Journal of Applied Geophysics 209 (2023) 104916

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Determining seasonal recharge, storage changes, and specific yield using repeat microgravity and water-level measurements in the Mesilla Basin alluvial aquifer, New Mexico, 2016–2018

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ARTICLE INFO

Keywords:
Microgravity
Groundwater/surface-water exchange
Recharge
Specific yield
Groundwater storage
Binational aquifer
Drought

ABSTRACT

Increasing water demand and multi-year drought conditions within the Mesilla/Conejos-Médanos Basin near the New Mexico-Texas- Chihuahua border have resulted in diminished surface-water supplies and increased groundwater withdrawals. To better understand recharge to the shallow aquifer, the spatial and temporal groundwater storage changes, and the variability of specific yield (Sy) in the aquifer, seasonal groundwater elevation and repeat microgravity measurements were made during the irrigation release and non-release seasons of 2016, 2017, and 2018 at a network of locations near Las Cruces, New Mexico.

The data collected during this investigation were able to capture seasonal change in groundwater elevations and storage from various sources of recharge at multiple sites in the shallow aquifer. Seasonal recharge in the study area was attributed to streamflow, the application and conveyance of irrigation water, and large or sustained precipitation events. However, increasing groundwater gradients in recent decades between piezometers close to the river and those more than a kilometer from the river suggests that recharge from river seepage has become localized at the seasonal scale. Overall, there was a net increase in storage of almost 8.4 cubic hectometers in the study reach between the start and end of the study, largely following the increased surface-water availability and above average precipitation in 2017. Specific yield, estimated by comparing the groundwater-level changes and storage changes at six sites in the study area, ranged from 0.14 (+/− 0.05) to 0.30 (+/− 0.06), which is slightly greater than previously reported estimates (0.10 to 0.25), but still within the error of the estimates. Most of the variability in the estimated storage change, that was not well-correlated with groundwater elevation change, is thought to be from soil moisture in the unsaturated zone.

This investigation demonstrates the value of adding repeat microgravity measurements to conventional groundwater monitoring to better understand the sources and extent of recharge as well as the variability of Sy in the aquifer. Continued monitoring, under a variety of available surface water and meteorological conditions, could provide a more comprehensive understanding of the water budget and reduce the specific yield estimation uncertainty. Evaluating water-levels and storage conditions prior to, and following, local recharge events may help managers identify threshold conditions for aquifer storage depletions and recoveries.

1. Introduction

Understanding the interactions between surface water and groundwater is critical to managing the conjunctive use of integrated water resources (Alley et al., 2002; Sophocleous, 2002; Wang et al., 2015; Fuchs et al., 2018). The storage of streamflow as groundwater in alluvial aquifers is an important factor governing the duration of perennial flow (Harvey and Bencala, 1993; Woessner, 2000) and can, in turn, act as a

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https://doi.org/10.1016/j.jappgeo.2022.104916
Received 28 April 2021; Received in revised form 3 August 2022; Accepted 19 December 2022
Available online 21 December 2022

reliable supplemental supply of water during drought conditions (Alley et al., 2002; Taylor et al., 2013). The amount of water that can be stored as groundwater is partially a function of the aquifer's specific yield. Specific yield (Sy) is typically poorly constrained using traditional methods (Chen et al., 2003), but an estimate of specific yield is important for water production and groundwater modeling purposes, especially when modeling the transient response to stresses (Gehman et al., 2009; Barlow and Leake, 2012).

The Mesilla/Conejos-Médanos Basin (Basin) contains a transboundary aquifer that underlies portions of Texas and New Mexico (U.S.) and Chihuahua (Mexico). Increasing water demand and multi-year drought conditions (National Drought Mitigation Center, 2019) within the Basin and the larger Rio Grande watershed (Fig. 1) have resulted in diminished surface-water supplies and increased groundwater withdrawals (King, 2021). Conjunctive management and use of these water resources is determined by a myriad of legal constraints including the Rio Grande Compact, an international treaty, and the Rio Grande Project (a U.S. federal water project) (Hanson et al., 2020).

In 1987, the U.S. Geological Survey (USGS) established the Mesilla Basin Monitoring Program (MBMP) to document and identify trends in groundwater conditions and stream/aquifer relations in the Basin. The data collection efforts of the MBMP have continued through the present (2022) in cooperation with a variety of federal, state, and local agencies. In 2016 repeat microgravity data was included in the MBMP and this

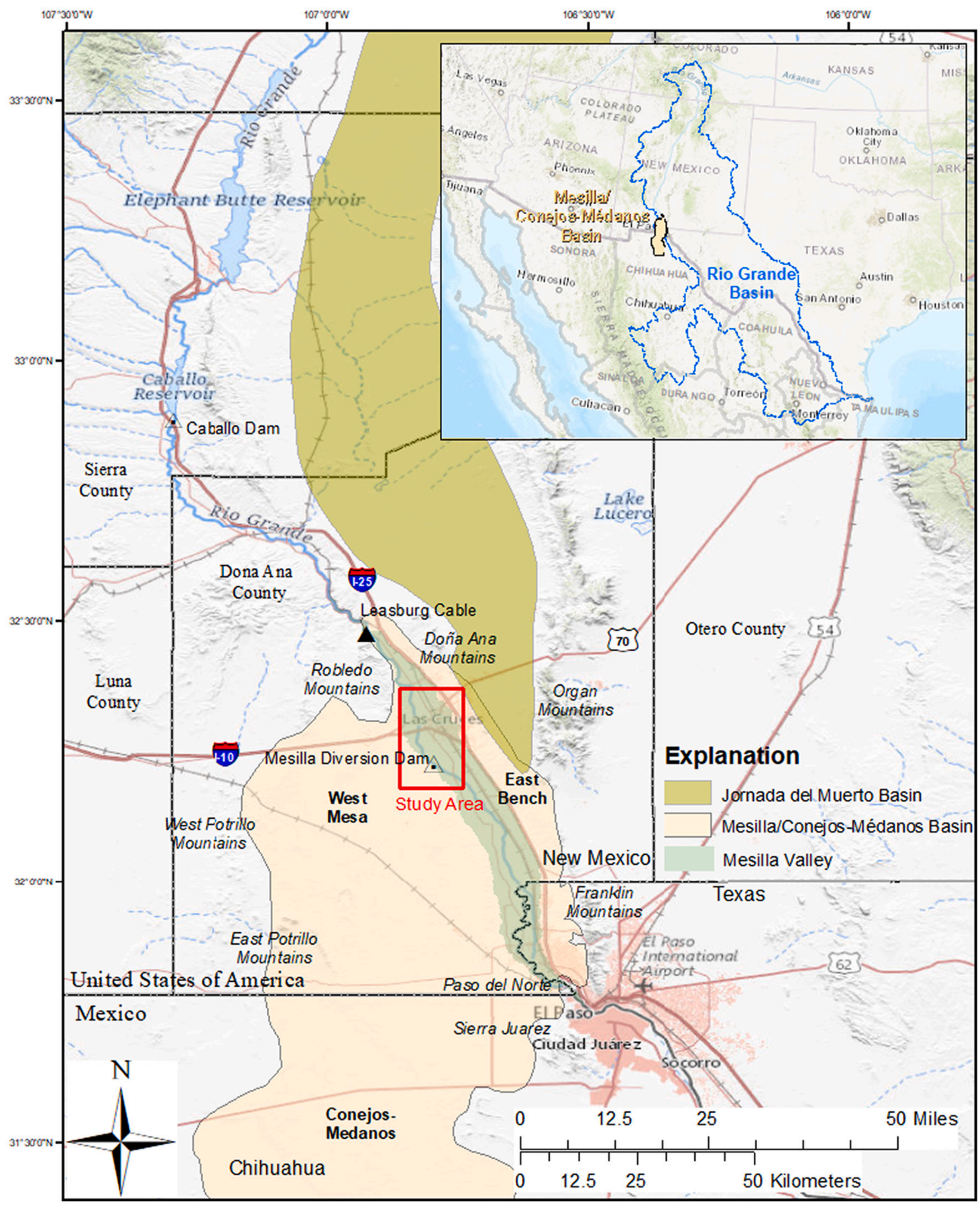

Fig. 1. Location of the Mesilla/Conejos-Médanos Basin study area in Doña Ana County, New Mexico. Base map and references from U.S. Geological Survey (2019a) and Teeple (2017). Geographic Coordinate System, North American Datum of 1983.

study analyses that data along with groundwater-elevation data to gain further insights into the recharge of the shallow aquifer, spatial and temporal groundwater storage changes, and the variability of specific yield in the aquifer. This was accomplished by precisely measuring the acceleration due to gravity and groundwater elevations two times annually for a total of 6 site visits between 2016 and 2018 at a network of 18 sites near Las Cruces and Mesilla, New Mexico (Fig. 2). The microgravity data are published in a data release by Kennedy et al. (2021b) and groundwater elevation data are available through the USGS National Water information System (NWIS; USGS, 2019b). Continuous groundwater elevation measurements, precipitation data and streamflow data from a stream-gage on the Rio Grande upstream of the study area were also included in the analysis to monitor the magnitude, location, and timing of groundwater storage changes in response to irrigation demands and streamflow in the Rio Grande.

The semiarid Basin is one of the southern-most basins within the tectonically active extensional Rio Grande Rift and covers about 8290 km^2 (km^2) with about 5960 km^2 in Chihuahua, Mexico (Hawley and Kennedy, 2004; Mexican Geological Service, 2011). The portion of the Basin in the U.S. is typically referred to as the Mesilla Basin, and the portion in Mexico is known as the Conejos-Médanos aquifer. The U.S. portion is further divided into the Mesilla Valley, the West Mesa, and the East Bench (Fig. 1). The entrenched Mesilla Valley of the Rio Grande crosses the eastern margin of the Mesilla Basin, where the cities of Las Cruces, New Mexico and El Paso, Texas pump groundwater from the basin-fill aquifer. Regional groundwater and surface-water flow is southeast toward El Paso through the Paso del Norte gap, which separates the Franklin Mountains from the Sierra Juarez to the south (Fig. 1; Robertson et al., 2022). Average annual rainfall in Las Cruces, New Mexico is about 25 cm (cm; U.S. Climate Data, 2020) and the total annual potential evapotranspiration in the area is estimated to be about 126 cm (Gabin and Lesperance, 1977).

The Basin aquifer system is made up of approximately 900 m (m) of alluvial, eolian and playa-lake sediments underlying a thin layer of upper Quaternary alluvium (the Rio Grande alluvium; Hawley and Kennedy, 2004) that are both part of the Santa Fe Group. Groundwater in the Santa Fe Group generally occurs under leaky-confined conditions as a result of interbedded clays (Nickerson and Myers, 1993). The Rio Grande alluvium is generally 18 to 24 m thick, but can range from 15 to 38 m thick, and is composed of river-channel and overbank depositional facies ranging in texture from sand and gravel to silt and clay (Wilson et al., 1981). Water-levels in the Rio Grande alluvium are shallow and unconfined and generally decrease from north to south following the land-surface at a gradient of about 0.8 to 1.1 m per kilometer (km) (Nickerson and Myers, 1993). Groundwater-flow directions are influenced locally by features such as seepage from streamflow in the Rio Grande, drains, canals, heavily irrigated fields, and by pumping (Hawley et al., 2001; Teeple, 2017). The hydraulic conductivity of the Rio Grande

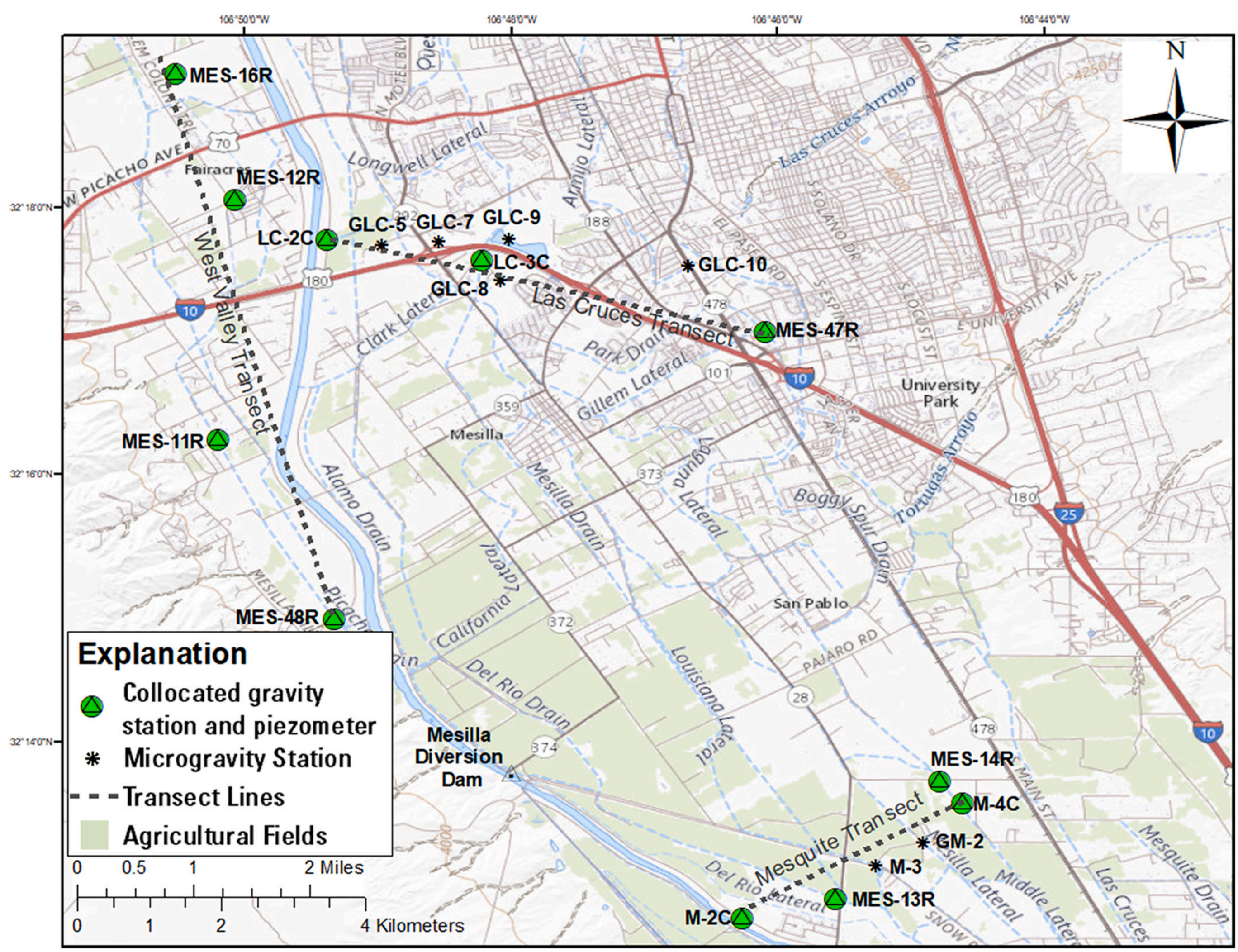

Fig. 2. Location of the microgravity stations and piezometers in Doña Ana County, New Mexico. Base map and references from U.S. Geological Survey (2019a). Geographic Coordinate System, North American Datum of 1983. See Fig. 1 for study area location.

