# River-Ditch Hydrologic Connections in a Traditionally Irrigated Agricultural Valley in New Mexico

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**Abstract:** Traditional irrigation systems of northern New Mexico are limited by river flow, and thus water scarcity due to drought and population growth menaces their permanence. This study was conducted to examine the relationship between river flow and ditch flow in an agricultural valley of this region to better manage these ancient systems. Daily flow records for the March–November 2010–2015 periods were analyzed. Positive moderate-to-strong associations were identified with Pearson correlation coefficients. Statistical evidence at a 5% significance level was found in the overall relationships using a model-based approach accounting for serial autocorrelation and heteroscedasticity. The overall change in flow from the main ditches to every unit increase in river flow ranged from 0.0561 to 0.1397. Covariance analysis indicates that ditch flow at a given point in time is best understood as a function of current river flow and recent-past river-ditch flow. Observations indicated dynamic irrigation management in this valley subject to water availability. The findings can be used to develop water management strategies to best use the limited water resources feeding these systems. **DOI:** 10.1061/(ASCE)IR.1943-4774.0001341.


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## Introduction

In the high elevation settlements of the semiarid environment of the southwestern United States, traditional gravity-driven irrigation systems called acequias remain as the main irrigation mechanism for agriculture. The origin of the word *acequia* (hereafter also referred to as ditch) is embedded in the Arabic as-sāqiya, defined as a water conduit. These man-made, open, and typically unlined ditches are largely the results of the irrigation knowledge brought by Spanish settlers in the late sixteenth century and have prevailed up to the present day (Rivera and Glick 2002; Rivera and Martinez 2009). There are around 700 acequias in New Mexico, and most were built over 200 years ago (Ackerly 1996). They vary significantly in length, irrigated acreage, and the number of members (Guldan et al. 2013).

For centuries, acequia systems have been the foci of the economy in their associated rural communities. The water supply from these ditches has served as a source of local food, forage, and revenue. Customary practices of land and water, such as water adjudication to priority crops, implemented hundreds of years ago, are still enforced. Currently, these community-managed irrigation systems produce crops such as chile, sweet corn, alfalfa, and grass on typically small farms. The irrigation structure coordination is organized within community-based water management institutions called acequia associations. Irrigator members of the associations are represented by an acequia commission and a mayordomo (superintendent) (Rivera 1998). The acequia commission represents the legal interests of the members of the community ditch. The mayordomo is responsible for the equitable allocation and distribution of the available water under the supervision of the acequia commission.

Acequias of northern New Mexico resemble small streams running through meadows. These hand-dug, ungauged irrigation ditches are characterized by a nonuniform geometry, a deeper thalweg within a varying bed cross section, and steep longitudinal bed slopes. Acequias are located at the outlets of snowmelt catchments, and most do not have water storage structures, so the timing and amount of snowmelt runoff controls the flow in the rivers that feed the acequias. During spring, summer, and early fall, streamflow is diverted from the river into the main ditch. This water is gravity-driven for multiple kilometers downstream and generally returns to the river from the same ditch. Along the total length of each ditch, lateral ditches or branches arise. The main function of these laterals is to distribute the water from the main ditch to the agricultural fields of their irrigated valley bottomlands.

Acequia irrigation systems are not like irrigation systems with storage that distribute water based on the growing-season needs of crop producers. Because river runoff hydrographs can vary substantially from year to year, some systems store excess river runoff in a reservoir (King and Maitland 2003). In other systems, water from other settings is pumped long distances from the original source to a reservoir (Autobee 1996). That flow is then released for irrigation during the irrigation season based on the available volume stored in

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the structure. Acequias were originally crafted and continue to rely on river runoff without storage.

Important surface water-groundwater interactions related to the use of acequias have been documented. Water level measurements have shown that the shallow groundwater table responds to ditch seepage within 1–2 weeks of the onset of the irrigation ditch (Fernald and Guldan 2006). Water level responses have been found to be highly correlated to the amount of water applied to the field, the permeability of the soil, and the depth to the water table (Ochoa et al. 2009). Hydrologic connections between the river and the shallow aquifer resulting from the use of these ditches have also been found (Fernald et al. 2010; Ochoa et al. 2013). During the irrigation season, deep percolation and seepage from ditch operations and flood irrigation applications recharge the local shallow aquifer that serves as temporary storage. Even after the end of the irrigation season, some of the water that was temporarily stored in the shallow aquifer continues to be slowly released back to the river as groundwater return flow extending the river hydrograph.

Projections for the availability of water resources in the United States, specifically in snowmelt-driven regions, show a possible trend of reduced early summer streamflow due to warmer temperatures. Different modeling efforts in the upper Rio Grande basin indicate temperature increases during the winter, expected earlier snowmelt and runoff, and subsequently reduced flow during the snowmelt season (Rauscher et al. 2008; Hurd and Coonrod 2012; Rango et al. 2013; Steele et al. 2014). Llewellyn and Vaddey (2013) reported decreases in overall water availability, changes in the timing of flows, and increases in the variability of flows. If stream flows are reduced as these estimates suggest, there will likely be negative impacts on water derived activities, water infrastructure, water delivery, water quality, and water-dependent ecological functions. Because of the close linkage between river flow and ditch function, these threats to hydrologic functions also threaten the permanence of the ditches of northern New Mexico.

Understanding the connectivity of these ditches with their related environments is critical to providing knowledge of the benefits of their linkages and of the susceptibility of these systems to the climate-related adversities of drought and chronically reduced streamflow. Current modeling efforts have provided predictions regarding river flow, but lack direct evaluation of the impact of hydrologic changes on inputs to and operations of these community ditches. Development of water planning strategies aimed at the best use of available water resources would be helped by increased specificity in describing the acequia flow impact of changing river flow, but metrics describing the river and ditch flow relationship have not been described to date. The objectives of this study were (1) to evaluate river-ditch flow hydrologic connections in a traditionally irrigated valley in northern New Mexico, and (2) to develop a statistically supported set of indices relating ditch flow to river flow. The data were provided by a six-year field experiment that included measurement of river flow and ditch flow in a remote agricultural valley of northern New Mexico.

## Methodology

### Study Site

This study was conducted in the agricultural valley along El Rito River, a tributary to the Rio Chama in the Rio Grande basin. Situated within this valley is the community of El Rito, New Mexico (elevation 2,096 m), 50 km northwest of Española, New Mexico. Annual average maximum and minimum temperatures are 17.7 and 1.2°C, respectively, and average annual total precipitation is 308 mm (WRCC 2015). Historical discharge for the water year at El Rito River averaged 533 L/s from 1932–1950, the only period for which data were available (USGS 2015). The USGS decommissioned the gauging station after that period of record; thus, more recent streamflow data other than those gathered for this study are not available. River flow is a direct response to snowmelt runoff contributions from the uplands. In El Rito River, high flow is present during the period from March–June, decreasing considerably during the other eight months of the year (USGS 2015). El Rito River runs through a valley that trends from northwest to southeast. Groundwater extraction in El Rito valley is available from shallow collection galleries, hand-dug wells, and springs (RCAA and Rio Arriba County 2006).

