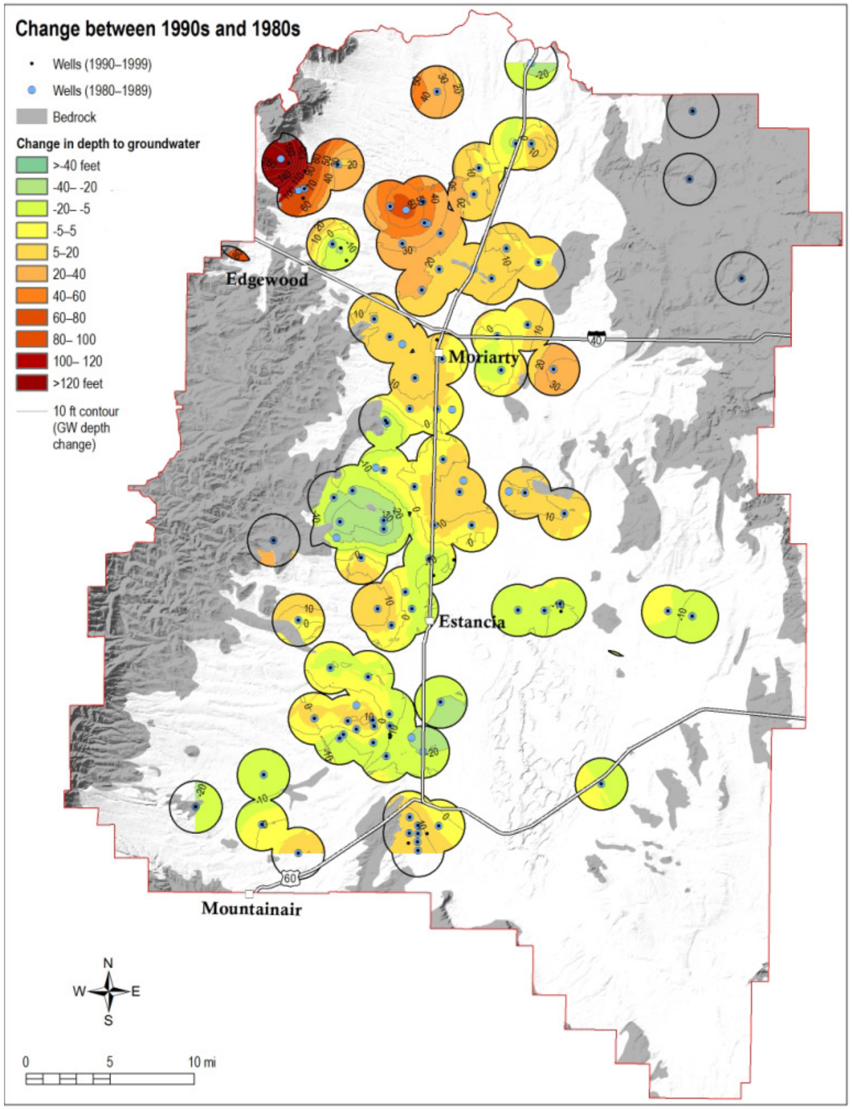

Figure 33. Difference between 1980-1989 and 1990-1999 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1980-1989 well field (large blue dots), the 1990-1999 well field (small black dots), and the edge of the statistically valid zone (black line).

