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Quantifying groundwater resilience through conjunctive use for irrigated agriculture in a constrained aquifer system

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ABSTRACT

The Rincon Valley in arid, south-central New Mexico, is especially impacted by reduced surface water supply because the contribution of groundwater is limited by aquifer constraints. Consecutive surface water allotment shortages in the Elephant Butte Irrigation District (EBID) have reduced recharge. The effects are compounded by farmers continuing to extract groundwater to meet crop requirements. Conjunctive use assumes aquifer resilience (i.e., ability to absorb pumping stress), but not necessarily in drought. This study further develops the water table fluctuation method by analyzing data from the EBID's groundwater monitoring program to reveal conjunctive use controls over the spatial and interannual variability of net storage changes from 2009 to 2016 in the Valley and introduces the term groundwater-surface water ratio of application (GSRA), that has potential for characterizing system resilience in conjunctive use settings. Regression modeling shows that variation in the annual EBID surface water allotment correlates strongly with year-end water table elevations, even more strongly than total annual groundwater extractions for irrigation, suggesting that variable surface water allotments are a primary driver of this system. Dewatering of the aquifer as of 2011 significantly altered the system hydrology such that from 2011 to 2016, net change in storage correlates strongly with the annual surface water allotment, corresponding to large river losses for the same period, but resulting in net gains in storage from 2014 to 2016. Rapid storage loss and rebound in this constrained aquifer system allowed quantification of aquifer resilience, enabling the development of a GSRA as a potential planning metric.

1. Introduction

Interactions between groundwater and surface water are a critical consideration for integrated, conjunctive river basin management (Hantush, 1965; Hunt, 1999; Turney, 1999; Woessner, 2000; Rushton, 2002; Simonds and Sinclair, 2002; Sophocleous, 2002; Kollet et al., 2003; Mair and Fares, 2010), especially during periods of protracted drought (Tao et al., 2011). Water scarcity generally impacts water resources in most of the world, but desert areas are more susceptible to drought (De Vries and Simmers, 2002). Groundwater storage variability over time and space is critical to sustainable water resources (Richts et al., 2011), and has become a focus in many parts of the world in recent years. Richey et al. (2015a) note that surface water is the principal freshwater supply appropriated to meet human water demand globally, but the importance of groundwater is increasing as surface supplies become less reliable and predictable (Kundzewicz and Döll, 2009). Groundwater is increasingly relied upon during times of drought as a presumed resilient, alternative water source (Famiglietti, 2014). However, upon conducting a groundwater stress assessment to quantify the relationship between groundwater use and availability in the world's 37 largest aquifer systems, Richey et al. (2015a) report that estimates of groundwater stress based on withdrawal statistics are unable to capture the range of characteristic stress regimes, which can be inferred as evidence that quantifying groundwater resilience remains a challenge.

Groundwater resilience within the Elephant Butte Irrigation District (EBID) in the arid Lower Rio Grande Basin of south-central New Mexico, USA has become an issue of interstate concern. Farmers in the Rincon Valley (Fig. 1) along the Rio Grande within the EBID are especially impacted by protracted drought because the unique geology of the area (Conover, 1954; Davie and Spiegel, 1967; King and Hawley, 1975; Wilson et al., 1981; Hawley et al., 2005) limits the use of groundwater for supplementation of limited surface water for irrigation. An extensive clay aquitard underlies the shallow yet finite,

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Fig. 1. Generalized map of the Rincon Valley and major features/boundaries of significance.

unconfined alluvium aquifer common to the Rincon Valley, the aquifer lateral extents are narrowly bounded, and lateral groundwater flow is insignificant compared to pumping and recharge flows. While the hydrogeology of the Rincon Valley shallow aquifer is well documented and further acknowledged in this study, no formalized research has been conducted to quantify the vulnerabilities of this system in response to protracted surface water shortage.

This study refers to conjunctive use as the supplementation, augmentation, or periodic substitution of variable surface water by pumping groundwater for irrigation in interrelated systems, and contends that the Rincon Valley shallow aquifer, like other aquifer systems in conjunctive use settings, is subject to hydrologic metrics that may be expressed in terms of resilience. Resilience is often discussed in the context of climate change as the ability of a system to absorb disturbances while retaining the same basic structure and ways of functioning, and the capacity to adapt to stress and change (IPCC, 2012). This study refers to groundwater resilience similarly, as the capacity of the aquifer to absorb variable pumping stress while retaining the same basic functionality in the context of variable surface water availability and recharge, in an interrelated system. However, this is not an expression of sustainability. Conjunctive use assumes aquifer resilience, such that pumping stress is absorbed, but not necessarily during drought, at least not indefinitely. If drought conditions are severe and persist long enough, then all other things being equal (i.e., groundwater extractions remain unabated and/or in excess of recharge), resilience limitations will eventually be reached, and the system may no longer be sustainable, regardless of the potential for resilience or how it is defined. Methods are lacking to assess the resilience of aquifer storage at a local level, where management potential is perhaps greatest. Knowledge of the relative limits of stress that local aquifers may sustain is a critical management consideration, and needs to be further evaluated (Richey et al., 2015a,b).

Sheng (2013) offers a timely, however broad account of the impacts of groundwater pumping and climate variability within the Rio Grande Basin downstream of Elephant Butte Dam and notes that the state of the science relative to water sustainability in this region has room for improvement. Integrated numeric modeling efforts that are specific to the Lower Rio Grande of New Mexico have endeavored to predict the interactions between surface water and groundwater in this area, although the earlier works were much more concerned with the immediate downstream Mesilla Valley, which is a much larger and deeper system relative to the Rincon Valley. Some of these earlier works include Frenzel and Kaehler (1992), Hamilton and Maddock (1993), and Lang (1995). Later works that are inclusive of the Rincon Valley include

Weedon and Maddock (1999), Papadopulus and Associates (2007), Schmid and Hanson (2009), Hanson et al. (2010), USBR (2015), and Knight (2015). Still, questions concerning groundwater resilience in this area persist, particularly as conditions favoring a reduced surface water supply in the Rio Grande Basin are predicted to intensify (USBR, 2011).

It is important to examine groundwater storage changes over time, and to consider multiple methods for doing so. An ongoing study that is not specific to the Lower Rio Grande or the Rincon Valley yet, but that has bearing on the nature of the work presented here, is documented by Rinehart et al. (2015) in which the goal, using geostatistical methods, was to provide groundwater storage change estimates in alluvial basins throughout New Mexico. Prior studies of regional aquifer storage include the work of McGuire (2013) in the Southern High Plains, which was similar in some respects to the work that is presented here as far as making use of groundwater elevation data to estimate storage. Other studies, such as Kumar (2007), Ahmadi and Sedghamiz (2008), and Chung and Rogers (2012) have compared different types of kriging interpolations to estimate storage. Another approach, originally introduced by Montgomery (1971) but receiving renewed interest (e.g., Gehman et al., 2009), is the use of temporal gravity surveys in which measurements of changes in gravity over time can be used to estimate variations in groundwater mass associated with a rise or fall in the water table. Fundamentally, studies of this nature are varied conceptualizations of the water table fluctuation (WTF) method, which depending on the fluid flow complexity, is a simple and effective approach widely used to determine groundwater recharge (Healy and Cook, 2002; Crosbie et al., 2005; Delin et al., 2007; Healy and Scanlon, 2010). For example, Wang et al. (2014) used the WTF method to effectively estimate the spatiotemporal variability of groundwater recharge for the largest rice production region in northeast China. The WTF method is simple and easy to apply, because it requires information regarding only the water table and specific yield of an aquifer. However, extension of the WTF method over space and time to examine changes in groundwater storage, rather than just recharge, may offer a relatively easy, effective way to evaluate conjunctive use and the impacts of drought on water resources management. Due to its relative simplicity and constrained groundwater flow system, the Rincon Valley in southern New Mexico is well suited to advance the WTF method for groundwater storage measurements, and to serve as an example of quantifying groundwater resilience.

The purpose of this study is to further develop the WTF method to evaluate groundwater resilience by analyzing data from the EBID's groundwater monitoring program to determine the spatial and inter-annual variability of net storage changes from 2009 to 2016 in the Rincon Valley shallow alluvium aquifer. This study explores these results as an indicator of aquifer resilience and river performance (i.e., net river loss or gain) in the context of hydrologic drought (later defined) and conjunctive use of water for irrigation, and offers a new term, the groundwater-surface water ratio of application (later defined). This study also examines controls and indicators of resilience by relating net storage and average water table elevation changes with the annual pro rata EBID surface water allotment and total annual metered extractions of groundwater for irrigation.

