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Climate Change Impacts on Agricultural Water Availability in the Middle Rio Grande Basin

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Research Impact Statement: Status quo irrigated agriculture in the Middle Rio Grande faces likely fresh groundwater depletion within the 21st Century as river water reliability declines in a projected warm-dry future.

ABSTRACT: We present a comprehensive analysis of water availability under plausible future climate conditions in a heavily irrigated agricultural watershed located in the middle section of the Rio Grande Basin in the United States Desert Southwest. Future managed streamflow scenarios (through year 2099) were selected from among 97 scenarios developed based on downscaled, bias-corrected global climate model outputs to evaluate future inflows to the principal surface water storage reservoirs, possible future reservoir releases, and groundwater pumping to sustain irrigated agriculture. The streamflow projections describe a wide range of dry and wet conditions compared to the average historical flows in the river, indicating significant uncertainty in future water availability in the Rio Grande Basin. We applied the Soil and Water Assessment Tool to illustrate the impact of climate futures on different components of the water budget at a watershed scale. Results indicate declining reliability of reservoir storage to meet the water demand of irrigated agriculture. The impact of declining surface water can be offset by increasing the pressure on the already-strained groundwater resources. However, the region should be prepared to use slightly saline (total dissolved solids [TDS] > 1,000 mg/L) and moderately saline groundwater (TDS > 3,000 mg/L) as fresh groundwater in the regional aquifer is depleted within the 21st Century under hotter and drier conditions and status quo agricultural land and water management practices.

(KEYWORDS: climate change; Soil and Water Assessment Tool; Rio Grande; irrigated agriculture; groundwater depletion; water sustainability.)

INTRODUCTION

Many areas around the world face water sustainability challenges tied to variability of renewable water resources and growing water demand due to population growth and higher standards of living (Döll et al. 2012; Wada et al. 2014; AghaKouchak et al. 2015; Grafton et al. 2017). Overexploitation of limited, nonrenewable water resources to cope with

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water shortages in arid/semiarid regions makes these regions particularly vulnerable to severe water stress under plausible hotter and drier conditions in the future (Castle et al. 2014; Ward et al. 2019). In the United States (U.S.), rising aridity is generally observed in the southwestern states (Seager et al. 2007; Cayan et al. 2010; Cook et al. 2015) and it is expected to become more severe in future decades. Rising aridity can reduce headwater snowpack and watershed soil moisture, increase evapotranspiration (ET), and alter the magnitude and timing of streamflows (Garfin et al. 2013; Dettinger et al. 2015). Understanding the implications of these hydroclimatic changes is essential for adaptive water resources planning and management in drought-prone basins in the southwestern U.S., including the Rio Grande Basin.

Water in the upper Rio Grande Basin is shared between the three states of Colorado, New Mexico, and Texas based on the 1938 Rio Grande Compact (RGC 1938). In addition, the 1906 treaty between the U.S. and Mexico governs surface water deliveries of about 74 million cubic meters (MCM) (60,000 acre-feet) annually to northern Chihuahua, Mexico in a normal year (IBWC 1906). The decreasing snowpack in the Rio Grande headwaters in Colorado is already evident in historical data (Elias et al. 2015; Chavarria and Gutzler 2018) with a significant corresponding decline in streamflow associated with rising temperature in the headwaters (Llewellyn and Vaddey 2013; Lehner et al. 2017; Udall and Overpeck 2017). The river, the main surface water source in the middle Rio Grande region, is fully allocated and net groundwater storage is declining (Sheng 2013; Fuchs et al. 2018). Agricultural activities in this region are predominantly concentrated along the main stem of the Rio Grande where surface water and groundwater are conjunctively used to sustain irrigation. Although domestic water demands are primarily met by groundwater resources (Mccoy and Shomaker 2017), growing water shortages can increase the competition between urban and agricultural water users in the future. The ecological functions of the Rio Grande are also at risk because of the difficulty of providing environmental flows in this heavily managed, fully appropriated water system (Lane et al. 2015; Blythe and Schmidt 2018).

Stakeholders (e.g., agricultural, urban, and environmental) in the middle section of the Rio Grande Basin are concerned by the prospect of adverse impacts of climate change on regional water availability (Hargrove and Heyman 2020). This paper provides a thorough assessment of water availability for irrigated agriculture, the largest single water user in the New Mexico-Texas portion of the basin, under plausible surface water projections throughout the 21st Century. The climate impact assessment framework is comprised of three components: (1) climate-based Rio Grande flow projections at the upstream boundary of the study watershed derived from bias-corrected intrabasin climate projections (i.e., temperature and precipitation) provided by the U.S. Department of Interior Bureau of Reclamation (2016) and adjusted by Townsend and Gutzler (2020) to account for upstream storage and diversions; (2) a calibrated semidistributed watershed hydrology model developed using the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998); and (3) a relationship between reservoir releases and groundwater withdrawal to represent the conjunctive use of surface water and groundwater for irrigation. We evaluate the impacts of surface water conditions on different components of the surface water budget, as well as groundwater storage. Sustainability of irrigated agriculture in this water-scarce region will increasingly depend on preparing to use slightly saline to marginal quality groundwater due to the mounting pressure on the already-strained fresh groundwater to cope with diminishing river flows.

MATERIALS AND METHODS

Study Area

The study watershed occupies about 6,000 km^2 in the middle section of the Rio Grande Basin (Figure 1) with approximately 400 km^2 of agricultural lands. The region is arid/semiarid with an average annual precipitation of approximately 270 mm and maximum and minimum mean daily temperatures of 33°C and −7°C, respectively. Rio Grande water is stored in the Elephant Butte (EB) Reservoir (completion: 1,916, capacity: 2,713.6 MCM [2.2 million acre-feet]) for irrigation and hydropower generation. EB Reservoir releases are regulated by Caballo reservoir with a capacity of 424.3 MCM (343,990 acre-feet) located 40 km (25 miles) downstream. In normal years, water is released from the Caballo regulating reservoir from March to September to meet irrigation demands. Two upstream U.S. Geological Survey (USGS) gauging stations (08358300 and 08358400) record inflow to the EB Reservoir and two downstream gauging stations record releases from EB (08361000) and Caballo (08362500) reservoirs. USGS gauge at El Paso (08364000) measures flow at the watershed outlet. Recent salinity measurements of surface water releases from the reservoirs indicate that the river water continues to have acceptable salinity for irrigation (total dissolved solids [TDS] = 520 mg/L) (Ma et al. 2019), even though the reservoir storage has been consistently low in recent years.