Irrigated agriculture and livestock are the main economic activities in El Rito valley. Ditches are used to distribute irrigation water. In this 31 $km^2$ valley, most of the ditches branch and connect to a downstream main ditch or lateral from which their surplus water may irrigate downstream fields or return to the river. The Eutroboralf and Pojoaque-Rough broken land soil associations are the predominant soils of El Rito valley (Maker et al. 1973). For the first association, most land is best-suited for forestry, recreation, and range activities; for the second, only small, scattered areas are suitable for irrigation because of the occurrence of rough, broken, and steep landscapes.

### Data Collection

El Rito River and the five main ditches were instrumented for stage and flow data collection during 2010 and 2011. Access to private properties where the measurement points were located required the participation of the irrigation system officers. The measurement point for El Rito River was determined near the old USGS stream gauging station (USGS 2015), a site located just above El Rito valley and before any ditch diversion. The measurement point for each ditch was located in the straightest stretch after the ditch headgate from the river and before any water diversion into laterals to individual fields. For the purposes of this study, the ditches were lettered according to their location in relation to the river gauging station (Fig. 1).

Water stage data were collected hourly during the March–November period in the years 2010–2015. The gauging stations were composed of stilling wells with weather-resistant enclosures (Models ENC16/18 and ENC12/14, Campbell Scientific, Logan, Utah). To measure water stage data, the stilling wells were equipped with pressure transducers (Model CS450, Campbell Scientific, Logan, Utah) attached to data loggers (Models CRX206, CRX200, Campbell Scientific, Logan, Utah). Ramp-type rectangular flumes (Models RF3.5 and RF20, Global Water Instrumentation, College Station, Texas) were installed in only two of the ditch gauging stations.

Multiple river and ditch flow measurements were taken every season through the study period. For channel flow, the 0.6-depth method for velocity measurement was used (Buchanan and Somers 1969), taken with a digital current velocity meter (Model 2100, Swoffer Instruments, Seattle, Washington). Discharge for the river and each ditch was calculated using the following equation (Carter and Davidian 1968; Fernald et al. 2010):

$$Q = \Sigma(V_i A_i) = V_i \times (d_i h_i) \tag{1}$$

where $Q$ = discharge ($m^3/s$); $V$ = velocity (m/s); $A$ = cross-sectional area ($m^2$); $d$ = depth; $h$ = width; and $i$ = interval number.

Information on the agricultural and irrigation practices was collected during the six-year study. In 2010, a weather station was installed in the valley. Daily precipitation and temperature were





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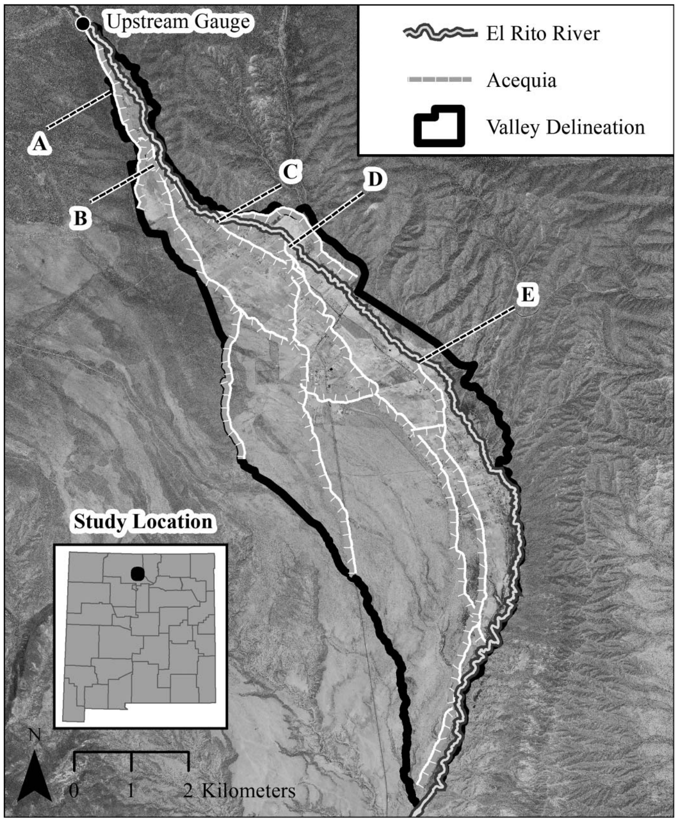


**Fig. 1.** Map of El Rito valley. (Image courtesy of Robert Sabie Jr., WRRI, NMSU.)

obtained at this site. Two wells, a private well located in the south valley and a community well in the north valley, were each equipped with water level loggers collecting hourly data (Model HOBO U20-001-01, Onset Computer Corp., Bourne, MA). The water level loggers were installed in 2010 (private well) and 2011 (community well). Historical annual precipitation and temperature were obtained from two sites as follows. Data from the Bateman Snow Telemetry (SNOTEL) site located approximately 32 km northwest of El Rito valley were retrieved from the National Resources Conservation Service (NRCS) National Weather and Climate Center website (NRCS 2016). Data from El Rito National Oceanic and Atmospheric Administration (NOAA) cooperative site at El Rito, New Mexico, were obtained from the Western Regional Climate Center website (WRCC 2017). The Bateman site at the upper mountain snow accumulation zone was particularly relevant to analysis of snowmelt runoff and streamflow in the valley, and data from El Rito site in the valley were particularly valuable for understanding streamflow usage in the irrigated fields.

## *Data Processing and Statistical Analysis*

The statistical analysis used for this study was particularly important both in new applications of statistical methods as a contribution to hydrologic science and in determining the specific relationship being tested.

### Agricultural and Irrigation Practices, Depth and Rise of the Water Table

Information on the crop pattern, the growing season, and the number of irrigation events in El Rito valley was obtained from field observations, interactions with the agent of the Rio Arriba County Cooperative Extension Service, ditch superintendents, and farmers. Average crop water requirements and average total precipitation for the growing season during the six-year study were estimated using daily weather data from the station installed in 2010. Reference crop evapotranspiration (ETo) was estimated using the Hargreaves and Samani method (Hargreaves and Samani 1985). Actual crop evapotranspiration (ET) was calculated assuming an average crop coefficient (Kc) equal to one, recommended for surface-irrigated grazing pastures (Bethune et al. 2008; Gutierrez-Jurado et al. 2017).

Averaged irrigation depth and groundwater level rise estimations were obtained from a paired study developed in 2013 in an irrigated field of this valley (Gutierrez-Jurado et al. 2017). From the private and community wells, values of daily depth to the water table were obtained by subtracting the water level measured in the logger from the depth of the sensor from the soil surface. The depth to the water table for the 2011–2015 period was obtained by averaging the largest daily depth to the water table value registered in each of the wells before the start of each year irrigation season. The logger in the community well was installed in 2011; the depth to the water table from the private well in 2010 was not used. Information about the scheduled irrigation events was obtained during the data collection campaign in 2015.

