GROUNDWATER LEVEL AND STORAGE CHANGES IN BASIN-FILL AQUIFERS IN THE RIO GRANDE BASIN, NEW MEXICO

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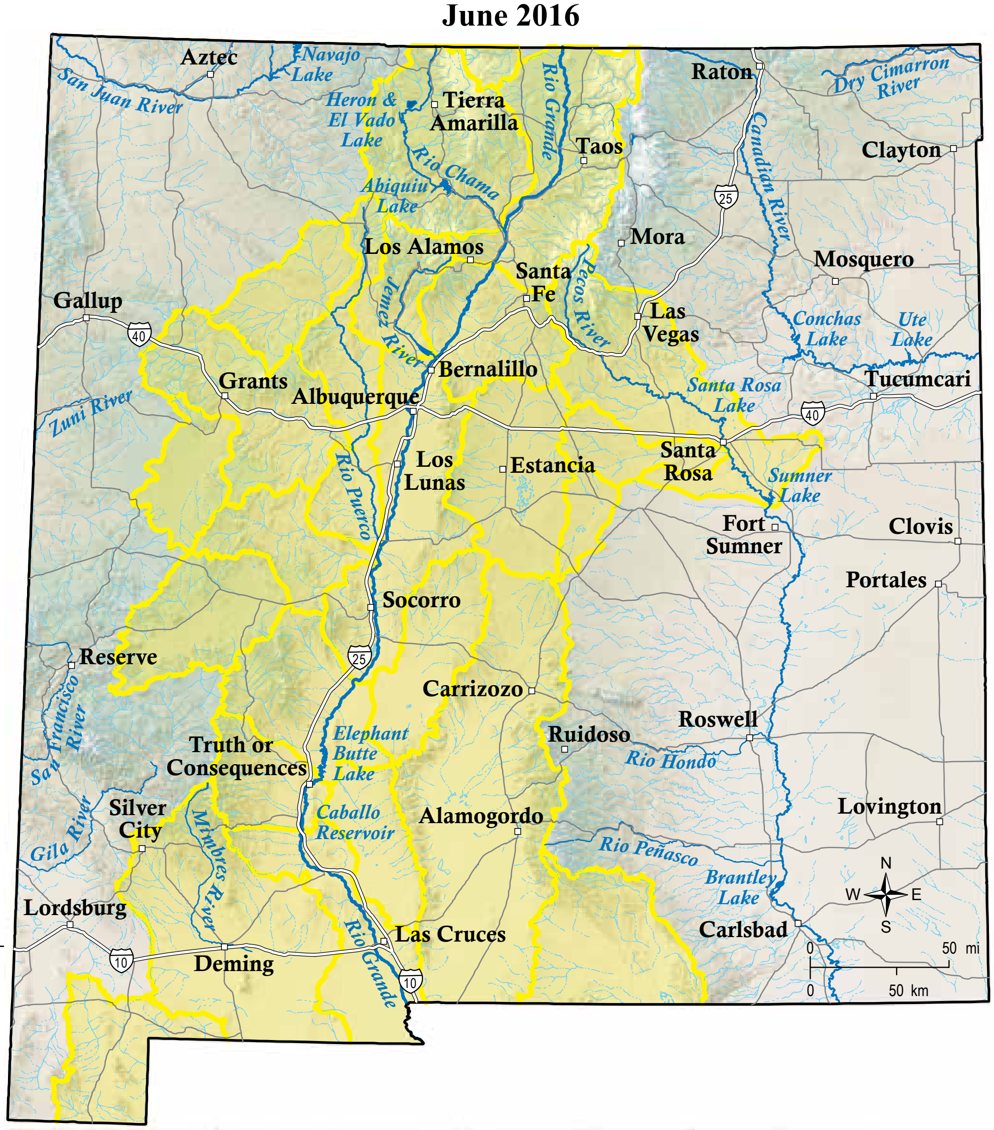
Final Progress Report
June 2016



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ABSTRACT

Unconfined aquifers in basin-fill form a major source of freshwater in the Rio Grande basins, and neighboring closed and ephemeral open basins. Groundwater withdrawals for use have been documented by the New Mexico Office of the State Engineer (NMOSE) every five years since 1975 (Wilson, 1992; Wilson and Lucero, 1998; Longworth et al., 2008; and Longworth et al., 2013).
It is, however, unknown how much aquifer storage has changed during the historical record. In this study, we provide a systematic analysis of water level changes and basin-wide groundwater storage changes for the alluvial aquifers of Rio Grande basins and the neighboring basins from the 1950s to the 2010s. We review well and water level data from local, state and federal sources to exclude either irrigation season and flagged water levels, or wells from irrigated lands with flags indicating pumping or local recharge effects. For each HUC-8 basin characterized, we estimate a correlation length of water level measurements and derive a specific yield from the literature. We then interpolate the depth-to-water measurements and find the differences through time between the interpolations. We exclude regions outside the correlation length of both well networks and regions in bedrock, and find the differences in water levels and storage at decadal intervals. Not all of the reviewed basins had adequate well and measurement coverage to be used. Overall, groundwater storage in basin-fill aquifers is declining in populated regions, especially in areas isolated from large perennial rivers. Areas without intensive irrigated agriculture or major population centers have shown smaller decreases or remained roughly static from the 1950s to the 2010s. Recharge appears to only come from mountain fronts or from major rivers. The Rio Grande, in particular, in part balances pumping in areas of the basins close to the river, but, as groundwater level declines have accelerated in the last two decades, the river has become increasingly isolated from the wider basin-fill aquifer.

Keywords: New Mexico, Rio Grande, basin-fill aquifers, groundwater storage change, regional hydrology.

ACKNOWLEDGMENTS

This research was funded by New Mexico Water Resources Research Institute (NMWRRI), under the Statewide Water Assessment project. Work on this project was a result of collaboration with multiple agencies and individuals including Mike Johnson (New Mexico Office of the State Engineer (NMOSE)), Nathan Myers (US Geological Survey), and Kenneth Carroll (New Mexico State University), who also reviewed this report. We wish to acknowledge helpful and thoughtful reviews by Ken Peterson (NMWRRI), Geoffrey Rawling (New Mexico Bureau of Geology and Mineral Resources(NMBGMR)), and Jesse Roach (TetraTech). Groundwater level data were essential and appreciated, and came from the New Mexico Groundwater Data Program (USGS and NMOSE collaboration) and Bernalillo County Public Works department—Sara Chudnoff.

Unit Conversions

1 km^3 = 810715 acre-feet = 810.715 kaf = 0.810715 Maf
1 km = 0.621371 miles
1 m = 3.28084 ft = 39.3701 in

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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, municipal, 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 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, basin-fill 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. After the data are collected and compiled, then it is necessary to develop a reasonable and internally consistent method for estimating storage changes. We then apply the method for unconfined basin-fill aquifers in the Rio Grande rift and upper Pecos valley

In this work, we discuss (a) the compilation of groundwater level well data collected by multiple agencies throughout New Mexico, (b) our method to estimate the change in groundwater storage for basin-fill aquifers, and (c) the patterns of groundwater level changes and storage change in the basin-fill aquifers in New Mexico. 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 range of data quality and sources requires decisions to be consistently made about data storage formats, which well information is pertinent, and which water level data are reliable, all in a geographically-oriented database 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. All of the compiled data needs to be reviewed on a basin-by-basin basis, and the unsteady or otherwise unreliable well measurements need to be removed. From these quality-controlled data, correlation length of the wells in each basin can be estimated. After the data review step, the interpolation of groundwater levels from well level data needs to reflect aspects of the aquifer structure, including differing depositional environments, geologic structures, and aquifer compartmentalization. After making the interpolations of water level data through time, the changes in water level need to be converted to volumes of water on a basin-wide scale using existing reliable storage coefficient data, mostly from publications and from the New Mexico Office of the State Engineer (NMOSE) regional water balance models.

This effort builds on the data compilation and methodological work of Rinehart et al. (2015). This year, we used the method of Rinehart et al. (2015) to attempt to estimate the storage change in all of the basin-fill aquifers in the Rio Grande rift and associated closed basins over the last 6 decades (Fig. 1).

We begin by summarizing in Sections 2.1 and 2.2 the compilations of groundwater level data into the Statewide Water Level Database. Then, we summarize our method for semi-automatically generating depth-to-water grids (Section 2.3.1) and briefly describe the basins of interest (Section 2.3.2). In Section 3, we provide an overview of our results both on a basin-by-basin basis and as an overview of all of the calculated total aquifer storage changes. Then, we briefly discuss the causes of groundwater changes and major hydrogeologic factors that control the overall groundwater storage dynamics (Section 4.1) and discuss needed future work (Section 4.2). We then summarize our major results (Section 5).

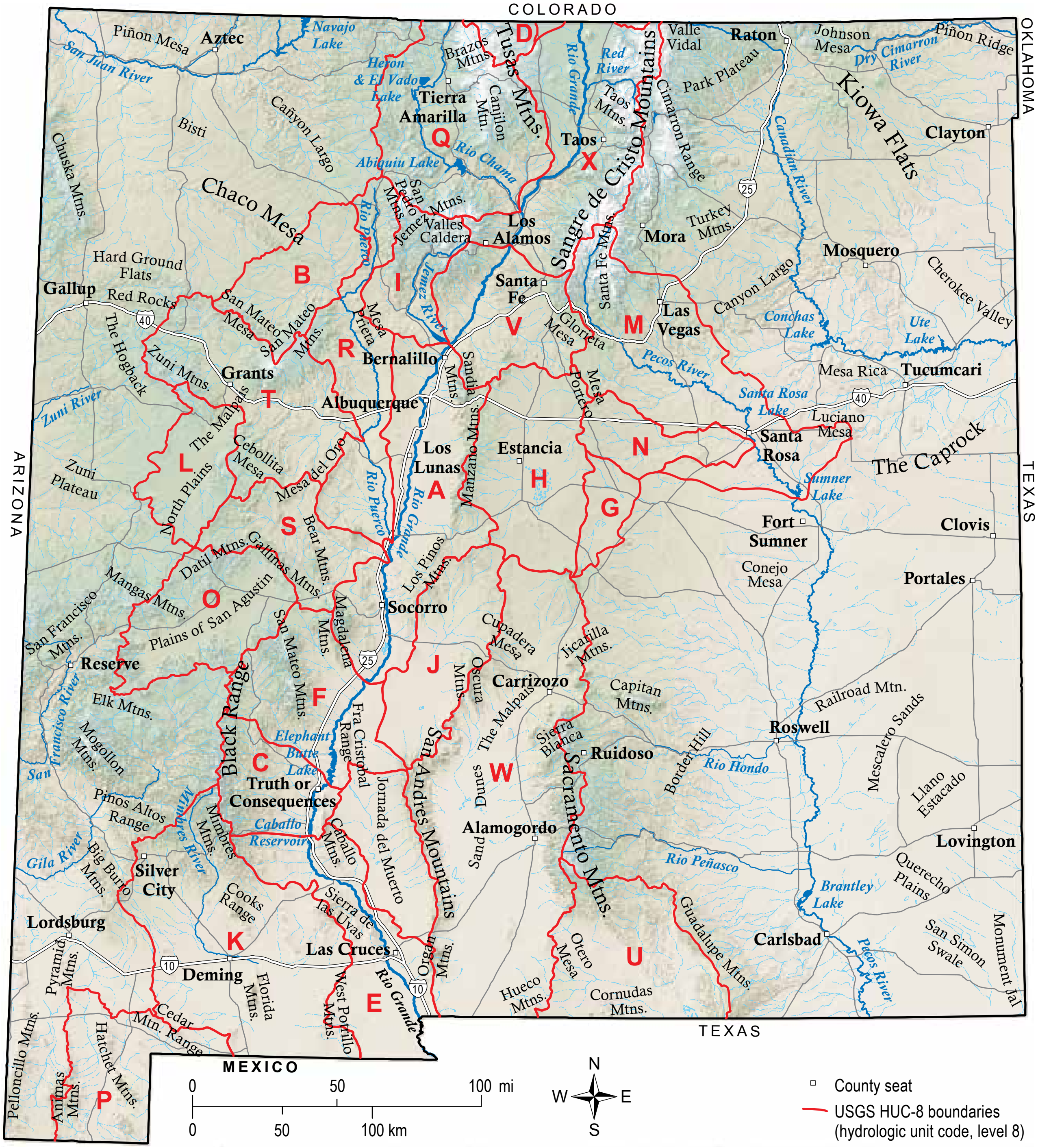


Figure 1. Map of major mountains, landforms, cities, and waterways of New Mexico, with HUC-8 boundaries highlighted in red for the basins of (a) Albuquerque (Rio Grande), (b) Arroyo Chico, (c) Caballo, (d) Conejos, (e) El Paso-Las Cruces, (f) Elephant Butte, (g) Estancia (Eastern), (h) Estancia (Western), (i) Jemez, (j) Jornada Draw, (k) Mimbres, (l) North Plains, (m) Pecos Headwaters, (n) Pintada Headwaters, (o) Plains of San Agustin, (p) Playas Lake, (q) Rio Chama, (r) Rio Puerco, (s) Rio Salado, (t) Rio San Jose, (u) Salt Basin, (v) Santa Fe (Rio Grande), (w) Tularosa Valley, and (x) Upper Rio Grande.

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, sampling periods, and sampling frequencies. The most comprehensive, long-term groundwater level monitoring network, the New Mexico Groundwater Data Program, is maintained in cooperation with the NMOSE and the U.S. Geological Survey (USGS) New Mexico Water Science Center. Historical records of water level measurements beginning in the early 1900s provide a valuable long-term record of water level changes. Beginning more recently, high quality measurements are being collected by county and water conservation entities, such as Bernalillo County and Elephant Butte Irrigation District.

In order for accurate assessments of water levels, the water in a well needs be in equilibrium with the surrounding aquifer and not impacted by spatially local or transient effects such as pumping or local irrigation. The monitoring networks in New Mexico are primarily composed of wells used for other purposes, such as domestic, irrigation or public supply wells, and they are not designated monitoring or observation wells. Given the multiple uses of the well, it is vital to include information on uses and construction of each well, and of possible effects on each water measurement in the well (e.g., recently pumping, pumping, transient surface water source nearby) 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. This comprehensive 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, we have additionally incorporated datasets from multiple agencies including the USGS, NMOSE, and other regional water level monitoring networks for this study.

For this project, we incorporated data retrievals from the USGS National Water Information System (NWIS) database, which has historic water level measurements across New Mexico, and the recent New Mexico Groundwater Data Program measurements. All records were cross-referenced by the USGS Site ID number. The first retrieval included all well points that are currently (as of 2014) within the monitoring network. Beginning in 2006, the current monitoring network was reconfigured to optimize use of OSE and USGS resources and provide better coverage over critical areas of 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. The fourth and final data retrieval in 2015 included water level measurements added to the USGS database between the fall of 2014 and August 2015.

Groundwater level measurements were also contributed from Bernalillo County Public Works monitoring network which began in 2010.

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 USGS sites already 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 uniformity in the database. The area in UTM Zone 12 projection is a relatively narrow strip along the Arizona-New Mexico border and does not have any major effects on the accuracies of locations.

2.2.2 Bernalillo County data processing by NMBGMR

The water level and well data delivered from Bernalillo County included well locations and water levels in 2015. There were 194 locations in the dataset and 1,432 water level records.

We added a data quality field to the Bernalillo County dataset. 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). 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). Essentially, these data quality fields were added to distinguish the lower data quality of acoustic sounder measurements. All data was either of data quality "1" or "2".

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, streamlined database called the "Statewide Water Level Database (SWLD) was developed to share these data, as per the 2014–2015 and 2015–2016 WRRI contract deliverables.

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 "PointID."

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 topographic 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 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_MeasurementMethod” 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. 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: 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.”

2.3. Water Level Contouring

2.3.1. From data quality assurance, change contouring and storage change calculations

The ultimate goal of this project is to provide storage change estimates in basin-fill aquifers throughout New Mexico. To achieve this within the contract period, a semi-automatic workflow is necessary to find the changing water levels throughout the basin. The method needed to be repeatable, robust in different basin-fill 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 and Sedghamiz, 2008; Chung, and Rogers, 2012). Other studies focus on interpolating the groundwater elevation or depth to water in local to regional groundwater studies (e.g., Snyder, 2008).

The current methods applied to estimate historical groundwater storage changes in basin-fill aquifers in New Mexico build from the method presented in Rinehart et al. (2015). For each basin, the method consists of data quality checks, variogram analysis, geostatistical interpolation, and restricting the interpolation to valid regions.

Before beginning more detailed review of the well hydrographs, we first exclude wells that are in non-alluvial sedimentary units, as identified from the USGS completion unit description code and from the 1:500,000 statewide geologic map (Scholle, 2003). In terms of units, we kept wells that were completed in non-specified units, in Quaternary-Tertiary sedimentary units such as the Upper Santa Fe Group or Gila Group and their subsidiary formations, or in units identified as young alluvium. If a well did not include the formation in which it was completed, we used a 1:500,000-scale statewide geologic map (Scholle, 2004) to determine if the well was located in Quaternary or younger sediments.