alluvium is estimated to range from about 30 to 100 m per day (Hawley et al., 2001). Based on the Sy measured for various sands and interpretations of the valley-fill composition in the Basin, Conover (1954) estimated that the Sy for the Mesilla Valley should be about 0.25. Leggat et al. (1963) estimated the Sy for the alluvium to be 0.10 on the basis of aquifer tests, and Hawley and Kennedy (2004) reported Sy estimates that ranged from 0.1 to 0.2. In a model of the lower Mesilla Valley, Gates et al. (1984) used a Sy of 0.15 for the shallow river alluvium, and a later groundwater model of the U.S. portion of the Basin (Frenzel and Kaehler, 1992) used a Sy of 0.2 for the upper layer of the model based on findings in previous studies.

Despite the large surface area underlain by the Basin aquifer system, desert vegetation creates large negative soil pressures that prevent deep percolation beneath the root zone over most of the Basin (Frenzel and Kaehler, 1992). Recharge in arid and semiarid lands is often considered to be the result of focused recharge from ephemeral stream losses or ponded water (Cuthbert et al., 2016). Underneath the Rio Grande and ephemeral stream channels, infiltration can exceed evapotranspiration and water can infiltrate to greater depths. As a result, recharge to the Rio Grande alluvium primarily occurs as vertical flow from the surface-water system (the Rio Grande, canals, laterals, drains, and irrigated cropland fields) and periodically from major ephemeral stream channels during runoff events (Hawley and Kennedy, 2004). Seepage investigations, conducted to estimate the losses of streamflow to the groundwater or gains of streamflow from the groundwater, have generally reported losses throughout the Basin, except where the Rio Grande enters and exits the Basin (Briody et al., 2016a; Briody et al., 2016b; Crilley et al., 2013). The Rio Grande alluvium is, in turn, a major source of recharge to underlying and laterally adjacent basin fill of the Santa Fe Group.

While surface-water availability in the Rio Grande watershed is largely driven by regional climate and upstream water use, the local climate can affect both supply and demand in the Basin, especially for irrigated agriculture (Hanson et al., 2020). About 60 to 75% of streamflow in the Rio Grande is derived from seasonal snowpack that accumulates throughout the winter season in the high-elevation headwaters of the Rio Grande watershed (Fig. 1; Rango, 2006; Llewellyn and Vaddey, 2013). Streamflow in the Rio Grande through the Basin is controlled by Rio Grande Project demands and available surface water. The Rio Grande Project releases water from the upstream Elephant Butte and Caballo Reservoirs during the summer growing season (irrigation season) to provide water to the Elephant Butte Irrigation District (EBID) in New Mexico (including the study area), the El Paso County Water Improvement District No. 1 in Texas, and the Juarez Valley in Mexico (Hanson et al., 2020). During the winter seasons, when no dam releases occur (non-irrigation season), much of the riverbed is dry within the study area (Driscoll and Sherson, 2016). At the onset of water deliveries, the river channel is generally disconnected from the alluvial aquifer and infiltration losses can be high.

There are approximately 255 km^2 of irrigated lands along the Mesilla Valley (Hanson et al., 2020). Surface water not obligated to downstream users is diverted from the Rio Grande near the Leasburg cable and Mesilla Diversion Dam (Fig. 1), where the water enters a network of irrigation canals and laterals that convey and deliver surface water to farm headgates for irrigation use. Historically the canals and laterals were unlined earthen structures and lost an estimated 15% to 30% of the diverted water to groundwater recharge (Wilson et al., 1981). Presently (2022), an increasing number of these structures have been lined or converted to pipe to reduce those conveyance losses (Hanson et al., 2020). In addition to surface-water allotments, irrigated agriculture, in keeping with the traditional practice of conjunctive use of water in the area, is also the largest user of groundwater in the Basin, particularly in times of surface-water shortages. In recent years (2011 to 2018) the groundwater component of irrigation deliveries ranges from about half to over 90% (New Mexico Office of the State Engineer [OSE], 2021a), and irrigated agriculture accounted for a little over 80% of the groundwater pumping between 2011 and 2018 (OSE, 2021a) in the Lower Rio Grande watershed. Over the same period, the city of Las Cruces, including New Mexico State University, pumped about 30 cubic hectometers (hm^3) per year of groundwater for municipal uses (OSE, 2021a). Changes in groundwater storage can vary considerably from year to year depending on surface-water availability, land use, pumping, and climatic conditions (Hanson et al., 2020).

2. Methods

The collection of repeat microgravity and groundwater-level data in this investigation was scheduled to capture seasonal differences in the shallow groundwater in response to streamflow and agricultural irrigation. Microgravity measurements were collected twice annually at 18 sites (Fig. 2), for a total of six visits per site between 2016 and 2018 (Kennedy et al., 2021b). The repeat microgravity method provides a direct, quantitative estimate of subsurface water-storage change (Crossley et al., 2013). Depth to water was measured by the USGS at selected piezometers at the time of the gravity measurements (USGS, 2019b). These data were acquired by using electric tapes while following standard USGS protocols for discrete water-level measurements (Cunningham and Schalk, 2011). The eleven piezometers selected for the analysis (Fig. 2) are assumed to be screened only in the Rio Grande alluvium because of their depth and purpose of construction (Nickerson and Myers, 1993; Souder, Miller and Associates, 2009).

The aquifer in the study area is assumed to be incompressible, and no surface elevation changes were observed. A differential global positioning system (DGPS) survey was performed prior to the start of this investigation (2015) and compared with a 2009 survey (Souder, Miller and Associates, 2009) of nine shared sites. The largest elevation change reported between the surveys was 8.3 cm and the average elevation change was 3.3 cm, generally close to the accuracy of a height difference measured by a repeat DGPS survey (Rydlund Jr. and Densmore, 2012). Inter-annual elevation change caused by hydrological loading/unloading was minimized by carrying out the surveys at the same time each year. The area is rated primarily “moderate” susceptibility to collapsible soil, and no collapse features have been observed in the area (Rinehart et al., 2017). Therefore, no elevation corrections were applied. Other precautions to minimize measurement noise, such as instrument shielding from the wind, delaying measurements during earthquakes, and scheduling measurements to minimize traffic and equipment noise were taken.

Gravity measurements were carried out using a Micro-g LaCoste, Inc. A-10 absolute-gravity meter and ZLS Corp. Burris relative-gravity meter (Kennedy et al., 2021a). The absolute-gravity meter measures the free-fall acceleration of an object in a vacuum to provide a direct measurement of gravity at a location. Standard corrections for Earth tides (ETGTAB model), ocean loading (Schwiderski model), air pressure, and polar motion were applied to absolute-gravity measurements (Micro-g LaCoste, 2021). The absolute-gravity measurement was used to calibrate and correct for the instrument drift of the relative-gravity meter, which determined the gravitational force by measuring the length of a spring with a weight. Earth tide corrections for relative-gravity measurements were implemented in V-GRAV software (ZLS Corporation, 2021). Relative-gravity measurements were carried out in double loops of up to six relative-gravity stations and one or two absolute-gravity stations. In this technique, each site is visited at least twice, and the site with the absolute-gravity measurement is visited three times to identify and correct for instrument drift of the relative-gravity meter. Drift correction was carried out using the time-interpolation technique of Roman (1946) as implemented in GSadjust (Kennedy, 2020). For each absolute-gravity station, a vertical gradient was measured to transfer the measured value to the relative-gravity meter sensor height. Vertical gradients in the study area varied slightly between −2.88 to −3.30 microGal per centimeter (μGal/cm) indicating no large gravity anomalies. Absolute-gravity measurements and relative-gravity differences between stations were combined using least-squares adjustment in GSadjust (Kennedy, 2020). Least squares adjustment provides the "best-fit" gravity value at each station, incorporating the uncertainty of each measurement type. Least squares statistics, including *a posteriori* standard deviation and chi-square tests, were used to evaluate measurement accuracy. The average station standard deviations for each measurement ranged from 2.1 to 3.7 μGal (0.05 to 0.08 m of free-standing water) (Kennedy et al., 2021b). The smallest and largest station standard deviations are 1.8 and 5.6 μGal, respectively (0.04 and 0.13 m of free-standing water). Because changes to storage are the difference of two gravity measurements, the errors combined by the root sum of the squares and the result is a maximum error of just under 0.15 m of free-standing water. We report 0.15 m for all gravity storage changes to fall slightly on the conservative side, without losing resolution.

Repeat microgravity stations were established to coincide with two existing groundwater monitoring transects (the Las Cruces and Mesquite Transects) and a north-south groundwater monitoring transect on the west side of the river (West Valley Transect) (Fig. 2 and Table 1). The Las Cruces transect includes three piezometers with collocated gravity stations and five gravity-only stations. Aside from a pecan orchard near the river, the majority of the transect runs through urban areas of Las Cruces (Fig. 2). The Mesquite transect includes four piezometers with collocated gravity stations and two gravity-only stations. The transect is dominated by agriculture including pecan orchards and row crops (Fig. 2). The West Valley transect includes four piezometers with collocated gravity stations that parallel the Rio Grande. The West Valley transect is characterized primarily by agriculture in the form of row crops, and open space surrounding MES-48R (Fig. 2). Absolute-gravity measurements were made at stations LC-2, GLC-9, M-4C, and MES-48R (Fig. 2 and Table 1).

Supporting climate and hydrology data included weekly precipitation, Rio Grande streamflow, continuous and monthly groundwater elevations, and the timing of surface-water irrigation deliveries. These data were used to contextualize the discrete microgravity and groundwater elevation measurements. Specifically, the data were used to understand the timing of potential recharge events and the groundwater response to those events. Average weekly precipitation was calculated from the weekly sum of daily precipitation data for 32 stations in the study area (National Oceanic and Atmospheric Administration, 2019). Only stations with greater than 90% record, indicating proper function and maintenance from the start of 2016 to the end of 2018, were included in the average. Rio Grande streamflow entering the Basin is monitored by the EBID at the Leasburg Cable near the mouth of Selden Canyon (Fig. 1) and is available through EBID's Water Resource Information System (EBID, 2019). Based on hydrograph comparisons, the travel time through the study area for streamflow from Leasburg Cable to the Mesilla Diversion Dam is estimated to be less than 12 h (Ball et al., 2020). Continuous groundwater-levels were collected using submersible pressure transducers at nine sites and discrete monthly data was collected at two sites. Continuous data for the sites LC-2C and LC-3C and monthly data for sites M-2C and M-4C are available from the USGS National Water Information System (USGS, 2019b). Continuous data for the sites MES-11R, MES-12R, MES-13R, MES-14, MES-16R, MES-47R, and MES-48R are available from the EBID Water Resource Information

Table 1
Microgravity and water-level measurement locations of the Mesilla Basin in Dona Ana County, New Mexico.