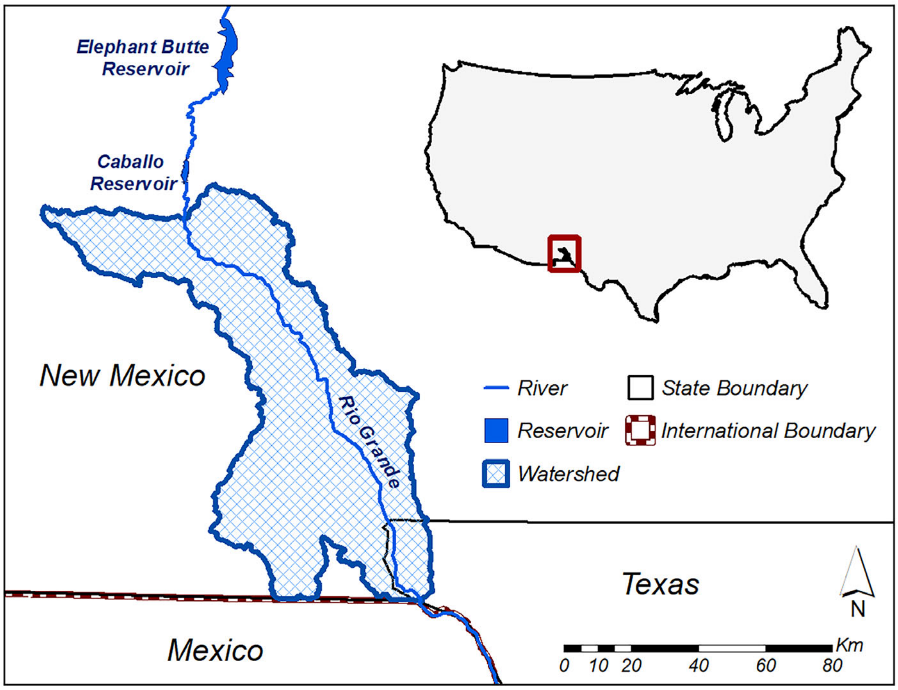

FIGURE 1. Study watershed in the New Mexico-Texas portion of the Rio Grande Basin.

The Mesilla groundwater basin (Mesilla Basin), the main groundwater resource in the watershed, is used in conjunction with reservoir releases to support irrigated agriculture. The area is known for pecan production, a major cash crop in the Elephant Butte Irrigation District (EBID). Three main diversion dams and five main diversion canals distribute water among irrigated lands. The historical variation of croplands shows significant drops in the acreages of different crops during drought periods except high-value perennial pecan. For example, drastically reduced reservoir releases during the 2011–2013 drought mostly affected cotton, corn, alfalfa, and other crops, while pecan orchards remained relatively unaffected (Figure 2). The acreages of crops do not decline at the same rate as the reduced reservoir releases because extensive groundwater pumping from Mesilla Basin compensates for surface water shortages. In addition, as a valuable perennial crop, pecan trees cannot be easily removed from the crop mix and farmers usually decrease the area of annual crops like cotton to save water for pecan orchards during droughts, hence the significant decline of cotton acreage during the dry years (Figure 2). The groundwater quality varies from fresh water in the deep zone to more saline in the shallower zones and toward the south. Estimates of fresh groundwater storage vary significantly (Sheng 2013). Hawley and Kennedy (2004) estimated the volume of recoverable fresh to slightly saline groundwater (i.e., TDS < 3,000 mg/L) storage in the Mesilla Basin to be about 62 BCM. Overexploitation of fresh groundwater has also caused intrusion or upwelling of brackish water, deteriorating the quality of water in the aquifer (Ashworth and Hopkins 1995; Sheng 2013).

Climate Change Impact Assessment Framework

We used measured Rio Grande flows to calibrate a SWAT model of the study area to evaluate the impacts of future climate conditions on surface water and groundwater resources, taking into account the conjunctive use of water from these sources for irrigation (Figure 3). The components of the climate change impact assessment framework are discussed in this section.

Climate-Based Surface Water Projections. Global climate models (GCMs) have been used to generate 97 different streamflow projections on the main stem of the Rio Grande (Reclamation 2016) using the variable infiltration capacity rainfall-runoff model (Liang et al. 1994, 1996). These GCM-based projections describe natural river flows, with no simulation of human impairments upstream that would affect the flows into EB Reservoir. To account for upstream developments, Townsend and Gutzler (2020) developed a statistical normalization procedure that parameterizes upstream water manipulation by calculating constants that force the first and second