2. Materials and methods

2.1. Study area

The annual surface water supply provided by storage in Elephant Butte and Caballo Reservoirs, located in the upstream extent of the Lower Rio Grande Basin in southern New Mexico (a primary feature of the U.S. Bureau of Reclamation Rio Grande Project), has been reduced substantially due to ongoing regional drought. Elephant Butte Reservoir is the primary means of storage servicing the Rio Grande Project, which is concerned with the irrigation of lands in southern New Mexico (EBID, inclusive of the Mesilla and Rincon Valleys) and lands in west Texas (El Paso County Water Improvement District No. 1). It is also an important means of meeting downstream delivery obligations by the U.S. to Mexico as per a 1906 International Treaty. Caballo Reservoir, located immediately downstream of Elephant Butte on the Rio Grande, serves principally as a regulating feature for Rio Grande Project seasonal releases. In a full supply year, irrigation releases from storage for all Rio Grande Project contract beneficiaries begin in March and end in September for a total volume of about 790,000 acre-feet (974.4 M cubic meters), inclusive of a full, pro rata EBID surface water allotment of 3.024 acre-feet (36.288 acre-inches) per irrigated acre (9217 cubic meters per hectare) for lands assessed to receive surface water within the EBID. A total of 90,640 acres (36,681 ha) are assessed to receive surface water throughout the EBID. The Rincon Valley contains about 28,064 acres (11,357 ha), of which 18,651 acres (7547 ha) are assessed to receive surface water (EBID, 2016), but on average, only about 17,000 acres (6880 ha) in the Rincon Valley are irrigated annually. Almost all (about 95%) of these lands are irrigated with a combination of surface water delivered through the EBID on a pro rata basis and groundwater pumped in varying amounts from individual, farmer-owned wells.

The Rincon Valley (Fig. 1) comprises the northern extent of the EBID. Floodplain elevation above mean sea level at the northern end by Caballo Dam is about 4160 feet (1268 m) and 4100 feet (1250 m) at the lower end of the Valley, which is about 32 miles (51.5 km) long. The width of the valley floor is constrained from one to two miles (1.6–3.2 km) in a classic Basin and Range Province that is characterized by rugged mountain ranges and gently sloping Chihuahuan Desert plains divided by the riparian corridor of the Rio Grande. The basin is bounded by near vertical faults associated with mountain ranges that are generally aligned in a north-south direction with the Caballo and Doña Ana Mountains bounding the Rincon Valley to the east, and the Black Range and Sierra de las Uvas Mountains to the west. Records from a weather station located at New Mexico State University show the average annual precipitation from 1976 to present to be 9.28 in. (236 mm), 54% of which falls during the summer monsoon months of July-September (WRCC, 2015). Using classic methodology described by Blaney and Criddle (1962), Gabin and Lesperance (1977) report that peak potential evapotranspiration (using alfalfa as a reference crop) in the area occurs during July wherein a monthly total of 9.25 in. (234.95 mm) of water is estimated to be evapotranspired on average, and that total annual potential evapotranspiration in the area is estimated to be 49.82 in. (1265.43 mm) on average. Local precipitation has traditionally been considered a very small part (essentially negligible) of the irrigation water budget in this area, but this certainly may not be the case in other study areas.

EBID pro rata surface water allotments for the last eight years (Table 1) have averaged only 12.9 acre-inches per acre (3270 cubic

Table 1
Total annual pro rata surface water allotments for the EBID and actual farm deliveries in the Rincon Valley, 2009–2016.

Year	Total EBID surface water allotment ($m^3 \times 1000$) (m^3/hectare)		Percent of a full allotment	Rincon Valley farm delivery ($m^3 \times 1000$)
2009	279,507	7620	83.3	54,023
2010	223,605	6096	66.7	41,502
2011	37,268	1016	11.1	6339
2012	93,169	2540	27.8	16,825
2013	32,609	889	9.7	5039
2014	69,877	1905	20.8	12,830
2015	102,486	2794	30.6	19,537
2016	121,120	3302	36.1	22,601
Mean:	119,195	3270	35.8	22,337
Sum:	959,639	26,162	n/a	178,695
Std dev:	82,309	2244	24.5	16,028

meters per hectare) per year, about 36 percent of a full allotment. Climate forecasts concerned with the regional Rio Grande Basin, inclusive of watersheds in southern Colorado and northern New Mexico (headwaters of the Rio Grande) suggest that an average of this nature may be more common than not for years to come (USBR, 2011). Rather than focusing on drought as localized, above average aridity reflecting local weather variation, this study defines hydrologic drought as a circumstance where protracted regional drought impacting upstream, upland watersheds leads to a persistent reduction in the volume of surface water in local reservoir storage, and therefore consecutive annual shortages of surface water available for local release. For the purposes of this study, an EBID pro rata surface water allotment that is less than 66.7 percent of a full allotment (less than 2.0 acre-feet per acre; 6096 cubic meters per hectare) is considered to reflect significant hydrologic drought conditions.

Very few domestic wells or other municipal and industrial wells exist in the Rincon Valley. The Village of Hatch, the largest urban area in the Rincon Valley, is the primary provider of water for drinking and sanitary purposes and imports potable water via pipeline from an alternative groundwater source, known as the Nutt-Hockett Basin. This groundwater source is located about 12 miles (19.3 km) to the southwest of Hatch and is hydraulically independent of the Rincon Valley. Irrigated agriculture is by far the dominant use of water, including extraction of groundwater, with or without hydrologic drought conditions in the Rincon Valley. Irrigation is predominantly by surface flood application to farmlands that in most cases are regularly laser-leveled but does include shallow subsurface drip-tape use combined with traditional flood practices in many instances. The Rincon Valley is world-renown for the famous Hatch-brand chile. In 2014, New Mexico ranked first in the U.S. for total acreage planted in chile (California was second) and ranked second (just behind California) for total onion production (NMDA, 1998). Hatch-brand chile and other vegetable production, particularly onions, is a significant component of the local economy (Hall and Skaggs, 2003). Irrigated agriculture is by far the foremost form of industry and source of income and tax revenue in the Rincon Valley.

2.2. Groundwater-surface water ratio of application

This study introduces a new term, the groundwater-surface water conjunctive use ratio of application (GSRA), defined as the total volume of groundwater extracted and applied for irrigation per unit time, divided by the total volume of surface water diverted and applied for irrigation per unit time, within a common river basin and hydraulically interrelated aquifer system. The term is specific to water resource settings that are, or should be, conjunctively used and managed. The significance of the GSRA as a metric of aquifer resilience is that over time, even in the absence of more detailed information specific to net depletion (i.e., evapotranspiration) that is typically much more difficult to accurately assess (Howes et al., 2014), the GSRA can serve as an indicator of aquifer stress relative to surface water availability and potential recharge. The GSRA can therefore also serve as a metric for determining steady state conditions (i.e., a circumstance where net change in aquifer storage equals zero).

Other terms have been suggested to characterize aquifer stress but are more concerned with generalized estimates of aquifer longevity in the context of sustainability, and not necessarily resilience. Richey et al. (2015a) offer the idea of a total groundwater stress ratio, defined as the ratio of total storage to the groundwater depletion rate to estimate timescales to depletion by accounting for the buffer capacity of aquifer storage. They found that the current state of knowledge of large-scale groundwater storage has uncertainty ranges across orders of magnitude that severely limit the characterization of resilience, at least in the numerous, large regional aquifers they studied around the world. This study suggests that the GSRA as a metric for groundwater resilience is a potentially practical, useful approach for localized management in conjunctive use settings where groundwater storage tends to remain in flux anyway, and that a focus on total storage may have limited utility in most irrigation projects since total storage and economically recoverable storage are typically very different things.