In areas with high population density and land-use intensity, there are generally denser well networks that are better sampled. This includes much of the central Rio Grande valley and the more populated basins flanking the central valley (Fig. 1). However, large swaths of studied basins in the state do not have dense enough well networks through time to apply the method of Rinehart et al. (2015). For these, less sampled basins, we have relaxed the data quality standards in a number of ways. Essentially, the Rinehart et al. (2015) method excludes well measurements with any flagged water level statuses, and only includes measurements from the non-irrigated season (Nov. 1 through Mar. 1). We refer to this data quality, in the November to March range excluding any flagged records, as the "non-irrigated season" standard. The less stringent method includes all measurements except for those from wells that were being pumped or were actively recovering from pumping during the measurement. Instead of removing all water levels collected during the irrigation season (March through October), only water levels collected from wells that were developed on agricultural land had the irrigation season removed. The National Land Cover Database (NLCD; Homer et al., 2015) was used to determine which wells were located on agricultural land. We refer to this data quality standard, applied only in the regions with sparse data, as the "non-irrigated lands" standard. For both the non-irrigated season and the non-irrigated lands standards, we visually examine the hydrograph of each well to ensure that spurious measurements are excluded, and that the appropriately flagged measurements for each standard are excluded.

Once the measurements from each well are checked for data quality and the well is confirmed in alluvial sediments, we find a correlation length, or the distance within which a water level at a well is predictive, for the depth-to-water measurements in each basin. We do this using variogram analysis (Fig. 2). A variogram is essentially a scaled covariance of measurements as a function of distance between well sites (Cressie and Wikle, 2011). At close distances, depths-to-water are well correlated and the variance between well measurements short distances together is low—the variance of measurements at no distance is called the nugget (Fig. 2a). With increasing distance, the variogram increases to the variance of the measurements (Cressie and Wikle, 2011). The distance at which the variogram reaches an asymptote, or sill, is called the range (Fig. 2a; Cressie and Wikle, 2011). It is the distance at which measurements are no longer correlated (Cressie and Wikle, 2011).

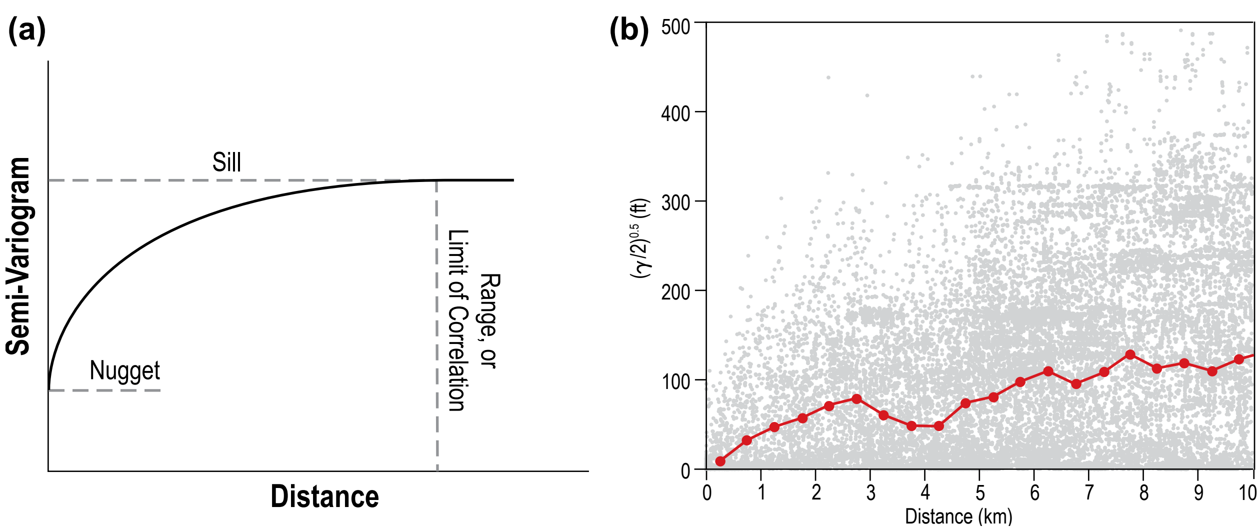


Figure 2. Explanation and example of variograms, with (a) a conceptual diagram with the names of the different variogram features labeled, and (b) the empirical variogram (solid red) overlain the raw covariance cloud (grey dots) for the 2000s Albuquerque (Rio Grande) HUC basin dataset. In both (a) and (b), the x-axis is distance (km) and the y-axis is the scaled semi-variogram (i.e., the variance (a) or standard deviation (b) as a function of distance)

To speed our analysis, we determine a single range from the variogram analysis for each basin. In Rinehart et al. (2015), for both the Mimbres and the Estancia basins, we found that approximately ten years of measurements were needed before there were enough data to perform the variogram analysis and subsequent interpolations. For each well, we use the median depth-to-water measurement in each decade. All of the depth-to-water measurements in a given decade and basin are compiled into a variogram. Figure 2b shows a relatively good example from the Albuquerque basin from 2000 to 2009, with the variogram scaled to show how the standard deviation varies as a function of distance rather than the variance. The background of grey points shows the variogram cloud (Fig. 2b). This cloud is then binned and averaged to find the mean variogram points (red, Fig. 2b). For each basin and each decade, it was often necessary to use varying scales and binning intervals to identify the range. It is common to have nested scales present in the variogram, with the variogram reaching a short distance, lower-valued sill, and then, after remaining relatively constant, moving up to a longer distance, high-valued sill. We have qualitatively decided which sill is most consistent through all decades sampled, and which has the clearest asymptote, and then used this range. For example, in Figure 2b, we have chosen the range to be between 2.0 and 3.0 km. Another sill may be present at approximately 6.0 km, but this range was not consistent between other decades we reviewed. The 2.0 km range was consistent between the decades of data and was chosen as the Albuquerque basin correlation length.

In basins with poor temporal and spatial data density, the estimates of correlation length are less certain and are more variable through time. The value chosen for correlation length effects all groundwater storage change estimates and is critical to our method. This importance implies that regions with poor data density will have less certain storage change estimates, even if for no other reason than a more uncertain correlation length.

The data qualification and variogram analysis was completed for each basin. This was performed using a series of MATLAB© scripts and functions, and manual examination of the data in tables. At this point, the investigator must make the decisions that impact the rest of the analysis: which wells to exclude and what correlation length to use. These decisions impact the size of the later interpolated region and the total volumes of water storage change calculated.

After the initial hydrograph review and variogram analysis is completed, we begin to iteratively restrict and interpolate the depth-to-water level measurements for each decade, and then find differences of the interpolated surfaces (Fig. 3). Ultimately, we are aiming to have changes of water levels through time. We achieve this in two ways. First, we find the difference for all subsequent decades from the earliest decade with enough data, generally the 1950s. In other words, we subtract an interpolated depth-to-water surface from the 1950s water level measurements from the interpolated depth-to-water surfaces from all of the later decades; we call this the total difference. The other approach is to find the moving difference through the decades. For example, we would find the difference between the interpolated water levels of the 1970s from the 1960s, rather than from the 1950s as in the total differencing scheme.

Immediately after finding the correlation lengths, and excluding the appropriate water level measurements and wells, we construct a buffer with the correlation length from each well measured in each decade (Fig. 3a). For each difference calculation (e.g., 1970s minus 1950s, or 1990s minus 1980s), we find the intersection of the buffered areas. Wells outside the remaining polygons are excluded from the following interpolations (Fig. 3b). We have found using wells outside of the interpolation leads to spurious changes on the edges of the depth-to-water interpolations.

With the remaining median water level measurements from each decade, the depth-to-water is interpolated using either ordinary kriging (OK) or inverse-distance-weighting (IDW) interpolations (Fig. 3c). Then, the interpolated surfaces are subtracted from one another, and the regions falling within bedrock as defined above on the 1:500,000 geologic map (Scholle, 2003) are clipped out of the differenced surfaces (Fig. 3d). This workflow has been automated using a Python script in ArcGIS. Once the data quality review and variogram analysis is completed, the well median depth-to-water measurements for each

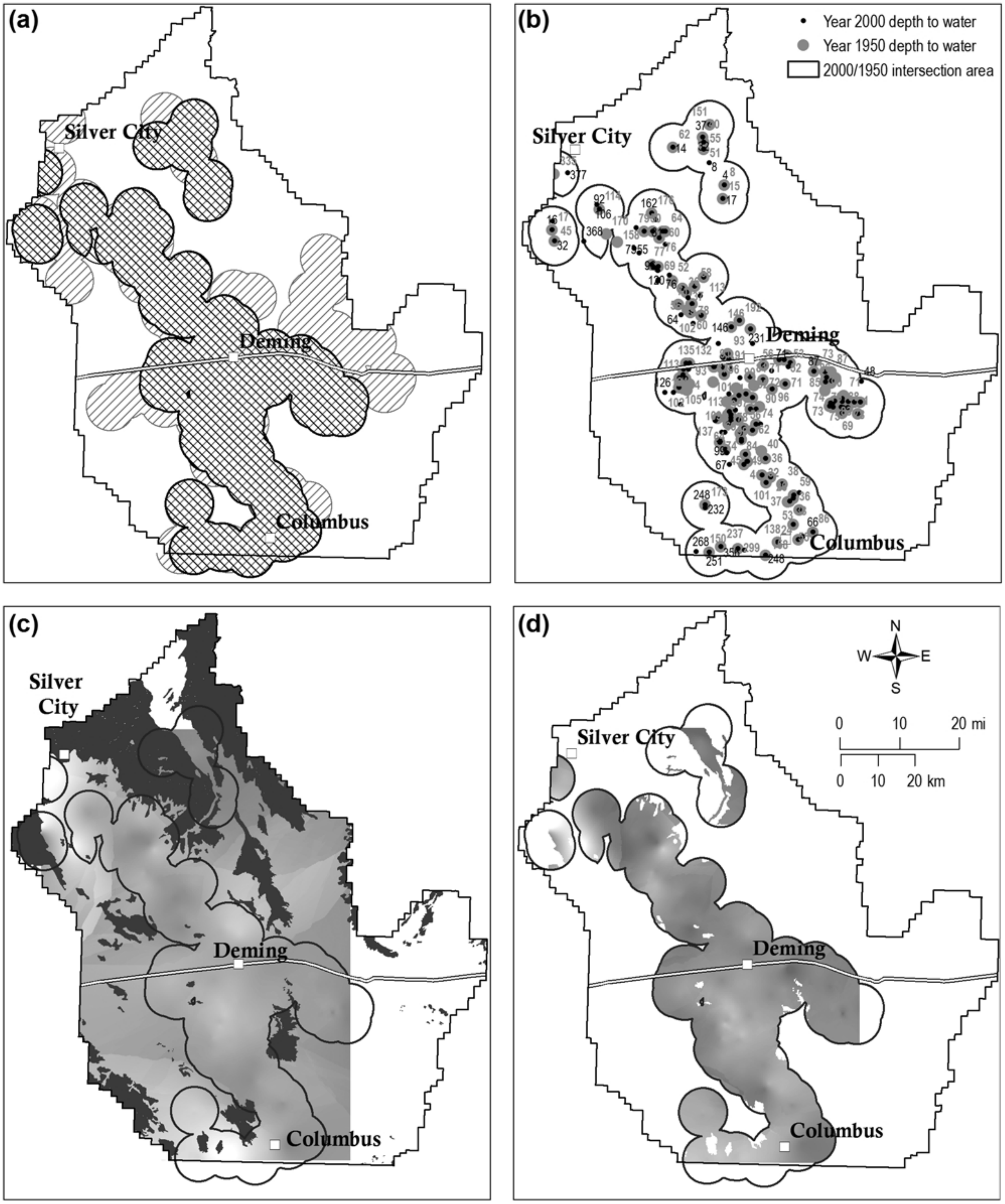


Figure 3. Illustration of interpolation workflow using the Mimbres basin data for the 1950s and the 2000s, showing (a) the correlation length out from all wells in the 1950s and 2000s datasets, (b) the intersected buffers and wells with depth-to-water (ft), (c) the difference between ordinary kriging depth-to-water interpolations between the 1950s and the 2000s with the bedrock units and buffer shown in the foreground, and (d) the final, spatially restricted difference in interpolations used for the storage change calculations. White regions are not covered by the interpolation.

decade and the basin correlation length from the variogram analysis are input into the script and geodatabases are output that include surfaces of the water level change as well as the well locations and other inputted information.

When using the non-irrigated season data quality, as done in Rinehart et al. (2015), both OK and IDW interpolations are used, producing a total of four sets of difference maps: differences from the 1950s using (1) OK or (2) IDW; and moving differences, decade by decade, using (3) OK or (4) IDW. The IDW interpolations have fewer artifacts within the interpolation, but tend to emphasize changes around the edges of the intersected correlation lengths—declining water levels are extrapolated as declining to the edge of the intersection area (Cressie and Wikle, 2011; and Rinehart et al., 2015). The OK interpolations have more artifacts within the interpolation, though still on the same order as the IDW interpolations, but do not extrapolate trends out toward the edge of the intersected correlation lengths—the extrapolated water levels are modeled as moving back to the mean depth-to-water of the basin (Cressie and Wilke, 2011; and Rinehart et al., 2015). However, for the non-irrigated season data quality, differences using OK and IDW interpolations are comparable.

Our base case, and highest quality data, is from using the non-irrigated season data. The non-irrigated land data quality, used when data coverage is too sparse to carry out the non-irrigated season data, is more prone to spurious measurements. As the non-irrigated land data uses less stringent requirements, the well networks are broader in area. It is necessary to compare the non-irrigated season-based interpolations and the non-irrigated land-based interpolations (Fig. 4). Early scoping of the non-irrigated lands method showed that the greater scatter in depth-to-water level measurements throughout the network led to banding artifacts in the OK interpolations. The IDW interpolations are less sensitive to local perturbations of depth-to-water measurements and will be used exclusively in water level change contouring and storage change calculations using the non-irrigated lands data quality.

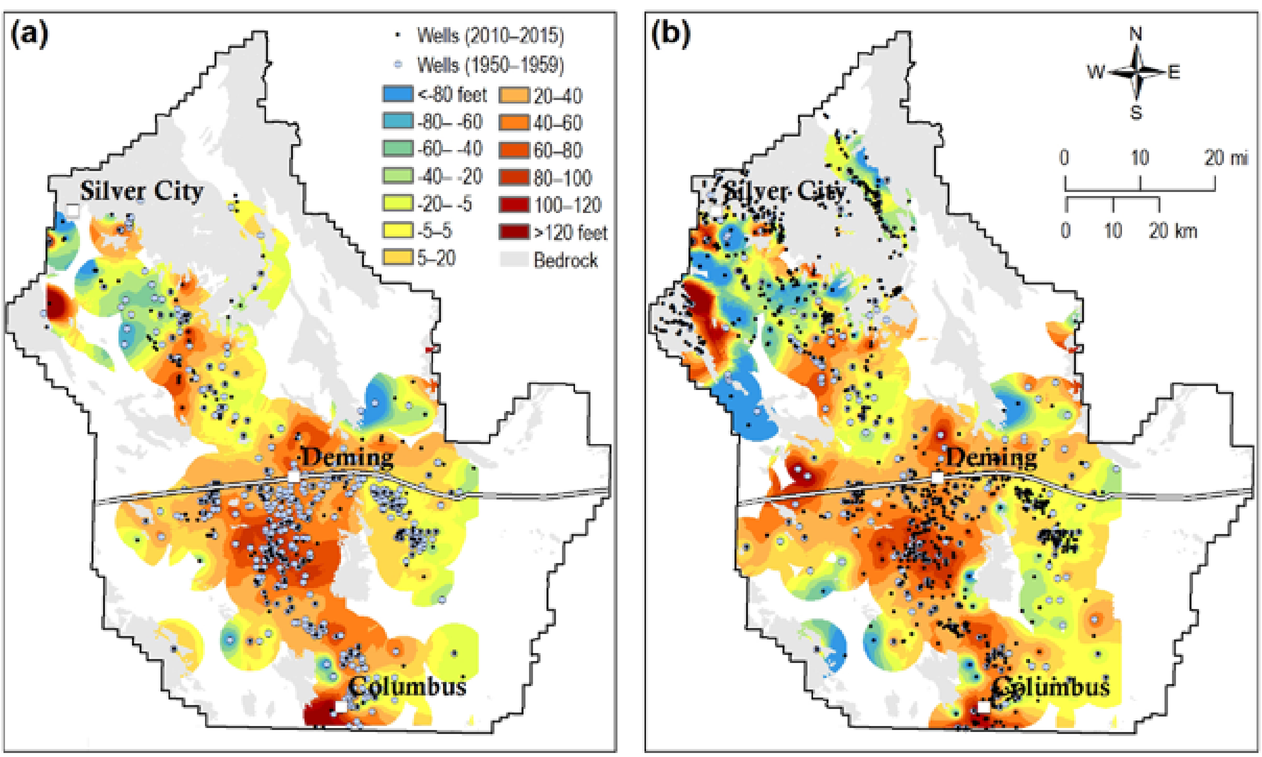


Figure 4. Comparison of changes in depth-to-water interpolation differences between the 1950s and 2000s in the Mimbres basin using (a) non-irrigated season quality data, and (b) non-irrigated land quality data.