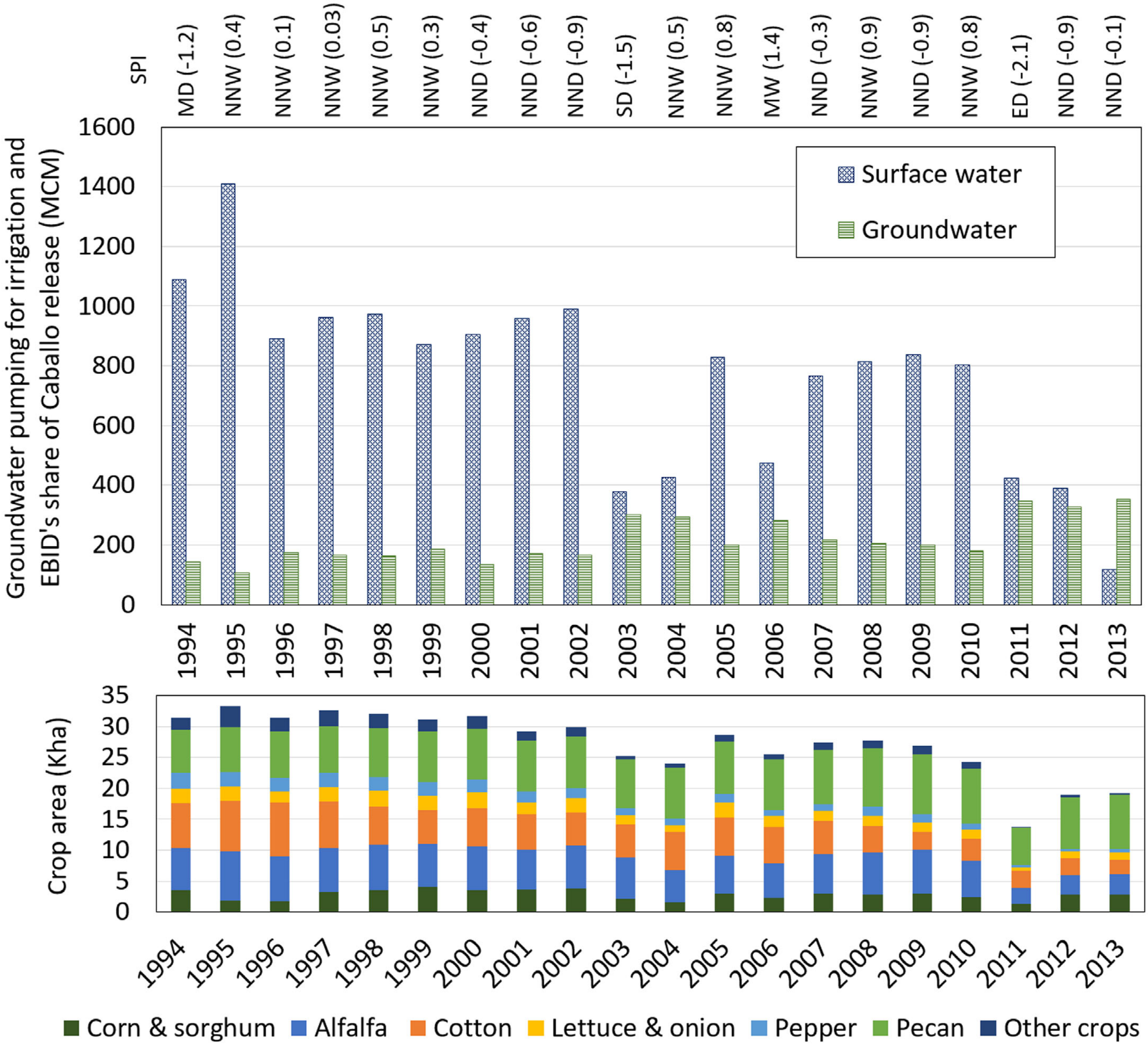

FIGURE 2. Water withdrawal and irrigated crop production in the study area: (a) conjunctive use of surface water and groundwater during wet and dry years characterized by standardized precipitation index (McKee et al. 1993) using parameter-elevation relationships on independent slopes model rainfall data (Daly et al. 2008): extremely dry (ED: −2.00 or less), severely dry (SD: −1.50 to −1.99), moderately dry (MD: −1.00 to −1.49), near normal dry (NND: −0.99 to 0.00), near normal wet (NNW: 0.00 to 0.99), moderately wet (MW: 1.00 to 1.49), very wet (VW: 1.500 to 1.99), extremely wet (EW: 2.00 and more); and (b) variation of crop acreages in response to renewable water availability. MCM, million cubic meter.

moments of model-simulated annual flows for a 50-year historical period at the San Marcial gauge just upstream of EB Reservoir to match the equivalent moments of observed flows during the same period. The parameterization constants are then applied to projected naturalized flows to obtain projected flows that account for upstream management. The effect of this normalization procedure is to reduce simulated natural flows into EB Reservoir during the historical period by 70%–75%, a reduction that closely matches the naturalization of observed flows estimated by Blythe and Schmidt (2018).

The 97 normalized Rio Grande flow projections (2020–2099) cover a variety of flow conditions as can be seen in the exceedance probability plots of the projections and the observed historical flow at San