		Site information					Depth to water range[a]	
Site name	USGS Station ID	Longitude (NAD83)	Latitude (NAD83)	Altitude (m above NAVD88)	Piezometer depth (meters)	Approximate distance to river (km)	Maximum depth (m below ls)	Minimum depth (m below ls)
	Las Cruces Transect							
LC-2C[b]	321745106492103	−106.8231	32.2959	1185.51	12.2	0.1	4.79	2.19
GLC-5[c]	n/a	−106.8161	32.2952	1186.59	n/a	0.8	n/a	n/a
GLC-7[c]	n/a	−106.8091	32.2958	1187.09	n/a	1.6	n/a	n/a
LC-3C	321740106481003	−106.8034	32.2947	1186.14	15.2	1.9	14.08	12.02
GLC-8[c]	n/a	−106.8014	32.2910	1185.44	n/a	2.3	n/a	n/a
GLC-9[b,c]	n/a	−106.8003	32.2960	1186.11	n/a	2.3	n/a	n/a
GLC-10[c]	n/a	−106.7777	32.2927	1185.58	n/a	4.3	n/a	n/a
MES-47R	321704106460601	−106.7682	32.2844	1182.46	14.9	5.3	UNK	10.68
	Mesquite Transect							
M-2C	321241106461603	−106.7712	32.2113	1176.35	15.2	0.1	3.93	2.20
MES-13R	321249106453401	−106.7595	32.2136	1175.55	10.7	0.8	6.35	2.77
M-3[c]	n/a	−106.7543	32.218	1176.41	n/a	1.3	n/a	n/a
GM-2[c]	n/a	−106.7484	32.2208	1177.60	n/a	1.8	n/a	n/a
MES-14R	321342106444701	−106.7464	32.2283	1177.80	13.4	2.7	UNK	9.11
M-4C[b]	321332106443703	−106.7441	32.2258	1177.39	12.2	2.6	11.09	8.93
	West Valley Transect							
MES-16R	321859106503101	−106.842	32.3166	1187.83	10.4	1.0	5.80	4.17
MES-12R	321803106500401	−106.8346	32.3008	1185.69	10.4	0.8	4.01	1.97
MES-11R	321616106501201	−106.8368	32.271	1183.66	10.4	0.8	3.23	2.57
MES-48R[b]	321455106492001	−106.8223	32.2486	1183.25	10.4	0.3	5.18	2.69

[ID, identification number; NAD83, North American Datum of 1983; NAVD88, North American Vertical Datum of 1988; m, meters; km, kilometers; ls, land surface; n/a, not applicable; UNK, unknown because water level was below bottom of piezometer]
[a] Depth to water range is for the study period calendar year 2016 through 2018.
[b] Absolute gravity site.
[c] Gravity-only site.

System (EBID, 2019) The accuracy of the water-level measurements is typically 0.3 cm.

The repeat microgravity method entails measuring small changes in gravity at a specified location. In hydrologic investigations, after appropriate corrections and absent other factors, changes in gravity are the direct result of changes in subsurface water mass (Pool, 2008). The gravitational effect of groundwater storage changes at the water table can be approximated by using the Bouguer slab (or "horizontal infinite slab") approximation (Telford et al., 1976):

$\Delta g = 2\pi \bullet G \bullet \Delta\rho \bullet b \bullet 10^8$ (1)

where Δg is the gravity effect in microGal (μGal) (1 μGal = 1.0 × 10^{-8} m/s^2), G is the gravitational constant (6.67 × 10^{-11} m^3 kilograms (kg)$^{-1}$ s (s)$^{-2}$), $\Delta\rho$ is the change in density of the body (kg/m^3), and b is the thickness of the slab in meters. For unconfined aquifers, the Bouguer slab represents an interval of thickness b at the water table that becomes saturated (previously air-filled pores are filled with water) or drains (water is replaced by air). For confined aquifers, the Bouguer slab represents the entire saturated thickness of the aquifer; in most situations the storage coefficient of a confined aquifer is very small, and therefore the change in density is small and the repeat microgravity method is impractical. The error in the Bouguer slab approximation is less than 5% for a body that has a diameter that is at least 40 times its depth (Pool and Eychaner, 1995). The use of this approximation is generally a reasonable estimate for storage change in many unconfined aquifers because storage changes at the water table are typically shallow compared to the lateral extent of the aquifer (Pool and Eychaner, 1995). The use of this approximation was verified by plotting the radial distance of twenty times the maximum depth to water at each site and confirming that there were no observable aquifer boundaries.

The density change of the slab, $\Delta\rho$, can be computed as.

$\Delta\rho = S \bullet \rho_w$ (2)

Where S is the aquifer-storage coefficient, equivalent to specific yield in an unconfined aquifer, and ρ_w is the density of water, commonly 1000 kg/m^3. Substituting eq. (2) into eq. (1) leads to.

$\Delta g = 2\pi \bullet G \bullet S \bullet \rho_w \bullet b$ (3)

The product $S \bullet b$ is the storage change, ΔS.

$\Delta S = \Delta g / (2\pi \bullet G \bullet \rho_w)$ (4)

If gravity is measured in μGal, and the density of water is assumed to be 1000 kg/m^3 then eq. (4), in units of meters of water, becomes.

$\Delta S = \Delta g / 41.9$ (5)

Therefore, a gravity change of about 41.9 μGal represents a storage change of 1 m of free-standing water (Christiansen et al., 2011; Pool and Eychaner, 1995). Seasonal storage changes for this study were calculated between each measurement to highlight the direction of change between the winter and summer measurements. By multiplying a change in free-standing water by an area over which this change is assumed to occur, one can calculate the volumetric change in groundwater storage at any two points in time.

Errors due to a sloped water table can be conceptualized by a tilted slab. The effect of a tilted slab is a nonlinear function of the size and depth of the slab. However, even with water table gradients of up to 5 degrees, the gravity effects are less than 1% (Montgomery, 1971). Errors resulting from the differences in water density (ρ_w) due to temperature and salinity variations expected in the Rio Grande alluvium are estimated to be less than 0.5%.

Specific yield (Sy) can be determined using a variety of field and laboratory methods, but spatial variability makes estimation at a representative scale difficult. Specific yield is often calculated from a pump test, which typically requires several assumptions including: the aquifer is homogenous and isotropic, with an infinite areal extent; the discharging well penetrates and receives water from the entire thickness of the aquifer; the well diameter is infinitesimal; and the water removed from storage is discharged instantaneously with the decline of the head (Cooper and Jacob, 1946). Using the repeat microgravity method, changes in groundwater-storage can be estimated directly, independent of Sy or depth to water. Repeat microgravity measurements integrate all the mass (storage) changes between the land surface and the water table. Therefore, in conjunction with water elevation measurements, one can determine Sy from the ratio of the change in storage (in one-dimensional length units) and the change in the groundwater elevation. Because the cumulative changes in storage and the groundwater elevations for this study were larger than the event-to-event changes, a more robust estimate for Sy was made calculating the changes between the groundwater elevation and storage from the initial measurements. Specific yield was estimated at each microgravity station collocated with a piezometer by fitting first-order least-squares linear regression between the change in groundwater elevations to the change in storage estimated by the change in gravity. The Sy is estimated as the slope of the line (that is, the change in storage per unit change in groundwater elevation) and reported herein with the standard error (Pool and Eychaner, 1995). Hydrogeologic conditions that can unduly influence the linear gravity/groundwater elevation relation include unaccounted for unsaturated soil moisture and perched, confined, multiple, and compressible aquifers; that is, storage changes not reflected by changes in groundwater elevation. Well construction in perched or multiple-aquifer systems influences this relation because well screens can allow flow into the well from single or multiple aquifers (Pool, 2008), resulting in a composite head not indicative of any single aquifer unit. Additionally, compressible aquifers cause land-surface elevation changes that result in gravity change in addition to those caused by storage loss. None of these conditions were noted to be present during the site selection.

3. Results

The surface-water conditions in the Mesilla Basin during the study (2016 to 2018) represent a reduced supply that has persisted since about 2000 (Fuchs et al., 2019). After remaining relatively stable in previous decades, long-term groundwater-elevation data in the Rio Grande alluvium show declines over the last two decades (2000 to 2020) accompanying reduced streamflow and irrigation deliveries (Fig. 3). Larger groundwater declines are recorded in alluvial piezometers farther from the Rio Grande, causing a shift in seasonal groundwater level variations and steeper groundwater gradients between the piezometers. Before 2000, water-level declines in piezometers more than 1 km from the river typically occurred in the winter as a result of decreased streamflow and reduced irrigation allotments and rebounded in the summer. Since 2000, water levels, in some years, increase in the winter and decline in the summer owing to a shift from surface water to pumped groundwater for irrigation (USGS, 2019b; Fig. 3). The annual mean streamflow in the Rio Grande below Caballo Dam (USGS station no. 08362500), New Mexico between 1984 and 2000 was about 33 cubic meters per second (cms) (USGS, 2019b). The rapid declines in groundwater elevations after 2000, particularly at LC-3C and M-4C are associated with annual mean streamflow below 20 cms (Fig. 3).

A full annual allotment of water for EBID irrigators is about 340 cubic hectometers (hm^3) (0.9 hm^3/km^2) and was delivered each year between 1979 and 2002 (King, 2021). However, drought conditions starting in the late 1990s have reduced surface-water availability in the Rio Grande and therefore irrigation deliveries have also been reduced. EBID surface-water allotments for 2016, 2017, and 2018 were approximately 120, 220 and 93 hm^3, respectively (OSE, 2021a; Fig. 4). Irrigators in the Mesilla Basin have historically developed groundwater rights to offset surface-water deficits, resulting in increased groundwater pumping when surface supplies are limited (Fig. 4).

The surface water available to irrigators in the Basin during the study varied largely due to regional climate patterns that affected runoff (OSE, 2021a) and thus useable water in Rio Grande Project storage. Locally, the annual rainfall totals showed a similar temporal pattern to the available surface water and were calculated from the annual sum of daily precipitation data for 32 stations in the study area (National Oceanic and Atmospheric Administration, 2019) to be about 24 cm in 2016, 32 cm in 2017 and 30 cm in 2018 for the study area.

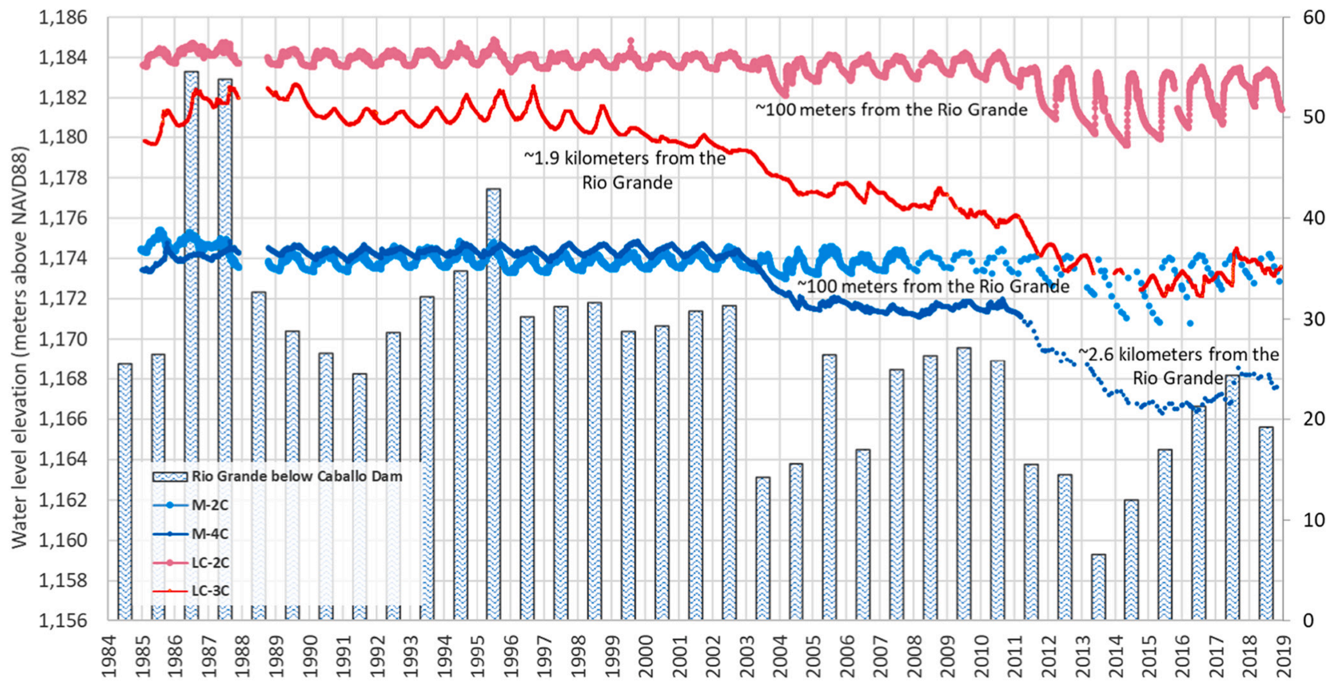

Fig. 3. Groundwater elevations in select piezometers screened in Rio Grande alluvium and annual mean streamflow in the Rio Grande below Caballo Dam, New Mexico from 1984 through 2018 in the Mesilla Basin. Data obtained from the U.S. Geological Survey National Water Information System database (USGS, 2019b) and the Rio Grande Compact Commission Reports (OSE, 2021b). Piezometer locations and other detailed information are provided in Table 1 and Fig. 2.

