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Improving groundwater recharge estimates in alfalfa fields of New Mexico with actual evapotranspiration measurements

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ABSTRACT

Quantifying groundwater recharge from irrigation practices of arid regions is necessary for efficient and sustainable groundwater resources management. Recharge is difficult to measure directly, many studies have quantified recharge from agricultural fields as a residual of the soil water balance method (WBM) or by other mathematical models estimating evapotranspiration (ET) and measuring soil moisture, rainfall, and irrigation. ET is often estimated using weather parameters from climate stations that are distant from crops. Flooding of fields is the most common form of irrigation used by farmers in the Mesilla Valley, New Mexico to grow alfalfa, one of the state's major crops. The objectives of this study were to quantify recharge in flood irrigated alfalfa fields in the Mesilla Valley, New Mexico using the WBM and actual ET measurements during the 2017 growing season. The study fields were different sizes, crop ages, and soil textures. Actual ET of alfalfa was measured on the largest field using the eddy covariance – energy budget method and applied to the two other nearby fields as estimated ET. All other WBM parameters were measured at each study site (i.e. soil moisture, rainfall, and applied irrigation). Recharge using ET referenced to grass (ETsz) was then calculated using weather parameters and compared with measured ET. Recharge ranged from 618 to 716 mm with no significant statistical differences between the three alfalfa fields (f-ratio of 0.8876 and a p-value of 0.42 using ANOVA). Recharge to irrigation ratio ranged from 37% to 45%. On-farm irrigation efficiency ranged from 54.86% to 59.94%. When compared to measured ET, ETsz underestimated recharge of alfalfa by 11% in the WBM and overestimated recharge by 6% when a reduction in ETsz during harvest periods are considered. The results show that the measurement of actual ET improved recharge estimates in the alfalfa fields.

1. Introduction

Irrigated river valleys of the western U.S. and arid regions worldwide are facing water shortages brought on by many factors such as prolonged drought, competing water uses from municipal and industrial users, and changing agricultural land use and cropping patterns that use more water per unit of land. Farmers and water managers need tools to more accurately quantify water budgets and enable better water management for the viability of irrigated agriculture. Better information is needed to characterize the interactions between surface water and groundwater that are so important in irrigated river valleys. Recharge to groundwater from surface water irrigation is particularly important for the longevity of the groundwater resource in dry regions.

The Mesilla Valley along the Rio Grande river in south-central New Mexico is emblematic of an arid region irrigated river valley with stressed groundwater and recharge from irrigation. The hydrogeology of the Valley is such that the surface water (i.e., the Rio Grande) is connected to the shallow flood plain alluvium aquifer (Wilson et al., 1981). According to Conover (1954), the average recharge from precipitation infiltration is small. The groundwater in the Valley is recharged from seepage in certain stretches of the river and canals, infiltration from irrigation, groundwater flow from mesas and other elevated areas, and precipitation in the floodplain (Conover, 1954). Flooding is the most common irrigation practice although sprinkler and underground drip irrigation methods are recently being introduced by some farmers (USDA, 2018). However, deep percolation beneath flood irrigated fields

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is not well understood and is difficult to measure directly (Bethune et al., 2008; Arnold, 2011; Ochoa et al., 2012). Alfalfa is an economically important crop in New Mexico that is commonly flood-irrigated (USDA, 2018; Lauriault et al., 2017). In 2017, the state reported a harvest of nearly 77,000 ha of alfalfa hay valued at $171,000,000 US dollars. In the Mesilla Valley, alfalfa ranks second by area behind pecans (USDA, 2018). As the demand for groundwater increases in the region due to prolonged drought, quantifying groundwater recharge through deep percolation from flood irrigation is necessary for efficient and sustainable groundwater resources management.

Quantifying groundwater recharge (deep percolation) of flood irrigation is important for water management in arid regions. Several techniques to quantify groundwater recharge have been described by Scanlon et al. (2002). A simple and commonly used method is the water balance method (WBM). The WBM has been used to estimate deep percolation below the plant root zone (Scanlon et al., 2002; Arnold, 2011; Ochoa et al., 2012; Gutierrez-Jurado et al., 2017), and the results have been used to calibrate and check other deep percolation models and methods (Deb et al., 2012). As mentioned by Scanlon et al. (2002), however, the limitations of estimating recharge as a residual in the WBM depend on the accuracy with which the components of the budget are measured. A major limitation is the actual measurement of evapotranspiration (ET). Actual measurements of ET using methods such as eddy covariance, Bowen ratio, and others rely on expensive sensors and equipment. Additionally, they require special expertise, experience, and large fields for adequate fetch distance (Rosenberg et al., 1983; Jensen et al., 1990; Brutsaert et al., 2005). Studies in a similar climate to the Mesilla Valley that incorporated the WBM estimated ET indirectly from climate data (e.g. Ochoa et al., 2012; Gutierrez-Jurado et al., 2017). Estimation of ET from climate data, however, is prone to errors due to the quality of climate data, the proximity of climate stations with respect to the fields, and the harvesting periods of crops (e.g. cutting of alfalfa) is often ignored. The objective of this study was to quantify the recharge (considered as deep percolation past the plant root zone) of groundwater from three flood-irrigated fields of alfalfa crop (*Medicago sativa* L) using measured soil moisture, precipitation, amount of irrigation applied, and actual measured ET (i.e. where measurements are possible) in the WBM.

2. Materials and methods

2.1. Site descriptions

The Mesilla Valley is part of the Rio Grande flood plain in south-central New Mexico. It extends from Leasburg Dam at Radium Springs, New Mexico to the west side of El Paso, Texas near International Dam, a distance of about 96 km. It includes about 36,400 ha of bottom valley land where agriculture has been active for centuries (Conover, 1954) due to fertile soil and availability of good irrigation water from the Rio Grande and groundwater. The flow of the Rio Grande in the Valley has been channeled; its flow is controlled by the releases of water from Caballo Reservoir, approximately 72 km north of the Mesilla Valley. Farmers in the Mesilla Valley often pump groundwater from their wells to supplement surface water to meet the crop irrigation needs during the water-scarce periods (Wozniak, 1998).

This study was performed on three alfalfa fields referred to as Horse Farm, Leyendecker, and Willie's (Fig. 1). New Mexico State University (NMSU) owns and manages the alfalfa fields in the Horse Farm and the Leyendecker Plant Science Research Center whereas Willie's is privately owned. The Horse Farm and Leyendecker fields were about 2 ha each and Willie's was the largest among the three fields with an area of 35.2 ha. The Horse Farm was about 5 km from the Rio Grande, whereas Leyendecker and Willies were located within a kilometer of river (Table 1).