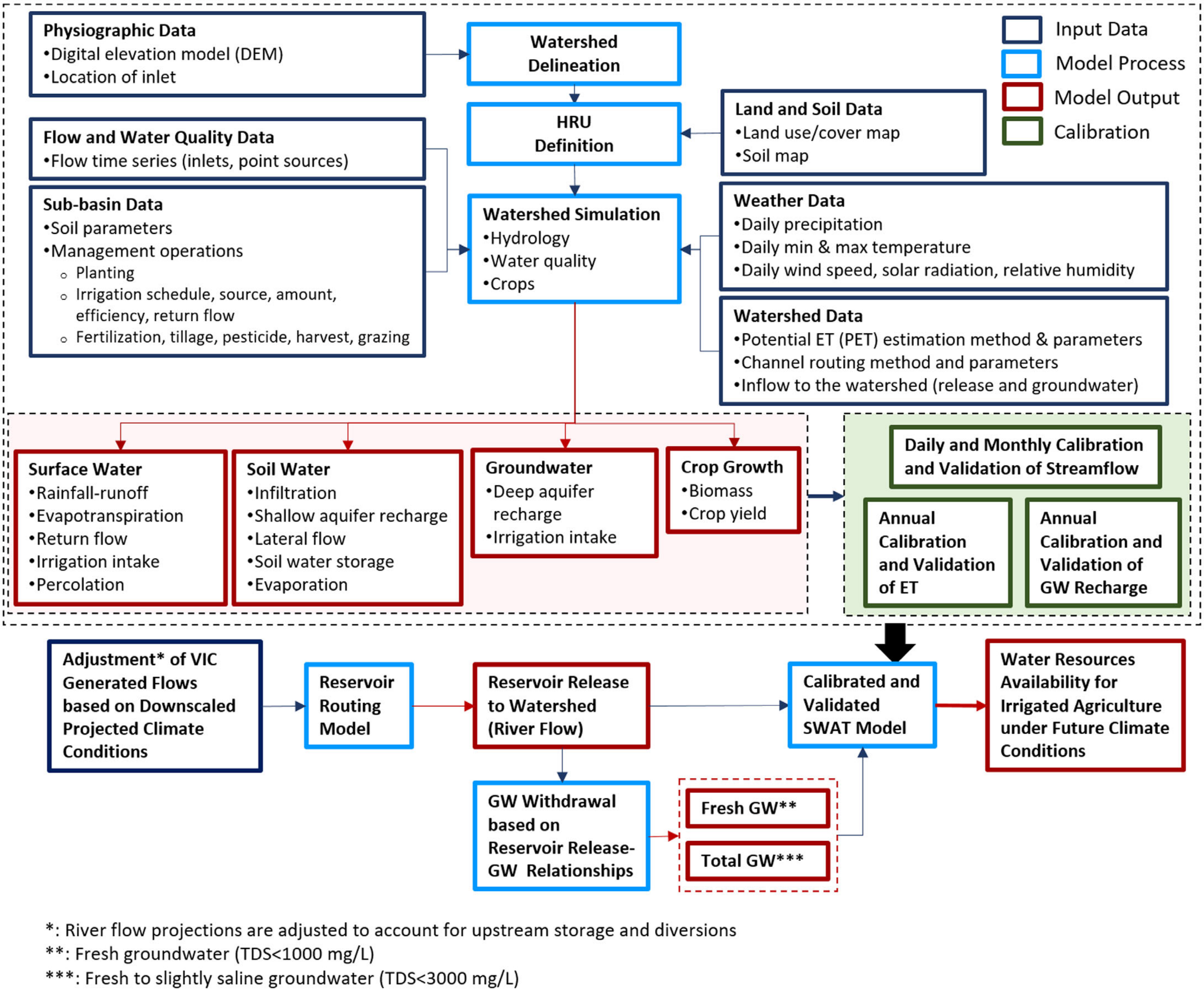

FIGURE 3. A general schematic of the climate impact assessment framework. ET, evapotranspiration; GW, groundwater; HRU, hydrological response unit; SWAT, Soil and Water Assessment Tool; VIC, variable infiltration capacity.

Marcial (Figure 4). Most projections have a median flow that is 20%–60% lower than the historical median flow, indicating increasing future surface water scarcity. A few scenarios include smaller flows in the early years and larger flows toward the end of the century (e.g., bcc-csm1-1_rcp26 and bcc-csm1-1_rcp45). Four projections were selected to represent Rio Grande flow scenarios (Table 1), namely Dry1 (access1-0_rcp85), Dry 2 (hadgem2-es_rcp85), Wet1 (fio-esm_rcp45), and Wet2 (cnrm-cm5_rcp85). In addition, at the request of agricultural water stakeholders, a no reservoir release scenario (NR) was also simulated, which represents the most extreme case of future surface water scarcity for downstream irrigation. The differences of monthly flows in the four selected streamflow scenarios relative to the average historical Rio Grande flows are shown in Figure 5 for visual comparison of the relatively dry and wet projections. Dry 1 scenario has the largest number of drier-than-average months, while Wet 2 scenario has largest number of wetter-than-average months. The two other projected scenarios, that is, Dry 2 and Wet 1, respectively, represent moderately dry and wet conditions that are consistent with the observational record. All the selected scenarios indicate declining streamflows up to 2099 based on the Mann–Kendall test (Z-values range between –2.74 and –6.27).

Reservoir Routing Model. The projected streamflows were routed through the EB-Caballo reservoir

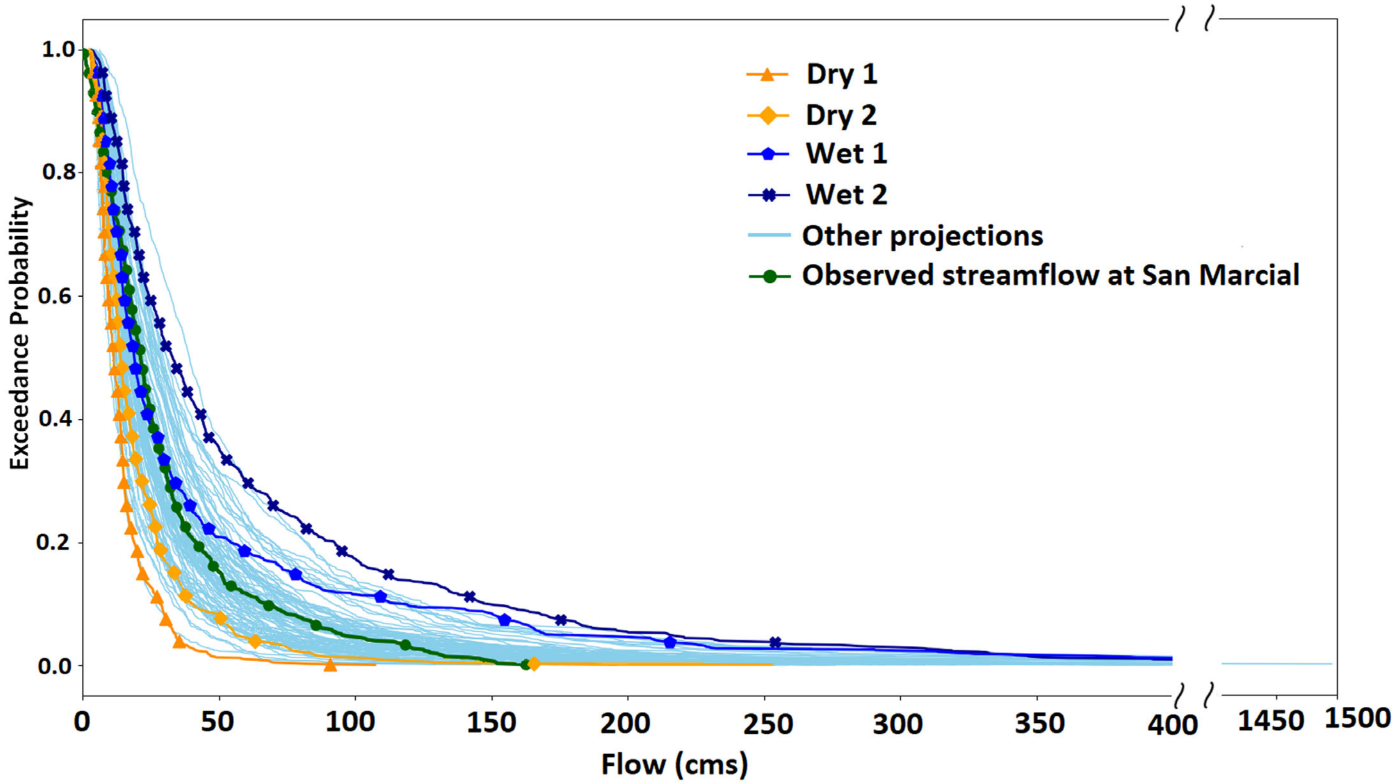

FIGURE 4. Exceedance probability plots for monthly streamflow projections and observed monthly historical flow rates (1994–2013) recorded at the United States Geological Survey (USGS) San Marcial gauge. The four climate-based flow scenarios selected for impact assessment include Dry1 (access1-0_rcp85), Dry 2 (hadgem2-es_rcp85), Wet1 (fio-esm_rcp45), and Wet2 (cnrm-cm5_rcp85).