### Ditch Flow Capacities and Distance from the River

The distances from the river gauging station to each of the ditch gauging stations were measured and the ditch flow capacities were calculated. The distances were measured along the stream-ditch network using ArcGIS® software, version 10.2.1. The cross section and slope information for the ditches was collected using an electronic total station (GTS-226 series, Topcon Positioning Systems, Inc. Livermore, CA) and a 50-m length fiberglass tape measure. Paired horizontal and vertical measurements along the ditch width were made to account for changes in shape and nonuniform bed (Ray and Megahan 1979). The ditch flow capacities were estimated allowing a freeboard of 15% of their maximum depth. For the slope, height readings at the centers of the ditch bed were collected every 3 m starting about 30 m upstream from each flow measurement point. This information was analyzed using the WinXSPRO software, version 3.0.

### Annual Accumulated Precipitation and Mean Annual Temperatures Comparison

Historical annual accumulated precipitation and mean annual temperature were processed for the water year (October–September) at the Bateman site and for the calendar year (January–December) at El Rito site (WMO 1989). At the Bateman site, precipitation and temperature records were available since 1980 and 1989, respectively. At El Rito site, precipitation has been recorded since 1928 and temperature data have been recorded since 1962. Ranking percentiles were applied to this information as a means of comparing annual weather conditions during the study period with the historical records.

### Missing Records

During the six-year field data collection period, electronic equipment failures and anthropogenic influences caused some missing records for the gauging stations. The gauging station in ditch B did not register information from late June to the end of September 2010. The gauging stations in El Rito River and ditch A did not register information from the middle of August to late September 2010. Ditches C and D started collecting data from the 2011 data collection campaign. Ditch E did not register water level data from the middle of September 2013 until the end of the same data collection campaign year. Ditch A was vandalized in 2014 and no records were registered for that station from the beginning of August



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that year until the middle of May 2015. During the 2015 data collection campaign, ditch B presented electronic failures that impeded collecting stage data for that season.

## Average Daily Flow Determination

A stage-discharge relationship was developed for each gauging station. All available hourly water stage data and discharge values were related. The rating curve equations were developed according to Rantz (1982) and Sauer (2002) using the following equation:

$$Q = p \times (G - e)^N \tag{2}$$

where $Q$ = discharge (m$^3$/s); $G$ = gauge height of the water surface (m); $e$ = gauge height of effective zero flow (m); $p$ = constant numerically equal to the discharge when $(G - e)$ equals 1.0 m; and $N$ = slope of the rating curve. These procedures were executed using SigmaPlot software, version 13.0.

Daily average discharge (m$^3$/s) for each of the gauging stations was obtained by using the average daily water level data in the rating curve equation. Only for ditch C, the ramp flume manufacturer's precalibrated equation was used. The daily average discharge was converted to L/s due to the low magnitude of flow values, mainly from the ditches.

## Model Construction

A descriptive and a model-based approach confined to a first-degree polynomial model were used. Annual and crossyear (based on pooling data across years) river-ditch relationships were developed. The descriptive approach included graphs, mean flow by year and month, and the Pearson's correlation coefficient ($r$) between an individual ditch and the river. The strength of the river-ditch flow relationship was defined according to the resulting $r$ values. For values of $r$ greater than +0.8 or less than −0.8 it was called a strong relationship; if $r$ was between −0.5 and +0.5 it was called a weak relationship; and otherwise, it was called a moderate relationship (Devore and Peck 1986).

The time-series nature of the data and visual analysis of scatter and regression plots suggested serial correlation and heteroscedasticity. Mixed models efficiently analyze data that are correlated or exhibit changing variability (SAS Institute 2015). In these models, the mean model parameters (fixed-effect parameters) are related to explanatory variables associated with the entire population or with specific repeatable levels of experimental factors (Hao et al. 2015). The variance-covariance model parameters, such as the random effect parameters, allow capture of more variation among and within individuals when unknown random variables are assumed to impact the variability of the data (Li and Jiang 2013).

A linear mixed model was the core of the model structure in the model-based approach. The flow data were analyzed using the MIXED procedure (SAS Institute 2016) under SAS software, version 9.4. In this approach, El Rito River flow was specified as the explanatory variable (independent), and ditch flow was defined as the response variable (dependent). Four models were used to fit the flow information, and their performance was evaluated. For Model 1, a line common to all years was fitted. Independence and constant variance were assumed for this model. In Model 2, a common line was fitted to all years and each year was allowed to have random coefficients (intercept and slope). In this model, nonconstant variance and some correlation within years were addressed. For Model 3, a common line to all years was fitted and serial autocorrelation was addressed with ARMA (1,1) (Dickey 2003; SAS Institute 2014). For Model 4, a common line to all years was fitted, ARMA (1,1) was used to account for serial autocorrelation, and random years (no random intercept) effect was defined to account for observed heteroscedasticity.

Model selection was based on Akaike's information criterion (AIC) (Akaike 1974). With fewer reported criteria from the model, the model performed better. In all the river-ditch relationships, Model 4 performed better. The restricted/residual maximum likelihood (REML) estimation method was used and the best linear unbiased predictors (BLUPs) (Dickey 2008; SAS Institute 2015) were computed to estimate the random coefficients of the model selected. The resulting slope values for each of the annual relationships were a combination of the crossyear slope parameter and the respective year's BLUP. A 0.05 alpha value was defined as the criteria for significance over the resulting $t$ statistic from the $t$-test.

The covariance parameters from the selected model were used to analyze how the model captured the variance and the correlation structure of the data using the following expressions:

$$VX_{ij} = Y_{ij}^2 \times G + R \tag{3}$$

where $VX_{ij}$ = variance of a ditch observation $X$ on year $i$ and day of the year $j$; $Y_{ij}$ = river flow observation corresponding to the same year $i$ and day of the year $j$; $G$ = year-to-year (slope) variance component; and $R$ = residual variance component

$$\mathrm{Cov}(X_{ij}, X_{ij-n}) = Y_{ij} \times Y_{ij-n} \times G + R_n \tag{4}$$

where $\mathrm{Cov}(X_{ij}, X_{ij-n})$ = covariance of two ditches' observations ($X$s) on year $i$ and day of the year $j$ separated by $n$ number of time periods (days) between observations; $Y_{ij}$ and $Y_{ij-n}$ = values of two river flow observations on the same year $i$ and day of the year $j$ as those of their respective ditch observations; and $R_n$ = corresponding value of the residual component driven by the number of lags $n$ between observations. For $n = 1$, $R_n = R \times \gamma$; for $n = 2$, $R_n = R \times \gamma \times \rho$; for $n = 3$, $R_n = R \times \gamma \times \rho^2$; and so on. In the previous three expressions, the moving average coefficient $\gamma$ and the autoregressive coefficient $\rho$ are components of the ARMA (1,1) covariance structure

$$AC(X_{ij}, X_{ij-n}) = \mathrm{Cov}(X_{ij}, X_{ij-n}) / \sqrt{VX_{ij} \times VX_{ij-n}} \tag{5}$$

where $AC(X_{ij}, X_{ij-n})$ = autocorrelation between two ditches' observations ($X$s) on year $i$ and day of the year $j$, $n$ lags apart.

## Analysis of Influential Observations

Scatter plots, regression plots, marginal studentized residuals (MSR), and conditional studentized residuals (CSR) scatter plots and analysis were used to isolate and evaluate the effect of high-leverage observations and outliers on the data (Cook 1977; Schutte and Violette 1994). Scatter and regression plots of river and ditch flow were used to identify and separate high-leverage observations from the data. Then, the chosen mixed linear model from the model-based approach was used to model the river-ditch flow relationship with and without the high-leverage data points. The resulting estimate values (coefficients and standard errors) from the mixed model were analyzed. The high-leverage observations with a larger impact on the estimate values than most of the other observations were considered influential.