2.3. Hydrogeology

The surface waters of the Rio Grande and the groundwater of the shallow alluvium aquifer of the Rincon Valley are a highly-connected, essentially singular resource (Conover, 1954; Wilson et al., 1981; Frenzel and Kaehler, 1992; Winter et al., 1998; Turney, 1999; Hawley and Kennedy, 2004; and others). Among the most complete hydrogeologic descriptions of the Rincon Valley and surrounding region is offered by Hawley et al. (2005), noting that the Rio Grande is the only significant surface water resource in the region, and therefore the main source of recharge. Conover (1954), King et al. (1971), and Wilson et al. (1981) report that the shallow alluvial deposits associated with the River in the inner valley in this area serve as the ultimate discharge zone for pre-development groundwater flow from adjacent basins and uplands. Hawley et al. (2005) stress that the essential hydrogeologic characteristic of the Rincon Valley in terms of groundwater resources is the absence of any significant basin-fill aquifer unit beneath the shallow alluvial fill of the inner valley. Test drilling of several exploratory wells in the area, the deepest to about 2000 feet (610 m), document the presence of a very thick (estimated about 2500 feet; 762 m) sequence of fine-grained basin-floor sediments (clays) deriving from a prehistoric playa lake below the inner-valley fill (King et al., 1971; Wilson et al., 1981) with virtually no potential for freshwater production due to very low hydraulic conductivity. The upper elevation of this sequence reflects the lower extent of the productive aquifer, and lateral extents providing a width of no more than one to two miles (1.6–3.2 km) are evidenced by steep vertical faults. Essentially, no aquifer exists in the Rincon Valley except the shallow alluvium, which on average is only about 80 feet (24 m) deep and renders a useable average of only about 55 feet (17 m) of saturated thickness (Wilson et al., 1981).

Within the modern floodplain of the Rincon Valley, a 30–40 foot (9–12 m) thick gravel layer occupies the lower part of the alluvium and is overlain by thin lenses and layers of sand, gravel, and clay, but is otherwise considered to be mostly homogenous aquifer material (Wilson et al., 1981) with transmissivity averaging about 17,100 feet squared per day (1588 m^2/day). Static depth to water in the valley floodplain alluvium is normally (following initial development; early 1950s through 1970s) from 8 to 15 feet (2–5 m) below land surface. The north to south flow of groundwater in the Rincon Valley is at about the same slope as the ground surface, about 5 feet per mile (1 m per kilometer). Wilson et al. (1981) further describe the groundwater resources of the Rincon Valley as a long, narrow, continuous aquifer comprised of Quaternary gravel, sand and clay deposits, which is entrenched in the red clay of the Santa Fe Group lacustrine facies.

2.4. Net change in groundwater table elevation

Within the Rincon Valley, the EBID maintains a network of thirteen (13) instrumented, shallow monitoring wells dedicated to tracking shallow groundwater levels in the area. Relative to the Rincon Valley spatial extent of about 28,064 acres (11,357 ha), the locations of EBID's monitoring wells are described in Table 2 and are situated to approximate uniform coverage of the Rincon Valley. Each monitoring well features a 2.0-inch (5.1 cm) casing and is completed to a total depth of approximately 25 feet (8 m) below the soil/water interface, about 40 feet (12 m) below ground surface. The bottom 20 feet (6 m) of each well is screened, and beyond that a blank sump of about 10 feet (3 m) occupies the very bottom of each well to accommodate eventual sediment accumulation. The screened interval of each well is within about the middle of the average saturated thickness of the aquifer. All sites were surveyed to establish appropriate benchmark elevations.

Table 2
EBID monitoring sites and related Thiessen polygonal areas, North to South.

EBID monitoring well and related Thiessen polygon	Benchmark elevation (m amsl NAVD88)	Thiessen polygonal area, *A* (hectares)	Latitude (WGS84)	Longitude(WGS84)
Rin 10R	1258.8	1683.0	32°49′ 12.95″	107°18′ 27.83″
Rin 1R	1253.5	959.7	32°46′ 11.81″	107°16′ 54.02″
Rin 11R	1251.0	437.1	32°45′ 19.18″	107°16′ 31.15″
Rin 9R	1249.7	697.3	32°44′ 48.14″	107°15′ 52.92″
Rin 2R	1244.2	1417.6	32°42′ 27.62″	107°14′ 30.02″
Rin 8R	1239.1	1386.3	32°40′ 44.21″	107°11′ 38.64″
Rin 3R	1235.5	1034.2	32°40′ 05.20″	107°08′ 16.89″
Rin 7R	1232.2	591.1	32°39′ 53.37″	107°06′ 36.21″
Rin 4R	1230.5	722.1	32°39′ 35.05″	107°04′ 39.95″
Rin 5R	1226.3	806.6	32°38′ 36.80″	107°02′ 13.31″
Rin 12R	1222.9	470.0	32°37′ 23.87″	107°00′ 51.16″
Rin 6R	1220.3	514.0	32°36′ 10.70″	107°00′ 11.99″
Rin 13R	1219.1	638.1	32°35′ 16.41″	106°59′ 51.01″
Mean	1237.2	873.6		
Sum	n/a	11,357.2		
Std dev	12.8	400.4		

Since 2009, groundwater table elevations – measured as a function of pressure head with submersible pressure transducers (Instrumentation Northwest, Inc., model PT2X) purchased and installed by the EBID very near (within 6.0 in; 15.24 cm) the bottom of the screen of each of the new monitoring wells – have been recorded continuously every thirty (30) minutes, and temporarily stored in data-loggers (Campbell Scientific, Inc., model CR10X) at each site powered with solar and battery backup for monthly data retrieval. These sensors were configured with a gauge option to include venting technology to compensate for variable barometric pressure effects (precision of ± 0.05%). EBID recently (mid-2015) replaced these instruments with simpler, more reliable pneumatic 'bubbler' sensors (Control Design, Inc., model CD103, precision of ± 0.05%) paired with Remote Telemetry Units (Control Design, Inc., model CD110) to achieve essentially real-time data acquisition. The change in instrumentation did not produce any discernible shift in measurement data, particularly since in-season (while irrigation well pumping is underway) fluctuations in the local water table are typically several orders of magnitude greater than the measurement error of the instrumentation, before and after the change in instrumentation.

This type of groundwater monitoring program to measure real-time fluctuations in the water table is useful for many reasons; however, this study is concerned with year-end (interannual; December 31 to December 31) groundwater table elevation changes at each monitoring site in the Rincon Valley. At year-end, groundwater table elevations at and between monitoring wells are subject to minimal influence by nearby irrigation production wells (fluctuating cones of depression), since very little or no irrigation is expected to be underway, or to have occurred for about a month prior. The potential for the static elevation of the groundwater table at each monitoring well location to have reached a point of new relative equilibrium will have reached a maximum at this time (i.e., after harvest). There is typically more uncertainty in groundwater pumping conditions at the early part of the growing season before the start of the next surface water release (beginning mid-late April to as late as June 1 in recent years of reduced surface water supply). In this study, the average December 31 groundwater table elevation at all sites at each year-end was compared to total annual groundwater extraction from all metered irrigation production wells (NMOSE, 2017) in the Rincon Valley that are used in conjunction with the total annual EBID pro rata surface water allotment, and comparison was also made to the calculated annual net river loss or gain.

2.5. Net change in groundwater storage

A spatial modeling approach utilizing analytical tools available in a Geographic Information System (ArcGIS® v.10.2, Environmental Systems Research Institute) framework adapted to the Rincon Valley was used to show where and to what extent year-end groundwater table elevation changes and net groundwater storage changes have occurred in recent years. It is assumed that each monitoring well location and the year-end groundwater elevation data associated with each monitoring well contributes equally to characterizing the collective response of the shallow alluvium aquifer to pumping stress and/or recharge.

Healy and Cook (2002) report that a basic assumption inherent in the WTF method and critical to its successful application is that specific yield is known and constant over the time period of the WTFs. However, variation in aquifer properties is generally area and depth dependent. The guidance offered by Yeh et al. (2015) clarifies that the challenges posed by aquifer heterogeneity are opportunities for stochastic approaches to characterizing aquifer properties, such as the use of hydraulic tomography. Nevertheless, spatial differences in specific yield and/or storage coefficients within the same stratigraphic layer of interest are generally not differentiated between individual cells within a typical groundwater flow model discretization grid. In the case of the Rincon Valley, the stratigraphic layer of interest is physically limited to the shallow alluvium. Because the unconfined, shallow alluvium aquifer in the Rincon Valley is finite and laterally bounded, and reported to be largely homogenous (Wilson et al., 1981), this study likewise assumes that specific yield is spatially uniform.