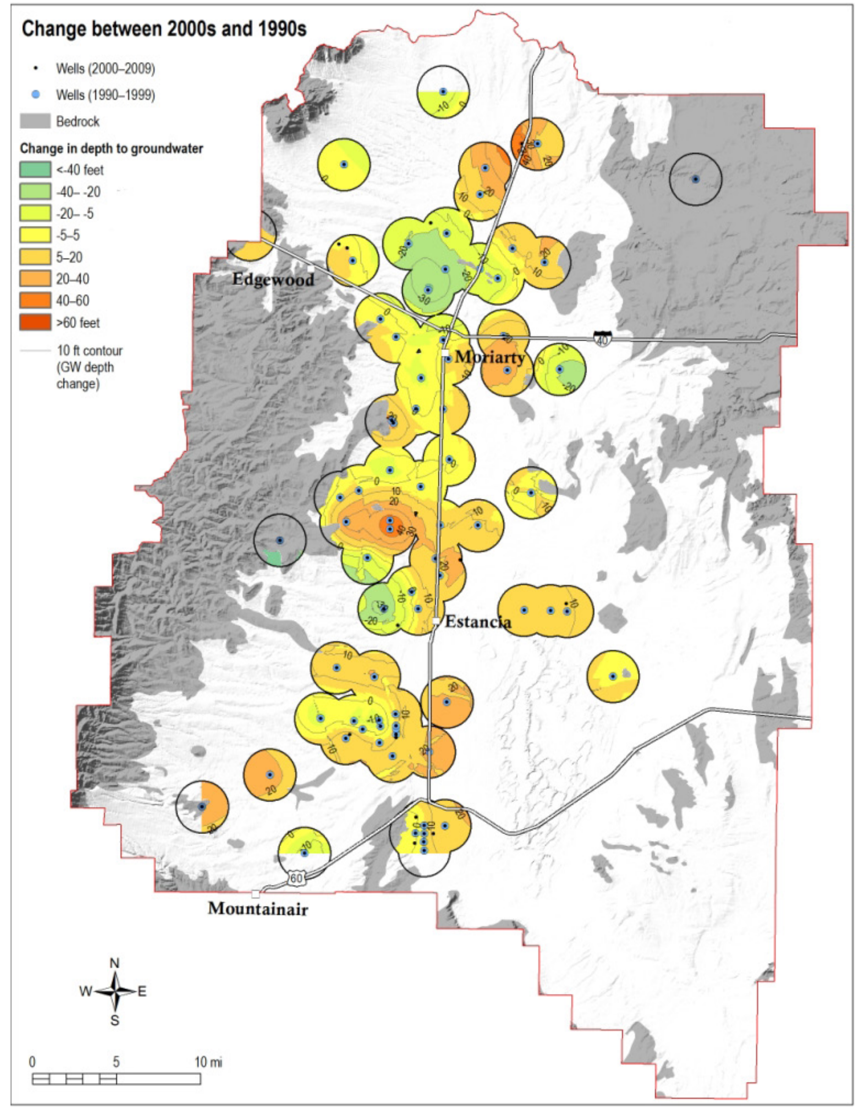

Figure 34. Difference between 1990-1999 and 2000-2009 median DTW kriging interpolations in the Estancia basin. Shown are changes in DTW with color (declining warmer colors, rising in cooler colors) and contours (10 ft), areas of bedrock (dark grey), the 1990-1999 well field (large blue dots), the 2000-2009 well field (small black dots), and the edge of the statistically valid zone (black line).

groundwater levels in the basin declined, with an area of large (30 ft) declines between Estancia and Moriarty. Little change is seen along the western boundary of the basin (Figure 31).

A significant change in overlapping well locations occurs between the 1980s and the 1990s, with the region north of Edgewood entering the network (Figure 33). Once again, the N-S axis of the basin shows general declines, though at a lower magnitude than for previous decades (Figure 33). Here, the groundwater level rises of up to 30 ft appear along the western edge of the basin halfway between Moriarty and Estancia (Figure 33). However, very large groundwater declines are apparent in the new portion of the network, north of Edgewood. Here, groundwater declines of more than 160 ft are present (contours, Figure 33). The 1980s well network and the 1990s well network nearly overlap throughout (Figure 33), implying these declines are real.