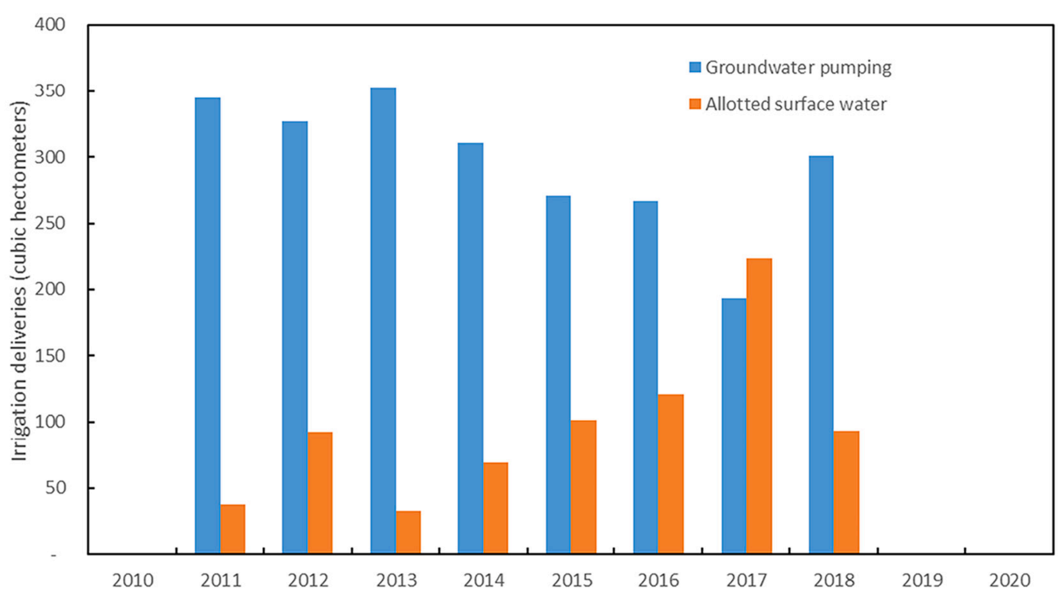

Fig. 4. Annual irrigation deliveries to the Elephant Butte Irrigation District, which includes the Mesilla Basin and the irrigators in the Rincon Valley. Data obtained from the New Mexico Office of the State Engineer District IV Water Master Reports (OSE, 2021a).

During the 2016, 2017, and 2018 release seasons, irrigation credits with El Paso County Water Improvement District No. 1 and treaty requirements to Mexico meant that water released from Caballo Reservoir was present in the Rio Grande channel and supplied to downstream users before, and after, water was diverted for irrigation by EBID users in the Basin (Figs. 5, 6, and 7). The microgravity and groundwater elevation measurements were coordinated with irrigation releases from Caballo Dam, however peak groundwater elevation changes were not always captured during the investigation.

3.1. *Groundwater elevations*

The seasonal response of groundwater elevations generally decreased with distance from the Rio Grande and proximity of irrigation deliveries. Groundwater elevations in the piezometers nearest the Rio Grande on each transect increased rapidly in response to recharge by streamflow. Piezometers located in agricultural areas typically recorded more slowly rising groundwater elevations from recharge following the start of irrigation. This recharge is reported to be from both the direct application of water to fields and seepage from the valley-wide

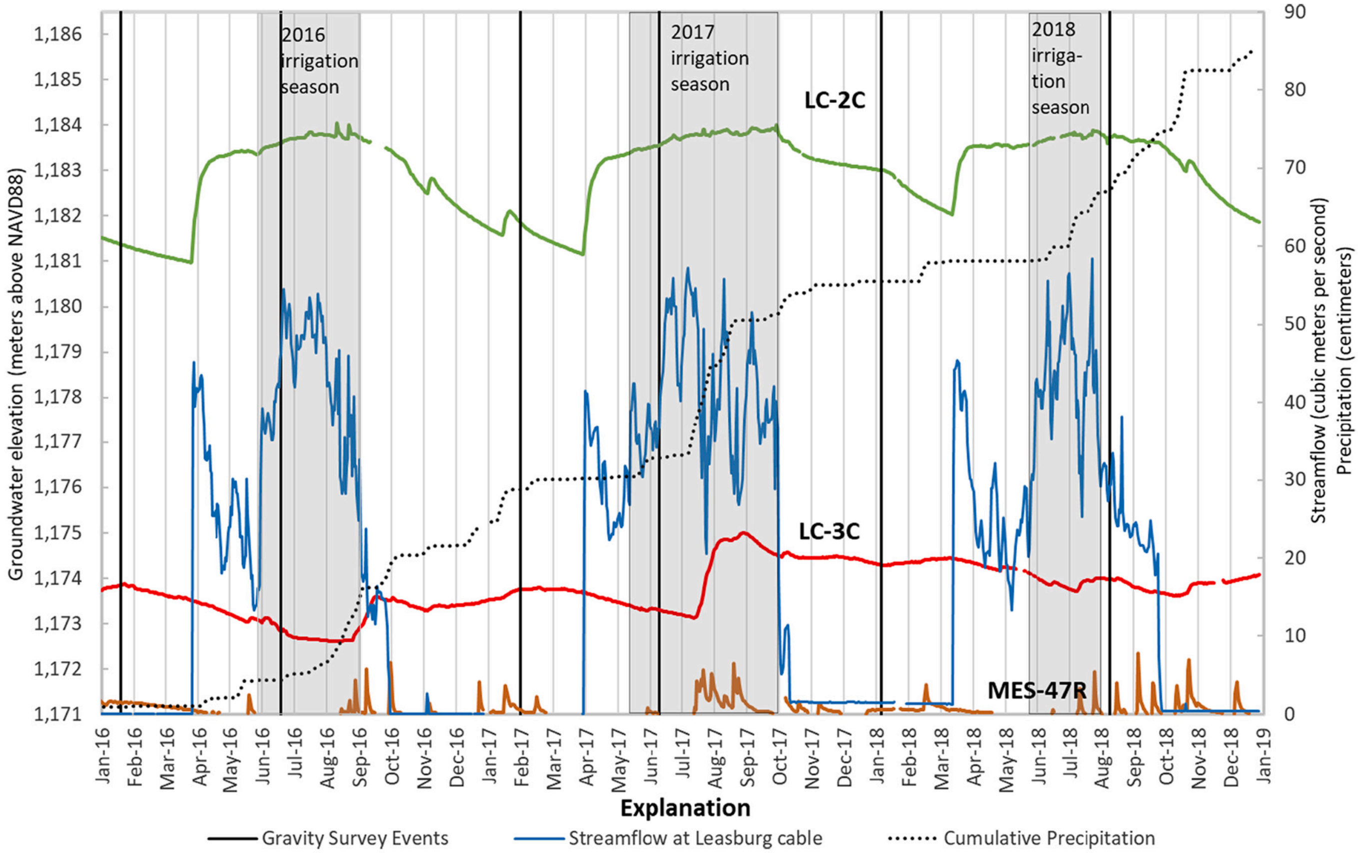

Fig. 5. Groundwater elevations in piezometers in the Las Cruces transect between January 2016 and December 2018, daily mean streamflow in the Rio Grande, cumulative weekly precipitation in the study area, and timing of the irrigation season in the Mesilla Basin.

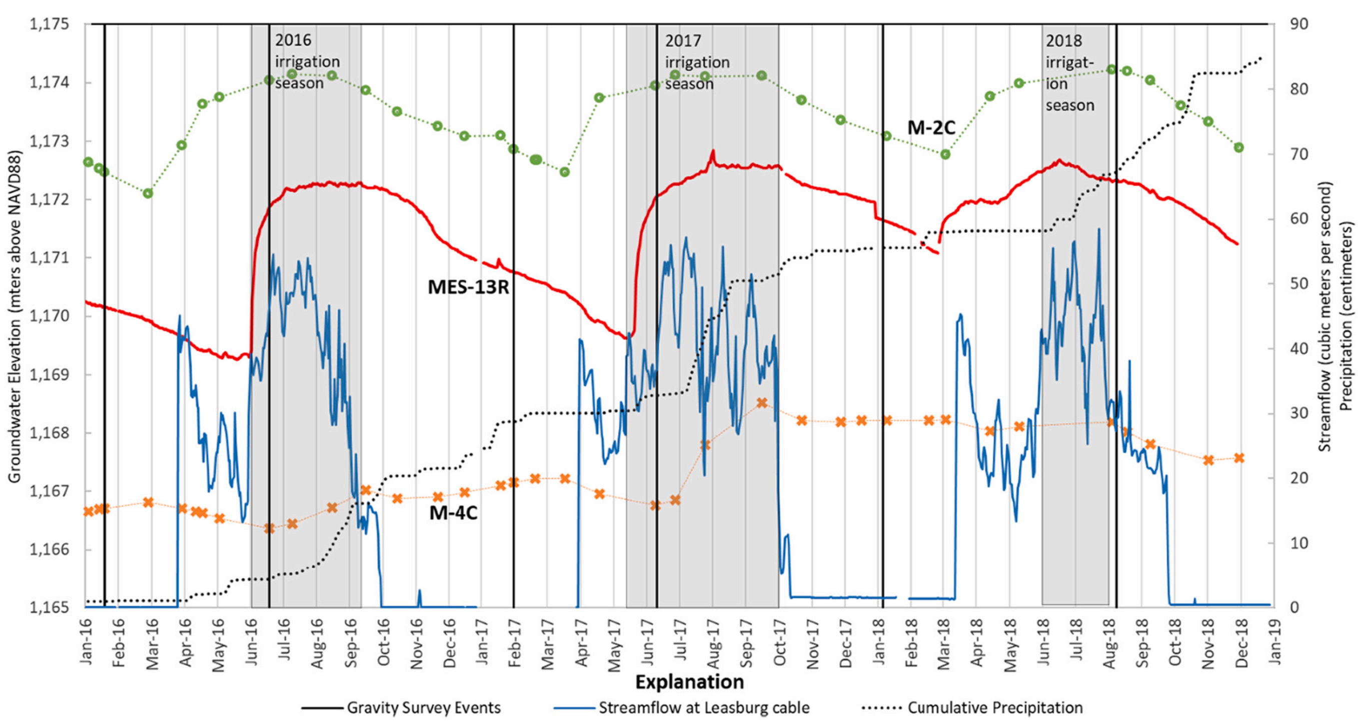

Fig. 6. Groundwater elevations in piezometers in the Mesquite transect between January 2016 and December 2018, daily mean streamflow in the Rio Grande, cumulative weekly precipitation in the study area, and timing of the irrigation season in the Mesilla Basin.

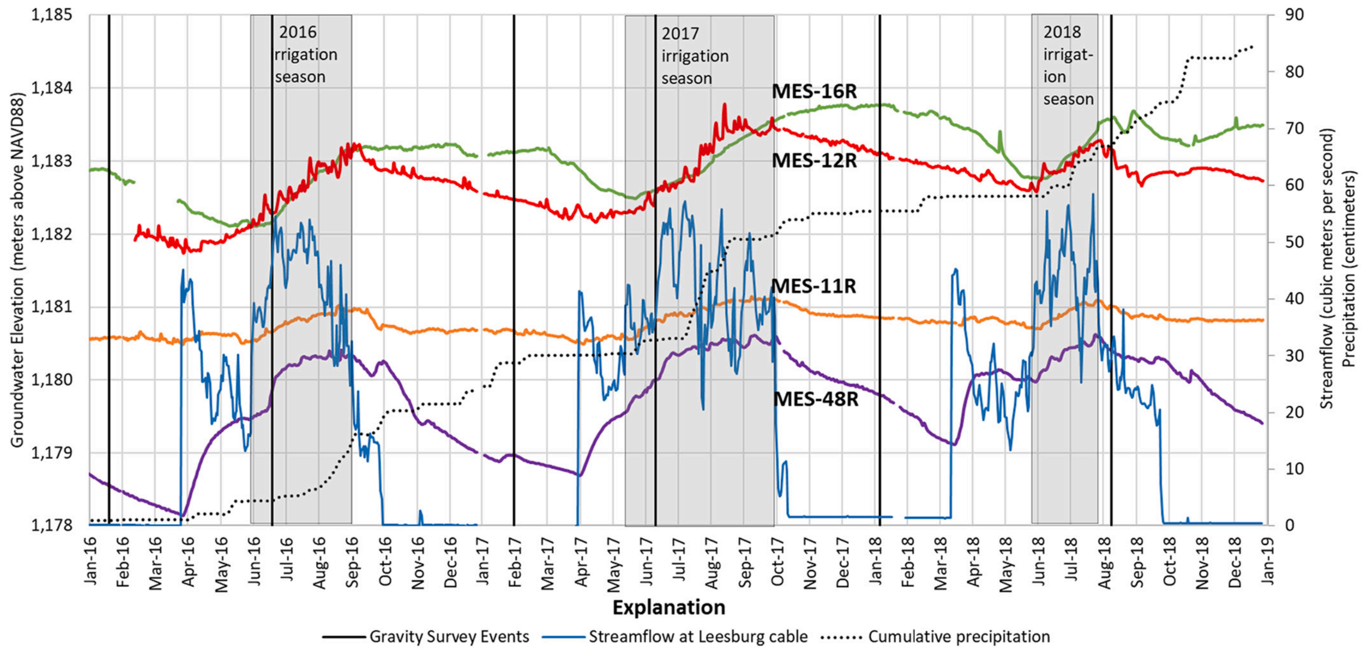

Fig. 7. Groundwater elevations in piezometers in the West Valley transect between January 2016 and December 2018, daily mean streamflow in the Rio Grande, cumulative weekly precipitation in the study area, and timing of the irrigation season in the Mesilla Basin.

irrigation conveyance system (laterals and canals) throughout EBID (Frenzel and Kaehler, 1992; Hanson et al., 2020). The groundwater elevations in piezometers farther from the river increased later than elevations in piezometers closer to the river and some increases coincide with local precipitation events. Groundwater elevations in several piezometers were below the recorder or the bottom of the piezometer for a large part of the investigation. These piezometers are some of the farthest from the river and include MES-14R in the Mesquite transect and MES-47R in the Las Cruces transect (Table 1 and Fig. 2).

3.1.1. Las Cruces Transect

In the Las Cruces transect (Fig. 5) the groundwater elevation at LC-2C, which is about 0.1 km from the river, was up to 12 m higher than LC-3C, which is about 1.9 km from the river, and 13–15 m higher than MES-47R, which is 5.4 km from the river. This represents a reduction in the groundwater gradient away from the river from as much as 6.9 m/km between LC-2C and LC-3C to less than 0.9 m/km between LC-3C and MES-47R and demonstrates local recharge from the river at this location.