TABLE 1. Selected climate-based monthly streamflow projections (up to 2099).

Scenario	Projection[1]	Source	MK[2]	Mean annual flow at San Marcial (cm)	No. of years with mean annual flow > historical
Dry1	ACCESS1-0_RCP85	Australian Community Climate and Earth System Simulator	−5.39	12.55	1
Dry2	HADGEM2-ES_RCP85	Coupled Earth system model By Met Office Hadley Center, U.K.	−4.23	18.70	12
Wet1	FIO-ESM_RCP45	First Institute of Oceanography-Earth System Model (FIO-ESM), China	−2.74	44.15	27
Wet2	CNRM-CM5_RCP85	Earth system model by Centre National de Recherches Meteorologiques, France	−3.39	61.83	42
NR	—	No release from upstream reservoir	—	—	0

[1]RCP stands for Representative Concentration Pathways of emissions and mitigation pathways. RCP 45 is an intermediate greenhouse gas (GHG) emission mitigation pathway in which radiative forcing is stabilized at approximately 4.5 W/m^2 after 2100. RCP 85 is a high GHG emission pathway with radiative forcing exceeding 8.5 W/m^2 by 2100 and continuing to rise (Flato et al. 2013).
[2]Mann–Kendall (MK) nonparametric trend test (Mann 1945; Kendall 1975).

system to establish upstream flow boundary condition for watershed analysis under different flow scenarios. The simplified reservoir water balance model (Equation 1) simulates the existing reservoir management scheme. It takes projected monthly inflow to the EB Reservoir and routes it to calculate monthly projected releases from the EB-Caballo reservoir system based on downstream demand and reservoir storage. In terms of water availability, the system is dominated by surface water storage in EB, whereas the downstream Caballo Reservoir is operated to regulate the river water flow into the study watershed. The releases from the lumped reservoir system are used as an input in the SWAT watershed hydrology model.

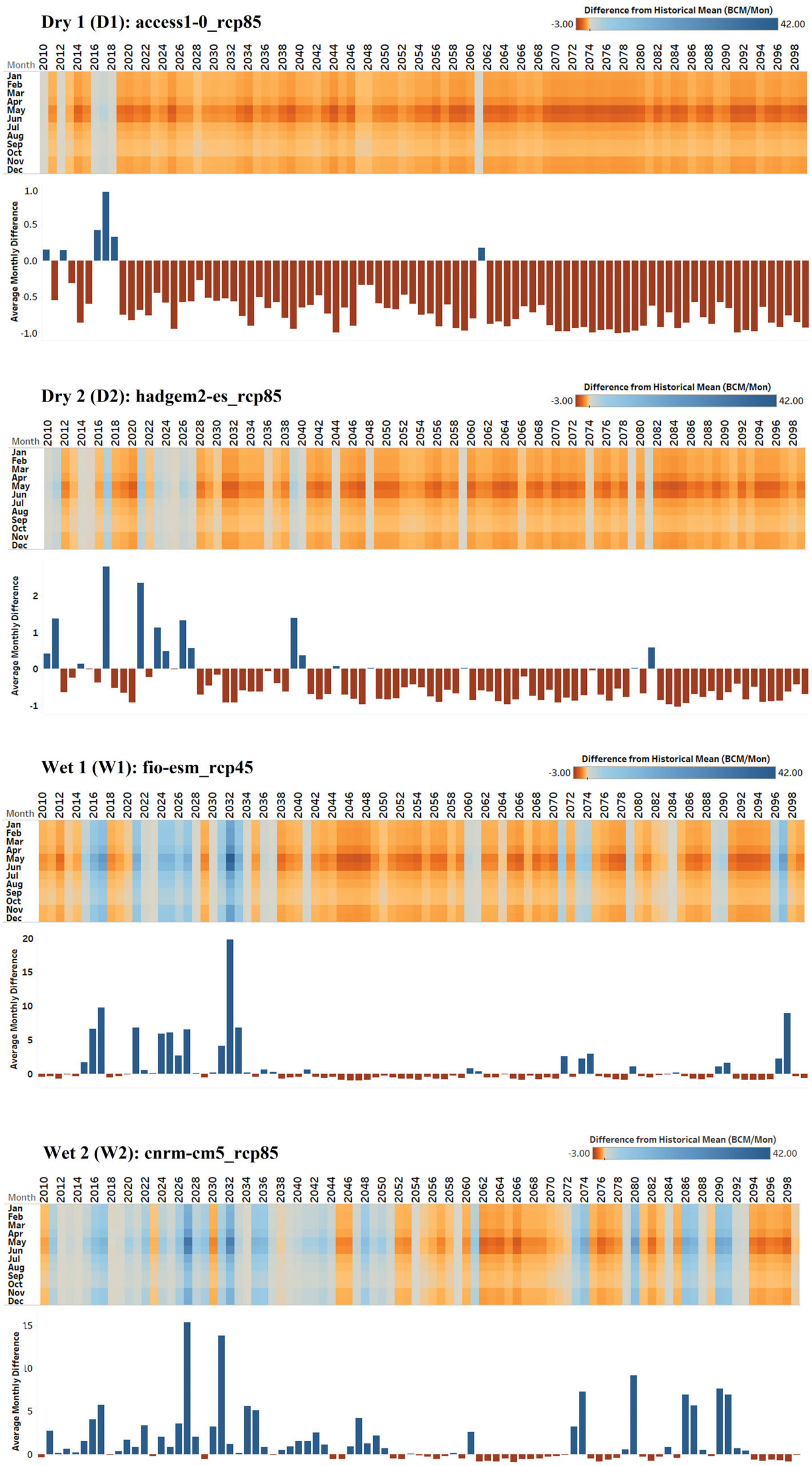

FIGURE 5. Projected Rio Grande volumetric flows representing dry (i.e., Dry 1 and Dry 2) and wet (Wet 1 and Wet 2) futures relative to the average observed historical flows at San Marcial gauge.

$$S_t = S_{t0} + \int_{t0}^{t} (P_t \times A_t + I_t - E_t \times A_t - R_t)dt, \quad (1)$$

where S is the storage of the reservoir system, P is the precipitation rate over the reservoir (negligible), A is the surface area of the reservoir, estimated based on the reservoir's elevation-area-capacity tables (Reclamation 2007), I is the inflow into EB, which is available through future inflow projections, E is the evaporation rate determined based on historical evaporation data from Reclamation for both EB and Caballo reservoirs, R is reservoir release (Reclamation 2017), which is a function of available water and demand, and t is the time index.