Unfortunately, between the 1990s and the 2000s, the sampling of the well network north of Edgewood was discontinued (Figure 34). This means that we cannot discuss if the major groundwater declines have continued using this well network. Moderate groundwater level rises immediately north of Moriarty are present, with a small zone of up to 30 ft water level rise to the northwest. From Moriarty south to Mountainair, 20 ft to 30 ft declines are prevalent, with a small zone with declines of up to 40 ft located in the basin halfway between the Estancia and Moriarty. This location previously had seen an rise between the 1980s and the 1990s (Figure 33). To the west of the Estancia, an area of up to 20 ft of groundwater level rises exists. However, as in the other decades, declines are more common and of greater magnitude than rises.

Overall, the patterns between the maps of total groundwater level change and moving differences of the interpolated levels are consistent. Some of the details from decade to decade are lost in the total calculations; it is challenging to see when things remain relatively constant. However, the total change maps (Figures 26 through 30) emphasize the zones of persistent declines relative to early-development levels. They also provide a consistent comparator, because the base, 1950s well network remains constant through all calculations. The moving difference maps (Figures 26, 31-34), however, can examine new areas as they are brought on-line. The moving difference map of changes between the 1980s and the 1990s, which have comparable well networks, highlights this by showing a previously unsampled region with large declines (Figure 33). This change was also indicated in the total difference map of the 1990s (Figure 29), but it was difficult to see if it was real because of the lack of 1950s well coverage in the region.

It appears to be important to track both the changes from a base network (i.e., total difference from the 1950s), and moving differences from decade to decade. This combined approach gives us two perspectives on groundwater level changes in basins. They appear to be consistent with each other within both the Estancia basin and within the Mimbres basin. Below, we discuss the total storage changes and compare the results from the different methods of calculating changes.

3.2. Groundwater storage changes

The change in volume of water stored in the Mimbres and Estancia basins is summarized in Figure 35. The results from the kriging interpolations are shown on the left hand side (Figure 35a,c) and the results from the IDW interpolations are found on right hand side (Figure 35b,d) for the Mimbres (Figure 35a,b) and Estancia (Figure 35c,d) basins. The total, moving and cumulative groundwater storage withdrawals for Mimbres and Estancia Basin are shown in Table 1.

The storage change calculations for both the kriging and IDW methods are consistent in the Mimbres basin (Figure 35 a,b). For both the total difference and cumulative moving difference schemes, the differences derived from the kriging interpolations show a total change of between 2.4 million acre-feet (Maf) and 2.6 Maf since the 1950s. The differences based on the IDW interpolations shows a similar change

(Figure 35b). The strongest difference between moving and total difference schemes, which necessarily require different well networks to be used in the interpolations, is that the total storage change calculations show near constant storage change from the 1950s between the 1980s and the 1990s, followed by a sharp groundwater storage decline between the 1990s and the 2000s (dark solid line, Figure 35a,b). The moving differences show a more constant rate of change in groundwater storage, with the highest rate of depletion between the 1960s and the 1970s, followed by relatively uniform total depletions. Considering that the moving differences sample a larger area and do not integrate changes over longer periods of time, the consistency of these results indicates either that the majority of groundwater storage change occurs in the area sampled by the total difference calculation, or that the differences between the two schemes cancel out.