The groundwater elevation in LC-2C, nearest the river, increased substantially and rapidly when streamflow was present in the Rio Grande and gradually declined when flow decreased (Fig. 5). Groundwater elevations fluctuated slightly as streamflow increased and decreased in response to local irrigation demands, and certain rain events appear to be recorded in the hydrograph. Rapid increases in groundwater elevations in LC-3C appear to be largely decoupled from streamflow and occur well after the start of releases and the onset of irrigation season. The increases do, however, correspond with large and/or sustained rainfall events, which occur within both the irrigation release and non-release seasons. While rapid increases in the groundwater elevations in LC-3C appear to be in response to precipitation events, the long-term groundwater conditions likely reflect available surface water (Fig. 3), and groundwater elevation changes due to surface-water availability this far from the river are likely to be characterized as highly attenuated signals. The groundwater elevation was below the recorder in MES-47R for much of the investigation, however rain events are captured in the groundwater level spikes in the hydrograph. Both LC-3C and MES-47R are located in urban settings and both are adjacent to unlined ditches that may collect storm water runoff, enhancing infiltration.

3.1.2. Mesquite Transect

In the Mesquite transect (Fig. 6) there is a 2.1 to 4.5 -m difference in the groundwater elevation between M-2C (located less than 0.2 km from the river) and MES-13R (about 0.8 km from the river) and a 3.0 to 6.1 -m difference between MES-13R and M-4C (which is about 12.2 km from the river). This yields a groundwater gradient range of 3.3 to 7.1 m/km between M-2C and MES-13R, which is slightly greater than the range of 1.7 to 3.4 m/km between MES-13R and M-4C indicating local recharge from the river.

The groundwater elevation in M-2C, nearest the river, increases quickly in response to streamflow in the Rio Grande and gradually declines when streamflow decreases. The groundwater elevation in MES-13R has little or no response to the start of Rio Grande streamflow in 2016 and 2017, and only a minor response in 2018, but the groundwater elevation responds quickly and dramatically to the start of irrigation deliveries from surface water. Some precipitation events are also observed in the hydrograph (Fig. 6). The water levels in M-4C do not clearly indicate a response to streamflow or irrigation, but an increase following significant precipitation in summer 2017 indicates that at least some recharge may result from precipitation in the area. Because M-4C is located within irrigated acreage, one would expect to see a groundwater response following the start of irrigation. However, the groundwater elevation response in M-4C was difficult to discern in 2016 and 2018, possibly due to restricted surface-water availability. While some groundwater elevation gains are observed following precipitation events, the sustained groundwater elevation gains in 2017 may be the result of increases in irrigation allotments. As with LC-3C, the long-term groundwater conditions likely result from available surface water in the Basin over multiple years (Fig. 3), and groundwater elevation changes are likely to be characterized as highly attenuated signals.

3.1.3. West Valley Transect

The West Valley Transect is parallel to the Rio Grande and groundwater elevation generally decreases in the downstream direction. Groundwater elevation differences in the West Valley transect piezometers ranged from about 2.1 to 4.6 m between the furthest upstream piezometer (MES-16R) to the furthest downstream piezometer (MES-48R; Fig. 7), which yields a groundwater gradient of about 0.2 to 0.4 m/km.

The groundwater elevation in MES-48R, nearest the river, increased relatively quickly in response to the start of streamflow in the Rio Grande and declined gradually when streamflow ceased. The groundwater elevations in MES-16R and MES-11R appear to be more responsive to irrigation deliveries from surface water than to streamflow or precipitation (Fig. 7), however groundwater fluctuations in MES-11R tend to be muted. One explanation for this muted response may be that this piezometer is located approximately 2.4 km downstream from the Las Cruces Wastewater Treatment Plant where treated effluent is discharged continuously (~0.3–0.6 cms; Ball et al., 2020; Briody et al., 2016a; Briody et al., 2016b; Crilley et al., 2013), maintaining streamflow past the site year-round. In addition, clay and silt in the upper 6 m of MES-11R (Souder, Miller and Associates, 2009) may result in locally reduced hydraulic conductivity in the aquifer and therefore muted groundwater response to recharge. Daily groundwater elevations in MES-12R fluctuate substantially more than in the other piezometers, possibly resulting from unknown discharges to the nearby drain or nearby pumping. Prolonged groundwater elevation increases and declines at this site cannot be attributed to any single source.

The groundwater gradient (0.2 to 0.4 m/km) along the West Valley transect is smaller than the equivalent north-south gradient between LC-2C and M-2C on the east side of the river (0.8 to 0.9 m/km). Based on groundwater elevations in LC-2C, MES-48R and M-2C, the steeper gradient appears to occur downstream from MES-48R and is likely related to a drop in the bed elevation of the Rio Grande downstream from the Mesilla Diversion Dam (Fig. 8).

Groundwater elevations in piezometers near the Rio Grande follow the bed elevation down the valley (Fig. 8). Piezometers greater than 1 km from the river do support a regional groundwater gradient from north to south, however, the substantially lower groundwater elevations in these piezometers, relative to those near the Rio Grande, indicate limited near-term recharge from the recent reduced streamflow in the Rio Grande. Seasonal fluctuations in these wells may result from conveyance and application of irrigation water, precipitation, and groundwater pumping. The distribution of groundwater elevations supports the conceptual model of a groundwater system that is locally recharged by streamflow, but large groundwater-storage deficits resulting from decades of reduced surface-water availability (Fig. 3), is not being overcome by recharge from recent, limited streamflow during this study. Some groundwater elevation gains from seasonal recharge, recorded in piezometers farther from the river, did, however, appear to persist in subsequent years.

3.2. *Storage changes*

Groundwater storage in the Rio Grande alluvium, as determined by the repeat microgravity method, slightly increased in the Las Cruces and Mesquite transects, and, to a smaller degree, in the West Valley transect between the start and end of the study. Changes in storage were computed between each site visit and many changes were associated with the seasonal groundwater elevation changes. The relatively large magnitude of seasonal gravity change shows the groundwater in the study area occurs in an unconfined aquifer (Table 2).

3.2.1. *Las Cruces Transect*

Seasonal storage changes in the Las Cruces transect ranged from −0.31 to 0.45 m of water. As with the groundwater elevation changes, storage changes at LC-2C increased in the summer as a result of recharge during the period of streamflow in the Rio Grande (Fig. 9). The gravity response at sites GLC-5, GLC-7, GLC-8, and GLC-9 (near piezometer LC-3C) are similar to one another and are generally in the opposite direction of LC-2C. The observations at sites GLC-10 and MES-47R, which are furthest from the river, did not respond predictably to seasonal changes and the magnitude of the storage changes was smaller (Fig. 9).

The largest increases were measured at sites GLC-5, GLC-7, GLC-8, and GLC-9 between summer 2017 and winter 2018 (Fig. 9). The changes in storage along the transect indicate that recharge from streamflow in the Rio Grande was not propagating very far in the alluvial aquifer underlying Las Cruces or that the recharge was lagged. While seasonal changes in storage were evident, there was also an overall net increase in storage along the Las Cruces transect at all sites except for GLC-7 and GLC-9. The average total storage increase at each of the Las Cruces transect sites over the study period was about 0.23 m of water, with the majority of the gains occurring following the relatively higher surface-water availability in 2017. It is important to note that because the timing of the gravity measurements was made to coincide with streamflow, the gravity measurements do not capture the largest

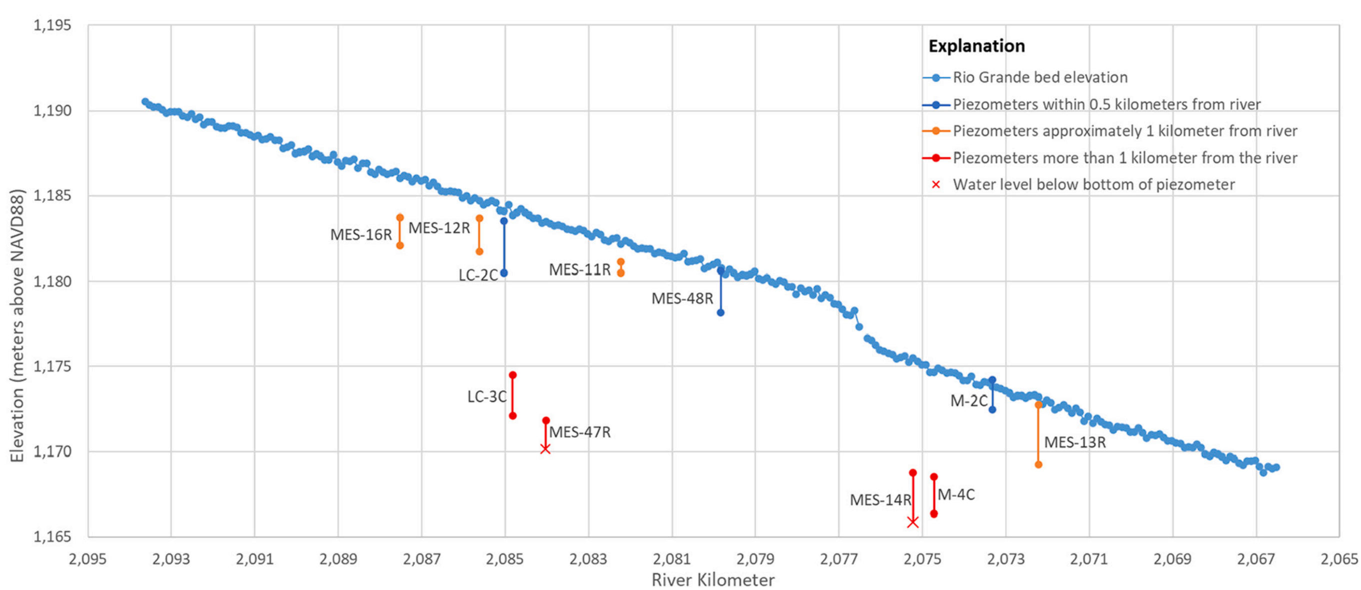

Fig. 8. Groundwater elevation ranges in piezometers throughout the study area in the Mesilla Basin between January 2016 and December 2018. The bed elevation is taken from bare-earth lidar data (International Boundary and Water Commission, 2015) and river kilometers are referenced upstream from the confluence of the Rio Grande with the Gulf of Mexico (Hendricks, 1964).

Table 2
Microgravity values and standard deviation of measurements made in the Mesilla Basin in Dona Ana County, New Mexico, 2016 to 2018.

Site name	January-16		June-16		January-17		June-17		January-18		August-18	
	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD
Las Cruces Transect												
LC-2C	979,105,530.6	3.0	979,105,535.3	2.1	979,105,525.4	2.3	979,105,539.6	4.1	979,105,535.3	3.2	979,105,547.2	2.3
GLC-5	979,106,344.0	3.2	979,106,339.3	2.1	979,106,348.9	2.3	979,106,341.7	4.2	979,106,358.4	3.0	979,106,358.7	2.4
GLC-7	979,107,564.2	3.2	979,107,551.1	2.1	979,107,561.4	2.1	979,107,548.8	4.2	979,107,567.4	2.7	979,107,559.5	2.2
GLC-8	979,108,566.0	3.2	979,108,559.2	2.1	979,108,566.7	2.0	979,108,563.5	4.2	979,108,581.5	2.4	979,108,576.0	2.1
GLC-9	979,109,775.6	3.1	979,109,765.5	2.1	979,109,774.0	1.9	979,109,761.5	4.1	979,109,782.3	2.2	979,109,769.5	2.0
GLC-10	979,116,270.1	3.2	979,116,281.9	2.1	979,116,279.3	2.5	979,116,279.7	5.2	979,116,287.6	3.0	979,116,286.3	2.5
MES-47R	979,118,586.9	3.2	979,118,597.0	2.1	979,118,607.2	2.9	979,118,601.7	5.6	979,118,603.6	3.7	979,118,607.0	2.9
Mesquite Transect												
M-2C	979,110,415.7	3.2	979,110,420.9	2.1	979,110,406.2	1.8	979,110,426.2	2.6	979,110,406.9	2.2	979,110,433.1	1.9
MES-13R	979,113,422.1	3.2	979,113,424.8	2.1	979,113,413.2	1.9	979,113,434.2	2.9	979,113,429.9	2.3	979,113,441.5	2.1
M-3	979,115,092.5	3.2	979,115,085.3	2.1	979,115,082.3	2.1	979,115,089.9	3.1	979,115,094.9	2.6	979,115,101.3	2.2
GM-2	979,117,129.1	3.3	979,117,111.5	2.1	979,117,119.7	2.4	979,117,124.1	3.4	979,117,141.0	3.1	979,117,139.5	2.5
MES-14R	979,117,530.4	3.3	979,117,520.7	2.2	979,117,513.3	2.5	979,117,522.2	3.6	979,117,527.0	3.3	979,117,533.9	2.6
M-4C	979,118,805.3	2.9	979,118,791.6	2.1	979,118,791.4	2.6	979,118,798.6	3.5	979,118,806.9	3.6	979,118,809.0	2.6
West Valley Transect												
MES-16R	979,105,795.6	3.2	979,105,778.1	2.2	979,105,800.0	2.4	979,105,814.8	3.2	979,105,798.7	3.3	979,105,800.4	2.5
MES-12R	979,104,705.9	3.3	979,104,704.4	2.2	979,104,710.0	2.6	979,104,730.4	3.4	979,104,717.1	3.7	979,104,711.6	2.6
MES-11R	979,101,324.2	3.1	979,101,310.2	2.2	979,101,321.5	3.3	979,101,332.7	4.0	979,101,312.0	4.9	979,101,320.1	3.2
MES-48R	979,101,691.4	2.9	979,101,684.9	2.1	979,101,687.1	3.2	979,101,706.3	3.8	979,101,687.6	4.7	979,101,692.3	3.0

[Date, Month-YY; SD, Standard deviation].