Alfalfa of the Horse Farm was the youngest; it was seeded in March 2017. Willie's and Leyendecker alfalfa were seeded in 2014 and 2013, respectively. The Horse Farm and Willie's alfalfa fields were dense,

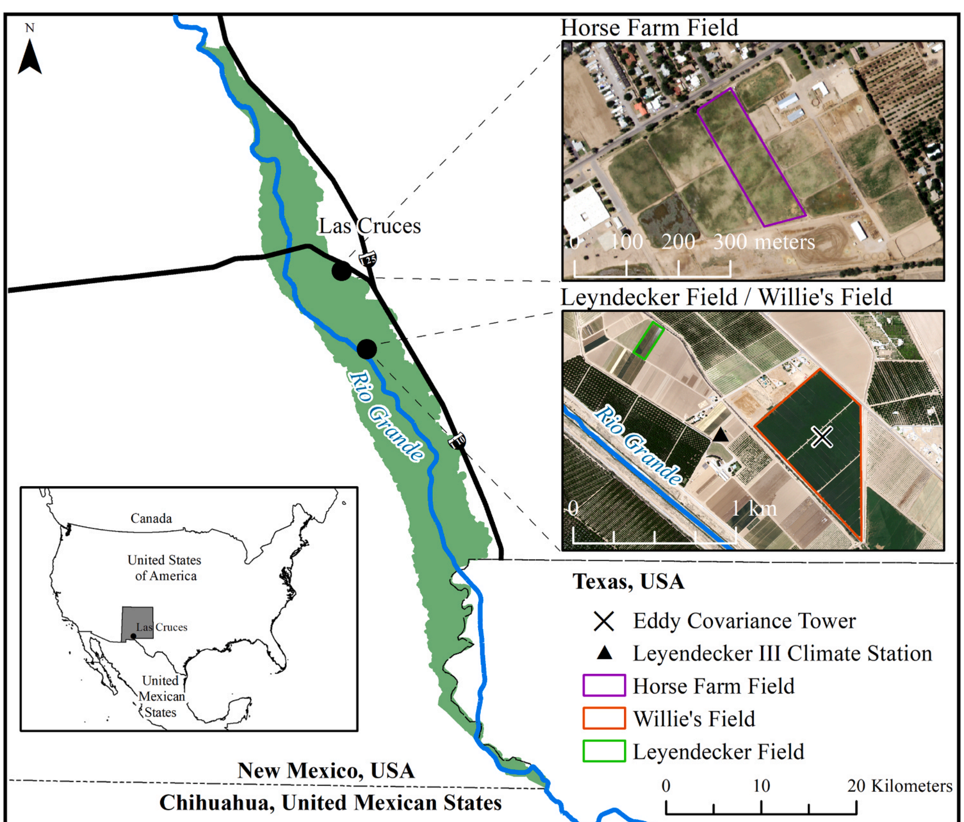

Fig. 1. Map of Mesilla Valley showing the location of the Horse, Leyendecker, and Willie's Farms.

Table 1
Location and area of Horse, Leyendecker, and Willie's fields, and their respective distances from the Rio Grande.

Name	Location	Elevation AMSL (m)	Area (ha)	Distance to Rio Grande (km)
Horse farm	32° 16' 14.70" N, 106° 46' 17.29" W	1177	2.19	4.7
Leyendecker	32° 12' 21.46" N, 106° 44' 50.74" W	1176	1.79	0.6
Willie's	32° 12' 03.07" N, 106°44' 09.90" W	1176	35.2	0.9

uniform, and monotypic. In contrast, the Leyendecker field was composed of 50% alfalfa and 50% native grasses including saltgrass [*Distichlis spicata* var. stricta (L.)] and yellow bristle grass (*Setaria pumila*).

2.1.1. Climate

The climate of the region is described by Malm (1994) as an arid southwestern United States climate with annual average precipitation of 222 mm per year. More than 75% of the precipitation falls during the warm monsoonal months of July through September. The mean annual temperature based on a 108-year climate record of the city of Las Cruces is 15.8° C and an average diurnal temperature of 17.8° C (Malm, 1994). Winds are usually light during summer months and moderately strong with occasional gusts in spring and winter.

2.1.2. Geology and soil texture

The Mesilla Valley is dominated by sediments largely derived from alluvial and fluvial process and are composed of mainly gravel, sand, silt, and some clay (Hawley et al., 2001). The US Department of Agriculture (USDA)−Natural Resources Conservation Service (NRCS) Web Soil Survey (USDA−NRCS WSS) shows that the surface soil of Willie's field is mainly silty loam, and Leyendecker and Horse Farm fields are clay loam. A total of 18 soil samples (3 samples at each depth) for subsurface textural analysis were collected at the center of each study site during the installation of the soil moisture profile. Sampling was conducted in 30 cm increments from the surface to 180 cm depth. A hydrometer method test was performed on soil samples to determine their respective textures at each depth (Table 2) following ASTM (2017) international standard for hydrometer testing. Willie's, Leyendecker, and Horse Farm's surface soil to 30 cm depth were determined as silt loam, clay, and clay loam, respectively. The tilling and mixing of the soils on these fields have changed the soil texture over time, but in general, our assessment of the topsoil texture is similar to those reported by the USDA-NRCS WSS. The textures of soil samples taken at different depths (30–180 cm) for the three fields range from fine to coarse texture. Two horizons of soils were visible during the installation of groundwater monitoring wells at all of the fields; generally, the top (0–90 cm) was fine-textured soils and (90–610 cm) was coarse sandy textured soils.

Table 2
Soil texture at incremental depths of Horse Farm, Leyendecker and Willie's.

Study site	Depth (cm)	Particle size distribution (%)			Texture
		Sand	Silt	Clay	
Horse farm	30	23.48	36.86	39.66	Clay loam
	60	88.48	3.36	8.16	Loamy sand
	90	93.48	1.36	5.16	Sand
	120	93.48	0.36	6.16	Sand
	150	94.48	1.36	4.16	Sand
	180	95.48	0.36	4.16	Sand
Leyendecker	30	12.20	39.82	47.98	Clay
	60	8.20	39.82	51.98	Clay
	90	12.20	31.82	55.98	Clay
	120	80.20	1.82	17.98	Sandy loam
	150	70.20	17.82	11.98	Sandy loam
	180	94.20	1.82	3.98	Sand
Willie's	30	20.74	54.82	24.44	Silt loam
	60	62.74	22.82	14.44	Sandy loam
	90	92.74	2.82	4.44	Sand
	120	94.74	1.82	3.44	Sand
	150	93.74	2.82	3.44	Sand
	180	95.74	0.82	3.44	Sand

2.2. Groundwater recharge

Groundwater recharge (D_w) is considered here as deep percolation beneath the crop root zone. It is determined as a residual in the soil-water balance equation (Eq. (1)) as,

$$D_w = I_r + R_e - \Delta S - ET \tag{1}$$

where I_r is the amount of irrigation in mm applied during the period, R_e is the amount of rainfall in mm that does not run off the area during the period, ET is the amount of evapotranspiration in mm during the period, and ΔS is the change in soil water storage in mm over the period. There was no runoff of irrigation water leaving the fields since all fields were laser leveled and bordered. The effects of groundwater contribution to the plant root zone as a source of water for plants were not considered since the groundwater was deep (> 3.25 m) at all the experiment sites. Field observation during excavation at the three farms showed alfalfa roots extending to a maximum of 1.2 m deep. Eq. (1) characterized the soil water status within the plant root zone of 120 cm and D_w below 120 cm assuming i) soil water content within the 120 cm profile varied in one-dimensional vertical direction, ii) surface to 160 cm depth soil textures are homogenous throughout the field, iii) capillary rise was negligible since the groundwater table was too deep, iv) the ΔS measurements represented the entire alfalfa field, and v) deep percolation is assumed to eventually reach groundwater.