To understand the effect that the non-irrigated lands data quality as compared to the non-irrigated season data quality had on the analysis, we processed the Mimbres basin with both methods (Fig. 4). The less stringent data quality allowed many more wells to be used in the analysis; increasing the number of water levels used from 3,024 with the non-irrigated season quality (Fig. 4a), to 4,040 records with the non-irrigated lands data quality (Fig. 4b). The rise in the number of wells and well records led to an increase in land covered by the analysis, from 4,683 km^2 (Fig. 4a) to 5,754 km^2 (Fig. 4b). With the increased number of wells, areas of already good data coverage from the non-irrigated season data method became crowded. This overcrowding of data can be seen between Deming and Columbus, where it leads to noise in the interpolation with many local maxima and minima. The water level change maps differ most on the edges of the interpolation where data coverage is sparse. The non-irrigated lands interpolations show greater variability in water level change, with some large zones of anomalously large water level changes. These zones are unusually associated with patches of poor data coverage where one or two anomalous water level measurements bias the analysis. For the most part, however, the maps constructed from the two data qualities are quite similar—areas of decline and rebound closely match each other, and the magnitudes of the water level change are comparable.

Once the water level change maps are constructed using either data quality, we find the total change in volume of the water storage in each basin. To do this in each basin, we sum the change in water levels, multiply by a basin-average specific yield, and then multiply by the grid cell area outputted by the interpolations. This yields an estimated change in total groundwater storage in the basin (Schwartz and Zhang, 2003). However, we assume an unvarying specific yield for each basin. Surprisingly, this parameter is poorly reported. We have performed a literature review for each basin, generally using average specific yields found from basin-wide modeling studies. If we could not find detailed descriptions, we have used either a specific yield based on sediment type (Johnson, 1967) or a specific yield of 0.1 as a compromise between values found in coarse sands and gravels and those of muddier sediments.

In comparing the final calculated storage changes for the Mimbres basin, the overall trend between the two data qualities are similar. The levels fall consistently through the 1980s. During the 1990s, both sets of data quality interpolations found a slight increase in storage, before declining again in the 2000s. The most dramatic difference between the storage change results from the two methods is the volume of change. The total storage change for the Mimbres basin from the 1950s to the 2000s using non-irrigated land data quality was -1.54 km^3 (-1.25 Maf) while the storage change using the non-irrigated season data quality was -2.74 km^3 (-2.22 Maf) of total storage change. The data artifacts seen on the edges of the water level change maps are likely the cause of the discrepancies.

2.3.2. Basins of interest

We are focused on basins that primarily have unconfined aquifers hosted in alluvial and fluvial sediments. In particular, we are focused on basins that are formed in Rio Grande rift and Basin and Range province extensional basins, or tributaries of the Rio Grande. In addition, we have examined the uppermost drainages of the Pecos River, where the developed aquifer is primarily close to the river in the shallow alluvium.

For this project, we have chosen to use the USGS Hydrologic Unit Code Level 8 (HUC-8) basins to define our basin boundaries (Seaber et al., 1987). The HUC-8 boundaries primarily reflect surface water and social boundaries, including major dams and reservoirs, surface water divides, and, to some extent, water management boundaries (Seaber et al., 1987). While the emphasis on surface water management leads to some ambiguities in analyzing the groundwater system, the monitored well networks generally occur toward the center of the HUC-8 basins, closer to surface water and away from bedrock-dominated uplands, rather than sprawling across the HUC-8 boundaries.

In the following, we provide a brief description of each HUC-8 basin that we analyzed. We did not analyze the Arroyo Chico, Caballo, Conejos, Elephant Butte, Estancia (Eastern), Jemez, North Plains, Pintada Headwaters, or Rio Salado basins (Table 1 and Fig. 5). We used non-irrigated season data quality for the Albuquerque (Rio Grande) basin, the Mimbres basin, the Santa Fe (Rio Grande) basin, the Tularosa Valley basin, and the Upper Rio Grande basin (Table 1). In the El Paso-Las Cruces (Rio Grande) basin, we used non-irrigated season data quality but restricted the depth-to-water to a minimum depth-to-water of 100 ft over the well record. In other words, at least one depth-to-water measured at each well is required to be less than 100 ft. This was because the deeper wells on the margins of the basin were too few and too coarsely spaced to produce reasonable interpolations. The non-irrigated land data quality was used for the Jornada Draw basin, Pecos Headwaters basin, Plains of San Agustin basin, Playas Lake basin, Rio Chama basin, Rio Puerco basin, Rio San Jose basin, and the Salt Basin basin (Table 1).

Albuquerque (Rio Grande)

The Albuquerque (Rio Grande) HUC-8 basin (3,215 sq mi) is an oblong, open basin with the Rio Grande flowing down its central valley and containing the city of Albuquerque and towns of Los Lunas and Socorro (Fig. 1). Land use includes urban land, grazing, and flood and sprinkler irrigated farmland. The Rio Grande has several irrigation diversions with associated systems of ditches and drains managed by the Middle Rio Grande Conservancy District. The Albuquerque (Rio Grande) HUC-8 basin encloses both the central and southern Albuquerque structural basin and the Socorro structural basin. In

Table 1. Summary of HUC units examined, including HUC name and ID, the correlation length (km), data quality and availability, specific yield and references used to estimate the specific yield.

HUC	Buffer (km)	HUC ID	Method	Specific yield (-)	Citation
Albuquerque (Rio Grande)	2.0	13020203	Exclude irrigation season	0.20	McAda and Barrol (2002)
Caballo	-	13030101	Not enough data	-	-
El Paso-Las Cruces (Rio Grande)	4.0	13030102	Exclude irrigation season and deep wells	0.20	Hawley et al. (2000)
Elephant Butte	-	13020211	Not enough data	-	-
Estancia (Eastern)	-	13050002	Not enough data	-	-
Estancia (Western)	3.5	13050001	Exclude irrigation season	0.10	Shafike (1999); Titus (1973); White (1999)
Jemez	-	13020202	Not enough data	-	-
Jornada Draw	5.0	13030103	Exclude irrigated lands	0.15	Shomaker et al. (1996); Rao (1988)
Mimbres	6.5	13030202	Exclude irrigation season	0.10	Hawley et al. (2000); Kennedy et al. (2000)
North Plains	-	13020206	Not enough data	-	-
Pecos Headwaters	3.0	13060001	Exclude irrigated lands	0.15	Rao (1989)
Pintada Headwaters	-	13060002	Not enough data	-	-
Plains of San Agustin	3.5	13020208	Exclude irrigated lands	0.15	Johnson (1967); Meyers et al. (1994)
Playas Lake	4.0	13030201	Exclude irrigated lands	0.08	Johnson (1967)
Rio Chama	4.0	13020102	Exclude irrigated lands	0.10	-
Rio Puerco	7.5	13020204	Exclude irrigated lands	0.15	Kernodle et al. (1995); Tiedum et al. (1998)
Rio Salado	-	13020209	Not enough data	-	-
Rio San Jose	8.0	13020207	Exclude irrigated lands	0.10	-
Salt Basin	3.5	13050004	Exclude irrigated lands	0.10	-
Santa Fe (Rio Grande)	2.0	13020201	Exclude irrigation season	0.15	McAda and Wasiolekk (1988)
Tularosa Valley	6.5	13050003	Exclude irrigation season	0.12	Kelly and Hearne (1976); Mclean (1970); Balance (1976); Garza et al. (1977)
Upper Rio Grande	6.0	13020101	Exclude irrigation season	0.15	Burke et al. (2004)

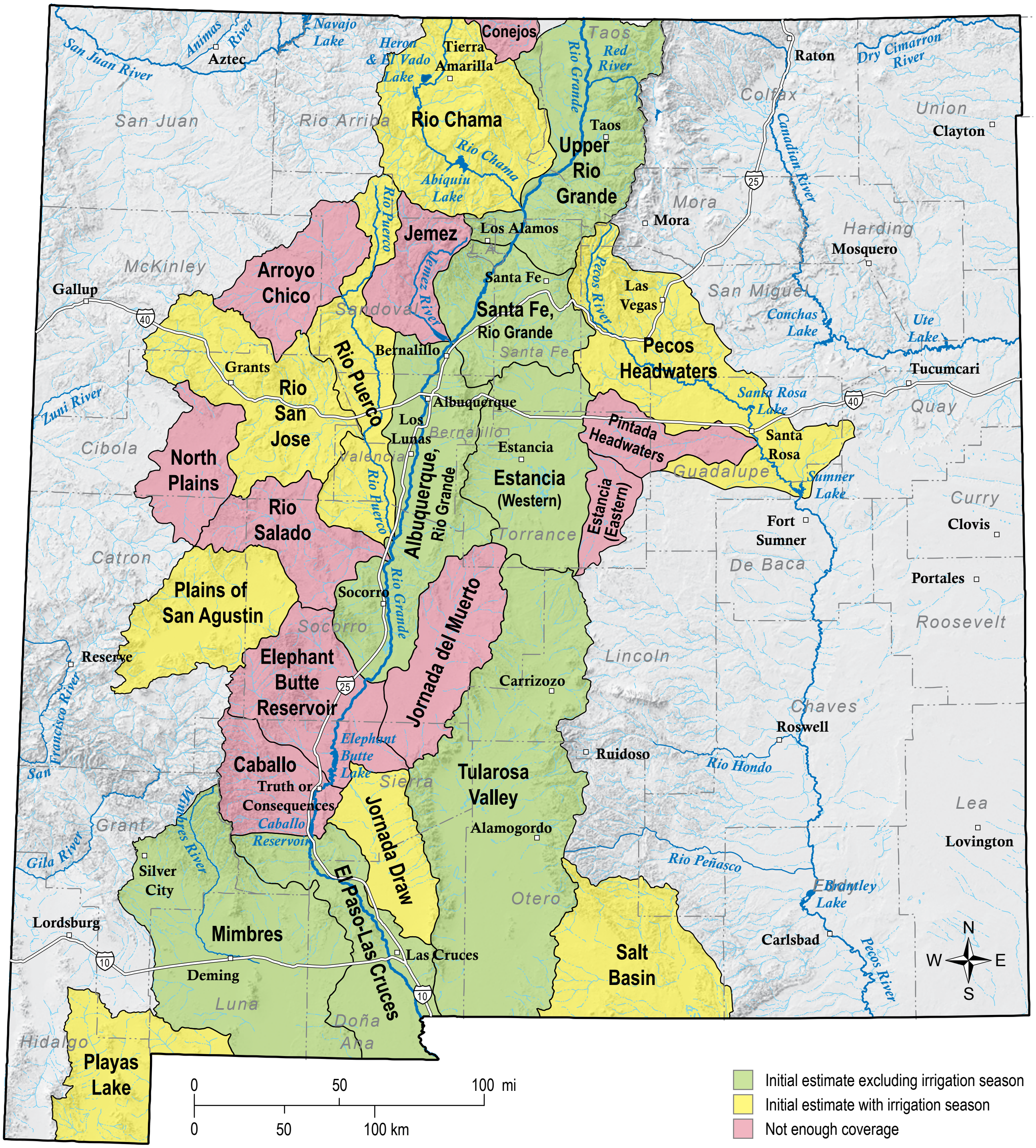


Figure 5. The HUC units examined overlain on the hydrography and county seats of New Mexico, with HUC units with non-irrigated season data quality (green), with non-irrigated land data quality (yellow), and without enough well coverage to perform reasonable analysis (red).

the Albuquerque structural basin, the basin is bounded to the east by the granite-cored Sandia, Manzano and Los Pinos Mountains and to the west by the Llano de Albuquerque, the maximal aggradation surface of the Rio Grande. The Socorro structural basin is a fault bounded basin flanked on the west by the Magdalena Mountains and on the east by badlands of Paleozoic through Mesozoic sedimentary rocks (Scholle, 2003). The basin is bounded to the north by the junction of the Jemez River and the Sandia structural embayment, and to the south at the hamlet San Acacia. The major basin-fill aquifer is made up of the upper Santa Fe Group axial river (ancestral Rio Grande) and piedmont deposits capped by Pleistocene axial river and piedmont sediments (Connell, 2004). The axial river deposits are moderately sorted cobbly sands, while the piedmont deposits range from poorly sorted to moderately sort silty to cobbly sands (Connell, 2004). The only perennial river currently flowing in the Albuquerque basin is the Rio Grande.

El Paso-Las Cruces (Rio Grande)

The El Paso-Las Cruces (Rio Grande) HUC-8 basin (2,444 sq mi) is a long, open basin containing the Rio Grande and the city of Las Cruces (Fig. 1). In the central valley, major land use is irrigated agriculture, grazing and urban land use. Outside of the central valley, most land is rangeland. There are several irrigation diversions along the Rio Grande with associated irrigation ditches and drain, which are managed by the Elephant Butte Irrigation district. The El Paso-Las Cruces (Rio Grande) HUC contains the southern portion of the Rincon and the entirety of the Mesilla Rio Grande rift-related structural basins (Hawley et al., 2000). It is flanked to the east by Organ Mountains, the southern Jornada del Muerto structural basin, and the Caballo Mountains. To the west, it is flanked by the southern mountains of the Black Range, the Sierra de las Uvas and the West Potrillo Mountains (Fig. 1). It is separated from the Mimbres basin to the west by a low divide which includes the West Potrillo Mountains (Fig. 1). On the north, it begins at the outlet of Caballo reservoir (Fig. 1). On the south, for this study, it is bounded by New Mexico's border with Texas and Mexico (Fig. 1), however this aquifer and basin does continue beyond the state boundary. It is a fault bounded basin whose uppermost volume is filled with a combination of the axial river and piedmont sediments of the Palomas Formation and younger Pleistocene sediments. The character of the sediments is similar to those in the Albuquerque basin. The only perennial river flowing in the El Paso-Las Cruces basin is the Rio Grande.

Estancia (Western)

The Estancia (Western) HUC-8 basin (2,425 sq mi) is located in central New Mexico (Fig. 1) and includes the population centers of Edgewood, Moriarity and Estancia. Several ephemeral arroyos, draws and washes drain toward the center of the basin where groundwater discharges into salt lakes. 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. It is flanked to the west by the Sandia and Manzano Mountains and to the west by a low divide that spills out onto the Southern High Plains. On the south, it is bounded by a low divide and the small highlands of Chupadera Mesa and the Jicarilla Mountains. 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).

Jornada Draw

The Jornada Draw HUC-8 basin (1,250 sq mi) is located in south-central New Mexico, between the Tularosa Basin the Rio Grande (Fig. 1). It contains no major municipalities (Fig. 1). To the west are the

Caballo Mountains, and to the east are the San Andres Mountains. The Dona Ana Mountains divide the Jornada Draw from the Mesilla Valley to the south. The ephemeral Jornada Draw channel runs through the middle of the basin, where numerous other draws that drain the surrounding mountains coalesce. The valley floor is dominated by sedimentary deposits made up of piedmonts slopes, and fan skirts being deposited from the mountains (Kludt et al., 2015).

Mimbres

The Mimbres HUC-8 basin (4,523 sq mi) includes the population centers of Silver City and Deming (Fig. 1). There is only one perennial flowing stream, the Mimbres River, which is perennial in its upper reaches until just north of Deming and is ephemeral from there to it terminus 15 miles east of Deming. 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 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 (Hawley et al., 2000). Overlying the basin-fill material is thin (several tens of meters) Quaternary valley fill, which is associated with surface water drainages (Hawley et al., 2000). The basin fill and Quaternary valley fill are the primary sources for groundwater in the Mimbres basin (Hawley et al., 2000), and the focus of evaluation for groundwater storage changes with this study.

Pecos Headwaters

The Pecos Headwaters HUC-8 basin (3,481 sq mi) stretches from the southernmost Sangre de Cristo Mountains to the southeast to Sumner Lake, and includes the municipalities of Las Vegas and Santa Rosa (Fig. 1). Primary land use includes rangeland, some mining and logging, and irrigated agriculture. The Sangre de Cristo Mountains to the north are made primarily of marine sedimentary rocks, such as limestones, and shales, but are granite- and Precambrian metamorphic rock-cored (Scholle, 2003). The Glorieta Mesa borders the Pecos watershed to the northwest (Fig. 1). The valley floors are covered by Quaternary basin-fill sediments (Scholle, 2003).

Plains of San Agustin

The Plains of San Agustin HUC-8 basin (1,991 sq mi) is located in west-central New Mexico, roughly 90 miles southwest of Albuquerque (Fig. 1). The only towns in the basin are Datil on the northwestern edge and Magdalena on the far eastern edge. The most prominent landmark in the basin is the Very Large Array (VLA), operated by the National Radio Astronomy Observatory. The basin falls in a fault-bounded extensional basin on the northern end of the tuff- and rhyolite-dominated Mogollon-Datil Volcanic Field. The central basin itself is a remarkably flat, closed basin, surrounded by numerous mountain ranges. The basin is bounded by the San Mateo Mountains to the east, by the Gallinas and Datil Mountains to the north, and by the continental divide that runs over the Elk, Tularosa, Mangas Mountains and the northern Black Range to the west and the south. The depth to bedrock is quite deep, with 3,500-4,000 ft of basin-fill sediments present (Koning and Rinehart, 2015). Large extinct lake beds cover much of the western portion of the valley floor, though currently only intermittent streams feed the basin (Meyers et al., 1994).