Only four river flow values, higher than 2,000 L/s and corresponding to the 2015 April–May period, were identified as influential when analyzing the high-leverage observations. They were removed from our analysis, limiting our study to develop a river-ditch flow relationship valid to river flow up to 2,000 L/s.

An outlier, a data point that does not follow the general trend of the rest of the data, was identified when the values of MSR and CSR fell outside a ±3 threshold. The chosen mixed model was run with and without those observations. The inclusion or exclusion of outliers in the river-ditch relationship was evaluated using the examination strategy proposed by Ramsey and Schafer (2002). From this analysis, some of the relationships for ditches A and D



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justified additional reporting in the model-based approach results section.

Fitting problems were observed in the 2011 river-ditch B flow relationship. During this year, the resulting fitted line from the model-based approach continuously alighted below the data points. The resulting parameter estimates of this relationship also affected those of the crossyear relationship and its covariance parameter values (mainly the residual term). For instance, a total of 240 observations recorded for ditch B in 2011 were removed from the inferential and the descriptive approaches.

### Mean Annual and Monthly Flow and Flow Seasonality

Mean annual and mean monthly flow were estimated for the river and the ditches for the March–November 2010–2015 periods using the data resulting from the analysis of the influential observations.

Plots with secondary *y*-axis were developed for each of the river-ditch relationships to indicate the seasonal flow behavior in El Rito valley during the March–November 2010–2015 periods. All the available daily flow records after removing the influential flow observations, as well as the ditch B 2011 year data points, were used in the development of the plots.



## Results and Discussion

### *Descriptive Analysis*

#### Agricultural and Irrigation Practices, Depth and Rise of the Water Table

Information of the agricultural practices, crop water requirements, and groundwater level fluctuations for El Rito valley are given in Table 1. During the study period, a consistent mix of grasses and alfalfa encompassed more than 90% of the irrigated area. Some scattered orchard fields were also observed. The growing season spanned from late May to early September. During this time, estimated evapotranspiration requirements averaged 668 mm. From the middle of April to late June 2015, a total of two to four scheduled irrigations from a rotation system occurred in the valley. Water in the ditches was available before the irrigation schedule. It was documented that this water, known locally as "free water," was not scheduled for irrigation but was either used in the fields or allowed to run free through the ditches, depending on weather conditions at that time.

After completion of the scheduled irrigation events, if the water in the ditches could sustain irrigation for big fields, the superintendents restarted the rotation system; otherwise, this water was used for irrigating small orchards and for livestock drinking. Precipitation events characteristic of the monsoon season supplied water to the crops after the end of the scheduled irrigations. During this study, the registered average precipitation for the growing season was 123 mm. Two forage crop cuts were documented in the valley, the first cut in late June and the second in late August or early September.

**Table 1.** Crop, irrigation, and hydrologic parameters for El Rito valley

| Parameter | Value |
|---|---|
| Crop | Grass + alfalfa |
| Growing season | May–September |
| Scheduled irrigation | April–June |
| Irrigation events | 2–4 |
| Evapotranspiration (mm) | 668 (15) |
| Precipitation (mm) | 123 (35) |
| Irrigation depth[a] (mm) | 249 (154) |
| Water table depth (m) | 3.56 (0.29) |
| Seasonal peak groundwater level rise[a] (mm) | 1,377 (333) |

Note: Standard deviation is shown in parenthesis.
[a]Gutierrez-Jurado et al. (2017).

Groundwater was replenished by seepage from the surface irrigation system. The collected groundwater level data during the 2011–2015 period showed a depth to the water table of 3.56 m. A paired study in 2013 documented an important benefit of the traditional management of water in the valley. In this study, average irrigation depths of 249 mm from flood irrigation were documented in an agricultural field. After each water application, the groundwater level rose an average of 1,377 mm from the baseline (Gutierrez-Jurado et al. 2017).

#### Ditch Flow Capacities

Different flow capacities were found across ditches in El Rito valley (Table 2). Ditches A, B, and D presented flow capacities above 1,000 L/s; ditches C and E reported flow capacities in the hundreds of liters per second. Ditch C reported the lowest water capacity (210 L/s); ditch D presented the highest (2,900 L/s). Distances between river and ditch gauging stations varied considerably, ranging from hundreds of meters (ditch A) to thousands of meters (ditches B, C, D, and E).

#### Annual Accumulated Precipitation and Mean Annual Temperature Comparison

For the 2010–2015 study period, accumulated annual precipitation and mean annual temperature averaged 498 mm and 5.8°C at the Bateman site and 304 mm and 9.9°C at El Rito site, respectively (Table 3). At both sites, the lowest accumulated precipitation and

**Table 2.** Ditch hydraulic information and distance to the river gauging station

| Ditch | Area ($m^2$) | Bed slope (m/m) | Capacity (L/s) | Distance (m) |
|---|---|---|---|---|
| A | 1.12 | 0.0189 | 1,400 | 208 |
| B | 2.31 | 0.0090 | 2,710 | 2,399 |
| C | 0.35 | 0.0066 | 210 | 5,047 |
| D | 2.31 | 0.0139 | 2,900 | 6,263 |
| E | 0.74 | 0.0136 | 566 | 9,949 |

**Table 3.** Annual precipitation, temperature records, and percentiles for the 2010–2015 study period

| Station | Year | Accumulated precipitation (mm) | Percentile rank | Mean temperature (°C) | Percentile rank |
|---|---|---|---|---|---|
| Bateman (water year) | 2010 | 508 | 24 | 5.0 | 64 |
| | 2011 | 513 | 27 | 5.5 | 82 |
| | 2012 | 434 | 11 | 6.1 | 89 |
| | 2013 | 445 | 14 | 5.5 | 79 |
| | 2014 | 452 | 19 | 6.4 | 96 |
| | 2015 | 638 | 65 | 6.3 | 93 |
| | Mean | 498 | — | 5.8 | — |
| El Rito (calendar year) | 2010 | 184 | 9 | 8.8 | 20 |
| | 2011 | 420 | 92 | 11.5 | 78 |
| | 2012 | 84 | 2 | 10.0 | 57 |
| | 2013 | 384 | 85 | 9.8 | 54 |
| | 2014 | 472 | 97 | 9.3 | 33 |
| | 2015 | 281 | 48 | 10.2 | 61 |
| | Mean | 304 | — | 9.9 | — |

Note: Percentile ranks apply to the periods: 1980–2015 (precipitation) and 1989–2015 (temperature) for the Bateman site; and 1928–2015 (precipitation) and 1962–2015 (temperature) for El Rito site.

mean temperature were registered in 2012 and 2010, respectively. The highest accumulated precipitation was documented in 2015 at the Bateman site and in 2014 at El Rito site. The highest mean annual temperature was registered in 2014 at the Bateman site and in 2011 at El Rito site.