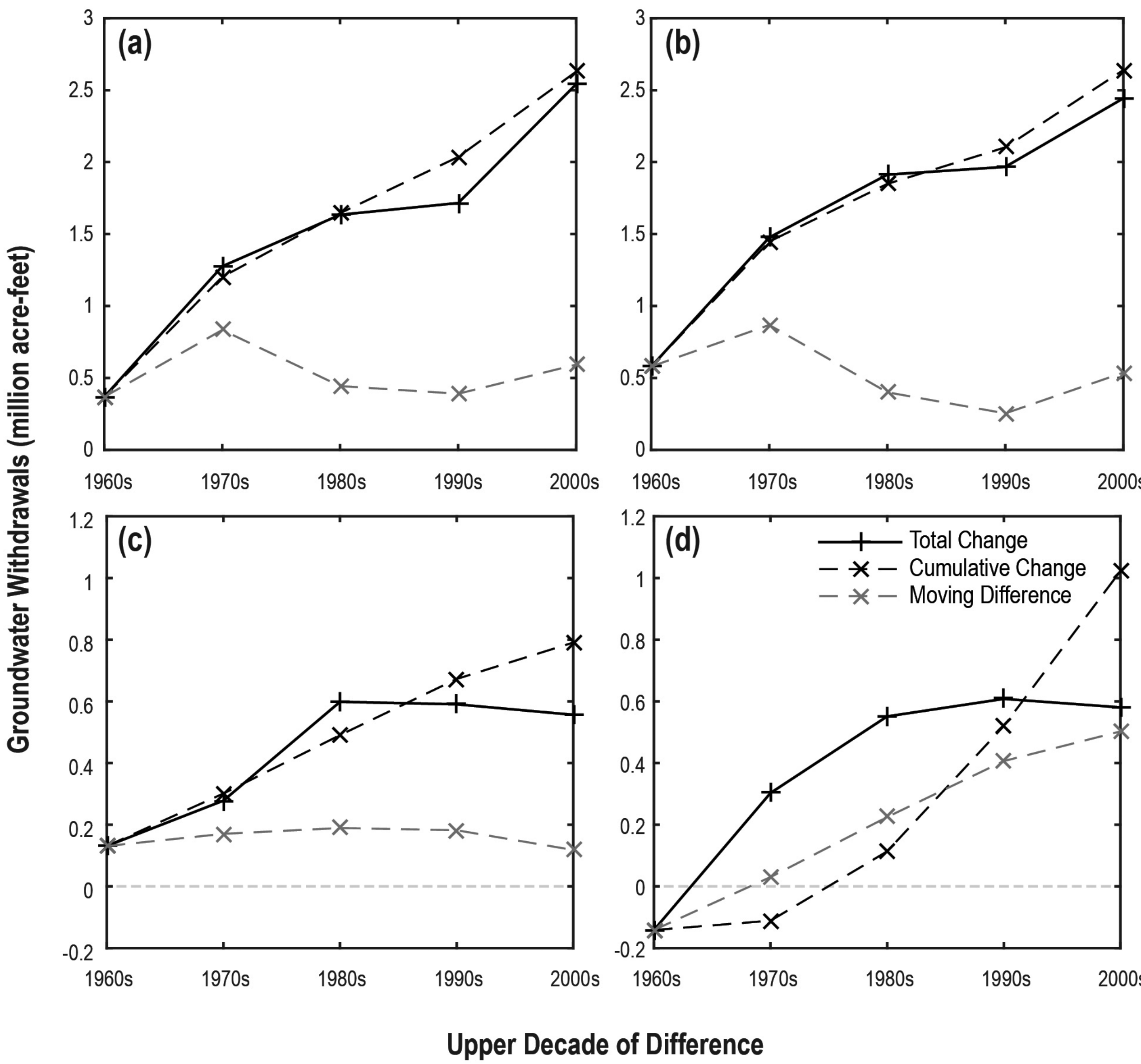

Figure 35. Estimated groundwater storage changes (million acre-feet) for each decade, with total changes (solid +), cumulative moving changes (black dashed x), and moving changes (dark grey dashed x) showing for (a) kriging interpolation in Mimbres basin, (b) IDW interpolations in Mimbres basin, (c) kriging interpolation in Estancia basin, and (d) IDW interpolations in Estancia basin. Zero line (light gray dashed) shown in (c) and (d).

Table 1. Calculated groundwater storage withdrawals for Mimbres and Estancia basins.