Playas Lake

The Playas Lake (1,678 sq mi) is in the south-western corner of the state, bordering Mexico to the south (Fig. 1). The basin is bounded to the west by the north-trending Animas and Pyramid Mountains, and to the east by the Cedar Mountains. Dividing the basin into an eastern and western section are the north trending Hatchet Mountains. The mountains in the region are primarily made of Precambrian fault blocks. The valley floors are gently rolling plains, flanked by fans and alluvial slopes, which extend from the surrounding mountains (Scholle, 2003). The valley floors consist of silty basin-fill deposits with playa deposits. Doty (1960) suggests that recharge primarily takes place in the alluvial fans at the basin margin.

Rio Chama

The Rio Chama HUC-8 basin (3,158 sq mi) is in north-central New Mexico and contains the towns of Tierra Amarilla, Abiquiu and Chama, and the El Vado and Heron Lakes along the Rio Chama (Fig. 1). The Rio Chama flows through the basin from the Colorado border to where it joins the Rio Grande in the town of Espanola. The western extent of the watershed is the continental divide, while the eastern boundary is made up of the southernmost extent of the San Juan Mountains. The southern boundary is made up of the northern volcanic Jemez Mountains (Fig. 1). The mountain ranges are composed of Paleoprotozoic aged granitic plutons or quartzite,and Tertiary aged volcanic basalts, and rhyolites, and pyroclastic flow breccias from the Jemez Mountains (Scholle, 2003). The valley floors consist of sedimentary units from the Cretaceous to the Tertiary period (Scholle, 2003). Basin-fill deposits of the Santa Fe Group are limited in extent to the southeastern portion of the Rio Chama basin within the Rio Grande Rift. Upstream of Abiquiu Reservoir only thin alluvial deposits exist in the form of fans and river channel deposits.

Rio Puerco

The Rio Puerco HUC-8 basin (2,112 sq mi) contains the headwaters and Rio Puerco, which is the largest in-state tributary to the Rio Grande (Fig. 1). The Rio Puerco basin is fed by two additional HUCs—the Arroyo Chico and the Rio San Jose (Fig. 1). The main stem that the USGS defines as the Puerco HUC is a very narrow drainage that runs parallel to the Rio Grande before joining it 20 miles south of Belen (Fig. 1). The headwaters are located along continental divide, or the east-southeast margin of the Colorado Plateau, along a transition zone with the Rio Grande Rift. To the northeast the San Pedro Mountains in the Sierra Nacimiento border the watershed, while the Mt. Taylor Volcanic field makes up the southern boundary. The Rio Puerco flows through sedimentary units made up of sandstones, shales, mud stones, and carbonate rocks. Flow in the Rio Puerco is governed almost entirely by summer monsoon rains which result in violent flash floods. Coupled with arroyo incision and massive land-cover change, these intense floods have caused the Rio Puerco to be one of the nation's most actively eroding watersheds (SWQB, 2010).

Rio San Jose

The Rio San Jose HUC-8 basin (2,597 sq mi) is located in west-central New Mexico and contains Grants (Fig. 1). The westernmost border is on the continental divide, halfway between Grants and Gallup. The Zuni Mountains make up the watershed's southwestern border, with the Cebollita Mesa bounding the southern extent. To the northwest the watershed's boundary is made up of the San Mateo Mesa and it is flanked by the Mt. Taylor Volcanic field, to the north. The river flows east as it carves through Jurassic and Cretaceous aged sedimentary rocks before joining the Rio Puerco (SWQB, 2010).

Salt Basin

The Salt Basin HUC-8 basin (7,921 sq mi) lies to the south-east of the Tularosa Basin, bordering Texas to the south (Fig. 1). The basin is bounded by the Sacramento Mountains to the north, the Guadalupe Mountains to the east, and the Otero Mesa to the west (Fig. 1). These mountains are primarily composed of Pennsylvanian to Permian limestone, dolomite and sandstone. Basin-fill sediments in this basin are estimated to be as thick as 750 ft. There is a mixture of rangeland and restricted irrigated agriculture. The basin's groundwater is supported by two small streams, the Sacramento River and the Piñon Creek, which flow south out of the Sacramento Mountains (Huff and Chace, 2006).

Santa Fe (Rio Grande)

The Santa Fe (Rio Grande) HUC-8 basin (1,872 sq mi) is a round, fault bounded basin in north-central New Mexico that contains Santa Fe, the capital of New Mexico (Fig. 1). The basin is bounded on the east and northeast by the southern Sangre de Cristo Mountains, and on the west and northwest by the Jemez Mountains. The northern boundary is defined by the river gauge on the Rio Grande at Otowi Bridge and the southern boundary is at the confluence of the Rio Grande and the Jemez River. Major land uses are irrigated agriculture, primarily using flood irrigation, rangeland, and municipal development. The basin is in a structural embayment, with much of the basin-fill being older than Pleistocene, but still in the upper Santa Fe Group of axial river gravels and piedmont-derived, poorly sorted sands. The major river in the basin is the Rio Grande, but it is far from the municipality. The Santa Fe River is a small semi-perennial stream in the basin that is a tributary to the Rio Grande. The largest surface water features are the Rio Grande and Cochiti Reservoir on the Rio Grande. Irrigated regions are fed using a system of ditches.

Tularosa Valley

The Tularosa Valley HUC-8 basin (6,711 sq mi) is an oblong, closed basin in south-central New Mexico that contains the municipalities of Alamogordo and Carrizozo (Fig. 1), as well as the majority of White Sands Missile Range and White Sands National Monument. The basin stretches 150 miles north to south, and 60 miles east to west at its widest point (Fig. 1). The basin is a fault-bounded extension basin related to the formation of the Rio Grande Rift. The high topographic relief of the Sacramento Mountains forms the eastern boundary of the basin. The basin is bounded to the west by the San Andres and Oscura Mountains. The major basin-fill units used for water production are classic alluvial fan sediments, spilling out of the Sacramento Mountains. With only a few perennial rivers that flow into the basin, the groundwater is primarily recharged by mountain-front run-off (Mamer et al., 2014).

Upper Rio Grande

The Upper Rio Grande HUC-8 basin (3,254 sq mi) has the Rio Grande running along its axis and contains the towns of Los Alamos, Espanola and Taos. Major, perennial tributaries to the Rio Grande in the Upper Rio Grande HUC basin include the Red River and the Rio Chama. The basin runs from the Colorado border in the north to the Otowi stream gauge in the south. To the east, the basin is bounded by the Sangre de Cristo Mountains, a Precambrian rock-cored mountain chain, and the basin is bounded to the west by the San Juan Mountains. Major land use includes rangeland, irrigated farmland, recreation, and municipal and industrial uses. The major aquifers are in the upper Santa Fe Group and Pleistocene-aged sediments, which consist of gravelly- and cobbly-sands in axial river deposits and poorly sorted, silty sands and cobbly sands in piedmont deposits. Irrigated lands are generally watered from ditches fed from the Rio Grande and other perennial rivers.

3. RESULTS

Total calculated storage change, basin-specific correlation length, basin-specific specific yields, and examples of water level change maps for all basins are shown. In Figures 6 through 20, we display the calculated storage changes (subfigure a in each figure) of the change in volume from the 1950s or other earliest interpolation (red solid), the storage changes decade-by-decade (gray dotted), and the sum of the decade-by-decade changes (red dashed). The solid lines (changes from 1950s and summed decade-by-decade changes) provide a consistency check internal to the basin. If the values are discordant, the differences are often from temporal changes in the spatial well network coverage. In basins with non-irrigation season data quality, we present the results from the OK interpolations (green title bar; Figs. 6–8, 10, and 18–20). In the basins with non-irrigated land data quality, we present the results from the IDW interpolations (yellow title bar; Figs. 9, and 11–17). Included in Figures 6 through 20 are maps of water level change for one decade. Table 1 shows the specific yield and the correlation length. Table 2 provides a summary of the calculated storage change in each basin for each decade.

Albuquerque (Rio Grande)

The Albuquerque (Rio Grande) HUC basin shows overall declining storage, with declines between 2 and 2.5 km^3 over the last fifty years, with the largest drop occurring between the 1990s and the 2000s (Fig. 6a, and Table 2). The map of water level changes show that the majority of declines occur outside of the central river valley near the city of Albuquerque (Fig. 6b). Much of the basin at some distance away from Albuquerque is poorly covered. The variogram analysis yields a correlation length of 2.0 km (Table 1). We used a specific yield of 0.20 to convert water level changes to storage changes (Table 1; McAda and Barroll, 2002).

El Paso-Las Cruces (Rio Grande)

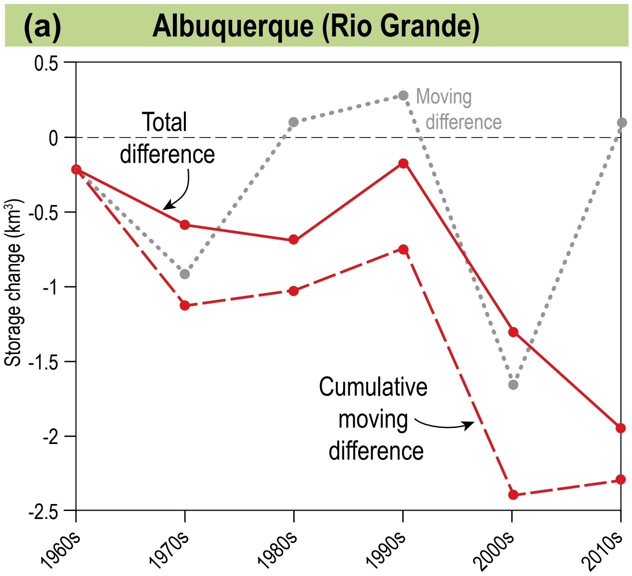
The El Paso-Las Cruces (Rio Grande) HUC for wells with at least one water level shallower than 100 ft shows a long period of little change (0.2 km^3) in storage, followed by a sharp decline is storage in the last 10 to 20 years (-0.6 to -0.8 km^3; Fig. 7a and Table 2). This does not reflect the deeper municipal water supply wells outside of the broad central Rio Grande valley and is a smaller storage change than in reality. Most of the well coverage is along the central valley, with a reasonable spatial pattern of sampling (Fig. 7b). We found a correlation length of 4.0 km and used a specific yield of 0.20 (Table 1; Hawley et al., 2000).

Estancia (Western).

The Estancia (Western) basin shows a steady pattern of declines from the 1950s until the 2000s, culminating in total storage changes between -1.25 km^3 and -1.50 km^3 (Figure. 8a and Table 2). The well sampling is relatively uniform in the basin and shows a broad swath of dropping depths-to-water along the central axis of the basin (Fig. 8b). We found a correlation length of 3.5 km and used a specific yield of 0.10 (Table 1; Shafike and Flanigan, 1999; Titus, 1973; and White, 1993).

Jornada Draw

The Jornada Draw HUC basin only has adequate data for estimating storage changes from the 1970s to the 2010s. In that time, the total difference from the 1970s has been low (between 0 and -0.3 km^3) while the cumulative decade-by-decade estimates show a -0.4 km^3 decline in the last between the 2000s and the 2010s (Fig. 9b and Table 2). The well coverage is sparse in the basin, likely complicating the storage change calculations (Fig. 9b). We found a correlation length of 5.0 km and used a specific yield of 0.15 (Table 1; Shomaker and Finch, 1996; and Rao, 1988).



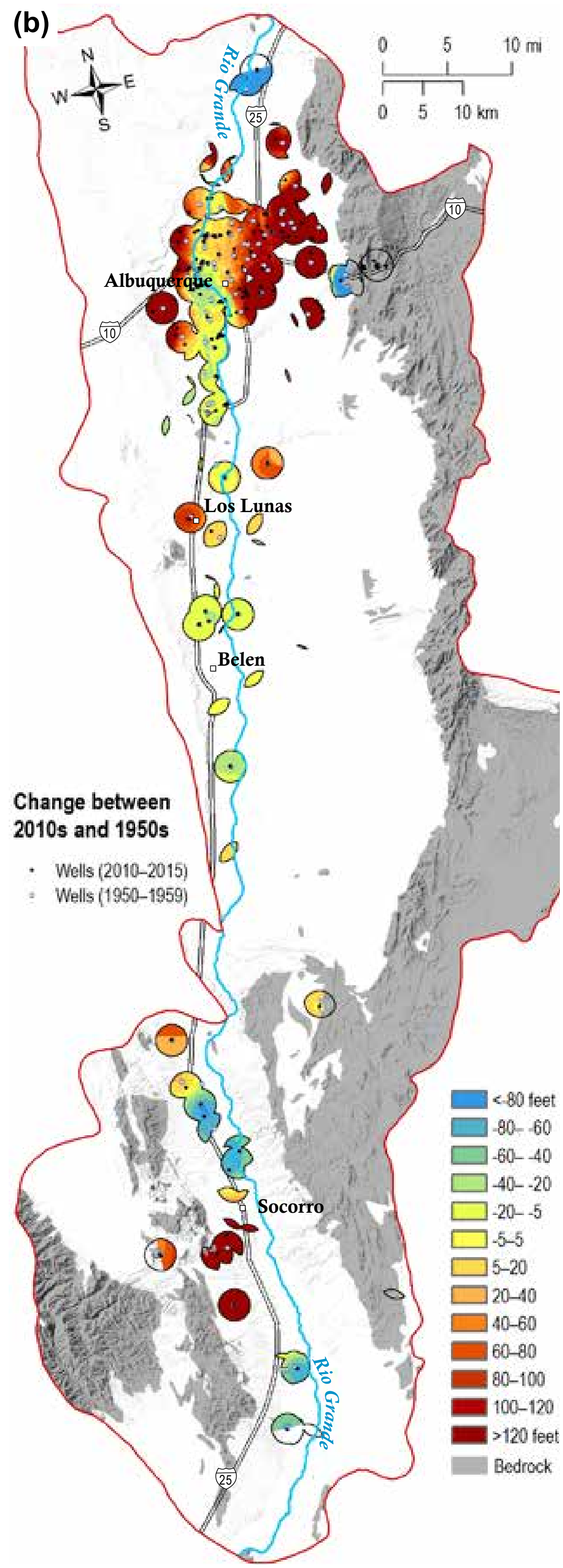


Figure 6. Storage changes in the Albuquerque (Rio Grande) HUC assuming specific yield of 0.2, 2.0 km correlation length, and requiring each well to have a minimum depth-to-water of at least 1000 ft (excluded only 2 wells). Calculated decadal storage changes (km^3) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Excludes data from irrigation season.

Table 2. Summary of calculated storage changes for all HUC basins and interpolations. To convert from km^3 to Maf, multiply by 0.810714 Maf/km^3.