For this study, an average specific yield (S_y) of 0.2 was distributed throughout the shallow alluvium aquifer. Conover (1954), Richardson et al. (1972), Lizarraga (1978), and Wilson et al. (1981) each independently reported a S_y of at least 20 percent for the shallow alluvium within the Lower Rio Grande Basin. Several previous modeling efforts in the Lower Rio Grande, including Frenzel and Kaehler (1992), Hamilton and Maddock (1993), Lang (1995), Weedon and Maddock (1999), and Papadopulus and Associates (2007) each assigned a value of 0.2 for S_y to the uppermost model layer reflecting the shallow alluvium aquifer, and each assumed that S_y is uniform across the uppermost model layer.

S_y is an important aquifer property, particularly for purposes of this study concerned with change in aquifer storage. This is evident in the following relationship noted by Fetter (2001):

$$V_w = SA\Delta h \quad (1)$$

where V_w is the volume of water (acre-feet or m^3) drained from a portion of the aquifer, S is the storativity (or S_y in an unconfined aquifer, dimensionless), A is the surface area overlying the drained portion of the aquifer (acres or hectares), and Δh is the change in groundwater elevation or hydraulic head (ft or m). In the context of aquifer resilience, S_y is especially important as the volume of water in

Fig. 2. Thiessen discretization of the Rincon Valley within the EBID based on monitoring well locations.

the aquifer relative to the aquifer volume, and if land subsidence is prevalent and collapse of aquifer material pore structure occurs, reductions in S_y can be expected, which limits the capacity of the aquifer to rebound. To the extent that Δh is found to be changing over time relative to some baseline elevation, then V_w can also express the volume of water gained by a portion of the aquifer, and therefore relates to recharge and the fundamental premise of the WTF method.

The basic assumption of the WTF method is that the rise of groundwater level in unconfined aquifers is caused by the response to the infiltration of water (rainfall, irrigation, etc.) arriving at the groundwater table (recharge). Recharge rate, R (L/time), can therefore be quantified as follows (Healy and Cook, 2002):

$$R = S_y \frac{\Delta h}{\Delta t} \tag{2}$$

where Δt is the time of recharge period. The flux, therefore, is reflected by change in aquifer storage, which may also be expressed as a volumetric discharge (or water use rate) by applying Eq. (2) over the aquifer area. This allows the WTF method to account for changes in groundwater storage associated with water use. To the extent that pumping stress on the aquifer over time exceeds recharge over time, then dewatering of the aquifer occurs and storage is necessarily reduced. The inverse is also plausible, in which case the aquifer storage would be in a gaining state. Aquifer storage, as with streams, can be gaining under recharge conditions and losing under discharge conditions. This dynamic can be convoluted in conjunctive use settings because R may reflect either river infiltration recharge flux or groundwater pumping discharge flux, and both may be occurring. Prior WTF applications for characterization of natural recharge through groundwater elevation measurement are extended here to an irrigated agriculture managed aquifer/river system where groundwater storage relates directly to conjunctive water use rates. Summation of volume change at each year-end from each monitoring well and associated area in the Rincon Valley are reported as the calculated net change in storage from the shallow alluvium aquifer for each year, and are also reported at each monitoring site, relative to December 31, 2009 groundwater table conditions in the Rincon Valley. Total annual net change in aquifer storage is then compared to the total annual EBID pro rata surface water allotment and total annual groundwater extraction.

Quantification of these relationships in the context of groundwater resilience and conjunctive use are feasible, because groundwater extractions, combined with the use of available surface water for irrigation are, in this study area, the predominant variables influencing change in aquifer storage. Accordingly, this study refers to the groundwater-surface water conjunctive use ratio of application (GSRA; dimensionless, defined previously). GSRA extends from Eq. (2) to address the convolution of recharge and discharge associated with conjunctive use as GSRA can be considered the ratio of groundwater pumping discharge flux to river infiltration recharge flux or groundwater use to surface water availability and use. This study postulates that if the GSRA consistently exceeds 1.0, then it is expected that the aquifer's capacity to buffer pumping stress, relative to a variable recharge flux volume, will eventually be reduced. This is not to suggest that the GSRA cannot average somewhat greater than 1.0 over time, and the resilience of the aquifer still be preserved. It is reasonable to expect that an average threshold, or range, for GSRA exists within which groundwater resilience in conjunctive use settings can be maintained such that net change in aquifer storage over time is ultimately equal or close to zero. Determination of a threshold GSRA such that net change in aquifer storage is equal to zero is expected to represent steady state conditions, but may not necessarily reveal a managerial target, or definitive metric of aquifer resilience.

This study furthers the WTF method by extending Eq. (2), building on the work of Healy and Cook (2002), to quantify interannual groundwater storage (V_w) change over the aquifer area. Individual area values, A, that could be attributed to groundwater monitoring wells throughout the Rincon Valley were discretized with Thiessen polygons (Thiessen, 1911) utilizing ArcGIS® spatial analysis software. The Thiessen method uses a weighing factor for each sampling point to adjust for non-uniform sampling point distribution. The weighing factor is based on the size of the area within the area of interest. The Thiessen method was chosen for this study because of its relative simplicity and potential for adaptation elsewhere. An imperfect distribution of monitoring wells, the narrow physiological features of the Rincon Valley itself, and the resultant irregular geometry (and corresponding areas) of the polygons produced by the Thiessen method in this case is somewhat coarse (Table 2). This is shown in Fig. 2, which is a discretization map of the Rincon Valley as bounded by the lateral extents of the aquifer and includes the names and locations of the several small communities in the Valley. Other spatial analysis methods, such as kriging or inverse distance weighting (whereby the field is discretized on the basis of pixels or groups of pixels), among other, could very well be adapted to the purposes of this work. Although not presented here, this study found that kriging methods provided no significant difference from, or apparent benefit over, the simpler Thiessen approach chosen for this study, at least with the available data.

2.6. River performance

Gains or losses in river discharge can result from seepage in the streambed or from bank storage, evaporation from the water surface, and transpiration by vegetation along the river banks. Discharge in the EBID reach of the Rio Grande is controlled almost exclusively by irrigation releases from Caballo Dam (Crilley et al., 2013). In this study, it is affirmed that seepage in the streambed is also controlled by the static (average year-end) groundwater table elevation. The mass balance equation used for calculating net annual river seepage gain or loss in the Rincon Valley subreach of the Rio Grande is as follows (Simonds and Sinclair, 2002):

$$Q_s = Q_{ds} - Q_{us} - Q_{in} + Q_{out}$$

where Q_s is the net seepage gain or loss for the subreach (acre-feet or m^3), Q_{ds} is the discharge measured at the downstream end of the subreach (acre-feet or m^3), Q_{us} is the discharge measured at the upstream end of the subreach (acre-feet or m^3), Q_{in} is the sum of inflows (acre-feet or m^3), and Q_{out} is the sum of outflows (acre-feet or m^3). Data were obtained from EBID river gauges at strategic locations along the Rio Grande within the EBID (Q_{ds} and Q_{us}), including metered diversion dams for purposes of delivering surface water to EBID farmers (Q_{out}). Further, the EBID has developed, and is continuing to expand, a network of weather stations and rain gauges within the immediate area watershed to anticipate flood events, but also to serve a storm water capture program (Q_{in}). The data available from EBID's storm water capture program were used for Q_{in}, however evapotranspiration (ET) was not separately estimated in this study. The result is the calculated net annual flux of water gained or lost from the streambed for this reach of the Rio Grande, which is compared to the average annual year-end groundwater table elevation in the Rincon Valley.

3. Results and discussion

3.1. Groundwater elevation and net storage changes

Table 3 provides a summary of the average annual year-end groundwater elevation change taken from year-end groundwater elevation measurements at all EBID monitoring wells in the Rincon Valley, and the corresponding calculated net change in aquifer storage totalized for each year during the study period. Results indicate that the groundwater table elevation in the Rincon Valley declined an average of 2.3 feet (0.7 m) over the course of the study period. This translated to an average 4.2% loss of the average saturated thickness of the aquifer relative to about 55 feet (17 m) reported by Wilson et al. (1981) as the average useable thickness. Between 2014 and 2016, gains in storage were calculated, and are an indication of aquifer resilience on the basis that a period of reduced aquifer stress and increased recharge demonstrates that the aquifer can and does remain functional with potential to rebound, if conditions conducive to recovery are present. This also suggests that change in storage is a function of supply and demand as assumed feasible for conjunctive use, which this study suggests is reflected by the GSRA. Nevertheless, major losses occurring in 2011 and 2013 had created a dominant deficit effect such that at the end of the study period, a cumulative storage loss of 12,524 acre-feet (15,448 K m^3) was sustained. As long as a storage void persists in the aquifer, the potential for continued gains will persist.