When compared with historical records, precipitation and temperature values at El Rito for the 2010–2015 period were distributed across all the percentile rank values; at the Bateman site precipitation ranked in the low percentiles and temperature ranked in the high percentiles (Table 3). At El Rito site, the annual 2010–2015 precipitation and mean temperature values were located along the low, high, and middle percentile ranks for the period of records (1928–2015 for precipitation and 1962–2015 for temperature). At the Bateman site, only 27% of the years in the period of records (1980–2015) registered precipitation values lower than the 2010–2014 years, while precipitation during 2015 was higher than 65% of the years analyzed. At this site, 64% of the years in the period of records (1989–2015) reported lower temperature values than those of the study period (2010–2015). This information indicated that, in general, the weather conditions during the study period at the Bateman site represented relatively hot and dry conditions, and at El Rito site they covered the full range of weather conditions registered in the valley.

## Mean Annual Flow Rate

In the river and some of the ditches, the years with the highest and the lowest mean flow rate were the same (Table 4). For the river and ditches C and E, 2013 had the lowest mean annual flow, and 2015 had the highest mean annual flow. Ditches B and D also had their lowest mean flow values in 2013. Ditch A did not have the same behavior in terms of lowest flow in 2013. However, the ditches with the highest mean flow for the period of record reported the highest flow capacities (Table 2).

There was no systematic condition related to mean annual flow to explain periods with missing records. Ditch D did not have missing records in 2015 and was only 8 L/s below the year with the highest mean annual flow (2011). Ditch A had missing records in 2010, 2014, and 2015. For this ditch, the mean annual flow for 2010 (22.9 L/s) and 2014 (18.8 L/s) was lower than that for 2013 (25.9 L/s). In 2015, the mean annual flow for ditch A (31.0 L/s) was just higher than that for 2013 but lower than the mean flow for 2011 (50.5 L/s) and 2012 (32.7 L/s).

**Table 4.** Mean annual flow rate for the March–November 2010–2015 periods in El Rito valley

| | | Ditch | | | | |
|---|---|---|---|---|---|---|
| Year | River (L/s) | A (L/s) | B (L/s) | C (L/s) | D (L/s) | E (L/s) |
| 2010 | 235.2 | 22.9 | 66.8 | — | — | 23.2 |
| 2011 | 299.6 | 50.5 | — | 19.8 | 109.6 | 29.7 |
| 2012 | 193.6 | 32.7 | 68.4 | 21.7 | 51.5 | 23.7 |
| 2013 | 144.6 | 25.9 | 57.2 | 12.5 | 35.9 | 17.6 |
| 2014 | 224.1 | 18.8 | 69.1 | 16.0 | 59.4 | 18.8 |
| 2015 | 483.5 | 31.0 | — | 31.2 | 101.0 | 33.8 |
| Mean | 261.0 | 32.3 | 64.8 | 20.1 | 70.8 | 25.0 |

## Mean Monthly Flow for the Period of Record

Similar to the river, the ditches had a four-month period with the highest mean flow values (Table 5). The March–June period corresponded to nearly 80% of the total flow in ditches A, B, and E and almost all the flow in ditches C and D. The month of April had the highest mean monthly flow value for the river and most of the ditches. Only ditch E had highest mean monthly flow in May.

Having the most water available for irrigation early in a four-month period represents a challenge in the use of the scarce water resources for traditional irrigation systems in El Rito valley. In this valley, limited resources make essential the efficient and effective management of irrigation amounts and timing. High temperatures during the period of low available water could result in higher water requirements and possible irrigation deficits.

Attempts to change current irrigation practices to high water-use-efficiency irrigation techniques and methods such as ditch lining may limit the beneficial seepage effects from the ditches and deep percolation from excess irrigation in the fields. From our 2013 study in the irrigated field of this valley, an average transient groundwater level rise of 1,377 mm was attributed to irrigation inputs (Table 1) (Gutierrez-Jurado et al. 2017). Similarly, our previous work in another nearby irrigated valley in northern New Mexico documented a resulting average shallow groundwater level response of 221 mm from irrigation inputs (Ochoa et al. 2007). In another of our studies in the same valley, groundwater responses during the first two weeks of the onset of the irrigation ditch were attributed to seepage from the irrigation ditch (Fernald et al. 2007). These variables need to be considered for proper management of the ditches of northern New Mexico.

## Seasonality of River and Ditch Flow

The river and the ditches had surprisingly similar annual hydrograph shapes (Fig. 2). They showed a sharp snowmelt peak, either in April or May. Toward the end of June, their flow rates decreased considerably, reaching the minimum shortly after that month. Contrary to systems where seasonal changes in the water source are not directly reflected in their operations (Autobee 1996; King and Maitland 2003), in the irrigated valleys of northern New Mexico, the river seems to be the natural force that drives the flow in the ditches.

The observed characteristic of the ditches to be driven by changing river flow plays an important role in the management of the irrigation in their associated communities. Rivera (1998) and Fernald et al. (2012) indicated that during the irrigation season and based on the water availability, the irrigation communities along a river develop or adjust their irrigation schedules in order to aim for an equitable allotment of this resource. This practice is known as water sharing, or "repartimiento," and has been practiced in these valleys for centuries.

**Table 5.** Mean monthly flow for the period of record (2010–2015) for El Rito valley

| | Month | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Location | March (L/s) | April (L/s) | May (L/s) | June (L/s) | July (L/s) | August (L/s) | September (L/s) | October (L/s) | November (L/s) |
| River | 395.6 | 809.5 | 786.5 | 191.6 | 87.1 | 80.4 | 45.1 | 39.5 | 71.7 |
| A | 72.5 | 85.9 | 74.4 | 28.3 | 15.6 | 12.5 | 14.3 | 13.4 | 15.7 |
| B | 112.1 | 228.5 | 144.5 | 40.5 | 28.0 | 18.3 | 21.9 | 26.7 | 36.9 |
| C | 5.5 | 94.4 | 72.5 | 11.3 | 0.2 | 0.3 | 0.4 | 0.8 | 0.8 |
| D | 85.2 | 235.9 | 215.4 | 46.4 | 9.4 | 7.9 | 4.0 | 7.3 | 8.3 |
| E | 35.3 | 52.9 | 61.4 | 24.3 | 10.7 | 12.6 | 11.7 | 12.0 | 9.6 |