2.2.1. Irrigation

The fields were irrigated by flooding using pumped groundwater and or surface water from the Rio Grande. Surface water in the Mesilla Valley is managed and supplied to farmers by the local irrigation district using a network of irrigation canals. All the fields were laser leveled and bordered before planting alfalfa. At Willie's, alfalfa was irrigated using groundwater (irrigation pump) and by surface water when available. The irrigation water from the well or surface water was conveyed by a concrete-lined trapezoidal canal to the field. The canal was 0.61 m at the base, 2.13 m at the crest, and 0.91 m deep. Flow in the canal was measured using a simple trapezoidal flume (ST Flume) with a circular stilling well as described by Samani (2017). The depth of water in the stilling well was measured using a pressure transducer model CS450 and a CR200 datalogger, both from Campbell Scientific Inc. (CSI) (Logan, Utah). Flow measured by the flume was verified using a current velocity meter model 2100 (Swoffer Instruments Inc., Federal Way, Washington) following the USGS velocity-area method (Turnipseed and Sauer, 2010). Accuracy of most discharge measurements considered qualitatively a "good" measurement is about 5% (Turnipseed and Sauer, 2010). The error of the current meter used in this study, when appropriately calibrated, is about 1% (Swoffer Instruments Inc. Manual, Federal Way, Washington). Groundwater at Willie's was pumped from the ground through a metered pipe where the total volume of water discharged was monitored every irrigation. The water from the well was discharged in the same canal, which was also used for surface water irrigation to deliver water to the field.

Irrigation infrastructures at Horse Farm and Leyendecker were connected to a groundwater well and a pump. Leyendecker had the capability of pumping surface water through the same system which conveyed groundwater, allowing both surface water pumped from a canal and groundwater to be measured during each irrigation. The amount of water pumped from each of the wells at Horse Farm and Leyendecker were monitored by a meter that was mounted in their respective discharge pipes. The meters were manually read before and after irrigations to determine the total volume of water pumped. The volume of water applied to the fields was divided by the irrigated land area to determine the depth in mm of irrigation water applied.

2.2.2. Rainfall

Precipitation in the Mesilla Valley is mostly in the form of rain. Rainfall was measured by a climate station known as Leyendecker III weather station (32°12'3.26"N, 106°44'34.00"W, elevation 1176 m AMSL) located inside the NMSU-Leyendecker Plant Science Research Center and near the Leyendecker alfalfa field. The station is located about 0.62 km from Willie's and 8.2 km from the Horse Farm. Rainfall was measured using a TB4 rain gage (CSI, Logan, Utah). The TB4 rain gage has a 203.2 mm orifice and measures rainfall in 0.254 mm increments using an internal siphon and a typing bucket mechanism.

2.2.3. Actual evapotranspiration

Evapotranspiration was measured using the energy budget method (Eq. (2)) at Willie's in the center of the field to ensure adequate fetch. The soil moisture profile and depth to groundwater were also measured alongside the ET. The location of the eddy covariance (EC) system is denoted by the symbol "X" in Fig. 1. The components of the energy budget including net radiation, soil heat, and sensible heat fluxes are measured and latent heat is determined as a residual following the methodology presented in Bawazir et al. (2014). Latent heat flux (LE) is converted to an equivalent depth of water, or ET in mm, by dividing latent heat flux by latent heat of vaporization of water (i.e. 2.45 MJ/kg at normal temperatures) and density of water (1000 kg/m^3):

$$LE = Rn - G - H \tag{2}$$

where LE is latent heat, Rn is net radiation, G is soil heat and H is sensible heat. All these energy fluxes are measured in W/m^2. Sensible heat is measured using the eddy covariance technique (Swinbank, 1951; Rosenberg et al., 1983; Brutsaert et al., 2005) where vertical wind speed and air temperature in the lower atmospheric boundary layer are correlated (Eq. (3)).

$$H = \overline{\rho} c_p \overline{[W'T']} \tag{3}$$

where $\overline{\rho}$ is the mean density of air, c_p is the air heat capacity at constant pressure and $\overline{[W'T']}$is the covariance between fluctuations of vertical wind speed (W′) and temperature (T′).

The instrumentation used in measuring the components of the energy budget in Eq. (2) included: Three-dimensional sonic anemometer model CSAT3 (CSI, Logan, Utah) to measure sensible heat, net radiometer model NR-Lite (CSI, Logan, Utah) to measure net radiation, two soil heat flux plates model HFT3 (REBS Inc., CSI) in combination with soil moisture sensor model CS 616 (CSI, Logan, Utah), and a pair of two-averaging soil temperature thermocouples model CAV (CSI, Logan, Utah) to measure soil heat flux. Additional sensors were installed to measure relative humidity and ambient air temperature; model HMP45C (CSI, Logan, Utah). CSAT3 and HMP45C were mounted on a tripod at 2.5 m above the ground in the middle of Willie's field. The CSAT3 was leveled and oriented towards prevailing wind with an adequate fetch distance of more than 250 m in each direction. An effort was made to minimize potential errors due to sensor mounting and measurement in the field. To check for energy budget closure of Eq. (2), open path LICOR 7500 (LI-COR® Biosciences, Lincoln, Nebraska) coupled with CSAT3 was used to measure LE following Burba and Anderson (2005),

$$LE = \lambda \overline{[W'q']} \tag{4}$$

where λ is the latent heat of vaporization of water and $\overline{[W'q']}$is the covariance between the fluctuation of vertical wind speed (W′) and vapor density, q′.

A net radiometer was mounted on a separate pole nearby at a height of 1.94 m from the ground surface. The two soil heat flux plates were installed at 8 cm below the ground surface and separated by about a meter. The plates were installed in such a way that they capture heat flux underneath the plants and in open spaces that would be exposed to sunlight during alfalfa cutting periods. The pair of averaging soil temperature sensors were then installed at 2 cm and 6 cm below the ground and above the soil heat flux plates. The soil moisture sensor was installed at a 45-degree angle to measure soil moisture in the upper soil layer for use in determining the rate of soil heat storage as part of soil heat flux calculations. Data were collected at 10 Hz using CR5000 datalogger (CSI, Logan Utah) and averaged every 30 min. The entire setup (i.e. system) was powered by a battery and solar panels.

The footprint of EC measurements at the site was determined using scaling procedure following Kljun et al. (2004). The footprint ranged from 2 m to 234 m with an average of 37 m for 30 min data (n = 13, 378) at 90% of the scaled footprint from the EC sensor (or receptor). The minimum distance to the edge of the field from the EC sensors was 230 m and located in the North-Eastern quadrant where the prevailing wind was minimum. The distance to the edge of the field for the rest of the quadrants was at least 274 m (> 234 m) and therefore satisfying the required footprint of ET measurements by the EC technique.