Table 3
Average annual year-end groundwater table elevation change and net change in aquifer storage for the end of year period 2009 through 2016 relative to Dec. 31, 2009 groundwater table conditions in the Rincon Valley.

Period	Average year-end groundwater table elevation change at all monitoring sites (m)	Net change in aquifer storage totalized at all monitoring sites ($m^3 \times 1000$)
2009–2010	−0.074	−2030.5
2010–2011	−0.914	−20288.2
2011–2012	−0.023	−393.6
2012–2013	−0.551	−11267.7
2013–2014	0.003	1173.7
2014–2015	0.474	9229.0
2015–2016	0.385	8128.8
Mean	−0.100	−2206.9
Sum	−0.700	−15448.5
Std dev	0.455	9720.3

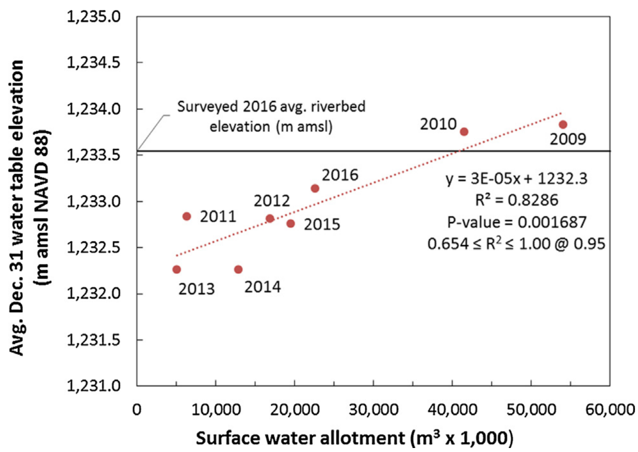

Fig. 3. 2009–2016 observed average Dec. 31 water table elevation in the Rincon Valley relative to the total annual pro rata EBID surface water allotment, and the surveyed 2016 average riverbed elevation.

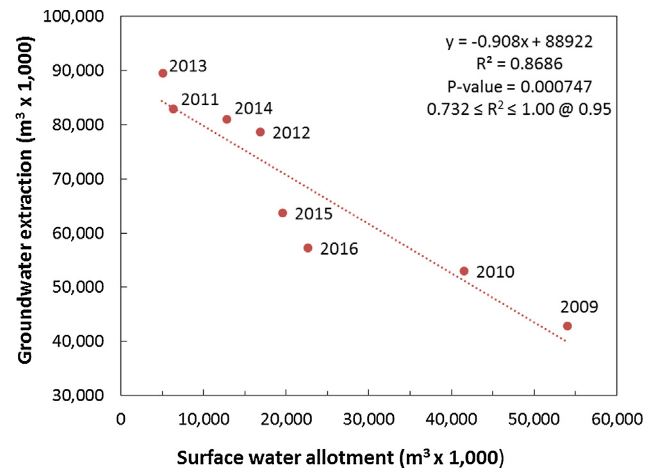

Fig. 4. 2009–2016 total annual groundwater extraction for irrigation of lands assessed to receive surface water in the Rincon Valley relative to the total annual pro rata EBID surface water allotment.

Fig. 3 contains data for the average year-end groundwater table elevation and the total annual EBID pro rata surface water allotment delivered to lands in the Rincon Valley for each year during this study. Included also is the 2016 surveyed (IBWC, 2017), average riverbed elevation in the Rincon Valley. Assuming that the 2016 average riverbed elevation is representative of the average riverbed elevation for the study period, it is revealed that after 2010, the average year-end groundwater table elevation had receded well below the base of the riverbed. This condition, following 2010, will have certainly increased the rate of recharge of available surface water to the aquifer, however limited in recharge volume by substantially reduced surface water allotments after 2010. The trend in Fig. 3 indicates that increases in surface water allotment increase groundwater storage due to recharge along the River and decreases in groundwater pumping when surface water is available. This trend reveals the dependence of resilience of aquifer storage on recharge from surface water and shows that the average year-end groundwater table elevation correlates well ($R^2 = 0.83$) within a reasonable confidence interval ($0.654 \le R^2 \le 1.00$ at 95%) with the total annual EBID surface water allotment. While the surface water allotments in 2009 and 2010 were much greater than subsequent years during the study period, the P-value calculated in this instance (0.0017) is much lower than 0.05, demonstrating that the effects of substantially reduced surface water allotments in years after 2009 and 2010 are in statistical keeping with the trend. On average over the aquifer, Fig. 3 shows a consistent trend. Additionally, the GSRA is intended to represent conjunctive use from year to year, regardless of spatial or temporal uniformity within a given irrigation season.

Fig. 4 presents total annual metered groundwater extractions for irrigation of lands in the Rincon Valley that are also irrigated with surface water, relative to the total annual EBID pro rata surface water allotments delivered in the Rincon Valley during this study. The data indicate that groundwater pumping has been inversely related to surface water use and availability. This trend demonstrates the conjunctive use of this system, proving that groundwater pumping for irrigation in the Rincon Valley is essentially a substitute for, and strongly correlated with ($R^2 = 0.87$), hydrologic drought impacts on the EBID surface water allotment. The calculated P-value (0.000747) and confidence interval ($0.732 \le R^2 \le 1.00$ at 95%) found in this instance tends to substantiate the significance of this relationship. 2009 and 2010 reflect years when the EBID surface water allotment was much closer to full, however subsequent years were dominated by hydrologic drought and elevated pumping levels, particularly in 2011 and 2013. Even so, a variable rate of substitution of groundwater extraction for surface water is apparent. On average over the aquifer, Fig. 4 shows a consistent trend, and the GSRA is intended to represent conjunctive use on an annual basis, regardless of spatial or temporal uniformity of applied water for irrigation in a given year.

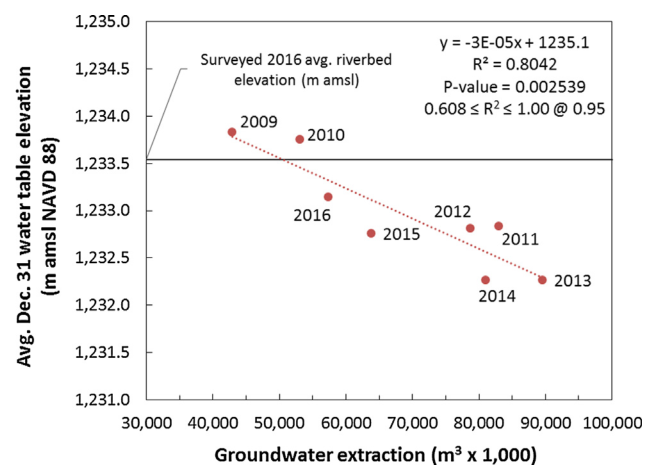

Fig. 5. 2009–2016 observed average Dec. 31 water table elevation in the Rincon Valley relative to total annual groundwater extraction for irrigation of lands assessed to receive surface water in the Rincon Valley, and the surveyed 2016 average riverbed elevation.

Fig. 5 presents the relationship between the average year-end groundwater table elevation and total annual metered groundwater extractions for irrigation, and indicates that in-season groundwater pumping is, as expected, well-correlated ($R^2 = 0.80$) with the average year-end groundwater table elevation. Increases in groundwater extraction directly result in decreases in groundwater storage within the aquifer. The P-value (0.002539) and confidence interval ($0.608 \le R^2 \le 1.00$ at 95%) calculated with this relationship is acceptable. In comparison, Fig. 3 reveals that the relationship with the EBID surface water allotment is slightly stronger ($R^2 = 0.83$), with slightly more convincing background statistics, however the explanatory variables (x-axis in either case) are themselves highly correlated. Figs. 3 and 5 indicate the two primary controls over changes in aquifer storage are the groundwater and surface water use in this conjunctive use managed aquifer. Fig. 5 also shows that aquifer storage resilience is certainly influenced by and may eventually be threatened by groundwater extraction. Surface water allotments may be considered the driving variable in this system, because variable groundwater extraction is largely in response to variable surface water allotments and because surface water allotments are the primary source of aquifer

Table 4
Area-specific net change in aquifer storage relative to Dec. 31, 2009 groundwater table conditions at EBID monitoring sites in the Rincon Valley from 2010 to 2016.