Basin	Specific Yield	Time Range	Total Withdrawal from 1950s		Moving Withdrawal from Previous Interval		Cumulative Moving Withdrawal	
		Date	Kriging	IDW	Kriging	IDW	Kriging	IDW
			Maf (km^3)	Maf (km^3)	Maf (km^3)	Maf (km^3)	Maf (km^3)	Maf (km^3)
Mimbres	0.1	1960–1969	0.3685 (0.4545)	0.5796 (0.7149)	0.3685 (0.4545)	0.5796 (0.7149)	0.3685 (0.4545)	0.5796 (0.7149)
		1970–1979	1.276 (1.574)	1.476 (1.821)	0.8335 (1.028)	0.8682 (0.4941)	1.202 (1.483)	1.448 (1.786)
		1980–1989	1.638 (2.020)	1.913 (2.360)	0.4436 (0.547)	0.4006 (0.4941)	1.646 (2.030)	1.849 (2.281)
		1990–1999	1.716 (2.117)	1.967 (2.426)	0.3905 (0.4817)	0.2540 (0.3133)	2.036 (2.511)	2.103 (2.594)
		2000–2009	2.542 (3.136)	2.443 (3.013)	0.5929 (0.7313)	2.640 (3.256)	2.629 (3.243)	0.5370 (0.6624)
Estancia	0.1	1960–1969	0.1308 (0.1614)	-0.1415 (-0.1745)	0.1308 (0.1614)	-0.1415 (-0.1745)	0.1308 (0.1614)	-0.1415 (-0.1745)
		1970–1979	0.2781 (0.3430)	0.3029 (0.3736)	0.1704 (0.2101)	0.0302 (0.0372)	0.3012 (0.3715)	-0.1113 (-0.1373)
		1980–1989	0.5986 (0.7384)	0.5512 (0.6799)	0.1894 (0.2336)	0.2248 (0.2773)	0.4906 (0.6051)	0.1135 (0.1400)
		1990–1999	0.5904 (0.7283)	0.6080 (0.7500)	0.1820 (0.2245)	0.4064 (0.5012)	0.6726 (0.8297)	0.5198 (0.6412)
		2000–2009	0.5565 (0.6864)	0.5806 (0.7161)	0.1181 (0.1456)	0.5025 (0.6189)	0.7907 (0.9753)	1.0223 (1.2610)

Estancia basin, however, does not show consistentcy between the kriging and IDW methods. The total storage change calculations from the 1950s to the 2000s for both kriging and IDW interpolations end at a similar total storage change of 0.56 Maf and 0.58 Maf, respectively (Table 1). There is a greater difference between cumulative storage change from the 1950s to the 2000s in the Estancia basin for the kriging-based and IDW-based calculations. The kriging-based cumulative storage change is 0.79 Maf, while the IDW-based storage change for the period is 1.02 Maf. The kriging interpolation shows positive groundwater declines (net withdrawal) through the entire period (Figure 35c; Table 1). The IDW scheme, however, shows an initial negative groundwater storage decline (net gain), followed by larger net withdrawals (Figure 35d; Table 1). In the kriging total difference (Figure 35c), sharp groundwater depletions in the 1960s and 1970s relative to the 1950s are followed by three decades of relatively constant total groundwater depletion (i.e., no change). The moving difference calculations from kriging interpolations show a more constant rate of depletion (Figure 35c). This difference is likely due to the incorporation of new regions in the calculation through time in the moving differences, which the area sampled during the total change calculation remains more constant.

A similar relative pattern in total change vs. cumulative moving difference for the storage change calculations based on IDW interpolations are similar to the kriging interpolation based calculations, with a constant level of withdrawal seen in the kriging-based calculation and a constant rate of increase of withdrawals through time for the cumulative moving storage change calculations. We suspect that the lack of storage change in the total storage change calculations is because new areas are not incorporated into the sample, which the moving difference calculations can incorporate newly developed regions. This is supported by the large changes in well networks seen in moving DTW maps in Estancia basin, while the maps of the well network used in the total change in DTW maps.