Measurement of fluxes such as (LE) and sensible heat (H) using the EC measurement technique have to be corrected due to assumptions in the methodology, instrumentation problems, physical phenomena, and terrain (Burba and Anderson, 2005; Aubinet et al., 2012). Data collected by CSAT3 were corrected for sonic temperature (Massman and Lee, 2002), frequency attenuation (Massman, 2000; 2001), and cross-contamination using a double rotation scheme (Tanner and Thurtell, 1969, Lee et al., 2004). Errors attributed to regular maintenance, precipitation, and sensor malfunction were corrected during data processing. Latent heat flux was also corrected for water vapor density effects according to Webb et al. (1980). The data considered as outliers or spikes were also removed. The 30-min data were totaled to obtain daily values (24-hr from midnight to midnight). Daily LE was determined using Eq. (2) and then converted to ET using λ (2.45 MJ/kg) and density of water (1000 kg/m^3). Because of the negligible difference over the expected range of temperatures at the study site, λ was assumed constant. The ET was measured only at Willie's due to the limitations of the EC technique which requires adequate fetch distance (a large area).

2.2.4. Reference evapotranspiration

Actual ET was not measured for the Leyendecker alfalfa field. Instead, a reference ET and a crop coefficient (ET = ETsz x Kc) were used to determine actual ET. The ETsz was determined using the American Society of Civil Engineers (ASCE) standardized equation for short crop or grass (ASCE−EWRI, 2005). Climate data were obtained from the Leyendecker III weather station. The station measured solar radiation, wind speed and direction, relative humidity, and air temperature. The data were collected every minute and averaged to an hourly and daily time step then stored on a CR1000 datalogger (CSI, Logan, Utah) for later download and processing. The station was powered by a 12 Vdc battery and a 20-watt solar panel.

2.2.5. Change in soil moisture storage

Change in soil moisture storage (ΔS) was determined as,

$$\Delta S = \sum_{i=1}^{n} (\theta_2 - \theta_1)_i \Delta d_i \tag{5}$$

where n is the number of layers to the depth of the effective root zone, θ_1 and θ_2 are the volumetric moisture contents on the first and second time of sampling, respectively in m^3/m^3, Δd_i is the thickness of each soil layer in mm.

Volumetric soil water content (VWC) at each field was measured using six – SC650 Water Content Reflectometer (CSI, Logan, Utah). The sensors were installed in a soil profile near the center of the field, in the vicinity where ET and depth to groundwater were measured, at incremental depths of 30 cm from the ground surface to 180 cm. The data were collected every minute and averaged every 30 min onboard a CR300 datalogger (CSI, Logan, Utah). Daily soil moisture values were determined as a mean of the 30-minute data collected during 24 h from midnight to midnight.

2.3. Depth to groundwater

The depths to groundwater at the three fields were monitored using 50.8 mm diameter galvanized piezometers. The piezometer at Willie's was 8.5 m long, reaching a maximum depth of 7.4 m below the surface, and screened at the bottom 2.4 m. Leyendecker and Horse Farm's piezometers were 7.62 m long, reaching a maximum depth of 6.5 m below the surface and screened at the bottom 1.5 m. Piezometers at all sites were installed with pressure transducers (Model CS450) and connected to a CR300 datalogger (both CSI, Logan Utah) to monitor depths to groundwater every 30 min. Depth to groundwater at all sites was also monitored using a water level sounder during field visits for redundancy. The 30-minute data were averaged to 24 h from midnight to midnight for determining daily depths to groundwater.

3. Results and discussion

3.1. Irrigation

Farm managers irrigated the fields based on their judgment of soil moisture, visual health of the crop, and experience aimed to produce a quality alfalfa crop. This was the case for all the fields. Willie's field was irrigated using both surface water and groundwater. Groundwater was used only when no surface water was available. Flow measured by the ST-flume averaged 0.52 m^3/s, while that measured by the current meter using the USGS velocity-area method averaged 0.51 m^3/s during an irrigation event. The two measurements compared reasonably well with near-identical volumetric flow rates (difference of 0.01 m^3/s).

The flows in the canal at Willie's were low during irrigation periods consisting of groundwater due to pump capacity when compared to irrigations using surface water. The flows using groundwater ranged from 0.12 to 0.16 m^3 /s. The amount of water for each irrigation event varied from 134 mm to 222 mm. The total depth of 6 irrigation events from groundwater during the season was 994 mm and from 5 irrigation events using surface water was 880 mm; irrigation from both sources totaled 1874 mm during the entire growing season. Willie's water balance for 2017 is presented in Table 3.

The complete water balance for 2017 can be found in Tables 4 and 5 for the Horse Farm and Leyendecker, respectively. The total depth of irrigation water pumped at Horse Farm was 1595 mm for 8 irrigation events (Table 4) and Leyendecker was 1419 mm for 10 irrigation events (Table 5).

3.2. Rainfall

Annual precipitation measured at the Leyendecker III weather station was 279 mm, which was above the annual average of 222 mm reported by Malm (1994). The highest percentage of rainfall in the Mesilla Valley often occurs during the monsoonal rainy season which starts in July and extends through September (Malm, 1994). Of the 279 mm, 196 mm (70.22%) occurred in July and August (Table 6). Precipitation is very low during the early part of the growing season from February through June and during the non-growing season from October through December. Irrigation is crucial during this time in order to sustain healthy plant growth and to leach out salts that accumulated during the previous season. Precipitation in 2017 was less than 12 mm per month from February through June and from October through December.

3.3. Evapotranspiration

Latent heat was measured directly using LICOR 7500 from May to August as a check for energy budget closure. The energy closure [(LE + H)/(Rn−G)] on daily basis using LE measured by LICOR 7500 and CSAT3, ranged from 0.67 to 1.31 with a mean of 0.96, a standard deviation of 0.138 and standard error of 0.0140 for N = 97 days (Table 7). Using ANOVA, a significance of energy closure among May to August was judged at $p < 0.05$ indicated a significant difference between the months.

To estimate the entire growing season recharge (N = 269 days), LE was determined as a residual in Eq. (2) assuming the energy budget closure of 1. LE in the equivalent depth of water or ET measured at Willie's was 1309 mm for a total of 269 days during the period of soil moisture measurements (Table 3). Total ETsz calculated using the Leyendecker III weather station for the same number of days was 1387 mm. Fig. 2 shows the daily fluctuations of measured ET and ETsz as well as the cutting periods.

Evapotranspiration of alfalfa decreased during the six harvesting periods and it took between 10 and 16 days (average of 12 days) after harvesting to reach maturity and transpire at its potential ET. The difference in ETsz and measured ET during the harvesting periods ranged from 19 mm to 47 mm with an average of 27 mm per harvest (Table 8).

Evapotranspiration of Horse Farm and Leyendecker were not measured but were estimated based on the measurements conducted at Willie's. The ET of Horse Farm was assumed the same as that at Willie's because of the following: alfalfa at Horse Farm was planted early in 2017 and quickly became lush as the season progressed similar to Willie's; the soil textures within 120 cm depth at Horse Farm were similar to Willie's (Table 2) and this is also reflected in measured soil moisture as shown in Figs. 3 and 4; the irrigation scheduling and alfalfa cuttings were in synchrony with Willie's; the climate at Horse Farm was similar to that of

Table 3
Willie's water balance within 120 cm root zone measured in 2017.