Site	2010 Δ Aquifer Storage ($m^3 \times 1000$)	2011 ΔAquifer Storage	2012 Δ Aquifer Storage	2013 ΔAquifer Storage	2014 ΔAquifer Storage	2015 Δ Aquifer Storage	2016 ΔAquifer Storage
Rin_1R	25.7	−1821.8	−107.3	−1160.1	414.4	488.5	586.9
Rin_2R	−571.2	−4038.1	−72.2	−1393.9	1244.4	867.6	1041.3
Rin_3R	−109.1	−1912.2	93.5	−997.4	−391.1	966.2	1218.7
Rin_4R	−4.5	−1205.5	32.3	−858.0	−322.0	800.6	648.3
Rin_5R	315.7	−824.1	−51.7	−725.7	53.4	616.3	181.1
Rin_6R	104.3	−881.5	221.7	−86.8	−86.8	298.7	139.9
Rin_7R	−296.9	−809.0	149.3	−540.5	−0.3	681.2	178.6
Rin_8R	−1017.5	−1108.8	−161.6	−1229.6	275.0	1047.4	662.8
Rin_9R	−110.9	−2838.1	−234.8	−1311.7	139.2	719.8	1076.8
Rin_10R	−96.4	−2550.5	361.2	−649.4	123.2	661.2	863.8
Rin_11R	−56.2	−1325.7	−40.1	−588.7	−148.0	701.6	390.2
Rin_12R	−209.2	−810.6	84.0	−1414.6	−402.4	1285.6	1015.8
Rin_13R	−4.3	−162.2	−668.0	−311.2	274.6	94.4	124.5
Mean	−156.2	−1560.6	−30.3	−866.7	90.3	709.9	625.3
Sum	−2030.5	−20288.2	−393.6	−11267.7	1173.7	9229.0	8128.8
Std dev	319.2	1015.8	241.0	409.4	416.1	297.8	380.3

recharge.

Table 4 provides results for the individual Thiessen polygon net changes in aquifer storage calculated at each monitoring site during this study. Notably, in 2011, sites Rin_2R, Rin_9R and Rin_10R (to the north in general) experienced substantially greater loss from storage than any other site at any other time during the study period, assuming a spatially uniform specific yield. The standard deviation across these three regions is about three times greater in 2011 than in other years, suggesting that pumping tended to be spatially concentrated in 2011 and in 2013, which reflect years of significant surface water shortage (and greatest groundwater extractions; Fig. 4).

Fig. 6 presents net change in aquifer storage in the Rincon Valley relative to December 31, 2009 groundwater table conditions, and relative to the total annual EBID surface water allotment for the period of 2011–2016 (linear trend), and 2009–2016 (non-linear trend). After 2010, a void in aquifer storage had been created as result of reduced recharge and increased groundwater extraction (decrease in groundwater storage during 2011 and 2013), and this void in storage allowed for the potential for gains in groundwater storage that were realized, particularly in 2014, 2015, and 2016. The period of 2009 to 2016 reflects a circumstance where and when the aquifer's buffering capacity

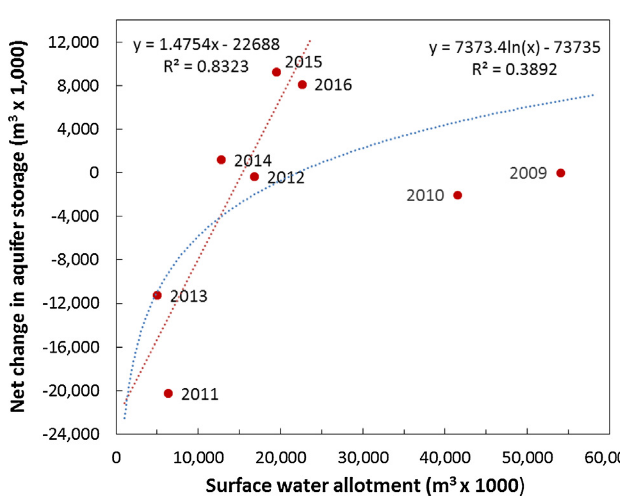

Fig. 6. Net change in aquifer storage in the Rincon Valley from 2011 to 2016 showing a linear trend relative to Dec. 31, 2009 groundwater table conditions and the total annual pro rata EBID surface water allotment, and the same from 2009 to 2016 showing a non-linear trend. In 2009 and 2010, the aquifer was at or near storage capacity. As of 2011, a void in aquifer storage had been established.

(or near-term resilience to mitigate pumping stress) is accounted for in the context of conditions in 2009 and 2010 when the aquifer was at or very near storage capacity because of large net annual gains in the River were calculated for 2009 and 2010 (discussed later). A non-linear trend was evident for the period 2009–2016, and the correlation coefficient is low ($R^2 = 0.39$), apparently because significantly different aquifer conditions are represented in the same plot. Eventually, when/if the aquifer returns to a fully recharged state, such as conditions observed in 2009, then a non-linear trend is expected to best represent net change in aquifer storage relative to surface water allotments.

The period from 2011 to 2016 was found to approximate linear behavior ($R^2 = 0.83$), suggesting that the hydrology of this system was at that time (as of the end of 2011) substantially altered. These results suggest that as of the end of 2011, stress on the aquifer from groundwater extraction, combined with reduced recharge from surface water shortage, may have led to the aquifer being disconnected from the River to one degree or another. Brunner et al. (2009) report that if the groundwater table below a stream is sufficiently deep (relative to streambed elevation), changes in the groundwater table position do not alter the infiltration rate, which is defined as a disconnected system. As noted above, the riverbed elevation in Fig. 5 indicates the River was a gaining stream in 2009 and 2010, the River was a losing stream during all other years, and the River may have become disconnected while it was a losing stream. Following full or closer to full consecutive annual EBID surface water allotments, the aquifer is expected to rebound, and the system would be expected to return to a connected status. The resilience of the aquifer therefore changes over time in response to changing surface water allotments, and the frequency and duration of hydrologic drought, particularly if groundwater extractions for irrigation remain dependent on available surface water. In this way, the resilience of the aquifer is dependent on the GSRA.

3.2. Groundwater-surface water ratio of application

The calculated annual GSRA for the study period is reported in Table 5 and includes total annual metered groundwater pumping from all irrigation wells in the Rincon Valley that are conjunctively used with surface water. Actual farm deliveries of surface water in the Rincon Valley (Table 1) were used in these computations. As expected (in keeping with Fig. 4), 2011 and 2013 are years when groundwater extractions were highest, combined with particularly low EBID surface water allotments, and therefore the highest calculated GSRAs were observed. Substantially more groundwater was pumped than surface water was available to irrigate with. The computed standard deviation over time (5.69) was about 92% of the mean (6.21) GSRA during the study period, indicating substantial variation in the annual proportion

Table 5
Metered annual groundwater extraction and the groundwater/surface water ratio of application for irrigation of lands assessed to receive surface water in the Rincon Valley from 2009 to 2016.

Year	Groundwater extraction ($m^3 \times 1000$)	Groundwater/surface water ratio of application
2009	42,915	0.79
2010	53,028	1.28
2011	82,955	13.09
2012	78,642	4.67
2013	89,486	17.76
2014	81,031	6.32
2015	63,749	3.26
2016	57,304	2.54
Mean	68,639	6.21
Sum	549,110	n/a
Std dev	15,616	5.69

of groundwater and surface water used to irrigate. However, the GSRA of 2.54 at the end of the study period (2016), having dropped from a high of 17.76 found for 2013, implies that conjunctive use of water for irrigation in the Rincon Valley may be fluctuating within a reasonable range of system resilience, and range of GSRA values, even though EBID surface water allotments for the last six years (majority) of this study remained well below half of a full allotment. This may point to adaptation of the Rincon Valley farming community to hydrologic drought.