		STORAGE CHANGE (km^3)											
		1960s		1970s		1980s		1990s		2000s		2010s	
HUC		IDW	Krig.	IDW	Krig.	IDW	Krig.	IDW	Krig.	IDW	Krig.	IDW	Krig.
Albuquerque (Rio Grande)	Total	-0.27	-0.21	-0.80	-0.59	-1.17	-0.69	-1.12	-0.16	-1.26	-1.30	-1.19	-1.96
	Cumul.	-0.27	-0.21	-0.77	-1.13	-1.02	-1.02	-0.80	-0.74	-1.15	-2.39	-1.13	-2.29
El Paso-Las Cruces (Rio Grande)	Total	-0.05	-0.02	-0.27	-0.16	-0.11	-0.12	-0.11	-0.07	-0.18	-0.15	-0.45	-0.47
	Cumul.	-0.05	-0.02	-0.21	-0.09	0.02	0.07	0.08	-0.05	0.01	-0.12	-0.36	-0.72
Estancia (Western)	Total	-0.27	-0.29	-0.61	-0.61	-1.01	-0.91	-1.15	-1.00	-1.33	-1.23	-	-
	Cumul.	-0.27	-0.29	-0.62	-0.65	-0.88	-0.88	-1.14	-1.14	-1.60	-1.59	-	-
Jornada Draw	Total	-	-	-	-	-0.10	-	-0.23	-	-0.17	-	-0.03	-
	Cumul.	-	-	-	-	-0.10	-	-0.10	-	0.01	-	-0.31	-
Mimbres	Total	-0.82	-0.15	-1.95	-1.18	-2.67	-2.04	-2.70	-2.34	-2.74	-2.34	-	-
	Cumul.	-0.15	-0.15	-2.02	-2.02	-3.40	-3.40	-2.75	-2.75	-2.54	-2.54	-	-
Pecos Headwaters	Total	-0.05	-	-	-	-0.00	-	-0.16	-	-	-	-0.01	-
Playas Lakes	Total	-0.11	-	-0.48	-	-0.46	-	-0.19	-	-0.46	-	-	-
	Cumul.	-0.11	-	-0.25	-	-0.25	-	-0.20	-	-0.29	-	-	-
Rio Chama	Total	-0.11	-	-0.00	-	-	-	-	-	-	-	-	-
	Cumul.	-0.11	-	0.13	-	-	-	-	-	-	-	-	-
Rio Puerco	Total	-1.61	-	-0.18	-	-1.82	-	-3.54	-	0.26	-	-3.32	-
	Cumul.	-1.61	-	-1.57	-	-2.70	-	-5.10	-	-4.98	-	-5.43	-
Rio San Jose	Total	-0.36	-	-0.32	-	-0.44	-	-0.13	-	-0.05	-	-0.23	-
	Cumul.	-0.36	-	-0.27	-	-0.41	-	-0.57	-	-0.53	-	-0.77	-
Salt Basin	Total	-0.01	-	-0.07	-	-0.10	-	-0.07	-	-0.07	-	-0.03	-
	Cumul.	-0.01	-	-0.04	-	-0.05	-	-0.03	-	-0.03	-	-0.05	-
Jornada Draw	Total	-	-	-	-	-0.13	-	-0.29	-	-0.20	-	-0.03	-
	Cumul.	-	-	-	-	-0.13	-	-0.13	-	0.01	-	-0.38	-
Plains of San Agustin	Total	-	-	0.08	-	0.02	-	-0.06	-	-	-	-	-
	Cumul.	-	-	0.08	-	-0.20	-	-0.27	-	-	-	-	-
Santa Fe (Rio Grande)	Total	-0.02	-0.04	-0.21	-0.16	-0.05	-0.02	-0.10	-0.09	-0.45	-0.31	-0.38	-0.23
	Cumul.	-0.02	-0.04	-0.33	-0.35	-0.29	-0.34	-0.37	-0.26	-0.59	-0.70	-0.55	-0.61
Tularosa Basin	Total	-0.02	-0.14	-0.61	-1.03	-0.35	-0.51	-0.66	-0.57	-1.69	-2.01	-1.24	-1.42
	Cumul.	-0.02	-0.14	-0.76	-1.53	-1.17	-1.22	-1.69	-1.94	-2.53	-3.29	-1.48	-2.25
Upper Rio Grande	Total	-0.51	-0.57	-0.05	-0.03	-0.48	-0.89	0.12	0.03	-	-	-	-
	Cumul.	-0.51	-0.57	-0.63	-1.19	-0.16	-0.91	-0.16	1.29	-	-	-	-

Mimbres

The Mimbres HUC basin shows substantial declines of between -2.0 km^3 and nearly -4.0 km^3 in storage from the 1960s through 1980s, with a tapering of storage change rates from the 1980s through the 2000s (Fig. 10a and Table 2). The well network coverage in the basin is well spread but concentrated along populated corridors, with the largest declines occurring between Deming and the Mexican border, and to the west of the Sierra de las Uvas (Fig. 10b). We found a correlation length of 6.5 km and used a specific yield of 0.10 (Table 1; Hawley et al., 2000; and Kennedy et al., 2000).

Pecos Headwater

The Pecos Headwater HUC basin shows small (less than 0.2 km^3) storage changes (Fig. 11a and Table 2). However, the well network is concentrated in a small corner of the basin to the southeast of Santa Rosa (Fig. 11b); the rest of the basin is dominated by bedrock. In the small area with reasonable coverage, there are substantial (greater than 40 ft) water level declines. However, the well network coverage was not consistent enough through time to construct a decade-by-decade estimate. We found a correlation length of 3.0 km and used a specific yield of 0.15 (Table 1; Rao, 1989).

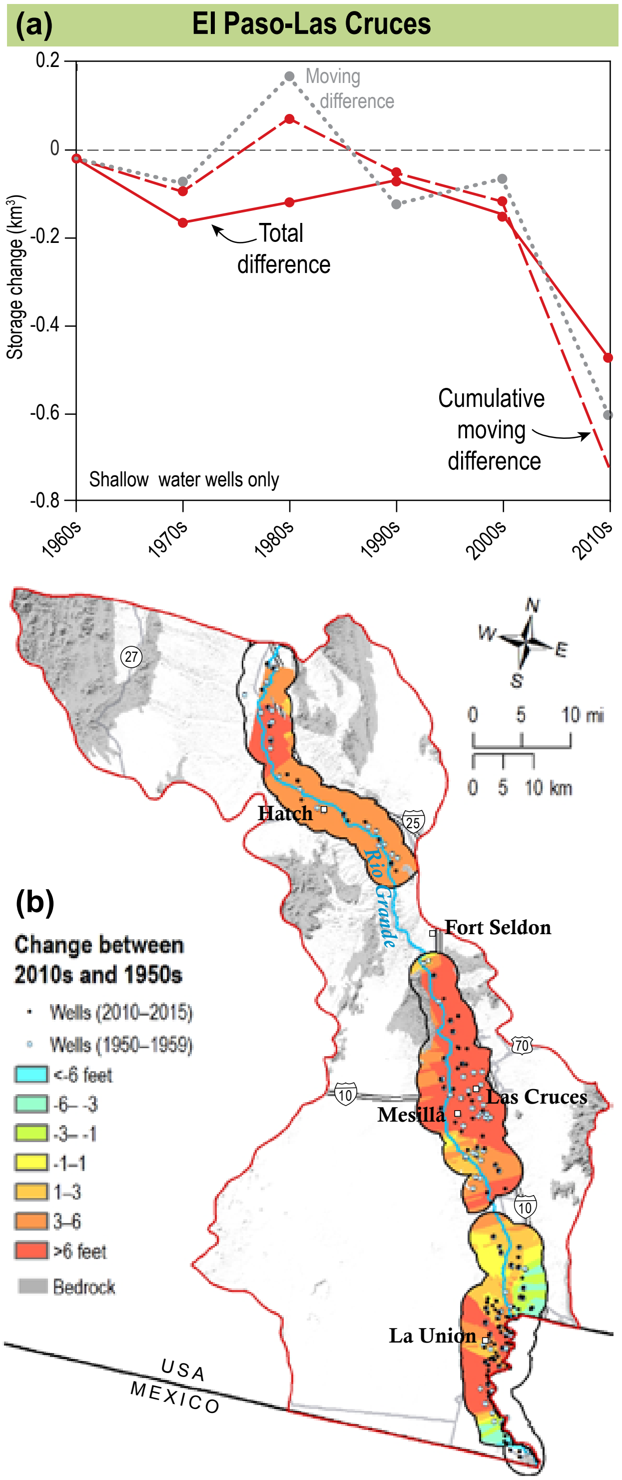


Figure 7. Storage changes in the El Paso-Las Cruces (Rio Grande) HUC assuming specific yield of 0.2, 4.0 km correlation length, and requiring each well to have at least one water level shallower than 100 ft. Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Excludes data from irrigation season.

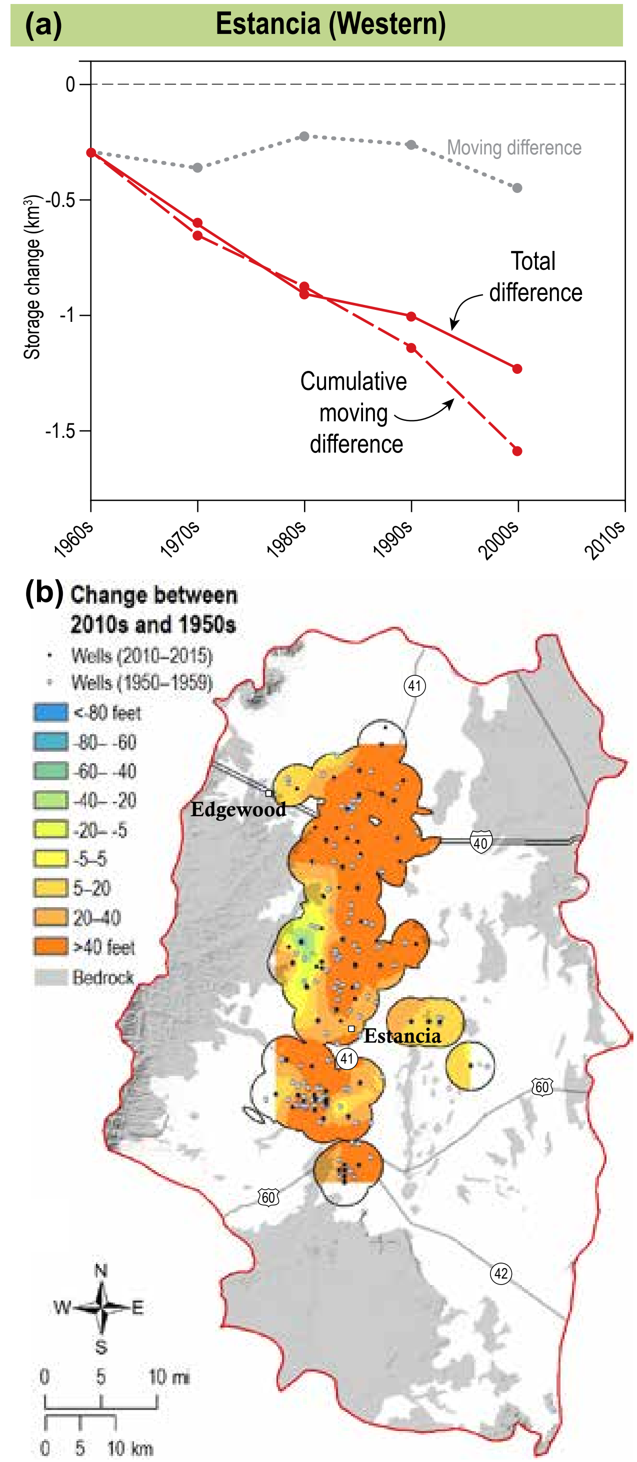


Figure 8. Storage changes in the Western Estancia HUC assuming specific yield of 0.1, 3.5 km correlation length. Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2000s. Excludes data from irrigation season.

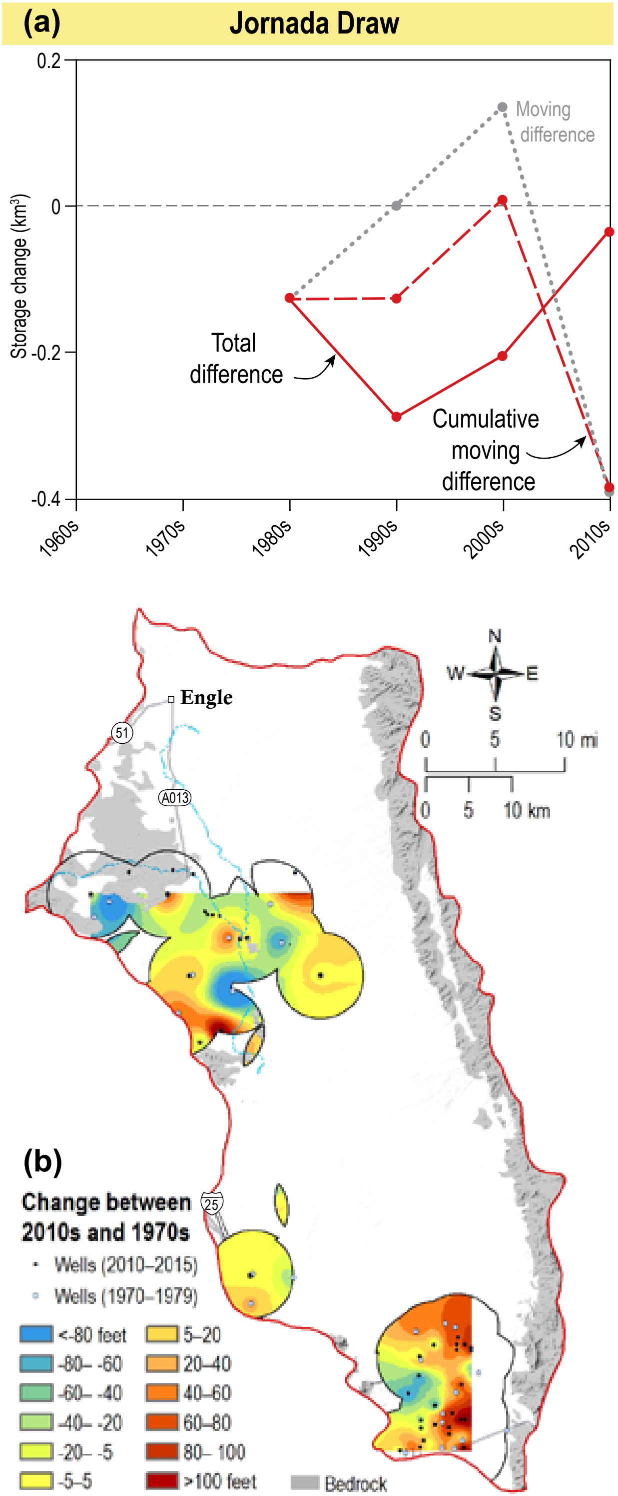


Figure 9. Storage changes in Jornada Draw HUC assuming specific yield of 0.15, 5.0 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 2000s. Calculated including data from the irrigation season.

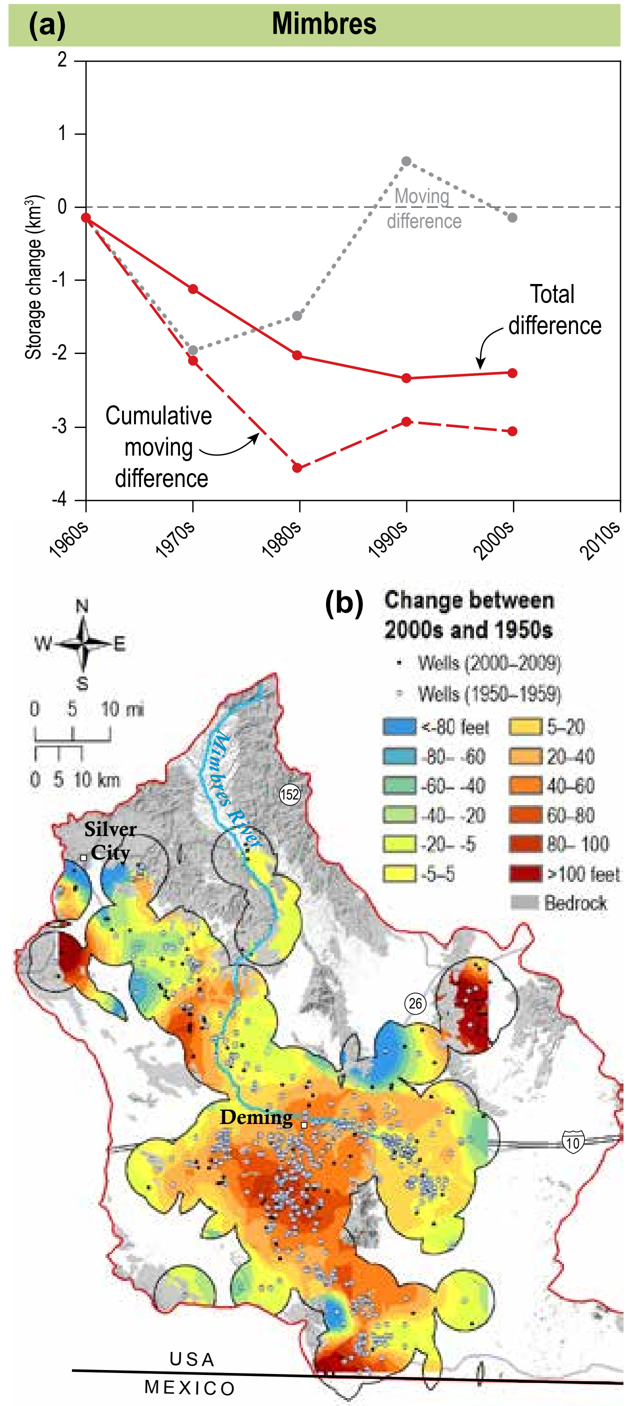


Figure 10. Storage changes in the Mimbres HUC assuming specific yield of 0.15, 6.5 km correlation length. Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2000s. Excludes data from irrigation season.

Plains of San Agustin

The Plains of San Agustin HUC basin shows storage changes of between -0.1 km^3 and -0.3 km^3 between the 1960s and the 1990s (Fig. 12a and Table 2). Data coverage before and since has been too sparse to perform our analysis. The well network is concentrated along State Highway 12 going south from Datil and the water level interpolations show overall declines around 20 ft to 40 ft from the 1950s to the 1980s (Fig. 12b). We found a correlation length of 3.5 km and used a specific yield of 0.15 based on sediment descriptions (Table 1; Johnson, 1967; and Meyers et al., 1994).

Playas Lake

The Playas Lake HUC basin shows decreases of between -0.2 km^3 and -0.5 km^3 from the 1950s to the 1970s (Fig. 13a and Table 2). From the 1970s to the 2000s, the groundwater storage has remained relatively constant (Fig. 13a and Table 2). The well coverage in the 2010s was not adequate to perform our analysis. Before then, the basin well network was concentrated along the axis of the main valley to the west of the Hatchet Mountains and provides reasonable coverage, though many of the areas of greatest water level changes are along State Highway 9, outside of the central valley (Fig. 13b). We found a correlation length of 4.0 km and used a specific yield of 0.08 based on sediment descriptions (Table 1; Johnson, 1967).

Rio Chama

The Rio Chama HUC basin has very little data showing small net increases between the 1950s and the 1970s (Fig. 14a; Table 2). The well network coverage was too sparse in later decades to include in the analysis. The well coverage included in the first three decades of analysis is primarily in the southeastern part of the basin along the Rio Chama and a tributary (Fig. 14b). The spatial extent of the well networks is primarily in the southeastern corner of the basin where the Rio Chama joins the trunk of the Rio Grande-associated basin fill. We found a correlation length of 4.0 km and used a specific yield of 0.10 (Table 1).