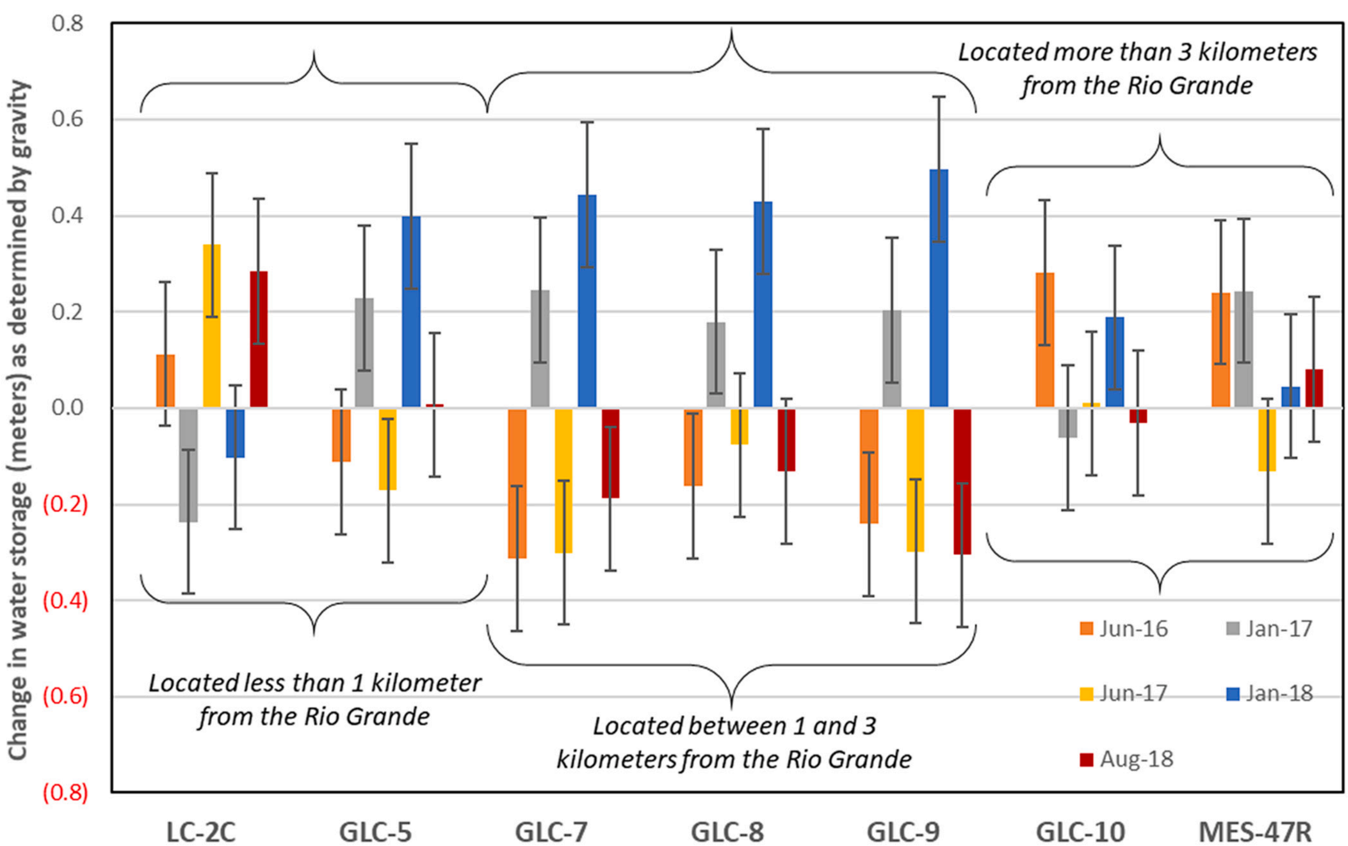

Fig. 9. Groundwater storage change at locations along the Las Cruces transect in 2016, 2017 and 2018. Warm colors symbolize summer measurements and cool colors symbolize winter measurements. Date shown as month and year.

changes in the aquifer, as indicated by the continuous groundwater elevation hydrographs. Therefore, while there is seasonal periodicity in the storage changes, there is not a preferred time interval to calculate a change.

3.2.2. Mesquite Transect

The Mesquite transect is in an area dominated by agriculture, particularly pecan orchards. The seasonal storage changes along the Mesquite transect ranged from −0.46 to 0.63 m of water (Fig. 10;

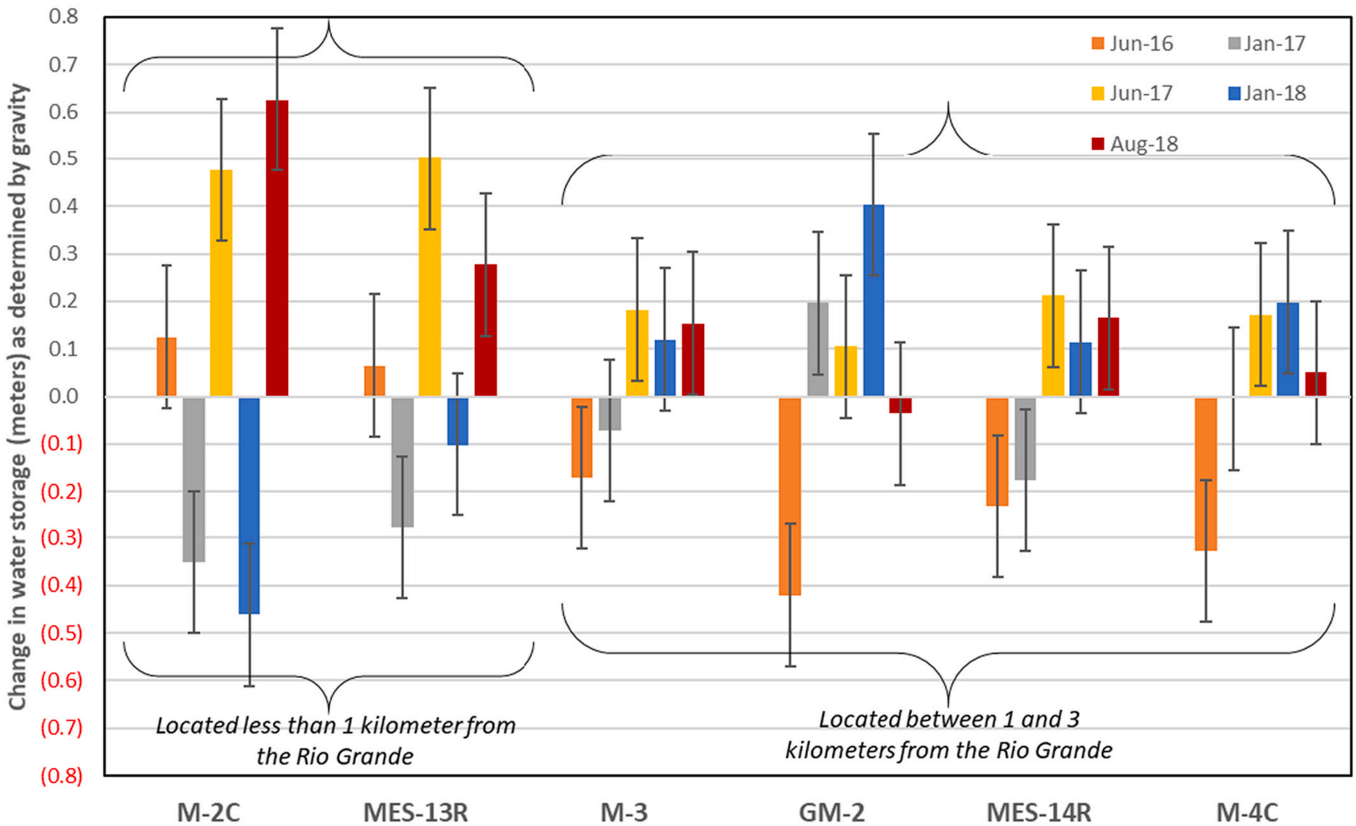

Fig. 10. Groundwater storage change at locations along the Mesquite transect in 2016, 2017 and 2018. Warm colors symbolize summer measurements and cool colors symbolize winter measurements. Date shown as month and year.

Kennedy et al., 2021b). The seasonal signal is evident at sites M-2C and MES-13R near the Rio Grande but was not observed at other locations.

The magnitude of the storage changes in the Mesquite transect are typically below 0.5 m of free-standing water. The largest change, an increase of about 0.6 m, occurred at M-2C between winter 2018 and summer 2018. Storage changes at M-2C and MES-13R, near the Rio Grande, increase in the summer and decline in the winter (Fig. 10), while the storage change observed at the sites farther from the river demonstrate a general decline in storage in the first year of monitoring, followed by an increase in storage the final year and a half. The average storage increase at each Mesquite transect site is about 0.25 m of water, with the majority of the gains occurring in summer 2017 and summer 2018.

The magnitude of the storage changes at sites within 1 km from the river in the Mesquite transect are greater than the storage changes at sites near the river in the Las Cruces transect and smaller than sites that were between 1 and 3 km from the river. The groundwater response to streamflow in both the Las Cruces and Mesquite transects indicates the limited areal extent of recharge from streamflow in the study area.

3.2.3. West Valley Transect

The storage changes at locations in the West Valley transect respond with far less seasonality than sites in the Las Cruces or Mesquite transect (Fig. 11; Kennedy et al., 2021b). The lack of seasonality in the West Valley transect may be attributed to the timing of the measurements and the buffered response of the water table to streamflow as previously discussed in Section 3.1.3.

The magnitudes of the storage changes at the West Valley transect sites were under 0.6 m and generally less than 0.5 m of free-standing water (Fig. 11). The largest storage change (0.52 m) was observed in MES-16R. Unlike the Las Cruces and Mesquite transect, the apparent lack of a clear seasonal storage response in the West Valley transect, despite the fact that each of the sites are within 1 km of the river, may be related to the groundwater flow conditions near the West Mesa (Robertson et al., 2022) that reduce the winter groundwater declines (Fig. 8). The average change in storage in the West Valley transect was an increase of about 0.04 m of free-standing water, with the majority of the gains occurring between winter 2017 and summer 2017.

3.3. Specific yield

Specific yield (Sy) was estimated at each microgravity station collocated with a piezometer, by comparing the change in storage and groundwater elevation to the initial measurement. Estimates ranged from 0.14 to 0.30 for seven locations, while two locations had Sy estimates that approached 0 (MES-11R and MES-48R). Two sites (MES-47R and MES-14R) were not used because the piezometers were dry for most of the investigation. Previously estimated Sy values for Rio Grande alluvium range from 0.10 to 0.25 (Conover, 1954; Leggat et al., 1963; Hawley and Kennedy, 2004; Gates et al., 1984; Frenzel and Kaehler, 1992).

3.3.1. Las Cruces Transect

Specific yield at LC-2C was calculated to be 0.14 (+/− 0.05), lower than many other sites in this study (Fig. 12). The consistent relation between the storage change and the groundwater elevation changes, as indicated by a high coefficient of determination ($R^2 = 0.65$), demonstrates that most of the storage change can be explained by changes in groundwater elevation. Small variations in the predicted relation may be due to changes in the lithology at various depths, added mass from water in the unsaturated zone, or measurement noise. The Sy at LC-3C, 0.30 (+/− 0.06), is about double that of LC-2C and has a higher