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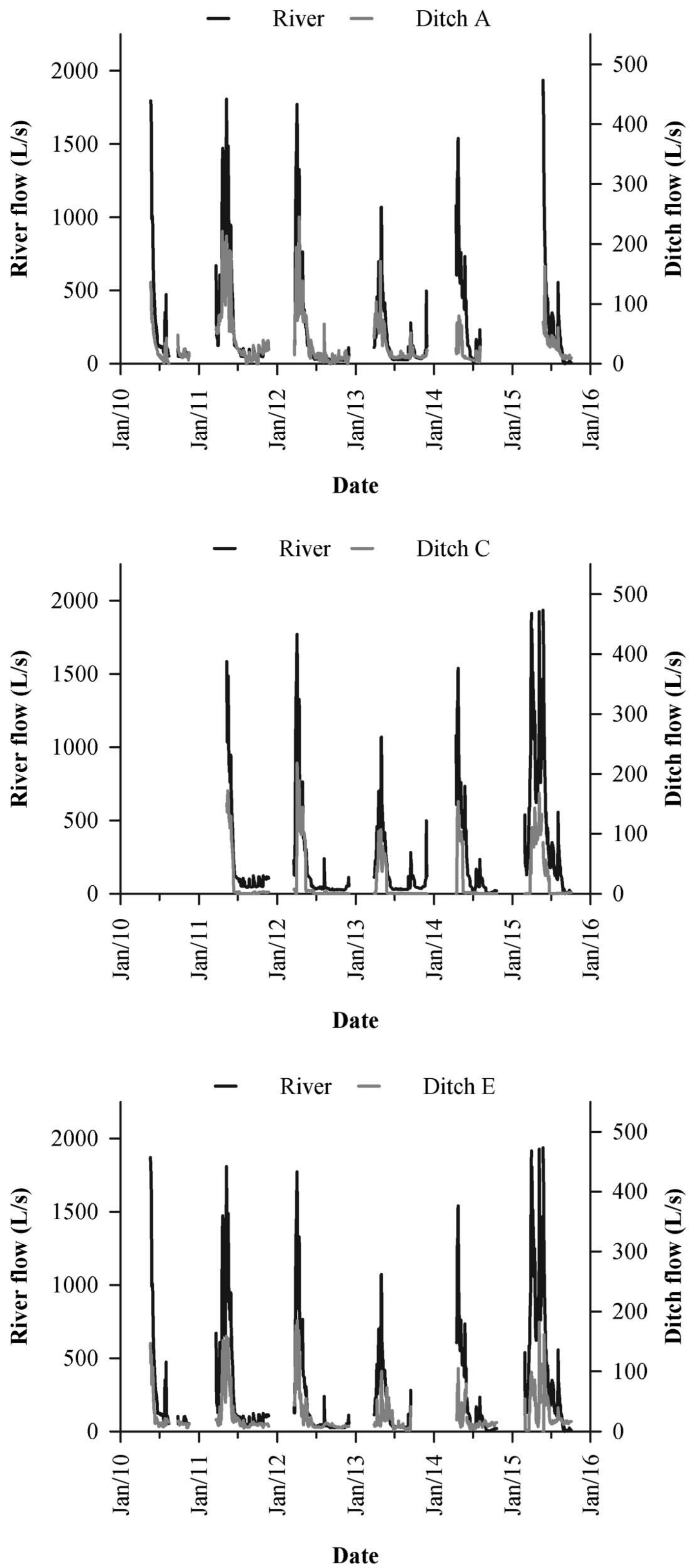


**Fig. 2.** River and ditch flow seasonality in El Rito valley, March–November 2010–2015 periods.

For El Rito valley, the direct response of the ditches to changes in river flow has resulted in dynamic management of the irrigation. Every year, the officers of the irrigation systems adjust acequia flow based on experience, observations of the timing and amount of water in the river, and on weather conditions. They define the beginning and end of the scheduled irritation period, attempting to equitably allocate the water in the ditches to all the users. The scheduled irrigation period covers the months with high water availability (Tables 1 and 5) and for a specific year could be moved days earlier or later depending on their observations. Sometimes, after the end of the scheduled irrigation period, water can still be used to irrigate the largest fields. If there is enough river water, the officers respond to this situation and restart the irrigation schedule.



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In our study in 2013, six irrigation events were registered in the studied field. This number of single-field irrigation events did not match the scheduled irrigation events defined for the valley (Table 1). This situation was possibly produced from available surplus water in the ditch once the scheduled water rotations ended. Another situation relating the river-ditch flow association to irrigation management was observed in 2015, the year with the highest mean annual flow from the period of record (Table 4). During this year, after the end of the scheduled irrigations in June, a considerable amount of water was still flowing in the ditches. The superintendents responded to this situation by restarting the irrigation rotation.

#### Crossyear and Annual Correlations for the River-Ditch Flow Relationships

Positive strong associations were found in most of the crossyear and annual river-ditch flow relationships. The crossyear relationships presented $r$ values between 0.79 and 0.87 (Table 6). Strong positive linear associations ($r > 0.80$) were found for the crossyear relationships for ditches B, C, D, and E; for the ditch A crossyear relationship, the linear association was at the high end of moderate ($r > 0.50$–$0.80$). However, the $r$ values for the annual river-ditch relationships ranged from 0.57 to 0.98. Roughly 65% of the annual river-ditch relationships had correlations corresponding to a strong relationship ($r > 0.80$); only 35% indicated a moderate relationship ($r > 0.50$–$0.80$). The graphs from Fig. 2 corroborate the $r$ values by demonstrating that fluctuations in river and ditch flows track well with one another.

### *Model-Based Analysis*

#### Model Selection

From the four models proposed to fit the river-ditch flow relationship, Model 4 repeatedly yielded the smallest AIC values in all the ditches (Table 7). See Tables 8 and 9 for Model 4 parameter estimates. Model 1 consistently reported the highest AIC values. This model, which is the simple linear regression model, has the advantage of simplicity and being widely used and well-understood, but the time series nature of the flow data violated its assumption of independence of errors (Zhang 2007). Under this circumstance, this model provides underestimated slope SEs that will lead to inflated rates of Type I errors (Montgomery et al. 2008). Tests based on this model will not be valid.

The models with random lines (Models 2 and 4) accounted for nonzero covariance among errors within a year, increasing variance with increasing river flow, and variations among years from unknown random variables (Li and Jiang 2013). The models with ARMA (1,1) structure (Models 3 and 4) accounted for serial correlation across time. For these models, the AIC values dropped substantially, indicating better model performance by accounting for the serial autocorrelation. Model 4, the selected model, combined the ARMA (1,1) structure and the random lines. This model presented greater complexity but approximated well to the variance and led to approximately unbiased SEs as a base for inference.

#### Crossyear and Annual River-Ditch Flow Relationship Parameters

The resulting linear model parameters for the river-ditch flow relationship varied across the crossyear and annual analyses (Tables 8 and 9). For the crossyear relationships (Table 8), the values of the slope ranged from 0.0561 (ditch C) to 0.1397 (ditch B). They were all statistically significant ($P < 0.05$). For the annual relationships (Table 9), the slope values ranged from 0.0082 in 2014 (ditch A) to 0.2628 in 2011 (ditch D). Only ditch A in 2014 did not show statistical significance ($P > 0.05$). From these results, the river-ditch flow association was statistically demonstrated.

The value of the slope represents the increase in ditch flow (L/s) in response to every unit increase in river flow (L/s). The range of overall responses from the ditches (0.561–0.1397) enhances our understanding of the substantial variability in flow responses across these systems to variable river flow. For centuries, water sharing, or "repartimiento," which allocates similar proportions of water during high flow and low flow conditions to all ditches, has for the most part worked very effectively in these irrigated valleys; however, there are some instances (e.g., severe drought) when equal distribution of water is not possible. These developed river-ditch flow relationships can help plan for irrigation scheduling that maximizes river water while maintaining ditch flow for certain valued crops.

From one of our studies in a nearby valley, the distribution of water for irrigation has resulted in 12.1% from ditch seepage, 21.1% from deep percolation from fields, 7.4% from crop evapotranspiration, and 59.3% from surface return flow (Fernald et al. 2010).