Water is released from the reservoir to meet the downstream demand if available water (A_w) defined as $S + I - P - E$ is greater than the demand at time t (i.e., D_t). The release is reduced when the water storage in the reservoir is insufficient for full river water allocation. Finally, the release will include spill to prevent overtopping when reservoir level nears maximum stage (Equation 2).

$$R = \begin{cases} D_t & \text{if} \quad A_w > D_t \\ A_w & \text{if} \quad D_t > A_w \\ A_w - S_t & \text{if} \quad A_w > D_t + S_t \end{cases}, \quad (2)$$

where A_w is the available water (or $S + I - P - E$) and D is the demand.

The initial total water storage of both reservoirs in 2010 (S_0) was 678 MCM (550 KAF) based on Reclamation data. Based on full water allocation (i.e., no river water deficit), annual downstream demand in a normal year is 974 MCM (790 KAF) (Reclamation 2009). The monthly distribution of demand was determined based on historical trends of releases from Caballo Reservoir (USGS station on Rio Grande below Caballo) during wet years. The total reservoir storage simulated for EB and Caballo was compared against the historical data (2009–2014) to evaluate the performance of the simplified model (see Figure S1).

Watershed Hydrology Model. We used SWAT, a public domain semidistributed, continuous-time watershed hydrology model (Arnold et al. 1998) to represent watershed processes and quantify different components of the water budget. SWAT accounts for the impacts of water and land management practices in the water balance calculations and simulates relationships between crop yield and soil moisture, which makes it a useful tool for agricultural watershed studies (Van Liew and Garbrecht 2003; Abbaspour et al. 2007; Ficklin et al. 2009; Schierhorn et al. 2014; Ahn et al. 2018). The model is widely used to simulate arid/semiarid irrigated agricultural watersheds around the world to facilitate diverse water resources investigations (Samimi et al. 2020), including many climate change impact assessment studies (Abbaspour et al. 2009; Tang et al. 2013; Ashraf et al. 2014; Hammouri et al. 2017; Li and Jin 2017; Nguyen et al. 2017; Reshmidevi et al. 2018; Aliyari et al. 2021). SWAT divides subbasins into smaller hydrological response units (HRUs) based on terrain slope, land use, and soil characteristics across the watershed (Figure 3). Water quantity and quality are simulated based on the water balance in each HRU and then routed along channel network in the subbasins and the watershed. The crop growth is modeled using the plant growth module and related databases (Neitsch et al. 2011).

We used 10 × 10 m digital elevation models, 2011 land use/cover data (NLCD 2011: Multi-Resolution Land Characteristics Consortium, 2015), and a combination of STATSSGO (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2006) and SSURGO (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2015) soil maps to delineate 10 subbasins and 7,175 HRUs in the study watershed. The SSURGO soil map, which provides more detailed soil information, does not cover the entire study watershed. Therefore, to use the best available soil data, we used STATSGO soil map information to complement the SSURGO soil data. The NLCD land use layer for 2011, an exceptional drought year based on SPI (Figure 2), was used to represent adaptive land management to cope with declining surface water availability in the future. Detailed crop pattern (percentages of each crop's area in the crop mix) is then incorporated into the model during HRU definition. Crops simulated in this study are pecan, alfalfa, corn, cotton, and vegetables. Weather data (e.g., precipitation, temperature, and humidity), runoff curve numbers, plant growth characteristics, and agricultural management operations (e.g., irrigation, fertilization, pesticides, tillage, etc.) are available in various editable built-in databases that allow capturing the specific conditions of different applications through model calibration (Arnold et al. 2012).

Characterization of streamflow, ET, and groundwater recharge is essential for regional water availability assessments in irrigated agricultural watersheds. We calibrated the SWAT model for all three components using available data while incorporating "soft data" where needed (i.e., hard-soft streamflow-ET-recharge calibration). The lack of sufficient observational data for ET and groundwater recharge poses a challenge for quantifying these water budget components. Thus, we used various measured datasets (i.e., hard data) such as streamflow, precipitation, temperature, and land use/cover along with a combination of literature values and expert judgements (i.e., soft data). For example, we used annual and monthly ET rates measured on selected pecan orchards in New Mexico for calibrating pecan ET (Sammis et al. 2004; Samani et al. 2009, 2011, 2013) along with water requirements for other crops estimated by a CROPWAT model based on information in FAO Bulletin 56 (Smith 1992; Allen et al. 1998).

Agricultural management information includes planting, irrigation, and harvest, which are available to varying extents from field operation reports and literature (Abdul-Jabbar et al. 1983; Sammis et al. 2004; Wang et al. 2007; USDA 2010; Ahadi et al. 2013). The plant growth database of SWAT currently does not include Pecan. We used walnut information in the SWAT database to simulate pecan orchards based on the similarity of the growth stages of the two crops. The maximum root depth in the database was corrected for pecan (~3 m) and LAI was adjusted through calibrating the crop ET. The tree maturity was assumed to be 10 years. The crop irrigation was calibrated based on available field information and literature values for each crop. Pecan is prone to permanent damage under severe and long-term water stress (Miyamoto and Storey 1995; Miyamoto et al. 1995). Thus, farmers commonly try to fully irrigate this high-value crop to the extent possible. We calibrated pecan irrigation specifically by comparing the average annual irrigation and ET simulation values with literature values (e.g., Sammis et al. 2004; Wang et al. 2007).