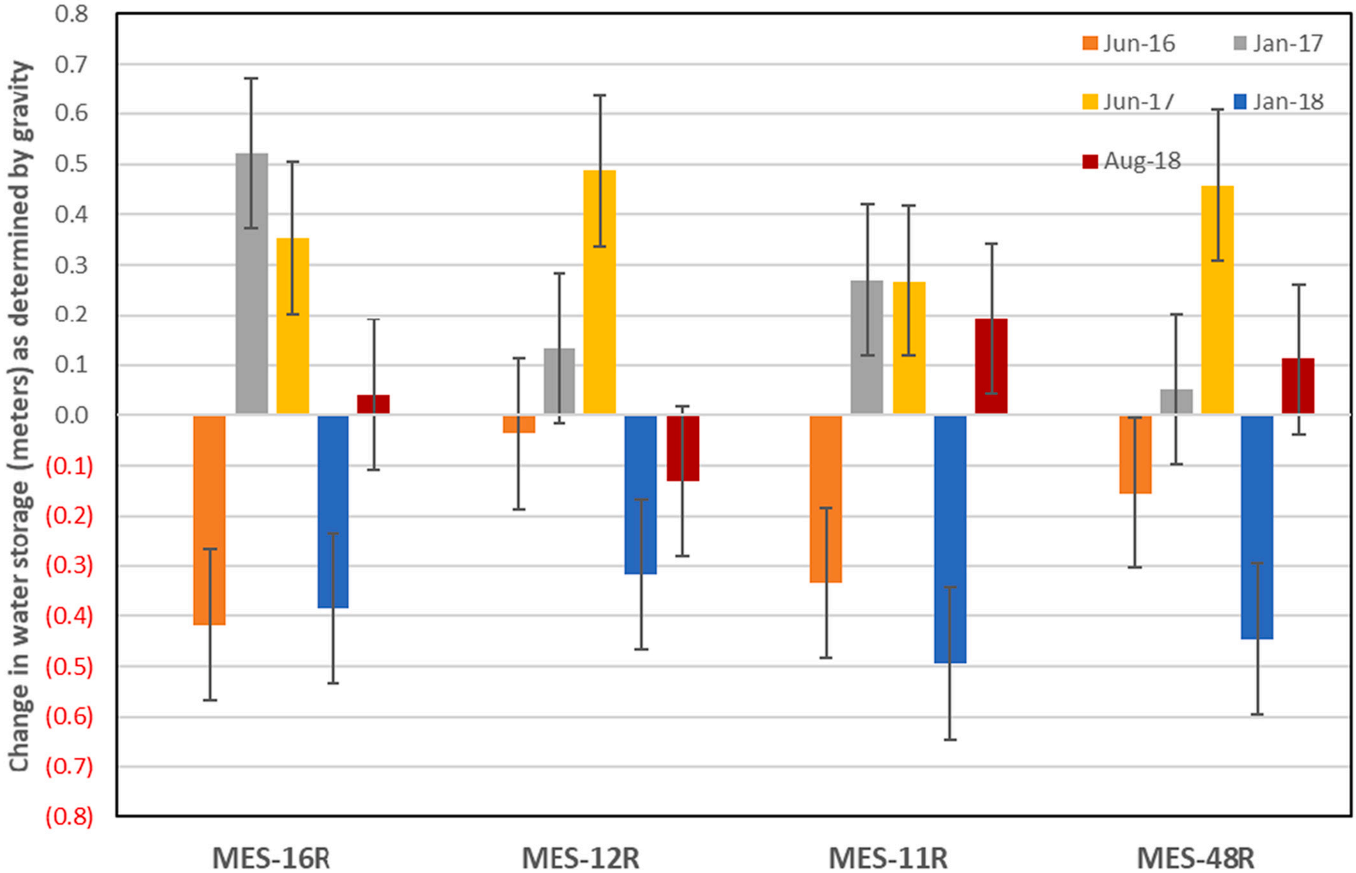

Fig. 11. Groundwater storage change at locations along the West Valley transect in 2016, 2017 and 2018. Warm colors symbolize summer measurements and cool colors symbolize winter measurements. All sites are within 1 km of the Rio Grande. Date shown as month and year.

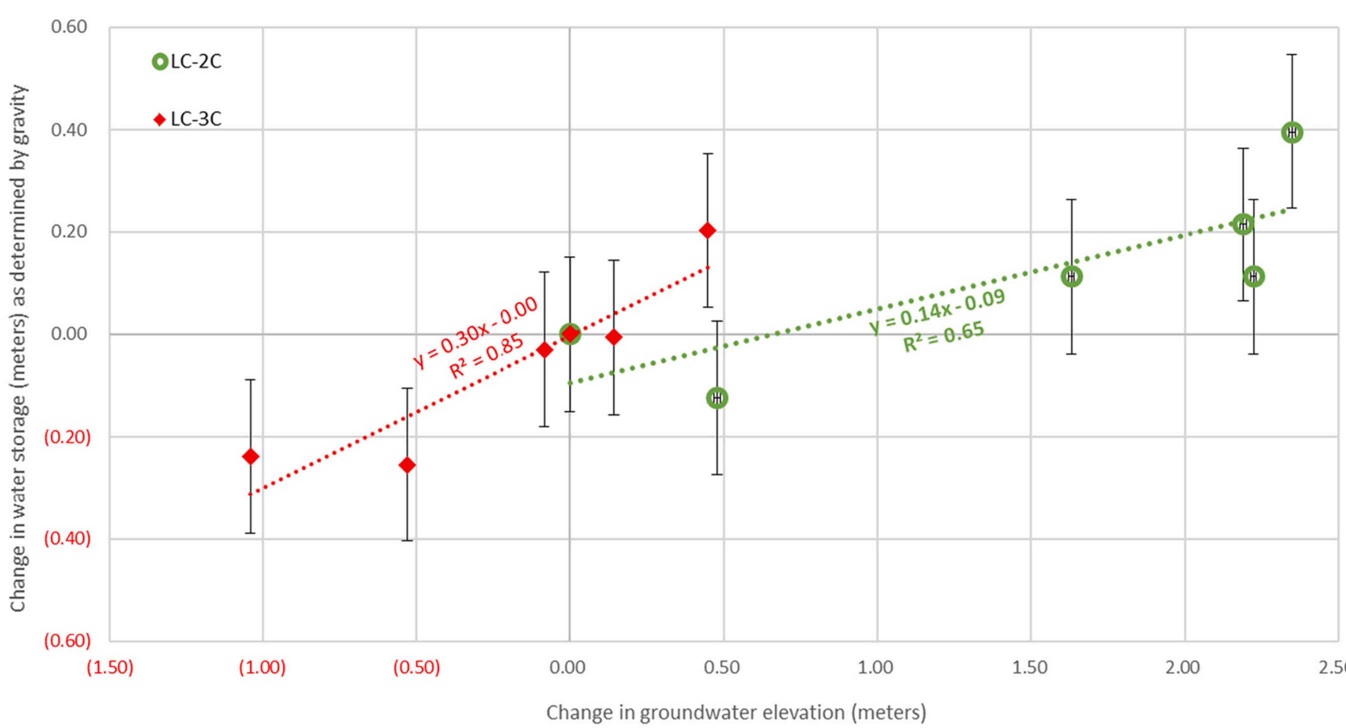

Fig. 12. Relation between groundwater storage and groundwater elevation changes and the specific yield estimate at piezometers located along the Las Cruces transect in the Mesilla Basin, New Mexico.

coefficient of determination ($R^2 = 0.85$) (Fig. 12). The change in water storage at LC-3C is computed as the average of the storage change at the gravity-only stations GLC-7, GLC-8, and GLC-9.

The Sy at LC-2C (0.14 +/− 0.05) is close to the lower end of previously reported estimates (0.10 to 0.25), whereas the Sy at LC-3C (0.30 +/− 0.06) is slightly greater than the highest previous estimate for the Rio Grande alluvium. Large differences in Sy could be expected in fluvial deposits where high- and low-energy deposits (coarse and fine grain, respectively) can exist in close proximity to each other.

3.3.2. Mesquite Transect

The specific yields calculated for the two near-river sites, M-2C and MES-13R, are 0.28 (+/− 0.11) and 0.22 (+/− 0.08) (Fig. 13), respectively, and are substantially larger than the river site in the Las Cruces transect, LC-2C (0.14; Fig. 12). The relation between the storage change and groundwater elevation change is moderately strong, as evidenced by the coefficients of determination ($R^2 = 0.62$ and 0.63, respectively). The value for the specific yield at M-4C (0.17 $\pm$0.09) should be used with caution because of the low coefficient of determination ($R^2 = 0.45$), owing largely to a couple of measurements. The depth to groundwater at M-4C (9 to 12 m) is about twice that of M-2C and MES-13R (2 to 6 m), increasing the potential for large soil moisture changes to affect the storage estimates.

3.3.3. West Valley Transect

Because all sites in the West Valley transect are in areas dominated by agriculture, higher groundwater elevations are expected in the summer because of recharge from streamflow and irrigation, and lower groundwater elevations are expected in the winter as the surface-water supplies are reduced. The groundwater elevations do generally follow the expected response (Fig. 7), but the groundwater storage change is less predictable (Fig. 11). Based on Fig. 14, it is apparent that the large variations in storage at these sites are not solely caused by changes in groundwater elevation at the water table. For example, the relatively large storage changes (over 0.3 m) compared to the groundwater-elevation changes (less than 0.3 m) in the MES-11R piezometer resulted in a poor Sy estimate (Sy = 0.00 +/− 0.82; $R^2 = 0.00$) (Fig. 14). In the absence of any observed changes to the land surface, the changes in gravity may indicate substantial soil moisture changes, measurement noise, or both. Soil moisture changes at locations where the water level is shallow (less than 6 m and typically around 3 m), may be affected by the application of surface water for irrigation and/or by evapotranspiration. Despite larger groundwater-level changes in MES-16R and MES-12R at the time of the gravity measurement, the specific yields (0.18 +/− 0.23 and 0.25 +/− 0.27, respectively) are also highly uncertain (R^2 = 0.13 and 0.17, respectively; Fig. 14). Several storage changes appear to be far larger than the corresponding groundwater level changes, resulting in the high uncertainty of these Sy estimates (Fig. 14). On average, there was very little storage change at MES-48R despite large changes in groundwater elevation (about 0.3 to 1.5 m). This may be because the piezometer was located farther from the river (about 180 m) than the gravity station.

The large storage changes accompanied by small groundwater-level changes suggest that soil moisture may be driving much of the storage change at MES-11R, MES-12R, and MES-16R. Without an observable surface disturbance that would significantly alter the mass at the site, and therefore the gravity field, ponded surface water or soil moisture, resulting from irrigation water percolating through the unsaturated zone but not reaching the water table, is the most likely source of storage changes that are not due to water-table fluctuations. In contrast, the small storage changes relative to the groundwater-level changes in MES-48R indicate either a locally semi-confined aquifer, a problem resulting from the microgravity monument siting, or is a consequence of wetland maintenance (ponded water) at the nearby state park.

4. Discussion

Groundwater elevations and storage change in the shallow piezometers near the Rio Grande (LC-2C, M-2C and MES-48R, Figs. 5, 6, and 7) increased rapidly in response to streamflow, indicating infiltration and lateral flow from the river as the primary source of seasonal recharge. Recharge from the infiltration of water through the irrigation

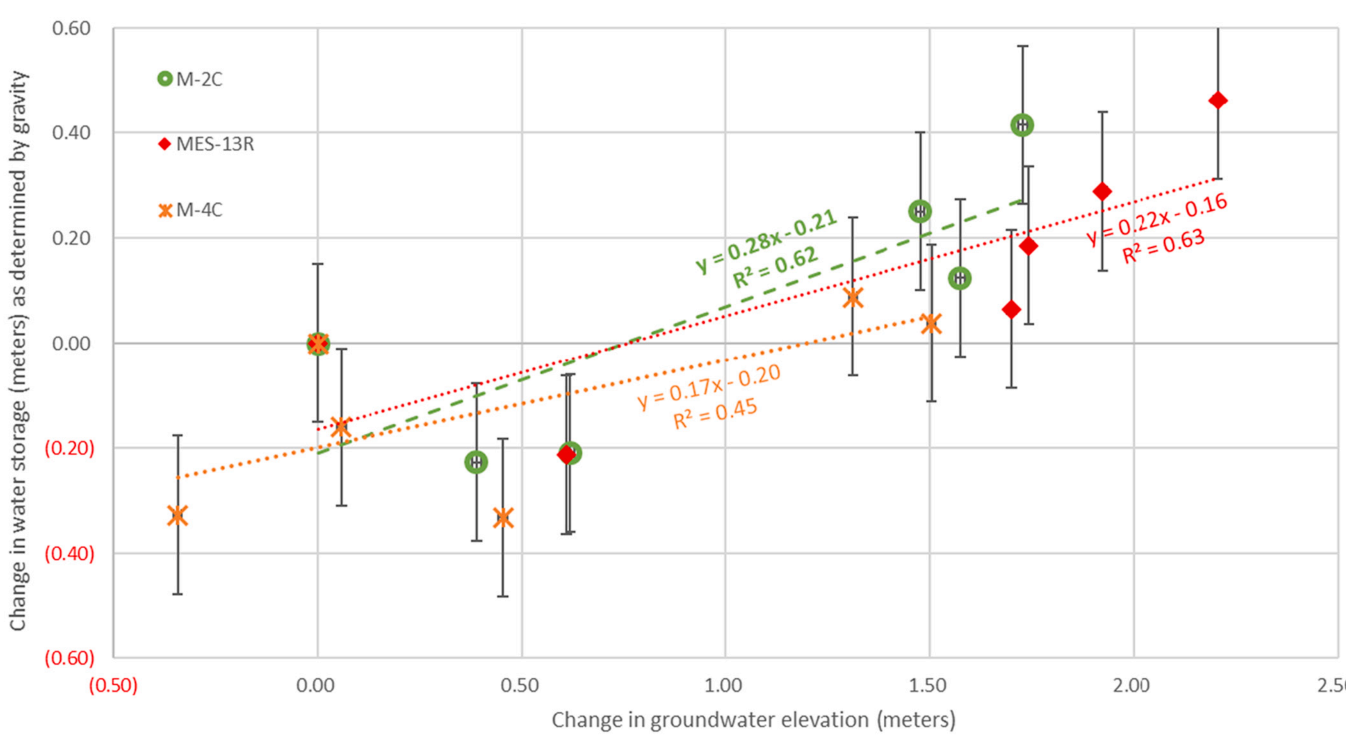

Fig. 13. Relation between groundwater storage and groundwater elevation changes and the specific yield estimate at piezometers located along the Mesquite transect in the Mesilla Basin, New Mexico.