Fig. 7 is a plot of the GSRA, relative to net change (A) and cumulative change (B) in aquifer storage where groundwater table conditions as of December 31, 2009 are taken to be a baseline for purposes of this study. Fig. 7A compares GSRA values with single-year storage changes and suggests that as the GSRA increases beyond about 4.63, then net loss from aquifer storage is predicted ($R^2 = 0.58$), with increasing groundwater storage loss as the GSRA increases. As of 2011, a void in aquifer storage had been created, therefore the potential for gains in storage had been established relative to the minor changes in storage calculated in 2009 and 2010 when the aquifer was at capacity (2009) or near capacity (2010). The correlation coefficient in this instance is low, and the confidence interval ($0.222 \le R^2 \le 0.936$ at 95%) and P-value (0.0283) indicates that this relationship is marginal. Regardless, the GSRA broadly captures the groundwater storage change impacts attributed to use of surface and groundwater for irrigation in the Rincon Valley within a given year, and the effects of this water use non-uniformity within a given year and from year to year are insignificant compared to impacts on net change in aquifer storage. A threshold value or range of GSRA values specific to a given surface-groundwater system may have utility as a guide to aquifer resilience over time, particularly in this system where groundwater extractions tend to be a substitute for limited surface water availability.

Fig. 7B presents data and a regression for cumulative net change in aquifer storage as a function of the GSRA and reports a non-linear relationship such that a GSRA found to be 4.63 (value for zero net change in storage from Fig. 7A) over time is predicted ($R^2 = 0.78$) to produce a cumulative loss from aquifer storage of about 16,870 acre-feet (20,808 K m^3). The mean GSRA found during the study period, 6.21 (Table 5), is predicted to result in a cumulative net loss from storage of about 19,360 acre-feet (23,880 K m^3). The actual cumulative net loss from storage calculated for the study period was 12,524 acre-feet (15,448 K m^3), which Fig. 7B predicts would be met with a GSRA averaging about 2.77. This discrepancy is most likely a reflection of the relatively small dataset (limited number of years of available, reliable data) used in this study, uncertainty in the data and regression, and the nonlinearity of the trend. Interestingly, however, the GSRA found for 2012 (4.67; Table 5) represents a time of the least amount of net change in storage during the study period (Table 3) and is very close to the threshold GSRA of 4.63 required for a change in storage of zero (Fig. 7A). The implication of this, as applied to Fig. 7B, is that a cumulative net loss from storage at least as large as that calculated through 2012, can be sustained, and if net change in storage is thereafter stabilized (further losses are minimal), then the aquifer will adjust to a new equilibrium. The existence of a dynamic equilibrium is in keeping with dynamic recharge flux, fluctuations in the proportions of surface and groundwater used to irrigate (conjunctive use), and therefore the GSRA. These results are indications that over time, management intervention and/or incentive to reduce the average GSRA, perhaps to approximate 1.0, if even temporarily in response to protracted hydrologic drought, could eventually be fundamental to system resilience. In this way, the GSRA analysis presented herein can help to inform groundwater resilience.

3.3. River performance

Fig. 8 contains data for net annual river loss or gain for the Rincon Valley reach of the Rio Grande, relative to the average annual year-end groundwater table elevation measured at all EBID monitoring sites in the Rincon Valley during this study. Fig. 8 also identifies the average riverbed elevation as surveyed at the center of the Rio Grande along the Rincon Valley reach of the River during the Winter (when the riverbed was dry) of 2016 (IBWC, 2017). Negative change in river volume (i.e., river loss) is in part transmitted as recharge to increase groundwater storage, positive change in river volume (i.e., river gain) and is

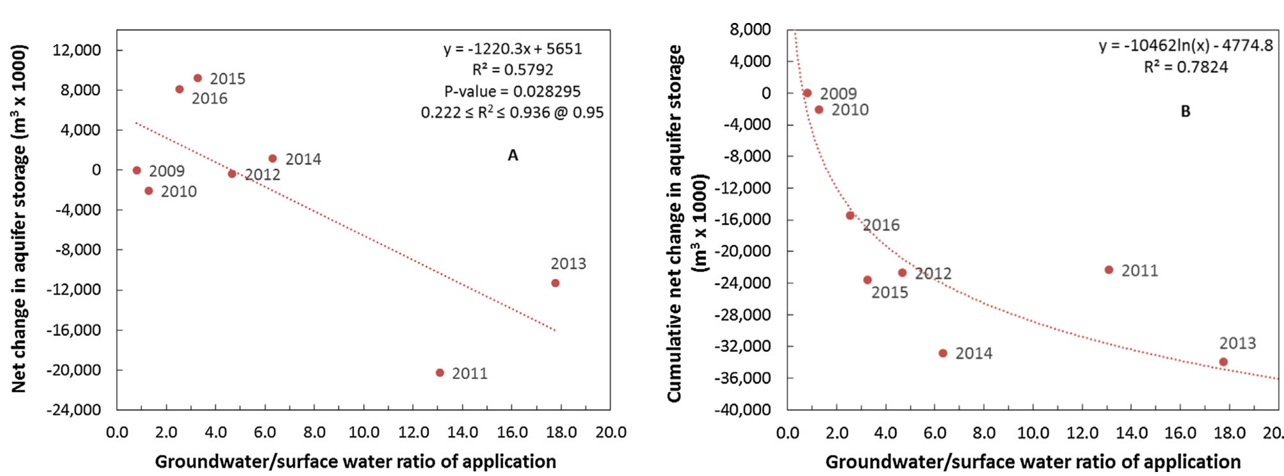

Fig. 7. (A) Net change and (B) cumulative change in aquifer storage in the Rincon Valley from 2009 to 2016 relative to Dec. 31, 2009 groundwater table conditions and the annual ratio of application of groundwater and surface water for irrigation. The non-linear, cumulative trend (B) reveals that increasing dependence on groundwater will eventually reach a point where/when the aquifer has essentially no more to lose, and groundwater resilience will be compromised.

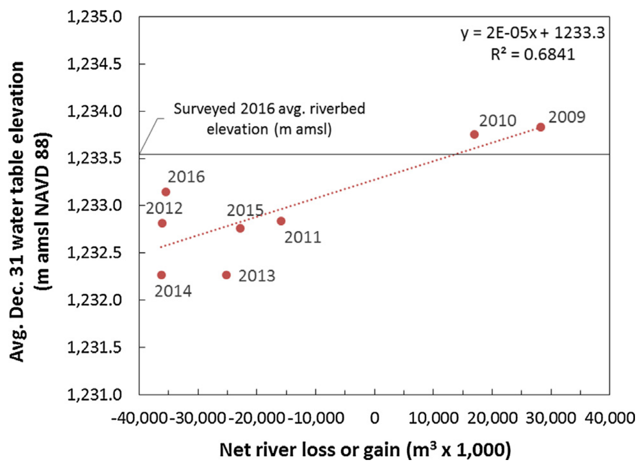

Fig. 8. 2009–2016 observed average Dec. 31 water table elevation in the Rincon Valley relative to net river loss or gain in this reach of the Rio Grande, relative also to the surveyed 2016 average riverbed elevation. As of 2011, the average static water table elevation had receded well below the base of the riverbed.

generally due to discharge from groundwater storage. The observed transition, shown in Fig. 8, of the Rio Grande from a gaining stream to a losing stream is consistent with the previous discussions from Figs. 3 and 5. As evidenced by the linearity in groundwater elevation response following the transition from a gaining river condition to losing, the groundwater system equilibrates within each year due to the constrained aquifer geometry in this case. This aids in the evaluation of groundwater resilience and system response to changes in stress through changes in surface and groundwater use. From 2011 to 2016, the average year-end water table elevation had receded well below the base of the riverbed, reaching a low of 4042.9 feet (1232.3 m) above mean sea level, suggesting that the aquifer may have been, in some places, disconnected (Brunner et al., 2009) from the River during this period.

In terms of annual river losses documented for most of the study period (2011–2016), compared with much larger annual groundwater extractions for irrigation relative to groundwater elevations (Fig. 5) for the same period, annual groundwater extractions can and at times do occur in volumes well in excess of potential annual recharge from the River. This highlights the importance of the alluvium aquifer of the Rincon Valley as a resource for buffering hydrologic drought, the feasibility of conjunctive use in this system, and the potential for limits to aquifer resilience. Dewatering of the aquifer as of 2011 introduced stress to the system such that from 2011 to 2016, net change in storage (Fig. 6) correlates strongly with the annual surface water allotment, suggesting that the recharge rate from the River may have reached a maximum during this time. The annual gains in storage from 2014 to 2016 are attributed to recharge in keeping with the annual EBID surface water allotment, however relatively small the allotments were during this time. The size of the allotments is relevant because to the extent that more surface water is available to irrigate with, and for a longer duration during the irrigation season, then less groundwater is pumped, resulting in less stress on the aquifer. The annual gains in storage from 2014 to 2016 can most likely be attributed to the lowering GSRA values observed during this time period. This further affirms the dependence of the alluvium aquifer storage in the Rincon Valley on the annual EBID surface water allotment, and management of water use to maintain low GRSA values.