Rio Puerco

The Rio Puerco HUC basin shows large decreases (-4 km^3 to -5.5 km^3) in aquifer storage from the 1950s through the 1990s, with little change since then (Fig. 15a and Table 2); the close to zero total change (Fig. 15a; solid red line) from the 1950s to the 2000s is likely a spurious result. Well coverage in the basin is sparse, which decrease confidence in the estimated storage change and increases vulnerability to outliers and interpolation artifacts (Fig. 15b). We found a correlation length of 7.5 km and used a specific yield of 0.15 (Table 1; Kernodle et al., 1995; and Tiedeman et al., 1998).

Rio San Jose

The Rio San Jose shows divergent storage change estimates (Fig. 16a and Table 2), with the summed decade-by-decade differences showing steady declining aquifer storage from the 1950s to the 2010s (Fig. 16a, red dashed) and the differences between the 1950s and later decades showing initial declines followed by a substantial rebound (Fig. 16a, red solid). This is probably caused by inconsistencies in coverage between the 1950s well network and later well networks (Fig. 16b); the summed decade-by-decade estimates of storage change are likely more reliable. We found a correlation length of 8.0 km and used a specific yield of 0.10 (Table 1).

Salt Basin

The Salt Basin HUC basin shows little storage change (less than -0.1 km^3) through time, though there is a general decline from the 1950s (Fig. 17a and Table 2). The well coverage is sparse, reflecting the lack of development in the basin (Fig. 17b) and complicating the analysis. We found a correlation length of 3.5 km and used a specific yield of 0.10 (Table 1).

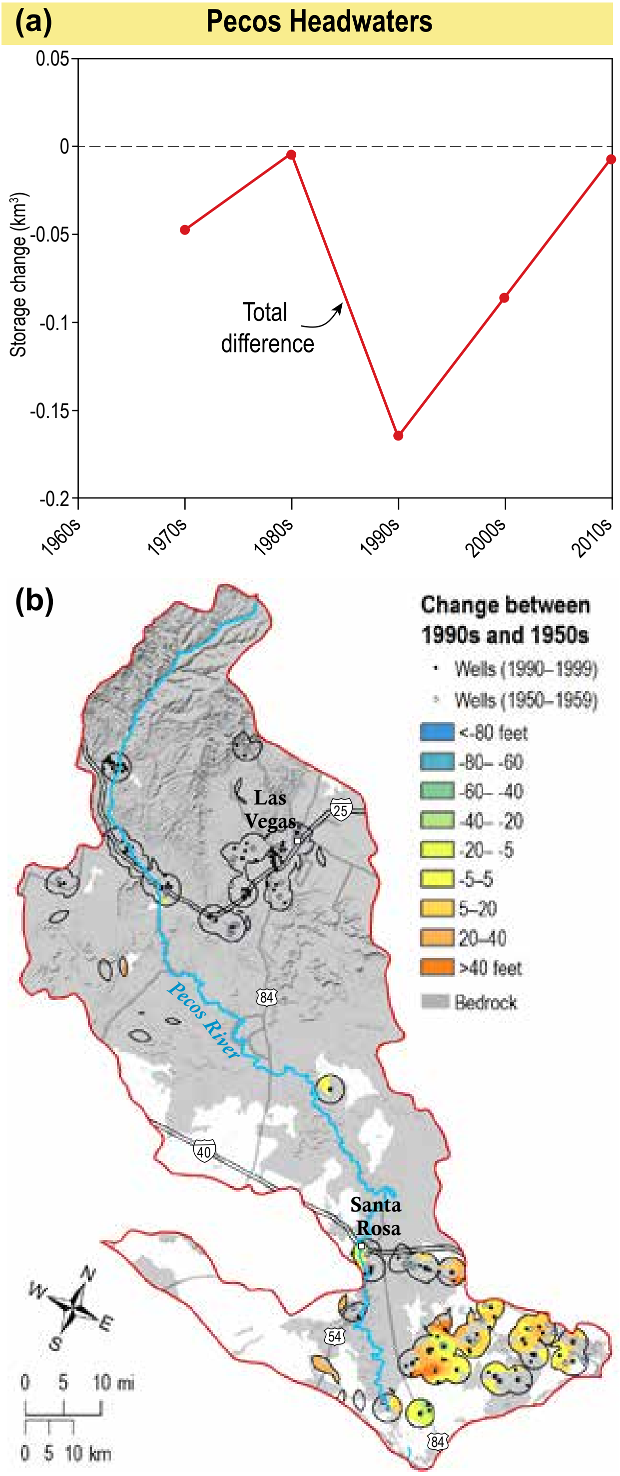


Figure 11. Storage changes in the Pecos Headwaters HUC assuming specific yield of 0.15, 3.0 km correlation length. (a) Calculated decadal storage changes (km^3) using change from 1950s (solid red), for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 1990s. Calculated including data from the irrigation season.

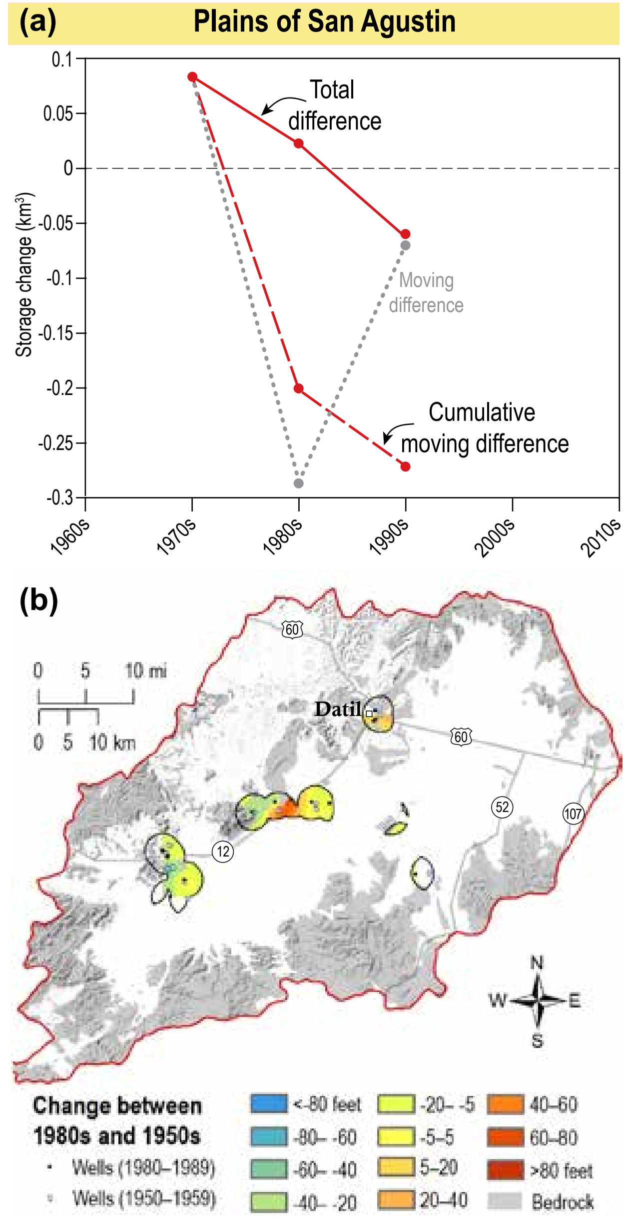


Figure 12. Storage changes in the San Agustin Plains HUC assuming specific yield of 0.10, 3.5 km correlation length. (a) Calculated decadal storage changes (km^3) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1970s to 1990s. Calculated including data from the irrigation season.

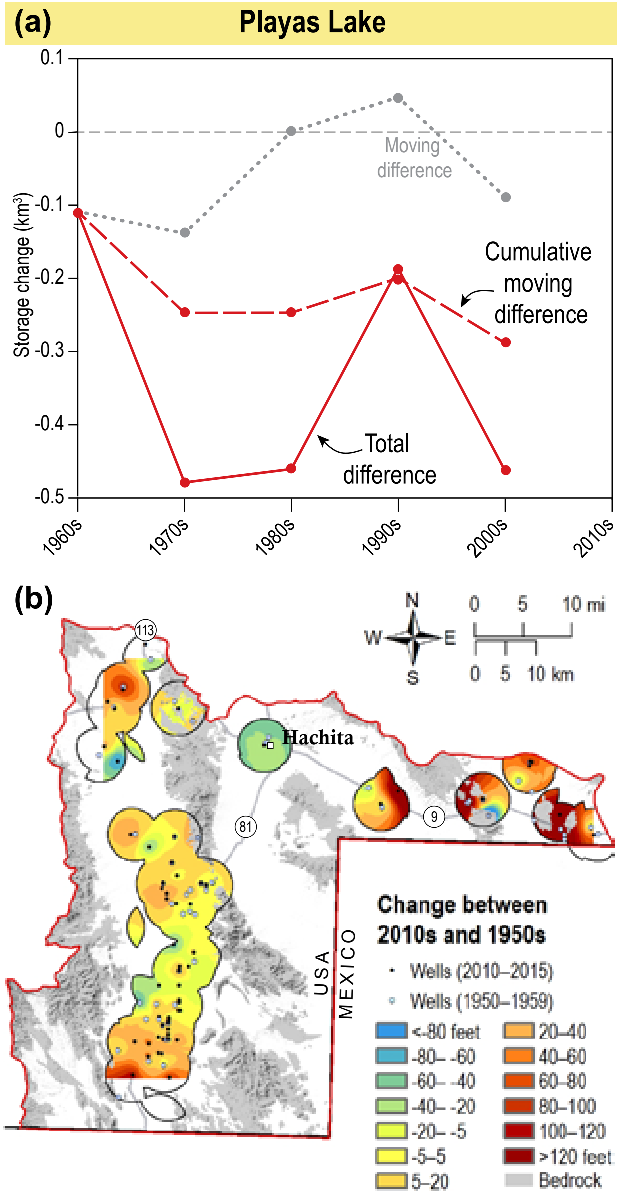


Figure 13. Storage changes in the Playas Lake HUC assuming specific yield of 0.15, 4.0 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 2000s. Calculated including data from the irrigation season.

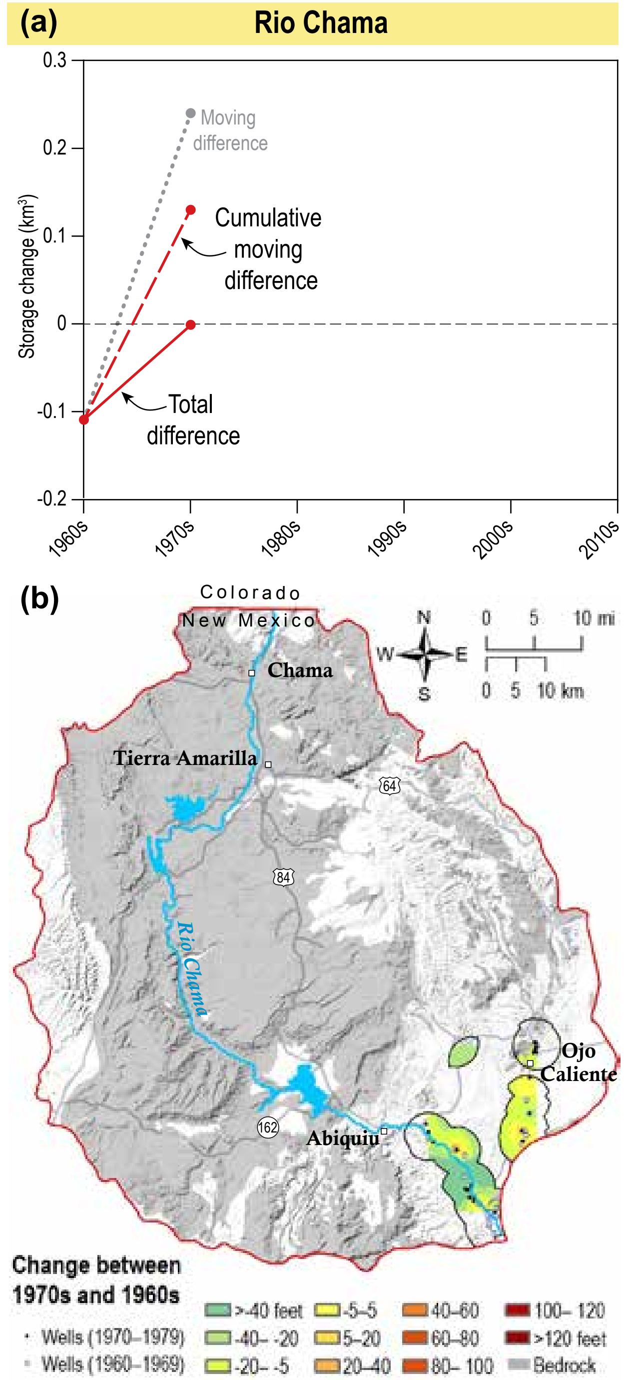


Figure 14. Storage changes in the Rio Chama HUC assuming specific yield of 0.10, 4.0 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1960s to 1970s. Calculated including data from the irrigation season.

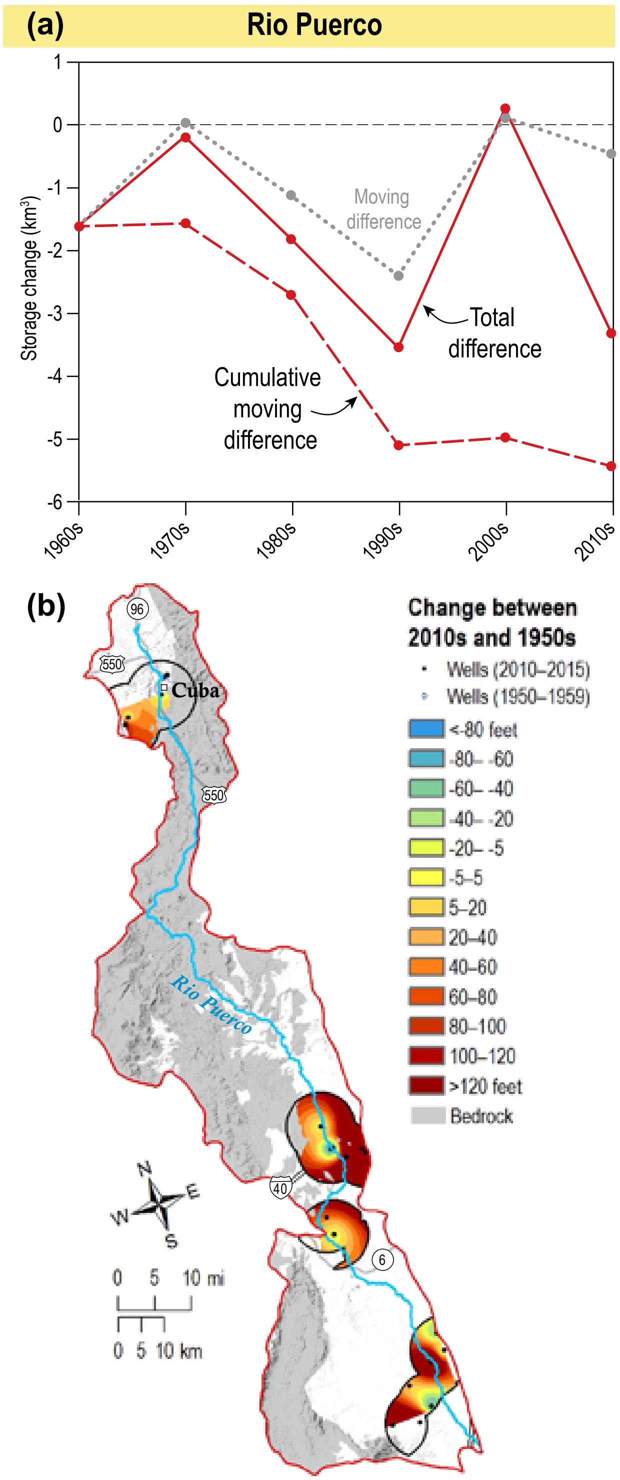


Figure 15. Storage changes in the Rio Puerco HUC assuming specific yield of 0.15, 7.5 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Calculated including data from the irrigation season.