Irrigation event	Date of irrigation	N (Days)	Irrigation (mm)	Rainfall (mm)	ET (mm)	Δ Storage (mm)	Recharge (mm)
1	3-Mar	18	202	0	71	135	−4
2	21-Mar	14	141	0	71	0	69
3	4-Apr	29	142	2	148	-89	85
4	3-May	13	137	0	91	68	−21
5	16-May	26	173	5	174	-73	77
6	11-Jun	29	160	1	170	-22	13
7	7-Jul	37	176	154	210	62	59
8	16-Aug	30	134	43	137	-5	45
9	15-Sep	11	222	1	55	59	110
10	25-Sep	36	188	15	120	-76	158
11	1-Nov	26	199	11	63	48	99
Total		269	1874	232	1309	107	690
Standard deviation		9.11	30.08	46.00	52.66	71.39	52.61
Mean		24.45	170.36	21.08	118.99	9.76	62.70

Table 4
Horse Farm water balance within 120 cm root zone measured in 2017. ET* denotes estimated ET based on actual ET measurements at Willie's Farm.

Irrigation event	Date of irrigation	N (days)	Irrigation (mm)	Rainfall (mm)	ET* (mm)	Δ Storage (mm)	Recharge (mm)
1	13-Apr	21	189	2	103	14	73
2	4-May	26	174	0	198	−53	29
3	30-May	22	173	5	137	−43	84
4	21-Jun	22	175	1	113	−4	68
5	13-Jul	35	189	155	198	10	137
6	18-Aug	29	211	41	130	8	114
7	15-Sep	48	226	16	177	−41	105
8	2-Nov	25	258	11	60	104	105
Total		228	1595	232	1116	−5	716
Standard deviation		9.12	30.31	39.51	48.69	49.97	49.97
Mean		28.50	199.35	27.63	139.53	−0.65	89.46

Table 5
Leyendecker water balance within 120 cm root zone measured in 2017. ET* denotes estimated ET based on actual ET measurement at Willie's Farm and saltgrass ET.

Irrigation event	Date of irrigation	N (days)	Irrigation (mm)	Rainfall (mm)	ET* (mm)	Δ Storage (mm)	Recharge (mm)
1	25-Feb	29	128	0	66	51	10
2	27-Mar	28	132	0	96	-9	46
3	24-Apr	21	137	2	84	-11	65
4	15-May	26	119	5	125	-108	107
5	10-Jun	30	162	1	139	-98	121
6	10-Jul	38	193	156	168	203	-22
7	17-Aug	28	126	41	104	-26	89
8	14-Sep	34	156	13	116	-41	94
9	18-Oct	13	136	2	22	132	-16
10	31-Oct	27	132	11	43	-25	125
Total		274	1419	232	964	69	618
Standard deviation		6.80	22.32	48.21	44.33	97.28	55.08
Mean		27.40	141.94	23.19	96.43	6.89	61.81

Table 6
Precipitation measured in 2017 at Leyendecker III weather station.

Month	Precipitation (mm)	Annual precipitation (%)
January	35	12.47
February	9	3.37
March	0	0.00
April	2	0.64
May	3	1.18
June	3	1.00
July	111	**39.71**
August	85	**30.51**
September	11	3.92
October	6	2.09
November	11	4.10
December	3	1.00
Total	279	100

Table 7
Energy Budget Closure of the eddy covariance measurement at Willie's alfalfa field.

Month	Sample, N (days)	Minimum	Maximum	Mean	Std. dev.	Std. error
May	22	0.72	1.10	0.885	0.0987	0.0210
June	30	0.67	1.30	0.930	0.1449	0.0269
July	31	0.80	1.31	1.015	0.1217	0.0219
August	15	0.75	1.22	1.005	0.1510	0.0390
Overall	97	0.67	1.31	0.959	0.138	0.0140

Willie's as the distance between the farms is relatively small and there were no abstractions of wind at both locations. Data from another climate station near the Horse Farm (Lat/Long 32°16'44.64"N, 106°46'15.80"W, Elevation 1187 m AMSL) known as Fabian Garcia (FG) station was used as a comparison to Leyendecker III climate station (i.e. near Willie's). Daily ETsz determined from the data collected at the two stations were compared using linear regression. The two sites' daily ETsz were highly correlated (ETsz (LYIII) = 0.9512 (FG) + 0.0774; R^2 = 0.9739; standard error of estimate of Y with respect to X of 0.32 mm). It can be concluded from these similarities that the actual ET of Horse Farm is similar to ET measured at Willie's as 1116 mm for 228 days (Table 4) during the growing season.

Evapotranspiration of alfalfa mixed with saltgrass and some bristle grass at the Leyendecker field was determined as a weighted average of ET of dense alfalfa, similar to Willie's alfalfa field, and ET of saltgrass. Actual ET measurements at Willie's was used as ET for the 50% alfalfa in Leyendecker. The ET of 50% grass portion was determined from ETsz and a crop coefficient of grass. The ET portion of riparian grass was determined by using a polynomial crop coefficient as a function of the day of the year (DOY) developed by Bawazir et al. (2014) for saltgrass multiplied by ETsz (ET = $Kc_{saltgrass}$ x ETsz). Saltgrass is native to New Mexico and grows in the Mesilla Valley alluvial deposits of the Rio Grande. The ET of saltgrass was used to represent ET of all the grass types in the Leyendecker farm since the percentage of other types of grasses was very low. The ET of Leyendecker Farm was determined as 964 mm for 274 days (Table 5).

3.4. Change in soil moisture storage

Change in soil moisture storage was determined from measurements of soil moisture within the root zones. Change in storage is most impactful in the root zone. Below the root zone is considered a "zero-flux plane" separating upward movement of water in soil due to ET from water draining downward to groundwater due to gravity (Arnold, 2011). We considered the zero-flux plane at 120 cm below the surface for calculations of the change in soil moisture storage. The effect of ET would be very low below 120 cm since no roots were observed while excavating at the three study fields. A similar zero-flux plane of 120 cm in alfalfa fields was reported by Arnold (2011). Additional VWC sensors were installed below the 120 cm root zone at 150 cm and 180 cm. During irrigation events, these two additional sensors measured the VWC average of approximately 13% and 6%, respectively showing

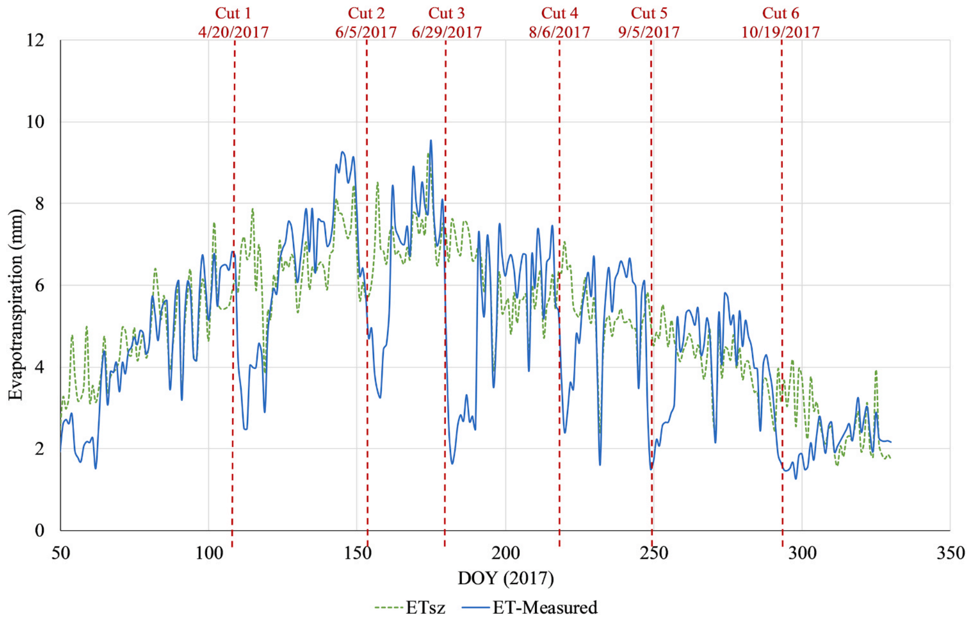

Fig. 2. Measured evapotranspiration (ET-measured) of alfalfa and calculated evapotranspiration referenced to grass (ETsz) showing harvesting periods during 2017.