4. CONCLUSIONS

4.1. Principal findings

The principle findings are:

- A combined approach of statistical and geologic reconnaissance and geostatistical analysis can create internally consistent maps of groundwater level changes in alluvial aquifers in New Mexico.
- It is necessary to perform a change analysis on a consistent well network from as early as possible, and cumulative moving difference calculations in order to both understand long-term consistent changes, and the effects of changing well networks and usage patterns.

Specific to the basins, the Mimbres basin shows consistent storage change values for all methods. Major areas of withdrawals are south of Deming and west of Columbus, with smaller or more local withdrawals occurring in the valley from Deming to Silver City. Groundwater levels remain relatively constant or even rise slightly at the edges of small mountain ranges in the eastern portion of the basin.

In Estancia basin, there appears to be consistent groundwater level rises along eastern flank of the Manzano Mountains and to the northeast of the Sandia Mountains. The central axis of the basin shows the largest and most temporally consistent declines. The calculated total and cumulative storage change calculations in the Estancia basin show consistent overall changes, but have differing internal patterns, which we believe are caused by changing well sampling through time.

4.2. Recommendations for future research

Future research efforts and funding should be directed toward the continuation, expansion and extension of long-term groundwater monitoring efforts, and toward performing this kind of analysis on other alluvial aquifers around the state. Additional regions may benefit from this type of assessment (non-alluvial basins); however this semi-automatic process would likely not work well in those geologic settings due to the compartmentalization of those aquifers and great ranges in specific yield values toward the calculation of groundwater storage changes.

This work highlights the importance of having continuous effort and funding directed toward water level monitoring in New Mexico. Currently the OSE and USGS work collaboratively to maintain broad coverage of the state, measuring various regions biannually, annually, or every five years. Despite this coverage, data gaps exist not only spatially, but also temporally, making long-term interpretation of water level changes more challenging. Funding should be sustained into perpetuity to support and build upon these and/or additional monitoring efforts to enable future water resource managers to accurately describe the water availability in New Mexico.

Maintaining periodic updates of the Aquifer Mapping Statewide Water Level Database (SWLD) would require time and funding. Currently it is expected that this will be supported by the New Mexico Bureau of Geology and Mineral Resources, with cooperation from the USGS. Additional contribution of regularly monitored groundwater level data from regional networks going into the SWLD would be highly valuable.

5. SUMMARY

In New Mexico, it is essential that we strive to quantify the available groundwater resources. In an effort toward addressing a component of regional groundwater availability, with data compiled from NMBGMR, USGS and OSE, we have developed a method to calculate groundwater level changes over 10-year intervals and estimate groundwater storage changes in the Mimbres and Estancia basins. This methodology will be applicable in other alluvial basin aquifers in the state where spatially and temporally dense, historical water level data are available.

Findings from our study indicate that a combined approach of statistical and geologic reconnaissance and geostatistical analysis can help develop internally consistent maps of groundwater level changes in alluvial aquifers in New Mexico. However, it is necessary to perform a change analysis on a consistent well network from as early as possible, and cumulative moving difference calculations in order to both understand long-term consistent changes, and the effects of changing well networks and usage patterns.

Specific to the basins, the Mimbres basin shows consistent groundwater storage change values (using all methods) of approximately 2.5 million acre-feet between the 1950s and the 2000s. Major areas of declines are south of Deming and west of Columbus, with smaller or local declines occurring in the valley from Deming to Silver City. Groundwater levels remain relatively constant or even rise slightly at the edges of small mountain ranges in the eastern portion of the basin.

In Estancia basin, there appears to be consistent groundwater level rises along eastern flank of the Manzano Mountains and to the northeast of the Sandia Mountains. The central axis of the basin shows the largest and most temporally consistent declines. The calculated total and cumulative storage change calculations in the Estancia basin show consistent overall changes of roughly 0.75 million acre-feet between the 1950s to the 2000s, but have differing internal patterns, which we believe are caused by changing well sampling through time.

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