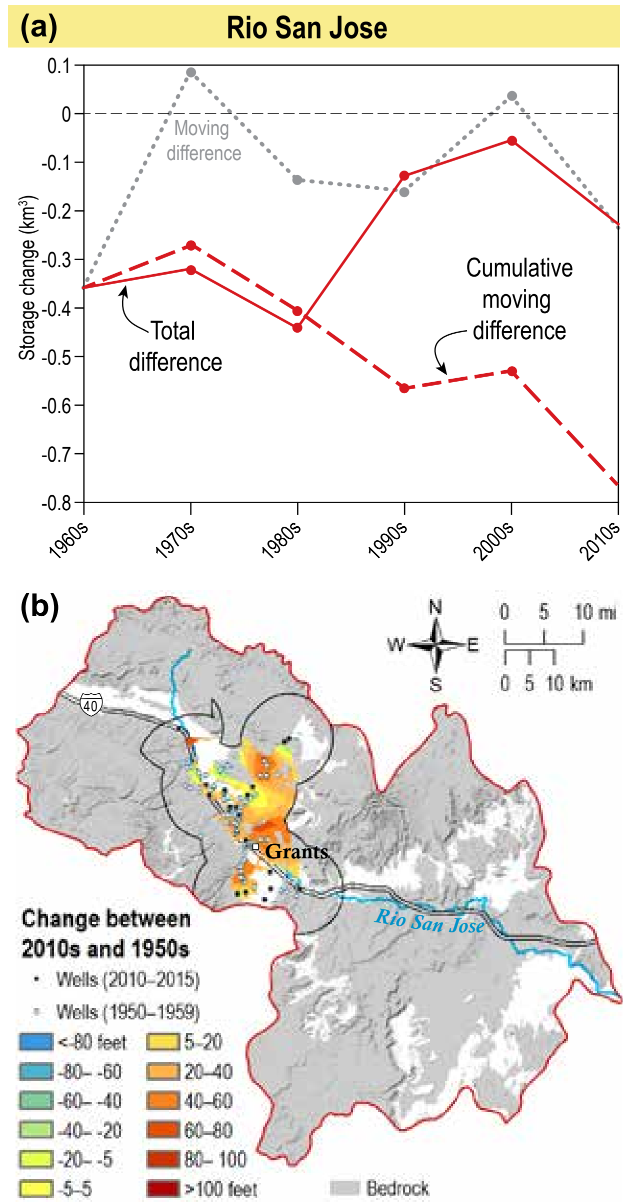


Figure 16. Storage changes in the Rio San Jose HUC assuming specific yield of 0.10, 8.0 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Calculated including data from the irrigation season.

Santa Fe (Rio Grande)

The Santa Fe (Rio Grande) HUC basin shows generally declining water storage between of -0.3 and -0.7 km^3 from the 1950s to the 2010s (Fig. 18a and Table 2). The well network is concentrated around the city of Santa Fe with little to no coverage away from the municipality (Fig. 18b). Near the southern Sangre de Cristo Mountains on the northeast of the city of Santa Fe, greater than 100 ft declines in water levels are observed (Fig. 18b). We found a correlation length of 2.0 km and used a specific yield of 0.15 (Table 1; McAda and Wasiolek, 1988).

Tularosa Basin

The Tularosa Basin HUC basin shows declines in water storage of between -1.5 km^3 and -2.5 km^3 between the 1950s and the 2010s (Fig. 19a and Table 2). The monitored well network is concentrated around the municipalities of Alamogordo, Tularosa and Carrizozo along the western front of the Sacramento Mountains (Fig. 19b). Almost no coverage exists outside of this region. Water level declines are generally near 50 ft, though some water levels have declined over 120 ft in the last 60 years. We found a correlation length of 6.5 km and used specific yield of 0.12 (Table 1; Kelly and Hearne, 1976; Mclean, 1970; Ballance, 1976; and Garza McLean., 1977).

Upper Rio Grande

The Upper Rio Grande HUC basin shows declines in water levels from the 1950s through the 1980s, followed by a recovery in the 1990s well network interpolations (Fig. 20 and Table 2). Not enough coverage was available past the 1990s to develop reasonable interpolations (Fig. 19a). The well network is quite variable through time. Spatially, the networks have concentrations of measurements in the southern San Luis Valley just south of the Colorado border, and around Espanola (Fig. 19b). We found a correlation length of 6.0 km and used a specific yield of 0.15 (Table 1; Burck et al., 2004).

Figure 21 shows the compilation of all of the calculated storage changes for all of the basins examined, with the non-irrigated season data quality presented with a green border and using the results of the OK interpolations (Fig. 21a-c, e, and m-o) and the non-irrigated land data quality presented with a yellow border using the results of the IDW interpolations (Fig. 21d,f-l). The current study does not normalize the results to a nominal total storage or to a basin area. There is an overall trend in basin-fill aquifers across the state of declining aquifer storage. More specifically, populated basins, basins with more irrigated agriculture land use, and basins that do not have a large perennial trunk stream (i.e., the Rio Grande) show the greatest declines. Less populated basins with less water-intensive land use show lower declines.

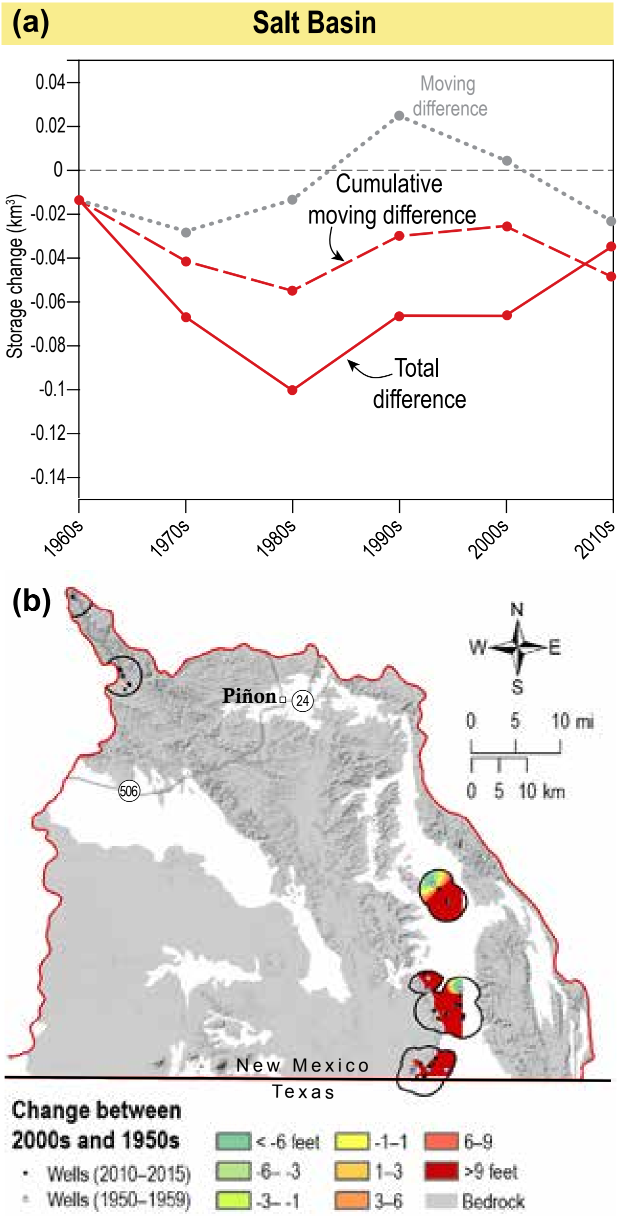


Figure 17. Storage changes in the Salt Basin HUC assuming specific yield of 0.10, 3.5 km correlation length. (a) Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for the inverse-distance-weighting interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Calculated including data from the irrigation season.

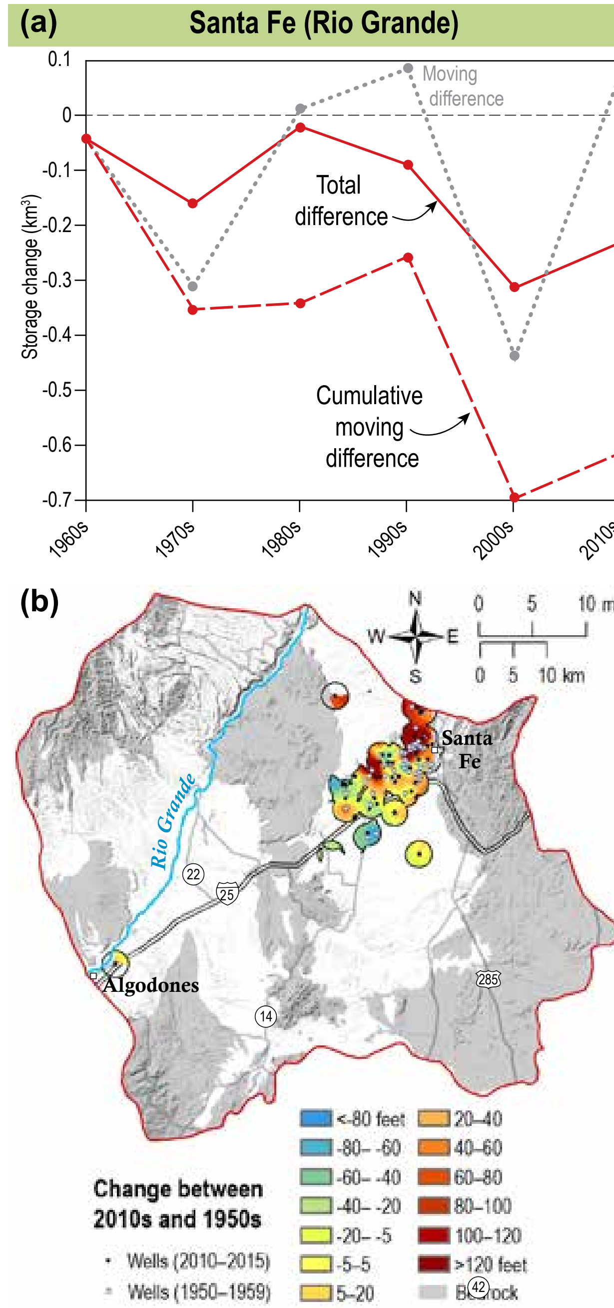


Figure 18. Storage changes in the Santa Fe (Rio Grande) HUC assuming specific yield of 0.15, 2.0 km correlation length, and requiring each well to have a minimum depth-to-water of at least 1000 ft. Calculated decadal storage changes (km³) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Excludes data from irrigation season.

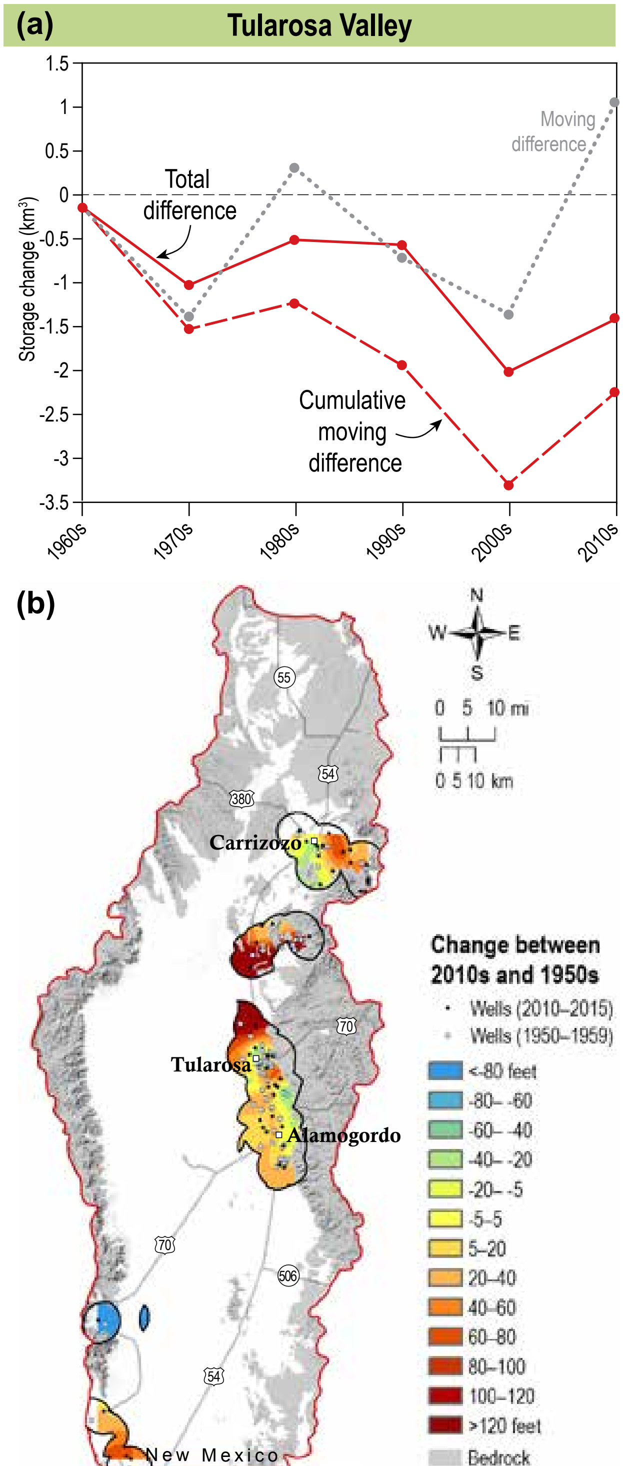


Figure 19. Storage changes in the Tularosa Valley HUC assuming specific yield of 0.12, 6.0 km correlation length. Calculated decadal storage changes (km^3) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 2010s. Excludes data from irrigation season.

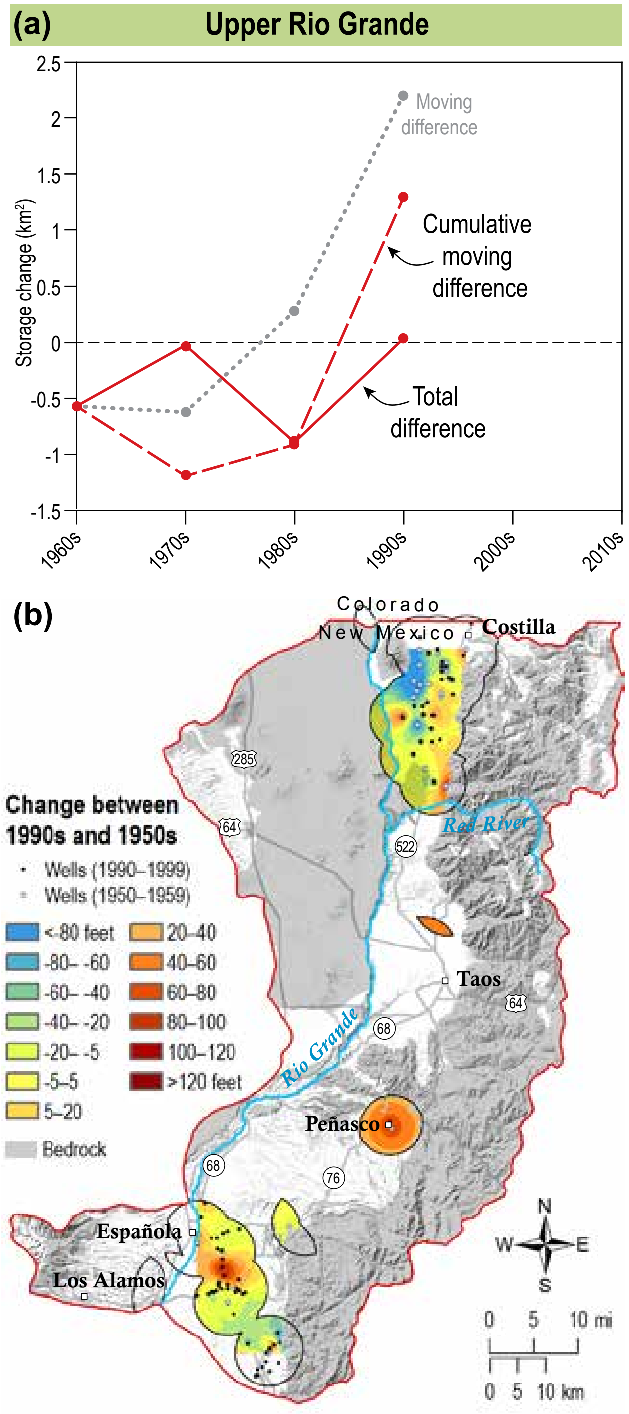


Figure 20. Storage changes in the Upper Rio Grande HUC assuming specific yield of 0.15, 6.0 km correlation length, and requiring each well to have a minimum depth-to-water of at least 1000 ft. Calculated decadal storage changes (km^3) using change from 1950s (solid red), change decade by decade (dashed black), and the cumulative decade-by-decade change (dashed red) for (a) the kriging interpolation; and (b) map of depth-to-water change from 1950s to 1990s. Excludes data from irrigation season.