Table 8
The difference in evapotranspiration between reference (ETsz) and measured ET (ET) during harvesting periods at Willie's alfalfa field.

	Willie's field harvesting periods 2017						Average
	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5	Cut 6	
Date of cut	20-Apr	5-Jun	29-Jun	6-Aug	5-Sep	5-Sep	
(ETsz–ET), mm	28	19	47	18	26	23	27
Days to maturity	16	10	11	10	10	14	12

water was percolating past the root zone. Capillary rise from groundwater water was not observed in the soil moisture measurements conducted at 150 cm and 180 cm.

Daily soil moisture measurements are shown in Figs. 3 through 5 and the changes in soil moisture storage were calculated using Eq. (4). Spikes in soil VWC occurred during irrigation events and heavy rains (e.g. Fig. 3). High VWC from heavy monsoonal rains (Table 6) can be seen in Figs. 3 through 5 on days 196–236 of the year.

At Leyendecker, the sensor at 90 cm depth malfunctioned and therefore reported erroneous data. Instead, data measured at 60 cm and 120 cm were weighted based on their incremental depths to determine daily VWC at 75 cm as shown in Fig. 5. The volumetric moisture content at Leyendecker during the first and second irrigations exceeded 60% at 30 cm depth due to water ponding and low infiltration rates of clay soil. Volumetric soil moisture at Willie's and Horse Farm followed a similar trend (Figs. 3 and 4). This is expected due to similarities in soil texture

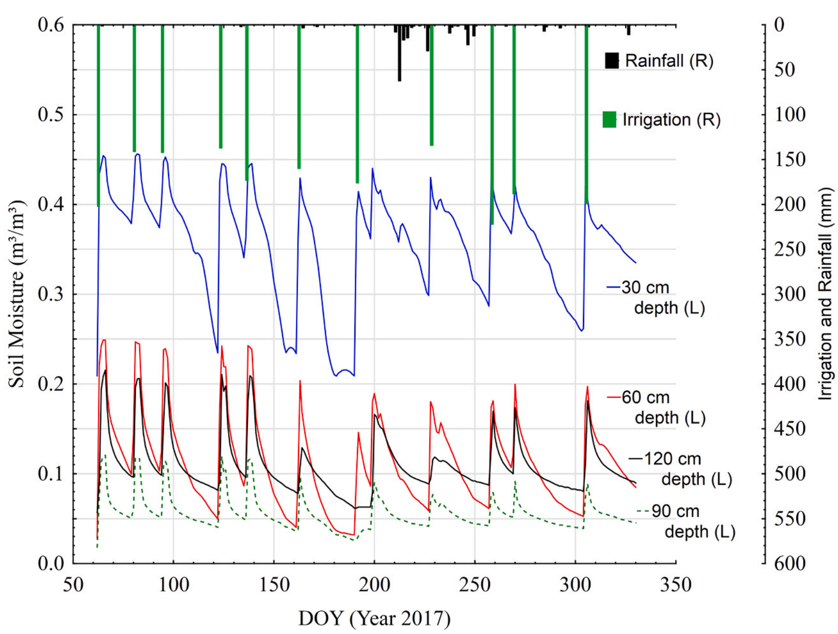

Fig. 3. Soil moisture profile measured at Willie's with irrigations and rainfall in 2017. (L) signifies the left axis, and (R) as the right axis.

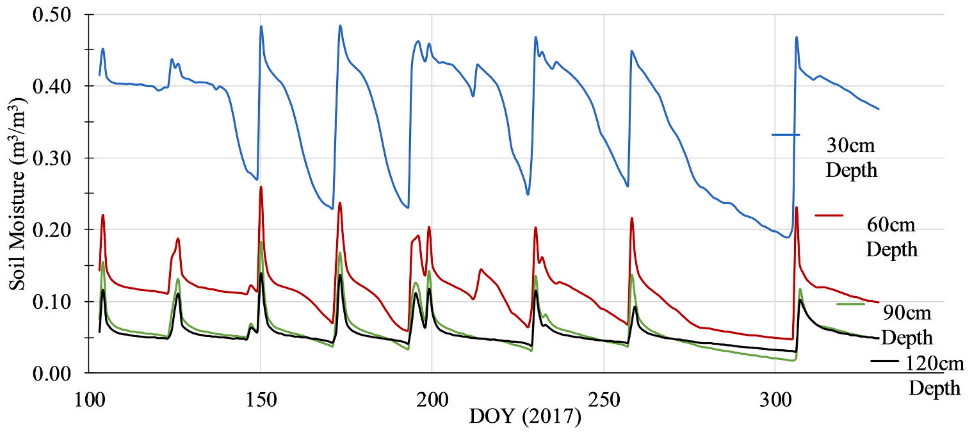

Fig. 4. Soil moisture profile measured at Horse Farm in 2017.

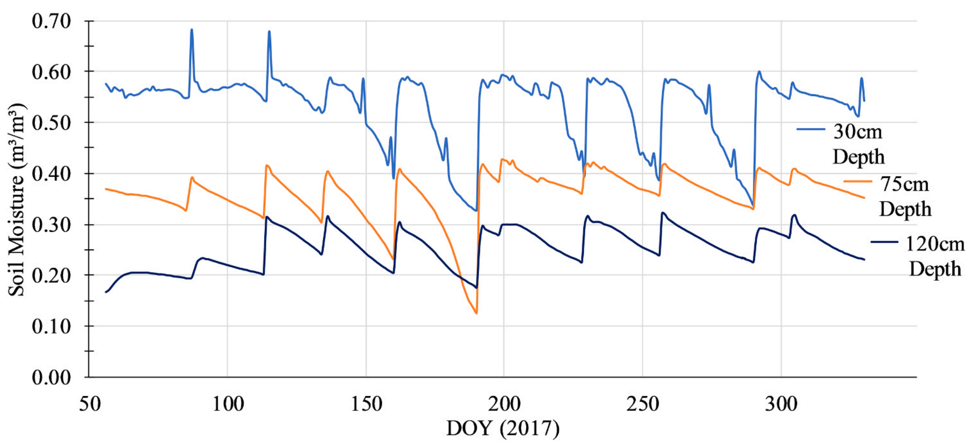

Fig. 5. Soil moisture profile measured at Leyendecker farm in 2017.