The Rincon Valley alluvium aquifer demonstrates losses in response to pumping stress rapidly due to the constrained geometry and hydraulic properties of the aquifer, but it is also quick to demonstrate gains in response to recharge, which is a measure of a resilient system. With a correlation of almost 70% ($R^2 = 0.68$), Fig. 8 suggests that the net annual flux of water gained or lost from the streambed for this reach of the Rio Grande may be stabilized (i.e., zero change in river storage) when the average year-end groundwater table elevation is maintained at least at 4046.3 feet (1233.3 m) above mean sea level, NAVD 88. It is important to note that this is a volatile number and depends on a number of external fluxes (themselves volatile) influencing the system, and therefore does not represent a particular managerial target. Rather, these results suggest that there are a range of average year-end groundwater table elevations, relative to the average riverbed elevation, that may help to inform where and when net annual loss from the streambed approaches a maximum recharge rate. This has implications for groundwater resilience, and also operational efficiency of the River itself.

3.4. Management implications

Relative to net change in aquifer storage as shown in Fig. 6, with a correlation of just over 80% ($R^2 = 0.83$) while dominated by hydrologic drought (2011–2016) during this study, a minimum, consecutive total annual EBID pro rata surface water allotment (applied in the Rincon Valley) of about 12,467 acre-feet (15,378 K m^3) was calculated as necessary to stabilize the system, at least relative to conditions observed from 2011 to 2016. This is only about 0.75 ac-ft per acre (2.29 m^3/hectare), about 25% of a full allotment, and is not suggested to represent a long term, minimum surface water allotment necessary to maintain system resilience, let alone sufficient for the farming community in the Rincon Valley to remain viable. Graphically, it is apparent from Fig. 6 that relatively little net change in storage occurred in 2012 or 2014 (Table 4), which in terms of negligible net storage change is comparable to 2009 and 2010 (a time when the aquifer was at or near storage capacity). Yet, the end of 2014 reflects a time when cumulative loss from storage (Fig. 7B) was by far the greatest during the study period, and actually the greatest for many years (decades) prior (since the early-mid 1950′s). The obvious cause of this was remarkably low surface water allotments in 2011 and 2013, combined with expansive groundwater extractions in response. Had Rio Grande Project operations (and/or upstream conditions) been able to adjust to deliver 25% of a full surface water allotment to the EBID in 2011 and 2013, rather than the 11.1% and 9.7% respectively (Table 1), then aquifer storage changes in the Rincon Valley during this study would have most likely been different (less).

Management goals that target the optimal use of available surface water to facilitate aquifer recharge, and that simultaneously, or at strategically planned times, reduce the stress of groundwater extractions in this system should be explored. An unexhaustive account of options include optimization analysis to quantify the potential for less on-farm groundwater extraction through increased on-farm surface water delivery efficiency by strategic, synthetic lining and/or piping of select, otherwise unlined, earthen canals and laterals. This should be approached cautiously and with attention to not compromising recharge potential with efforts to modernize conveyance infrastructure. It is realized that the existing unlined, earthen canals and laterals do serve in part as a vehicle for aquifer recharge while surface water deliveries are underway. However, the River itself and subsequent on-farm flood application of surface water for irrigation may be the predominant source of recharge in this system. To the extent that enhanced, more efficient conveyance of available surface water for irrigation may reduce groundwater extractions in otherwise problem areas to meet crop requirements, then less stress on the aquifer is expected, and should be explored. Sediment removal and channel maintenance may be used to avoid decreases in recharge associated with lower hydraulic conductivity sedimentation. Further effort could be undertaken to capture and quantify incidental storm water events that normally reach or can be practicably engineered to safely reach the River for diversion and use, or strategically impounded and allowed to infiltrate in the interests of aquifer recharge. For example, storm waters occurring below Caballo

Dam within the EBID are accounted for independent of Rio Grande Project surface water releases from reservoir storage, including those for downstream delivery obligations, and so may be utilized this way.

Depending on fluid flow complexity, aquifer characteristics and water allocation schemes, the purposely simple, straight-forward methodology used in this study may have potential in other conjunctive use settings. However, additional consideration and limitation may exist for systems that exhibit moderate heterogeneity in specific yield/storage coefficients and/or hydraulic conductivity, including irregular, unconstrained and/or partially constrained aquifer geometry, differing aquifer properties, or hydraulically connected aquifers, at various depths, and unmanaged (not reclaimed) river and attendant surface water operations (among other considerations). The methodology presented in this study may serve as a start to characterizing conjunctive use and groundwater resilience in more complicated systems, but should be followed by more exhaustive efforts, including hydrologic modeling. Above all, hydrologic monitoring and measurement is fundamental to this methodology, and to the modeling efforts that may follow.

4. Conclusions

This study further developed the WTF method by quantifying storage changes as a function of annual groundwater and surface water conjunctive use irrigated agriculture managed aquifer-river systems. This approach was also used to investigate groundwater conjunctive use and resilience with application of data from the EBID's Rincon groundwater monitoring program to reveal the spatial and interannual variability of net storage changes from 2009 to 2016 in the Rincon Valley in the arid Lower Rio Grande Basin of south-central New Mexico and to examine the vulnerabilities of the aquifer to protracted hydrologic drought.

In this study, regression modeling showed that variation in the annual, pro rata EBID surface water allotment correlates strongly with year-end water table elevations, and with total annual groundwater extractions for irrigation. This confirms that groundwater pumping for irrigation in the Rincon Valley is essentially a substitute for hydrologic drought impacts on the annual EBID surface water allotment. Added evidence that annual flows in the Rio Grande tend to govern this system was observed in the dewatering of the aquifer as of 2011, which significantly altered the system hydrology (i.e., transition to losing stream) such that persistent, large net losses from the River (recharge to the aquifer) occurred for most of the study period. From 2011 to 2016, net change in aquifer storage correlated strongly with the annual EBID surface water allotment, providing for net gains in aquifer storage from 2014 to 2016 relative to December 31, 2009 baseline conditions. Major storage losses occurring in 2011 and 2013 created a dominant deficit effect such that by the end of the study period, a cumulative storage loss of 12,524 acre-feet (15,448 K m^3) was sustained. Given an average 4.2% loss of the average useable saturated thickness of the aquifer during the study period, if surface water shortages to the EBID remain as they have, then the need for an eventual reduction in groundwater depletions is surely unavoidable. These results affirm the above noted relationship of lower annual EBID surface water allotments (therefore less recharge) with greater groundwater extractions for irrigation tended to lower the average year-end groundwater elevations, which resulted in greater annual net losses from aquifer storage. However, these results also prove that the reverse (gains) can be expected, and at essentially the same rate in this system. The Rincon Valley alluvium aquifer is quick to demonstrate losses, but it is also quick to demonstrate gains.

This study introduced a new term, the GSRA, as the ratio of the conjunctive surface and groundwater uses and the ratio of fluxes into and out of the aquifer that contribute to changes in storage, which has potential for characterizing resilience of surface and groundwater interactions in conjunctive use settings. A range of GSRA values that are system-specific can help to inform groundwater resilience, but more should be done to examine the applicability, controls and limitations of the GSRA. The GSRA calculated at the end of this study, 2.54, relative to a peak GSRA of 17.76 calculated for 2013, implies that conjunctive use of water for irrigation in the Rincon Valley is fluctuating within a range of GSRA values on the backdrop of hydrologic drought, yet groundwater resilience in this system appears to thus far be preserved. Lower values of GSRA approximating 1.0 may reflect an idealized circumstance (e.g., similar to safe yield), and may not be practical in the context of enduring uncertain hydrologic drought conditions in most conjunctive use settings, at least not for very long. It may, however, serve as a temporary management metric if groundwater resilience is found to be in or very near a compromised state. Should this be the case, monitoring of GSRA as a metric for aquifer resilience and sustainability is expected to be useful. The GSRA appears to be a transferable metric with potential to promote or at least characterize groundwater resilience. Knowledge of the aquifer-specific range of GSRA values and associated hydrologic effects may be determined through the methodology offered by this study as specific to an aquifer of interest and perhaps associated with water resource management alternatives appropriate to a conjunctive use setting of interest.

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