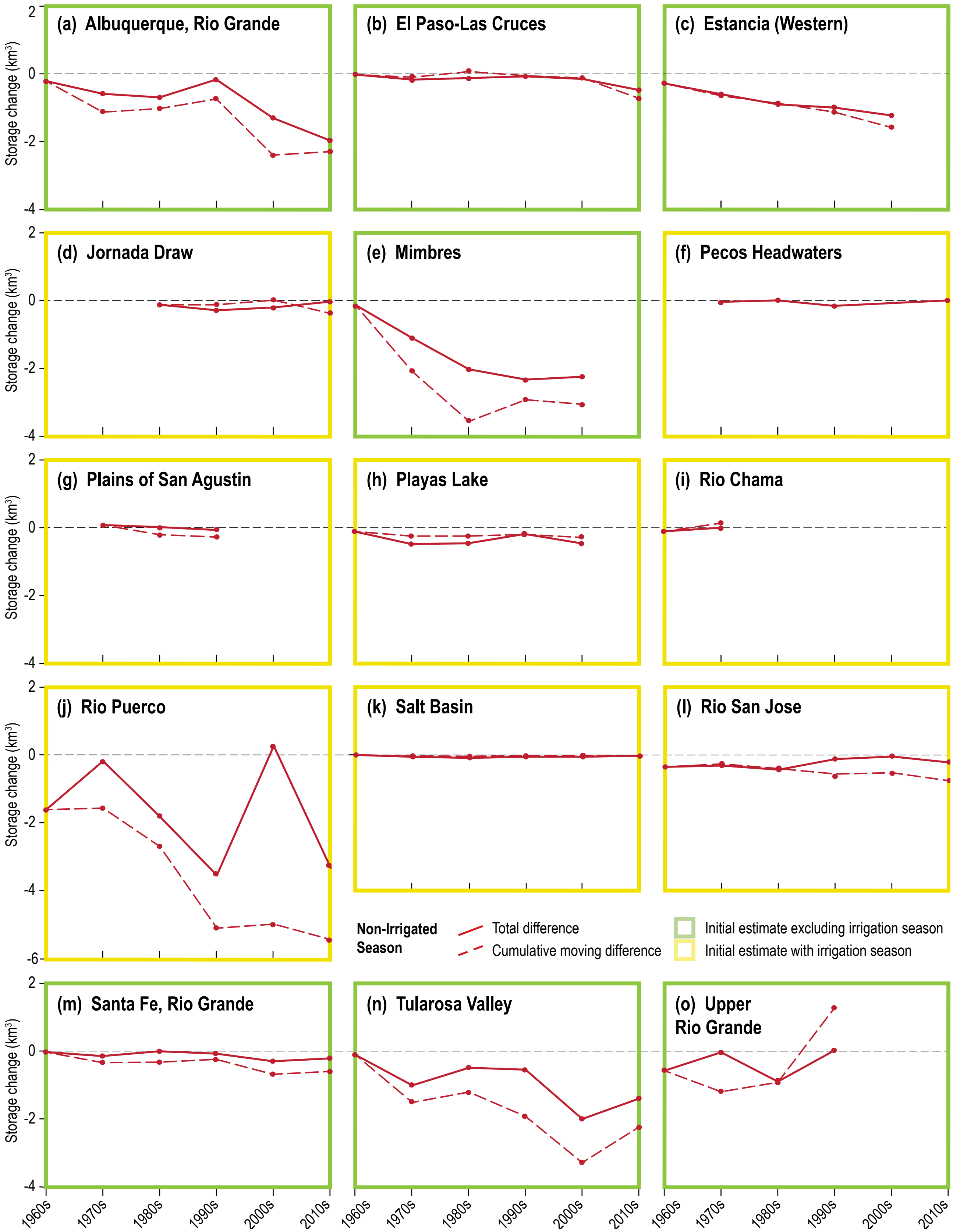


Figure 21. Compilation of all of the storage change calculations for non-irrigation season data quality (green labels, a-c, e, m-o, OK interpolation) and the non-irrigated land data quality (yellow labels, d, f-l, IDW interpolation).

4. DISCUSSION

4.1 Principal Findings and Synthesis

In closed basins and basins with ephemeral or small perennial streams, the long-term changes in groundwater storage are a function primarily of the size of population centers and irrigated land (i.e., pumping) and the availability of mountain-block and focused mountain-sourced tributary recharge. Closed basins without large population centers or irrigation (Jornada Draw, Plain of San Agustin, Playas Lake, and Salt Basin; Figs. 9, 12, 13, 17, and 21d, g, h, and k) show little change with some zones of increases immediately next to the mountain front. These basins are also bounded by mountains composed of fractured sedimentary or silicic volcanic rocks, enhancing deep infiltration of precipitation. Closed basins with large population centers and irrigation (Estancia (Western), Mimbres, and Tularosa Valley; Figs. 8, 10, 19, and 21c, e and n) show patterns of large decreases along the center of the basin where irrigation commonly occurs or where the municipalities exist. The margins of the basins show modest water level increases which do not outweigh the losses to groundwater pumping. Interestingly, we did not see increases in the center of closed basins that have ephemeral playas. Apparently, the volume of water inputted into the aquifer is not significant.

In basins with ephemeral and smaller perennial streams, the pattern of withdrawals is similar to those of closed basins—withdrawals around regions with agriculture, mining and towns, recharge occurring along the periphery of the basin, and some stabilization of the aquifer storage by the streams (Pecos Headwaters, Rio Chama, Rio Puerco, and Rio San Jose; Figs.11 14, 15, 16, and 21f, i, j and l). Most of these basins, however, do not have large populations in the areas in basin-fill aquifers. In general, our estimates are likely underestimates of the total groundwater storage change of these basins.

In the basins with a large perennial river (Albuquerque, El Paso-Las Cruces, Santa Fe, and Upper Rio Grande), some overall trends in spatial water level change patterns and temporal storage change patterns arise. Where the well network is in the aquifer near the Rio Grande, the water levels are relatively constant compared to those away from the river (Figs. 6b, 7b, and 20b). This counterbalances the declines in the rest of the basin away from the river through focused recharge from the river. Where the well network is a greater distance from the river system, generally in the neighboring high terrace surfaces and piedmont deposits, the water levels and corresponding storage varies as a function of pumping and distributed mountain block recharge, rather than being buffered by the Rio Grande (Figs. 6a and b, 18a and b, 20a and b, and 21a, m and o). In the case of the Albuquerque basin, the central river valley shows little change in storage through time, while the outlying aquifer shows large water level and storage declines. The rate of recharge from the river has not balanced these reductions in storage. For the El Paso-Las Cruces basin, the shallow aquifer system was held at a nearly constant level by the river recharge from the 1950s until the early 2000s. Beginning in the early 2000s and through the 2010s, however, the shallow aquifer appears to have detached from the river and the shallow aquifer water levels appear to be dropping quickly despite any recharge from the river. The Santa Fe basin well network is too far from the Rio Grande to be strongly influenced by recharge from the river; the Santa Fe basin well network responds essentially as a closed basin both in the spatial pattern of water level changes and the overall basin storage change.

To summarize, both the spatial pattern of water level change and the cumulative basin-wide storage changes reflect the balance between pumping rates, distributed recharge and recharge from streams and rivers. Closed basins (Fig. 22a) and basins with small streams (Fig. 22b) are especially sensitive to losses from pumping. The sources of recharge tend to be at the margins of the basins along mountain fronts. We observe, in some basins, local groundwater level increases along mountain fronts, which do not

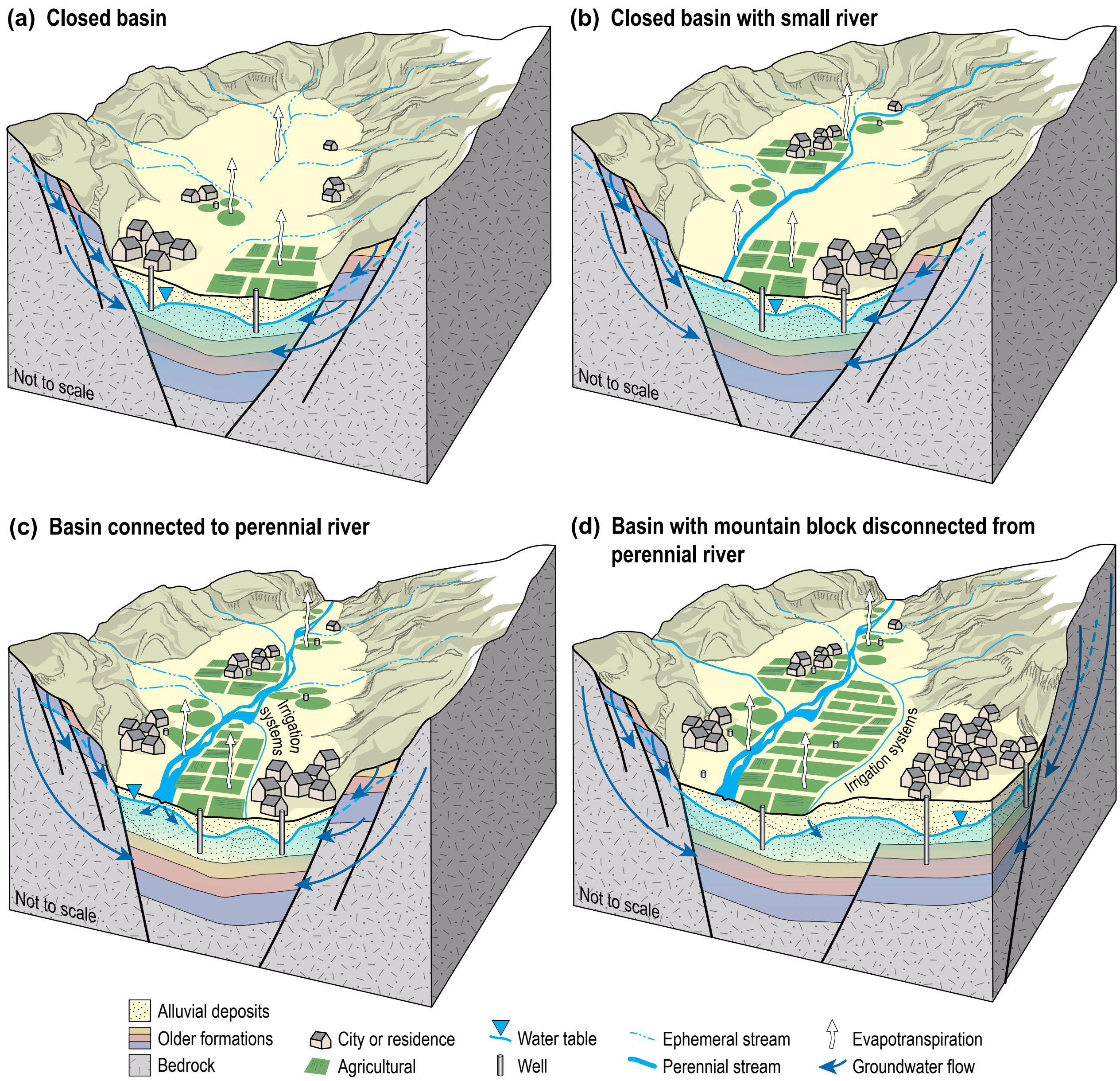


Figure 22. Schematic of controls of basin structure, societal use and surface water on alluvial aquifer levels, showing (a) closed basin without major streams, (b) a closed basin with a perennial or large ephemeral river; (c) an open surface water basin that has a large perennial river well connected to the local aquifer; and (d) a open surface water basin with a large river or stream that is not well connected to the alluvial aquifer either because the infiltration capacity of the streambed is not high enough to allow water to penetrate to the saturated zone, or because the distance from the stream to the exploited aquifer is too great.

propagate further into the basin where pumping occurs. If there is a stream, it is often either not well connected or of too small a flow to impact the large area of the aquifer (Fig. 22b).

In basins with a large trunk stream, such as the Rio Grande, the losses from the river into the local aquifer can act to buffer the overall aquifer losses (Fig. 22c). However, at large distances from the river, the transmissivity of the aquifer is not high enough to balance the effects of pumping and large declines in water storage are possible (Fig. 22c and d). In the case of pumping occurring in a structural embayment far from the basin, as in the Santa Fe basin, the basin behaves more like a closed basin than a basin with a basin-fill aquifer that is well-connected to the river. Slightly more subtle than this, if the water level of the basin-fill aquifer declines enough and if the flows in a river are smaller and shorter in duration, then the infiltration capacity under the stream may be too low to allow the river to balance aquifer losses away from the channel (Fig. 22d).

Overall trends of water storage change in basin-fill aquifers in New Mexico show a strong dependence on societal use. In areas with large populations or with other water needs, the aquifer storage is, in large part, decreasing throughout the basins examined. In areas with lower populations or during periods when the water flux into the aquifer could balance demand, the basin-fill aquifer storage remains stable but does not generally increase.

4.2. Recommendations for Future Research

There are several future research directions we would recommend. In the near term, two challenges exist. First, the current method needs to be extended to more complex aquifer systems that include both unconfined and confined aquifers in a single basin and may include stacked aquifers. This covers the San Juan Basin, the Roswell basin, the Permian and Delaware basins, and portions of the southern Central High Plains in northeastern New Mexico. Once this analysis is completed, then the changes in storage of the majority of aquifers in the state will have been assessed. At this point, we suggest a comparison of our data-driven results with the NMOSE calibrated groundwater flow model calculations in the basins with adequate well coverage. This comparison is likely to improve both the our data-driven method and model-based understanding.

The second near term challenge would be to provide confirmation of the rates of groundwater declines in the Southern High Plains Ogallala system estimated by the USGS (McGuire, 2013). incorporating the spatial estimates of specific yield into the to total aquifer storage change calculations (McGuire, 2013).

In the longer term, at least two major challenges exist. First, there is no comprehensive understanding of the lateral and vertical extent of freshwater aquifers around the state. While we are studying changes in storage, and a range of new techniques are being brought to bear on the question of storage change, we need to know how much water is left in the aquifers—what is the percentage of change relative to the total? Second, much of the state has sparse well and water level measurement coverage. There is little coverage away from populated regions in much of the state. While we may hypothesize about water storage changes in rural aquifers, there is no direct data supporting these ideas. This is a significant challenge, especially when coupled with our need for comprehensive understanding of the volumes of our existing water resources.

Finally, other researchers in the NMWRRI Statewide Water Assessment plan on using our results to understand the water balance for water planning areas, county and basin scale. This requires our results at the HUC-level to be aggregated or clipped to the desired area. Our results produce a gridded 100 m resolution estimate of water level changes, which we have also converted to 100 m resolution grids of storage change per area. This will aid the reanalysis process. Major limitations of our approach include (1) an assumed homogeneous specific yield within a HUC, (2) interpolation artifacts at high resolutions, especially in the OK interpolations and when using the lower, non-irrigated lands data quality, and (3) artifacts around the edges of the region of interest which can be significant. In general, because we are limited to the wells that we have long records for, our estimates of storage change at the HUC level are underestimates. This will additionally complicate further analysis. Also, some regions within a HUC, which may encompass many counties or water planning areas, do not have enough data to be reliable at higher resolutions. An example of this is Socorro County, which has very limited well coverage and does not have reliable estimates, but is largely within the Albuquerque (Rio Grande) HUC. So, an estimate can be generated for Socorro County, but it will not be reliable.

5. SUMMARY

In this study, we used depth-to-water well measurements from the last six decades to develop maps of water level changes and basin-wide total storage changes in the basin-fill aquifers of the Rio Grande-rift basins and the headwaters of the Pecos River. We chose to use the USGS HUC-8 surface water boundaries, which encompass major social and surface water boundaries and mostly respect geological and groundwater boundaries in the basins of concern.

In the end, poor spatial and temporal coverage of data in many of the basins was a major challenge. The well water level measurements were too sparse in space and time for this analysis in the Arroyo Chico, Caballo, Conejos, Elephant Butte, Estancia (Eastern), Jemez, North Plains, Pintada Headwaters, or Rio Salado basins. We had to adapt our data quality review to include the summer irrigation season and some flagged records in order to have enough datafor our later interpolations in the Jornada Draw basin, Pecos Headwaters basin, Plains of San Agustin basin, Playas Lake basin, Rio Chama basin, Rio Puerco basin, Rio San Jose basin, and the Salt Basin basin. Using this quality of data, it was found that only the IDW interpolations were free enough from artifacts to compare to higher quality interpolations. Additionally, the lower data quality led to a wider, less spatially consistent well network which introduces errors at the edges of the interpolated area. The highest quality standard that used only unflagged measurements from the non-irrigated season was applied to the Albuquerque (Rio Grande) basin, the Mimbres basin, the Santa Fe (Rio Grande) basin, the Tularosa Valley basin, and the Upper Rio Grande basin. For these basins, we constructed water level change maps using both IDW and OK interpolations. Except for the Pecos Headwater basin, all storage change calculations included both a total change from the earliest interpolations (normally the 1950s interpolation), and the summed decade-by-decade changes. Because our method restricts the produced maps to the intersection of the well coverages, the total change from the 1950s levels and the summed decade-by-decade changes included different spatial well networks, but, generally, produce consistent results.

In almost all cases, groundwater levels in the basin-fill aquifers of the Rio Grande and uppermost Pecos systems are declining. Basin-wide declines are generally greatest in closed or open ephemeral basins with high societal water demands:

- Estancia—2 km^3 declines since 1950s.
- Mimbres—2.5 km^3 to nearly 4 km^3 declines since the 1950s.
- Rio Puerco—roughly 4 km^3 declines since the 1950s.
- Tularosa Valley—2 km^3 declines since the 1950s.

Less populated and utilized closed and open ephemeral and small perennial basins showed smaller (less than 0.5 km^3) declines over their records. Their data were more sparse, causing some of the estimates to only cover a subset of the decades desired. In most of the closed and small river open basins, water level declines were observed around population centers with some mild water level increases along the mountain fronts. The perennial open basins with a through flowing Rio Grande showed a combination of behaviors. Near the river and under low pumping requirements, the water levels remained static or possibly rebounded over the last 60 years. Away from the river and when the aquifer next to the river has been excessively depleted, the river recharge cannot balance depletions. In these cases, the basin-fill unconfined aquifer behaves similar to those in the closed basins.

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