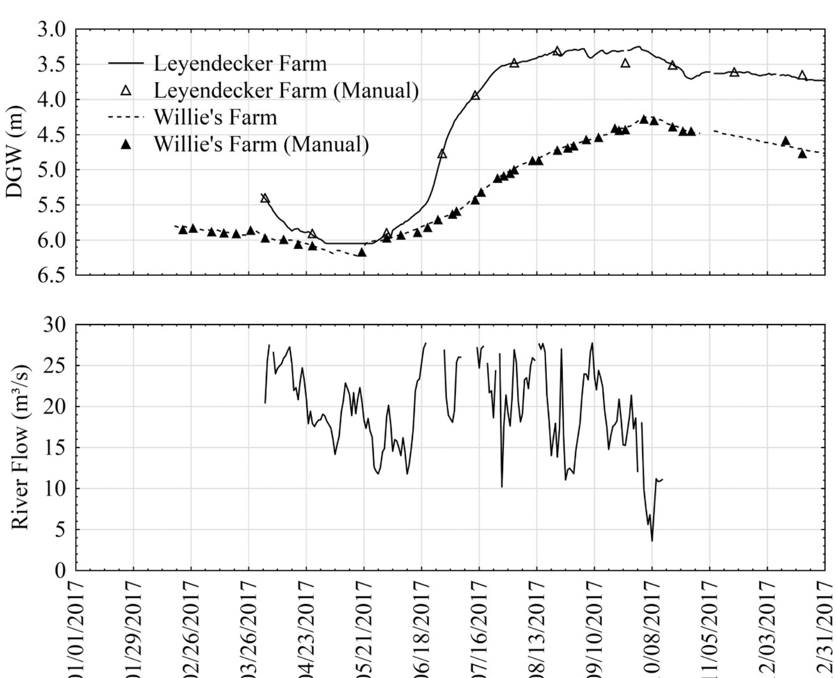

Fig. 6. Measured depth to groundwater (DGW) using a pressure transducer and manually using a sounder at Willie's and Leyendecker Farms as it correlates with the flow in the Rio Grande.

and drainage properties. The daily (24 h) changes in soil moisture storage were summed for the periods between irrigation events to determine deep percolation (Tables 3 through 5). The changes in soil moisture storage at Willie's, Horse Farm, and Leyendecker during the growing season totaled to 107 mm, −5 mm, and 69 mm, respectively.

3.5. Groundwater recharge

The irrigation frequency and amounts varied among the fields. Water applied during each irrigation was consistently lower at Leyendecker when compared to Willie's and Horse Farm. Based on the total irrigation of water applied during the growing season and the number of irrigation events, the Horse Farm received more water than Willie's and Leyendecker on average. The actual ET of Leyendecker was low (963 mm) due to the mixture of grasses with alfalfa and high matric potential of clay soils. Depth to groundwater was greater than 3.25 m at all the study sites (Fig. 6). No water was detected in the 6.5 m depth piezometer at the Horse Farm and therefore depth to groundwater was considered more than 6.5 m. Groundwater at all the study sites was too deep to contribute water to the root zone by capillarity. Negative values in recharge are possibly due to matric potential pulling water into the root zone from the soil below it or lateral flow of water within the soil strata.

The rise in groundwater elevation during the study period coincided with releases of water (i.e. flow) in the Rio Grande (Fig. 6). Depth to groundwater at Leyendecker responded faster to high flow in the Rio Grande than at Willie's due to its proximity to the river; the Rio Grande is hydrologically connected to the groundwater as described by Wilson et al. (1981). When water is released in the river and is distributed to the farmers in the Mesilla Valley for irrigation, most farmers stop pumping groundwater for irrigation. During this period, groundwater elevation increased at both Willie's and Leyendecker due to the combination of a decrease in groundwater pumping, seepage from the river and irrigation ditches, and infiltration from increased surface water irrigation in the Valley.

Groundwater recharge was determined using the water balance method (Eq. (1)). Recharge during the growing season was 690 mm at Willie's, 716 mm at Horse Farm, and 618 mm at Leyendecker. Statistical analysis using an analysis of variance (ANOVA) test was performed using recharge results to determine if there are any statistical differences among the three study sites. The ANOVA test yielded an *f*-ratio of 0.8876 with a *p*-value of 0.42 indicating the recharge at the three sites is not significantly different at $p < 0.05$. Therefore, no further analyses were performed. The similar recharge amounts are likely due to farming irrigation practices; farmers adjust irrigation amounts based on field conditions such as soil type or crop water needs.

Percent recharge, determined as total recharge divided by total irrigation, ranged between 36.82% and 44.89% (Table 9). These values are comparable to a recharge ratio of 47% during a growing season reported by Ochoa et al. (2012) for a flood irrigated alfalfa field in northern New Mexico using the WBM. A similar percentage recharge range of 31–38% was reported by Gutierrez-Jurado et al. (2017) for flood irrigated alfalfa in northern New Mexico. Arnold (2011) found a percentage recharge range of 40–52% in Weld County, Colorado for flood irrigated alfalfa using the WBM.

On-farm irrigation efficiency, $[(ET - \text{effective prec.})/I_r) \times 100]$, for Willie's, Horse Farm, and Leyendecker was determined as 59.93%, 58.31%, and 54.83%, respectively. Effective precipitation was determined as 80% of rainfall (Martin and Gilley, 1993). Similar on-farm irrigation efficiency of 60% for flood irrigated fields within EBID was reported by New Mexico's Office of State Engineer by Wilson et al. (2003).

Measurement of ET using an EC system requires special expertise and expensive equipment. However, climate data are readily available in most areas. Utilizing nearby climate data to calculate ASCE-Standardized ETsz could be used for recharge estimates in alfalfa fields in the Mesilla Valley or similar areas. As observed in this study, growing season ETsz was 1429 mm for 281 days compared to measured alfalfa ET of 1336 mm for the same number of days; a difference of only 93 mm.

Recharge estimates based on ETsz without consideration of ET reduction due to harvesting periods would underestimate recharge for Willie's field by 11%. However, by considering 27 mm of average ET reduction per cut for 6 cuts during the season (Table 8), recharge would be overestimated by only 6%. Water management agencies and farmers can use ETsz with readily available climate data and taking into account the decline of ET (average ET reduction of 27 mm) during harvesting periods to better estimate ET of alfalfa and recharge. An average ET reduction of 27 mm per harvest is a simple way to adjust ETsz, which takes into consideration the number of alfalfa harvests which vary with season and farming practices. We acknowledge that this reduction may not be the same in other regions as alfalfa plants may develop differently and may need some adjustment; further studies are warranted. Other methods, such as remote sensing-based crop coefficient, which use time series of high resolution images (data) could be used to estimate ET of alfalfa or other crops (Consoli and Vanella, 2014; Consoli et al., 2016).

4. Conclusion

Recharge was determined as a residual in the WBM for three alfalfa fields of different sizes, crop ages, and soil textures. The ET parameter in the WBM was measured at Willie's large field using eddy covariance – energy budget method, rather than estimated from climate stations to determine groundwater recharge. Similar ET was estimated at Horse farm based on the climate, soil characteristics, and plant vigor. ET at Leyendecker was estimated using a weighted average of alfalfa ET measured at Willies, climate data, and crop coefficient of grass. The other parameters of the WBM: applied irrigation, soil moisture, and rainfall were also measured at each field. When applying ET referenced to grass (ETsz) instead of actual ET in the WBM equation, the recharge in Willie's field is underestimated by 11%. If an average of 27 mm reduction in ETsz per cut is considered, the recharge is overestimated by 6%. Farmers and water managers could consider an average of 27 mm reduction in ETsz per cut to better estimate ET of alfalfa and groundwater recharge in the WBM assuming alfalfa fields have a similar crop development.