We used SWAT's auto-irrigation function since details of irrigation schedule for several crops were unavailable. The auto-irrigation function set for this study triggers irrigation based on soil water content. The threshold for soil water content to trigger was defined by soil water deficit parameter in SWAT, AUTO_WSTRS. The amount of irrigation water used in each event (AUTO_MX) and the start and end dates of the irrigation period was also defined based on the existing information in the literature (Abdul-Jabbar et al. 1983; Sammis et al. 2004; Wang et al. 2007; USDA 2010; Ahadi et al. 2013) as well as local information (e.g., 4–5 acre-feet per acre for pecan). Efficiency of flood irrigation was considered 60%–75% for different crops (Skaggs and Samani 2005; Ahadi et al. 2013; Ganjegunte and Clark 2017). The accuracy of the threshold and amount of irrigation settings was then evaluated by comparing the range of simulated average annual crop irrigation and ET with the available information (see Figure 9).

A combination of manual calibration and automated SWAT-CUP SUFI2 calibration (Abbaspour 2013) was applied for parameter estimations and sensitivity/uncertainty analysis to obtain satisfactory model calibration at monthly and daily scales. The streamflow was calibrated automatically using SWAT-CUP followed by manual calibration of ET and recharge while checking the relative effect of each parametrization step. After each parameter was changed, the impact of the change on all the other components was assessed before going to the next step. This was done by checking how the change in each parameter in calibrating one component affects the other two components, so that the errors in all three components were reduced. The performance of the SWAT model during the calibration and validation stages were determined using the nash-sutcliffe efficiency (NSE), r^2, and percent bias (PBIAS) goodness-of-fit factors (Moriasi et al. 2007).

Conjunctive Use of Surface Water and Groundwater. To account for the conjunctive use of surface water and groundwater, estimated monthly groundwater pumping was lumped with monthly reservoir releases and introduced to the model as total available water for irrigation. The annual groundwater pumping data for agricultural purposes from 1961 to 2004 (Papadopulos and Associates 2007), including 13,148 groundwater wells were used to characterize the conjunctive use of surface water and groundwater. For irrigation wells, each year was divided into growing season (March–October) and nongrowing season (November–February). Farmers usually pump groundwater to make up for the surface water shortage for irrigation during the growing season (Fuchs et al. 2018), which creates an inverse relation between Caballo releases and groundwater withdrawal (Figure 6). The simulated growing-season groundwater pumping during the 1961–2004 period using the release-pumping regression equation matches the historical groundwater withdrawal. Since no trend is detectable for the pumping rates during the nongrowing season, the maximum of historical pumping at each well during this period was assigned as future pumping rate for the well. Though conservative, this assumption does not lead to significant overestimation of groundwater withdrawal because groundwater is predominantly withdrawn for irrigation during the growing season. For the rare extremely wet conditions, historical minimum groundwater pumping rates were used. This piecewise approximation of groundwater pumping as a function of reservoir release improves estimates of groundwater withdrawals when reservoir releases exceed 1,200 MCM per year (Figure 6).

The reservoir release-groundwater withdrawal relationships were used to project groundwater withdrawals into the future using the scenario-based reservoir releases. A lumped groundwater balance model was set up to evaluate the potential impacts of the selected climate-based surface water projections on long-term groundwater availability. The groundwater

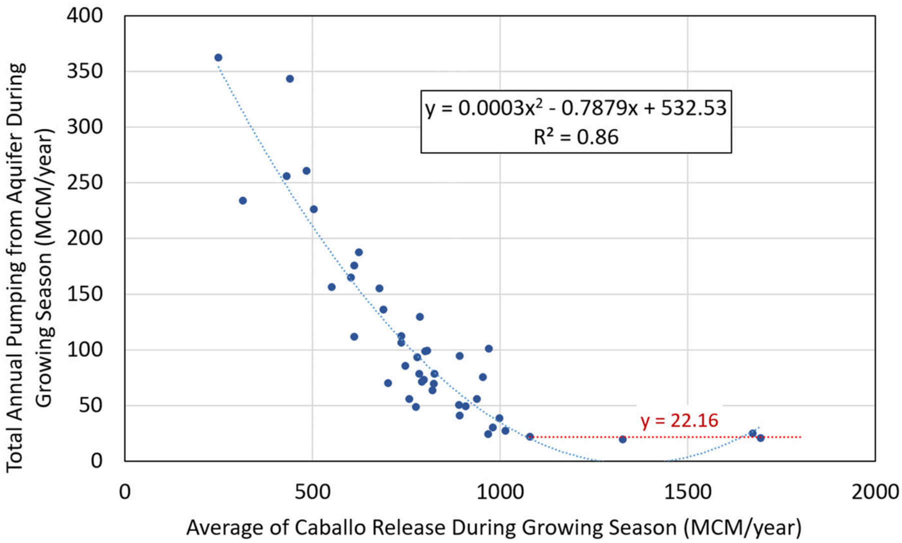

FIGURE 6. Regression relationship between total annual groundwater pumping and releases from Caballo Reservoir during the growing season.

balance accounts for scenario-based SWAT-generated recharge and corresponding projected groundwater withdrawals for agricultural and urban purposes (i.e., EBID and the City of Las Cruces, New Mexico). In the absence of recent measurements of recharge rates, literature values and expert opinions were used as first estimates of average groundwater recharge amounts when calibrating the SWAT model (e.g., Sheng 2013). Annual water uses from the U.S. portion of the Mesilla aquifer from 1993 to 2015, which includes public water supply, irrigated agriculture and other use in New Mexico, was calculated based on data from New Mexico Office of the State Engineer (NMOSE) reports for Doña Ana (New Mexico) and Sierra (New Mexico) counties (Wilson 1992; Wilson and Lucero 1997; Wilson et al. 2003; Longworth et al. 2008, 2013; Magnuson et al. 2019). Note A in Supporting Information provides more information about the groundwater balance model.