**Table 6.** Crossyear and annual Pearson correlation coefficients ($r$) for the river-ditch flow relationships

| | Ditch | | | | |
|---|---|---|---|---|---|
| Year | A | B | C | D | E |
| Crossyear | 0.79 | 0.87 | 0.81 | 0.85 | 0.82 |
| 2010 | 0.95 | 0.98 | — | — | 0.97 |
| 2011 | 0.96 | — | 0.98 | 0.97 | 0.96 |
| 2012 | 0.86 | 0.89 | 0.77 | 0.85 | 0.90 |
| 2013 | 0.76 | 0.91 | 0.85 | 0.79 | 0.60 |
| 2014 | 0.57 | 0.92 | 0.83 | 0.94 | 0.77 |
| 2015 | 0.73 | — | 0.81 | 0.80 | 0.66 |

**Table 7.** Performance criteria for the linear mixed model selection

| | AIC | | | |
|---|---|---|---|---|
| Ditch | Model 1 | Model 2 | Model 3 | Model 4 |
| A | 10,427.0 | 9,729.7 | 8,665.2 | 8,549.5 |
| B | 7,952.6 | 7,741.4 | 6,263.5 | 6,261.0 |
| C | 10,204.1 | 10,021.7 | 7,428.1 | 7,417.4 |
| D | 12,641.9 | 12,223.3 | 10,233.8 | 10,156.7 |
| E | 10,375.0 | 10,062.7 | 8,759.4 | 8,741.5 |

Note: Model 1 = independence and constant variance; Model 2 = random lines; Model 3 = ARMA (1,1); and Model 4 = ARMA (1,1) and random slope.

**Table 8.** Model parameters and statistical components for the crossyear river-ditch flow relationships

| | | | | Slope CL | |
|---|---|---|---|---|---|
| Ditch | Intercept | Slope | Slope SE | Lower | Upper |
| A[a] | 16.6738 | 0.0580[b] | 0.0165 | 0.0160 | 0.1000 |
| B | 36.0639 | 0.1397[b] | 0.0146 | 0.0954 | 0.1839 |
| C | 5.1010 | 0.0561[b] | 0.0077 | 0.0345 | 0.0777 |
| D | 28.8916 | 0.1376[b] | 0.0347 | 0.0421 | 0.2331 |
| E | 6.5533 | 0.0675[b] | 0.0063 | 0.0517 | 0.0833 |

Note: Slope SE = slope standard error; Slope CL = slope confidence limits (95%).
[a]MSRs removed [Slope = 0.0470 (significant at the 0.05 probability level), Slope SE = 0.0176)]; CSRs removed (Slope = 0.0449, Slope SE = 0.0215).
[b]Significant at the 0.05 probability level.





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**Table 9.** Model parameters and statistical components for the annual river-ditch flow relationships

| Year | Slope | SE | CL Lower | CL Upper |
|---|---|---|---|---|
| Ditch A[a] | | | | |
| 2010 | 0.0366[b] | 0.0083 | 0.0202 | 0.0531 |
| 2011 | 0.1146[b] | 0.0059 | 0.1030 | 0.1261 |
| 2012 | 0.0920[b] | 0.0074 | 0.0773 | 0.1066 |
| 2013 | 0.0478[b] | 0.0099 | 0.0284 | 0.0672 |
| 2014 | 0.0082 | 0.0081 | −0.0078 | 0.0242 |
| 2015 | 0.0489[b] | 0.0079 | 0.0333 | 0.0646 |
| Ditch B | | | | |
| 2010 | 0.1383[b] | 0.0216 | 0.0919 | 0.1848 |
| 2011 | — | — | — | — |
| 2012 | 0.1463[b] | 0.0138 | 0.1188 | 0.1738 |
| 2013 | 0.1609[b] | 0.0144 | 0.1320 | 0.1897 |
| 2014 | 0.1132[b] | 0.0147 | 0.0838 | 0.1426 |
| 2015 | — | — | — | — |
| Ditch C | | | | |
| 2010 | — | — | — | — |
| 2011 | 0.0683[b] | 0.0086 | 0.0512 | 0.0853 |
| 2012 | 0.0744[b] | 0.0072 | 0.0601 | 0.0887 |
| 2013 | 0.0494[b] | 0.0068 | 0.0361 | 0.0628 |
| 2014 | 0.0415[b] | 0.0074 | 0.0269 | 0.0561 |
| 2015 | 0.0467[b] | 0.0043 | 0.0383 | 0.0552 |
| Ditch D[c] | | | | |
| 2010 | — | — | — | — |
| 2011 | 0.2628[b] | 0.0153 | 0.2328 | 0.2928 |
| 2012 | 0.1201[b] | 0.0198 | 0.0812 | 0.1591 |
| 2013 | 0.0798[b] | 0.0211 | 0.0383 | 0.1213 |
| 2014 | 0.1339[b] | 0.0214 | 0.0919 | 0.1758 |
| 2015 | 0.0913[b] | 0.0123 | 0.0672 | 0.1154 |
| Ditch E | | | | |
| 2010 | 0.0639[b] | 0.0063 | 0.0514 | 0.0765 |
| 2011 | 0.0844[b] | 0.0047 | 0.0752 | 0.0936 |
| 2012 | 0.0811[b] | 0.0060 | 0.0692 | 0.0929 |
| 2013 | 0.0651[b] | 0.0087 | 0.0478 | 0.0824 |
| 2014 | 0.0528[b] | 0.0069 | 0.0392 | 0.0665 |
| 2015 | 0.0577[b] | 0.0037 | 0.0504 | 0.0649 |

Note: SE = standard error; and CL = confidence limits (95%).
[a]MSRs removed [(2010 Slope = 0.0207 (significant at the 0.05 probability level), 2010 SE = 0.0086; 2013 Slope = 0.0194 (significant at the 0.05 probability level), 2013 SE = 0.0095; 2014 Slope = 0.0027, 2014 SE = 0.0084]; CSRs removed (2010 Slope = 0.0061, 2010 SE = 0.0093; 2013 Slope = 0.0145, 2013 SE = 0.0083; 2014 Slope = -0.0048, 2014 SE = 0.0075).
[b]Significant at the 0.05 probability level.
[c]CSRs removed (2013 Slope = 0.0347, 2013 SE = 0.0226).



The developed metrics connecting the water source with the irrigation system may allow modelers to not only evaluate the effect of variable streamflow in the structure and operations of these ditches but also to evaluate the effect of those variations on the developed water budget components characterizing the irrigation system.

## Covariance Parameters for the Crossyear River-Ditch Flow Relationships

The random coefficients and the ARMA (1,1) parts of the model contribute to the covariance terms and consequently to the autocorrelations [Table 10; Eqs. (3)–(5)]. The ARMA (1,1) structure implied strong correlations among observations at consecutive time points in an exponentially decaying function. The random coefficient portion $G$ modeled a considerable fraction of the estimated variability in the ditch observations corresponding to high magnitude river flow [Eq. (3)], implying, in most of the cases, a correlation between river flow at different time points within a year did not decay over time.