During the growing season of 2017, 36.82–44.89% of the irrigation amount contributed to recharge. On-farm irrigation efficiency ranged from 54.83% to 59.93% based on farming irrigation practices. These seemingly high recharge amounts are not necessarily a loss, but rather beneficial for leaching excess salts from the root zone and recharging groundwater. An ANOVA test determined no statistical differences between the recharge of the three alfalfa fields (*f*-ratio of 0.8876 with a *p*-value of 0.42). Also, no significant differences in recharge amounts were observed due to varying field sizes, crop ages, and soil textures. This

Table 9
Annual Results for recharge, percentage recharge, and irrigation efficiency for Willie's, Horse, and Leyendecker farms during the growing season of 2017; R_e is rainfall, Effec. R_e is effective rainfall, ET is evapotranspiration, and ΔS is the change in water storage.

Location	N (days)	R_e (mm)	Effec. R_e (mm)	I_r (mm)	ET (mm)	ΔS (mm)	Recharge (mm)	Percent recharge (%)	Irrigation efficiency (%)
Willie's	269	232	186	1874	1309	107	690	36.82	59.93
Horse Farm	228	232	186	1595	1116	−5	716	44.89	58.31
Leyen-decker	274	232	186	1419	964	69	618	43.55	54.83

study emphasized the importance of calculating recharge in flood irrigated fields of arid regions, particularly the Mesilla Valley. However, to quantify recharge within the entire Mesilla Valley, other crops would need to be evaluated.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Arnold, L.R., 2011. Estimates of deep-percolation return flow beneath a flood- and a sprinkler-irrigated site in Weld County, Colorado, 2008–2009.

ASCE−EWRI, 2005. The ASCE standardized reference evapotranspiration equation. Tech. Comm. Rep. to Environ. Water Resour. Inst. ASCE from Task Comm. Stand. Ref. Evapotranspiration.

ASTM, 2017. Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer) analysis.

Aubinet, M., Vesala, T., Papale, D., 2012. Eddy Covariance: A Practical Guide to Measurement and Data Analysis. Springer Science & Business Media,.

Bawazir, A.S., Luthy, R., King, J.P., Tanzy, B.F., Solis, J., 2014. Assessment of the crop coefficient for saltgrass under native riparian field conditions in the desert southwest. Hydrol. Process. 28, 6163–6171.

Bethune, M.G., Selle, B., Wang, Q.J., 2008. Understanding and predicting deep percolation under surface irrigation. W. Resour. Res. 44.

Brutsaert, W., et al., 2005. Hydrology: An Introduction. Cambridge University Press,.

Burba, G., Anderson, D., 2005. A brief practical guide to eddy covariance flux measurements: principles and workflow examples for scientific and industrial applications. Li-Cor Biosci.

Conover, C.S., 1954. Ground-Water Conditions in the Rincon and Mesilla Valleys and Adjacent Areas in New Mexico. US Government Printing Office,.

Consoli, S., Licciardello, F., Vanella, D., Pasotti, L., Villani, G., Tomei, F., 2016. Testing the water balance model criteria using TDR measurements, micrometeorological data and satellite-based information. Agric. W. Manag. 170, 68–80.

Consoli, S., Vanella, D., 2014. Mapping crop evapotranspiration by integrating vegetation indices into a soil water balance model. Agric. W. Manag. 143, 71–81.

Deb, S.K., Shukla, M.K., Mexal, J.G., 2012. Simulating deep percolation in flood-irrigated mature pecan orchards with RZWQM2. Trans. ASABE 55, 2089–2100.

Gutierrez-Jurado, K., Fernald, A., Guldan, S., Ochoa, C., 2017. Surface water and groundwater interactions in traditionally irrigated fields in northern New Mexico, USA. Water 9, 102.

Hawley, J.W., Kennedy, J.F., Creel, B.J., 2001. The Mesilla Basin Aquifer System of New Mexico, West Texas, and Chihuahua − an overview of Its hydrogeologic framework and related aspects of groundwater flow and chemistry. Aquifers West Tex. Tex. W. Dev. Board 356, 76–99.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements.

Kljun, N., Calanca, P., Rotach, M.W., Schmid, H.P., 2004. A simple parameterisation for flux footprint predictions. Bound. Layer Meteorol. 112, 503–523.

Lauriault, L.M., Ray, I.M., Pierce, C.A., Burney, O., Flynn, R.P., Marsalis, M., O'Neill, M. K., Cunningham, A., Havlik, C., West, M., 2017. The 2017 New Mexico alfalfa variety test report.

Lee, X., Massman, W., Law, B., 2004. Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Springer Science & Business Media,.

Malm, N.R., 1994. Climate Guide, Las Cruces, 1892-1991, 100 years of Weather Records. State Univ. (Res. report/New Mex).

Martin, D.L., Gilley, J., 1993. Irrigation Water Requirements, Chapter 2, Part 623, National Engineering Handbook. Soil Conserv. Serv,, Washington, DC.

Massman, W.J., 2001. Reply to comment by Rannik on "A simple method for estimating frequency response corrections for eddy covariance systems". Agric. For. Meteorol. 107, 247–251, 107, 247–251.

Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agric. For. Meteorol. 113, 121–144.

Ochoa, C.G., Fernald, A.G., Guldan, S.J., Tidwell, V.C., Shukla, M.K., 2012. Shallow aquifer recharge from irrigation in a semiarid agricultural Valley in New Mexico. J. Hydrol. Eng. 18, 1219–1230.

Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. Microclimate: The Biological Environment, 2nd edn..,. Wiley,, New York.

Samani, Z., 2017. Three simple flumes for flow measurement in open channels. J. Irrig. Drain. Eng. 143, 4017010.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10, 18–39.

Swinbank, W.C., 1951. The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. J. Meteorol. 8, 135–145.

Tanner, C.B., Thurtell, G.W., 1969. Anemoclinometer Measurements of Reynolds Stress and Heat Transport in the Atmospheric Surface Layer. United States Army Electronic Command. Atmos. Sci. Lab. Fort Huachuca,, Arizona (Final Report).

Turnipseed, D.P., Sauer, V.B., 2010. Discharge measurements at gaging stations.

USDA, 2018. Agricultural Statistics 2017.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100.

Wilson, B., Lucero, A.A., Romero, J.T., Romero, P.J., 2003. Water Use by Categories in New Mexico Counties and River Basins, and Irrigated Acreage in 2000. New Mexico Office of the State Engineer.

Wilson, C.A., White, R.R., Orr, B.R., Roybal, R.G., 1981. Water resources of the Rincon and Mesilla Valleys and adjacent areas, New Mexico.

Wozniak, F.E., 1998. Irrigation in the Rio Grande Valley, New Mexico: a study and annotated bibliography of the development of irrigation systems. Proc. RMRS-P-2. Fort Collins, CO US Dep. Agric. for. Serv. Rocky Mt. Res. Station. 204 p. 2.