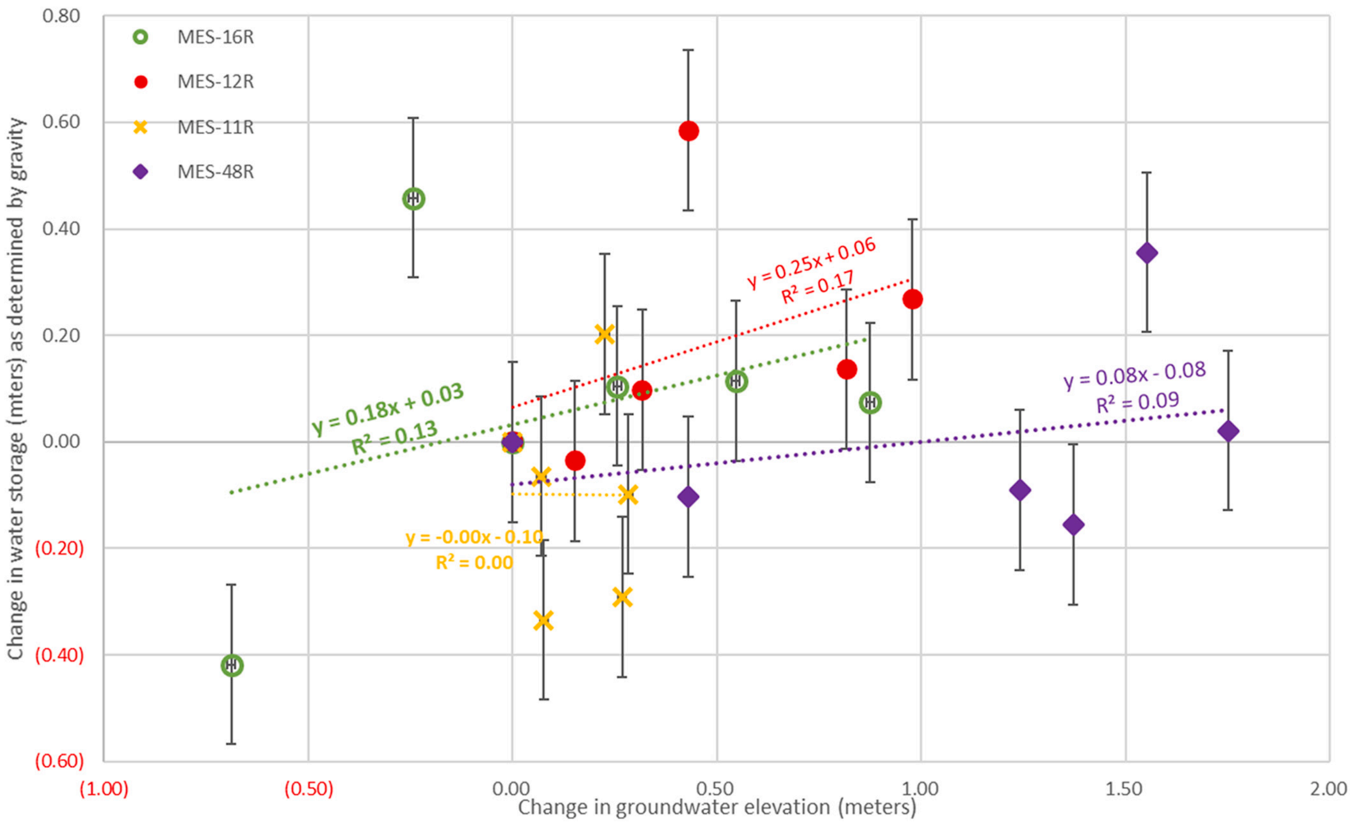

Fig. 14. Relation between groundwater storage and groundwater elevation and the specific yield estimate at piezometers located along the West Valley transect in the Mesilla Basin, New Mexico.

conveyance system and the surface application of irrigation water is the most likely source of seasonal recharge in piezometers MES-13R, MES-16R, and MES-11R (Figs. 6 and 7) because the groundwater elevation increases following the onset of irrigation deliveries and declines following cessation of deliveries. Seasonal recharge from precipitation is inferred at several piezometers farther from the river (LC-3C, MES-47R, and M-4C) (Figs. 5 and 6) where groundwater elevations were observed to increase following large or sustained precipitation events. A consistent relation between streamflow, irrigation deliveries, and groundwater levels at MES-12R was not observed, so a primary recharge source could not be determined. In most cases, increases in groundwater elevations and storage across the network were widespread, suggesting that recharge from summer streamflow and irrigation can increase storage throughout the aquifer. An indication of this is the groundwater response to the increased surface-water availability in the summer of 2017 that resulted in smaller groundwater storage and water-level declines at all sites for the remainder of the study. This confirms that inflows during interdecadal wet years can partially replenish water in aquifer storage as reported by Hanson et al. (2020). However, large groundwater-storage deficits resulting from decades of drought are not being overcome by recent surface-water availability (Fig. 3). While it is beyond the scope of this paper to determine whether there are long-term effects from the limited river seepage, recent work by Fuchs et al. (2019) in the upstream Rincon Valley demonstrates that reconnection of stream seepage to the shallow aquifer caused little change in the storage properties and aquifer response following the disconnection of the two. Therefore, it is unlikely that current groundwater deficits have resulted in aquifer compaction or land subsidence that would adversely affect the aquifer storage potential.

Higher groundwater elevations near the Rio Grande and a groundwater gradient in the direction of streamflow that is similar to the bed-elevation gradient of the Rio Grande (Fig. 8), supports the conceptual model of a groundwater system that is locally recharged by streamflow from the Rio Grande (Frenzel and Kaehler, 1992; Hanson et al., 2020; Robertson et al., 2022). However, large and, in recent decades, increasing (Fig. 3) groundwater gradients between piezometers close to the river and those more than a kilometer from the river indicates that recharge from river seepage has become increasingly localized at the seasonal scale. River seepage and agricultural irrigation likely play a larger role in long-term aquifer storage, but recharge has been reduced because of shorter, controlled release periods over the past two decades (Figs. 3 and 8). The limited extent of recharge to the Rio Grande alluvium in the study area is supported by the storage changes measured at locations along the Las Cruces transect (Fig. 9). Storage changes at sites beyond the river levees (GLC-5 and GLC-7) look similar to sites surrounding the LC-3C piezometer (GLC-8 and GLC-9), in which groundwater elevations are interpreted to respond seasonally to large or sustained precipitation events rather than streamflow. Because the Mesquite and West Valley transects are close to the river and are in areas dominated by agriculture, resolving storage changes from irrigation or streamflow is more challenging.

Overall, there was an increase in storage and groundwater elevations at most sites during the study, largely following the increased surface-water availability and above average precipitation in 2017 (Figs. 3–11). The total change in aquifer storage can be calculated by multiplying the average storage change by the representative area of the aquifer. The average increase at the Las Cruces transect sites from January 2016 to August 2018 was 0.23 m of free-standing water and the storage changes were reasonably well distributed along the transect (Fig. 9). The average storage change was 0.25 m at the Mesquite transect, but increases were more pronounced closer to the river. In contrast to the larger increases in sites on the east side of the river, there was only about a 0.04 m increase in the West Valley transect sites. Because the storage changes are calculated from discrete gravity measurements, these changes reflect the total cumulative change at two moments in time. Continuous gravity measurements, which would be required to integrate the total storage change, are impractical in most hydrologic settings, so utilizing continuous hydrologic data to help constrain the storage change interpretations, as demonstrated here, is extremely helpful. Nevertheless, using the storage change calculated over the length of the study and applied over some area, one can estimate the volume of water lost or gained. Assuming a 3-km width of alluvium east of the Rio Grande, the area between the Las Cruces transect and the Mesquite transect is approximately 33 km^2. The approximate area of alluvium west of the river, between MES-16R and MES-48R, and between the Rio Grande and the bluffs defining the transition between the Mesilla Valley and the West Mesa, is about 13 km^2. Given those areal approximations and the average storage increases, the estimated gains in groundwater volume for this reach from January 2016 to August 2018 were about 8.4 hm^3; 7.9 hm^3 for the east bank and 0.5 hm^3 for the west bank.

Linear regression between groundwater elevation changes and storage changes was used to estimate Sy in the unconfined aquifer (Figs. 12, 13, and 14). Specific yield estimates were possible at seven out of nine sites that had complete groundwater-elevation data and storage -change estimates, suggesting that the conditions of an unconfined aquifer were largely met. The Sy estimates ranged from 0.14 (+/− 0.05) to 0.30 (+/− 0.06), slightly greater than previously reported estimates (0.10 to 0.25), but still within the reported error of the Sy estimate.

The Sy estimates were made with the most confidence at piezometers LC-2C, LC-3C, M-2C, and MES-13. The better correlation obtained at these piezometers is likely due to the relatively large changes in groundwater elevation, which creates a stronger "signal" that is influenced less by the mass changes due to unsaturated soil moisture and dilutes the accuracy limitation of the measurements. Two locations (MES-11R and MES-48R) had Sy estimates that approached 0, possibly indicating partially confined conditions, challenges with field conditions or location, or other anthropogenic factors discussed above. Two sites (MES-47R and MES-14R) were not used because the piezometers were dry for most of the investigation. The individual specific yield estimates could benefit from additional data points; however, the use of these estimates is supported by the consistent applicability over all sites.

Most of the variability in storage change estimated for the study that is not attributed to groundwater elevation change is thought to be from soil moisture in the unsaturated zone. To illustrate this, the thickness of the unsaturated zone was typically more than 3 m in the study area; if there was a 5% change in water content in a 3-m thick unsaturated zone, the result would be a 0.15 m change in storage. Evidence for this comes from storage changes not associated with groundwater elevation changes or observed surface disturbance (for example MES-11R; Fig. 14). If the change were a surface disturbance or subsidence, the result would be a permanent shift in the storage estimates. Soil moisture monitoring could help determine the seasonal changes in unsaturated zone water content in the area and allow this signal to be accounted for in the gravity data. Shallow depths to water and lateral groundwater flow as the primary source of recharge may also minimize soil moisture variation (Pool and Eychaner, 1995). Shallow depths to water would limit the amount of soil water variation simply by limiting the thickness of the unsaturated zone. Recharging the groundwater with lateral groundwater flow, rather than surface application, results in recharge water not passing through the unsaturated zone.

This investigation identified several sources of seasonal recharge and documented storage recoveries in the Rio Grande alluvium following a year of increased surface-water supplies and above-average precipitation. This data can assist water-resource managers in identifying threshold streamflow or agricultural irrigation limits that create groundwater deficits or contribute to aquifer recoveries. For example, the EBID surface-water allotment in 2017 was 0.6 hm^3 per km^2, which indicates that a surface-water allotment about this amount may be necessary to promote aquifer storage rebounds, at least partially. This information could inform how to manage the annual or interannual conjunctive use, such as the concentrated use of available surface water for irrigation in certain areas of the aquifer. Continued monitoring, under a variety of surface water and meteorological conditions, may help further determine the relative contributions of different recharge sources and perhaps quantify the minimum recharge needed to sustain a given groundwater elevation or groundwater elevation range.

5. Conclusions

Seasonal groundwater elevation and repeat microgravity measurements in the Mesilla Basin were made in 2016, 2017, and 2018. Continuous groundwater elevations, Rio Grande streamflow, weekly precipitation, and irrigation season data were used to estimate the major sources of recharge at selected locations. Seasonal recharge in the Rio Grande alluvium in the study area was attributed to streamflow, the application and conveyance of irrigation water, and large or sustained precipitation events. However, large and, in recent decades, increasing (Fig. 3) groundwater gradients between piezometers close to the river and those more than a kilometer from the river suggest that recharge from river seepage has become increasingly localized at the seasonal scale. These data were able to capture seasonal change in groundwater elevations and storage from various sources of recharge at multiple sites in the shallow aquifer near Las Cruces and Mesilla, New Mexico. Overall, there was a net increase in storage of about 8.4 hm^3 in the study reach during the study, largely following the increased surface-water availability and above-average precipitation in 2017. Specific yields (Sy) were estimated by comparing the groundwater-level changes and storage changes. Sy estimates were made at seven out of nine sites that had complete groundwater elevation and storage change estimates suggesting that the conditions of an unconfined aquifer were met. The Sy estimates for six sites in the study area ranged from 0.14 to 0.30, which is slightly greater than previously reported estimates (0.10 to 0.25) but still within the reported error. Most of the variability in storage change estimated for the study, that was not well-correlated with groundwater-elevation change, is thought to be from soil moisture in the unsaturated zone.

The results of this investigation demonstrate the value of adding microgravity measurements to better understand the sources and extent of recharge as well as the variability of specific yield in the aquifer. Continued monitoring could aid in developing a more comprehensive understanding of the water budget and reduce Sy estimation uncertainty. Evaluating the persistence, or return, of water-levels and storage to conditions prior to a recharge event may help managers identify threshold conditions for aquifer storage depletions and recoveries.

CRediT authorship contribution statement

Andrew J. Robertson: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Jeffrey R. Kennedy:** Software, Validation, Formal analysis, Writing – original draft. **Libby M. Wildermuth:** Validation, Data curation, Writing – review & editing. **Meghan T. Bell:** Validation, Data curation, Writing – review & editing. **Erek H. Fuchs:** Resources, Funding acquisition, Writing – review & editing. **Alex Rinehart:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Irene Fernald:** Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Andrew Robertson reports financial support was provided by US Bureau of Reclamation. Andrew Robertson reports financial support was provided by US Geological Survey. Andrew Robertson reports financial support was provided by New Mexico Office of the State Engineer.

Andrew Robertson reports financial support was provided by City of Las Cruces. Andrew Robertson reports financial support was provided by Elephant Butte Irrigation District. Andrew Robertson reports financial support was provided by New Mexico State University. Andrew Robertson reports financial support was provided by Camino Real Rural Utility Association.

Data availability

Data is available at DOI: 10.5066/P94SN60M and https://doi.org/10.5066/F7P55KJN

Acknowledgements

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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