**Table 10.** Covariance parameters for the crossyear river-ditch flow relationships

| Ditch | $G$ | $\gamma$ | $\rho$ | $R$ |
|---|---|---|---|---|
| A[a] | 0.0016 | 0.8473 | 0.8215 | 369.24 |
| B | 0.0006 | 0.9553 | 0.9329 | 2128.59 |
| C | 0.0002 | 0.9615 | 0.9323 | 738.44 |
| D[b] | 0.0057 | 0.9555 | 0.9346 | 4810.84 |
| E | 0.0002 | 0.8334 | 0.7478 | 268.06 |

Note: $G$ = year to year variance component; $\gamma$ = moving average coefficient; $\rho$ = autoregressive coefficient; and $R$ = residual variance component.
[a]MSRs removed ($G = 0.0018$, $R = 432.06$); CSRs removed ($G = 0.0027$, $R = 353.41$).
[b]CSRs removed ($G = 0.0076$, $R = 4706.3$).

The previous statements suggest that the fitted model shows that ditch flow is positively related to river flow (Tables 8 and 9). The observed strong autocorrelation suggests that errors from one day to the next are highly positively correlated. When actual ditch flow today has a large positive/negative error, it is likely that the ditch flow tomorrow will also be above/below the expectation from river flow alone. The random coefficient also implies positive covariance among errors within a year and an overall slightly increasing variance with increasing river flow. By simultaneously considering the estimated expectation from the model and the variance structure, the ditch flow at a current point in time is best understood as a function of both the current and recent-past river flow as well as recent-past ditch flow.

## Outliers Effects

The number of CSR outliers ranged from 1.1% to 2.8% of the observations across all the ditches. There were always fewer MSR outliers, with only one ditch having more than 2.0% (ditch B) and the other four ditches having between 0.0% and 1.5%. Ditch D did not report MSR outliers. All these observations were associated with high river flow. Osborne and Overbay (2004) suggest that outliers may arise from errors in the data, such as sampling errors. However, the presence of outliers can also indicate issues with model fit (Byrne 1998). In this study, it may be possible that measurement errors were bigger at higher river flow or that a minor model issue resulted in conditional variance slightly higher at those higher river flow values.

A total of 25 out of 1,138 observations in ditch A and 13 out of 1,148 observations in ditch D were considered outliers. For ditch A, similar to the analysis without removing outliers, the crossyear, 2010, and 2013 relationships remained significant ($P < 0.05$) after the only five MSR outliers were removed from the analysis. No statistical significance ($P > 0.05$) was found for those relationships after the CSR outliers were removed from the analysis (Tables 8 and 9). Contrary to these findings, the nonstatistical significance ($P > 0.05$) observed in 2014 for this ditch remained the same after removing both MSR and CSR outliers (Table 9). Some minor changes were noted in ditch D after outliers were removed. Contrary to the analysis when the outliers were not removed, only the 2013 relationship presented no statistical significance ($P > 0.05$) (Table 9). Osborne and Overbay (2004) and Cousieau and Chartier (2010) indicate that the SEs should be smaller for re-analysis with outliers removed. In this study, larger SEs were found in the cross-year and some of the annual river-ditch relationships for ditches A and D. This inconsistency was caused by larger values of the $G$ variance component and usually lower values of the $R$ variance component (Table 10).

### Relevance of the Analysis of the River-Ditch Flow Relationship

This study identified strong associations between irrigation ditch flow and source river flow in a remote agricultural valley of northern New Mexico. We quantified that the overall responses (L/s) in the ditches to every unit of river flow increase (L/s) range from 0.0561 to 0.1397. We established that ditch flow at a specific point in time is related to current river flow as well as recent-past river and ditch flow. Although water managers use empirical knowledge and observations of river flow and weather conditions to define an irrigation schedule in an effort to coordinate an equitable and efficient water distribution to irrigated fields, we learned that the irrigation system responds to river flow availability independently of the crop growing season. We also learned that annual variations in water availability cause the irrigators to adjust their water applications to get the most benefit from the limited resource.

The strong relationship we described between the river and the ditches has important implications for the management and permanence of the irrigation systems. Population growth and urbanization place pressures on these irrigation systems functions (Ortiz et al. 2007; Rivera and Martinez 2009). Shifts from irrigated agriculture to residential development and increased water demands for industrial and other purposes may result in less flow for farming activities and the reduction of the shallow aquifer recharge provided by these systems. Movement of younger generations to urban areas for employment and settlement and the presence of newcomers with varying knowledge of the traditional management of land and water may result in the loss of the wisdom of harnessing the river-ditch flow association developed by the past generations of irrigators.

Model predictions consistently indicate temperature increases and diminished runoff (Llewellyn and Vaddey 2013; Udall and Overpeck 2017). Those predictions, accompanied by water transfers from agricultural to other water uses, will likely result in an irrigation system managed under the effect of lower river flow, which may disrupt the capability of these systems to equitably distribute water to the irrigated landscapes.

Irrigation ditches of the agricultural valleys of northern New Mexico have important and complex connections with human and natural systems. From our research and modeling efforts, we have documented important linkages in locations where the use of irrigation systems defines the lifestyle of their associated communities (Fernald et al. 2012, 2015). The communities of these irrigation systems perform grazing, firewood, timber, hunting, and recreation activities in the forest uplands. In the irrigated valley bottomlands, villagers share responsibility for the maintenance of the water system. Customary rules of water management are rooted in the community, and rules such as "water sharing" and water allocation to priority crops are still enforced. Water diverted from the river for irrigation is conducted through the irrigated landscape, extending the riparian vegetation and its related biodiversity. Seepage inputs and field irrigation deep percolation recharge groundwater that feeds the river late in the season, prolonging streamflow hydrographs.

This research enhances base knowledge of traditional irrigation systems still prevalent in some parts of the Southwest and in other regions worldwide. The statistical analysis provided in this paper allows for the development of critical metrics (e.g., indices) that can be incorporated into larger-scale models such as the snowmelt runoff model (Rango et al. 2013), which explores the role of traditional irrigation systems in modulating snowmelt peak runoffs by the seasonal retransmission of river flow onto relatively small agricultural valleys near their headwaters. Another model in which the relationship indices could be used is the acequia system dynamic model (Turner et al. 2016), which studies the effect of community management practices and community structure on irrigation system functions. The outputs from those models may help to develop water planning strategies for irrigation management in the valley.

## Conclusions

To better understand the linkages between a traditional irrigation system in remote New Mexico and its related environment, this study developed a linear relationship between river flow (predictor) and irrigation ditch flow (response). The relationship was analyzed and quantified descriptively and statistically during the period from March–November (2010–2015).

From the descriptive approach, we documented that the flows in the ditches and the river are strongly related. The irrigation system is dynamic and directly responds to seasonal changes in river flow. We also observed that users of the system adapt to those changes and adjust their irrigations to harness the available water for irrigation.

From the model-based approach, we established that ditch flow at a specific point in time is related to river flow at the same time and river and ditch flow in the recent past. An important finding was our determination that for every flow unit increase in river flow (L/s) there is an increase in ditch flow response (L/s) that ranges from 0.0561 to 0.1397. The developed parameters relating river flow and ditch flow could be incorporated into models aimed at evaluating and improving the functioning of the irrigation ditches in the face of impending change factors like population growth and environmental changes. In the isolated agricultural valleys represented by this study, additional work will be important to improve river irrigation models that can be used to develop better irrigation practices.

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