Two scenarios of conjunctive use of surface water and groundwater were simulated. The first scenario (i.e., River+FGW) includes Rio Grande water (i.e., releases from Caballo Reservoir) along with fresh groundwater (TDS < 1,000 mg/L) because of the sensitivity of pecan crops to salinity. By reviewing data from Frenzell and Kaehler (1992), Balleau (1999) estimated fresh groundwater storage in the upper 100 ft of saturated fill in the study area to be 17.3 BCM (14 million ac-ft). Hawley and Kennedy (2004) integrated the major hydrogeological components of aquifer-system lithology and stratigraphy, groundwater basin boundaries, and internal basin structure. Using this hydrogeologic framework, they estimated recoverable fresh groundwater storage in the top 200 ft to be 16 BCM (13 million ac-ft) (Hawley and Kennedy 2004). To arrive at this estimate, Hawley and Kennedy (2004) assumed a specific yield of 0.1 for surficial fill with an estimated average thickness of about 61 m (200 ft) in an area of about 2,590 km^2 (1,000 mi^2), forming the confined and semiconfined parts of the aquifer system containing fresh groundwater.

The second scenario (i.e., River+GW) addresses the possibility of using fresh to slightly saline groundwater (TDS < 3,000 mg/L) along with Rio Grande water. The fresh to slightly saline groundwater can be used for salt-tolerant crops like cotton and alfalfa. However, this scenario entails adverse impacts on pecan production if agricultural desalination units are not used. The fresh to slightly saline groundwater storage is estimated to be 62 BCM (50 million ac-ft), which can theoretically be recovered subject to economic, technological, environmental, and sociopolitical constraints (Hawley and Kennedy 2004). This estimate assumes confined or semiconfined aquifer zones with an available porosity value of 10% more than 61 m (200 ft) below the potentiometric surface up to 305 m (1,000 ft) in an area of about 1,940 km^2 (750 mi^2) (Hawley and Kennedy 2004).

RESULTS AND DISCUSSION

SWAT Calibration and Validation

An initial calibration was performed by focusing on reproducing monthly and daily flows for the time period of 1994–1999. Common goodness-of-fit factors (NSE = 0.73, r^2 = 0.95, and PBIAS = −15%) indicated satisfactory initial model calibration (Moriasi et al. 2007) using a time-period that includes both historical low and high flow conditions. The parameter values obtained from manual calibration of streamflow, ET, and groundwater recharge were then compared with SWAT-CUP SUFI2 algorithm results for streamflow to further improve the calibration (NSE = 0.84, r^2 = 0.96, and PBIAS = 6.2%). The model performed comparably well during the validation period (NSE = 0.74, r^2 = 0.90, and PBIAS = 0.61%). Parameter values were fine-tuned separately for agricultural and nonagricultural lands to account for the impact of irrigation and larger infiltration rates in agricultural lands. The initial and final values of key calibrated parameters are summarized in Table 2.

Figure 7 shows the simulated flows compared with observed Rio Grande flows at El Paso station. The streamflow is governed by upstream dam releases and rainfall in the area was practically insignificant in terms of runoff contribution during the droughts of 2006 and 2012–2013. Validation results confirmed that the calibrated model captured the seasonality of the outflow hydrograph during the simulation period. The model overestimated peak flows and some low flows, especially toward the end of the simulation period. The model also captured the spatial distribution of ET and groundwater recharge, which are larger along the main stem of the Rio Grande due to irrigation and river channel seepage losses (Figure 8). Comparing the simulated ET of pecan and alfalfa with measured values in the study area shows that the calibrated model simulations are close to the observed ET values in the same period. Aquifer recharge generated by the model was also compared with available literature values and technical reports (Conover 1954; Sheng 2013; Ahn et al. 2018) (Figure 9). Based on these performance evaluations, the watershed model was deemed suitable for climate impact assessments.

TABLE 2. Calibration parameters in the hard-soft streamflow-ET-recharge calibration.

Parameters	Definition	Initial range	Final estimate
ALPHA_BF	Base flow recession constant (days)	0.1–1	0.9
GWQMN	Return flow threshold depth (mm)	0–5,000	1,000
SOL_AWC	Available soil water capacity (mm/mm)	Varies	Varies (0.04–0.1–0.8)
EPCO	Plant uptake compensation factor	0.01–1	0.85
ESCO	Soil evaporation compensation factor	0.01–1	0.8
GW_REVAP	Groundwater “revap” coefficient	0.02–0.2	Ag.: 0.1; non-Ag.: 0.02
SOL_K	Soil saturated hydraulic conductivity	Varies	Varies (0–1,523 in different layers)
GW_delay	Groundwater delay time (days)	31	Ag.: 35; non-Ag.: 300
CN2	Curve number condition 2	35–98	Varies (40–75)
IRR_ASQ	Surface runoff ratio	0–1	0.3
LAI	Initial leaf area index	Varies	4

Future States of EB-Caballo Reservoir System

The monthly ranges of reservoir system release and storage for each streamflow scenario are shown in Figure 10. As expected, dry scenarios resulted in lower monthly reservoir releases (i.e., up to 0.17 BCM for Dry 1 and 0.41 BCM for Dry 2) compared to wet scenarios (i.e., up to 0.42 BCM for Wet 1 and 0.66 BCM for Wet 2, excluding outliers). All scenarios include periods of nearly no release even during the irrigation season. The reservoir system never reaches full capacity under the extreme Dry1 scenario (the largest storage is about 2.8 BCM) and it rarely fills up under Dry 2 scenario. The prospect of a full reservoir system in the future is also dim under Wet 1 scenario, whereas an extremely wet future (Wet 2 scenario) can potentially fill up the reservoirs relatively frequently. The storage in the reservoir system is disproportionately affected during dry conditions due to continuous evaporation. For example, an average 58% decrease in monthly inflow to EB Reservoir under Dry 1 would reduce reservoir system storage by about 87% in the future (Table 3). As reported in Table 3, the reservoir storage will frequently drop below 10% full under dry scenarios and it will be less than 50% full most of the time even under a plausible relatively wet projected future (Wet 1).

Impacts on Agricultural Water Availability

Table 3 summarizes the average annual values of major water budget components simulated under baseline and future projections. The baseline simulation uses historical releases and NOAA weather data (precipitation and temperature) from four weather stations inside and around the study area from 1993 to 2013 (with one year warm-up period). Future precipitation and temperature conditions are based on hadgem2-es model rcp 8.5 projections. The Dry1 and Dry2 scenarios generated similar results because of the role groundwater plays in alleviating agricultural

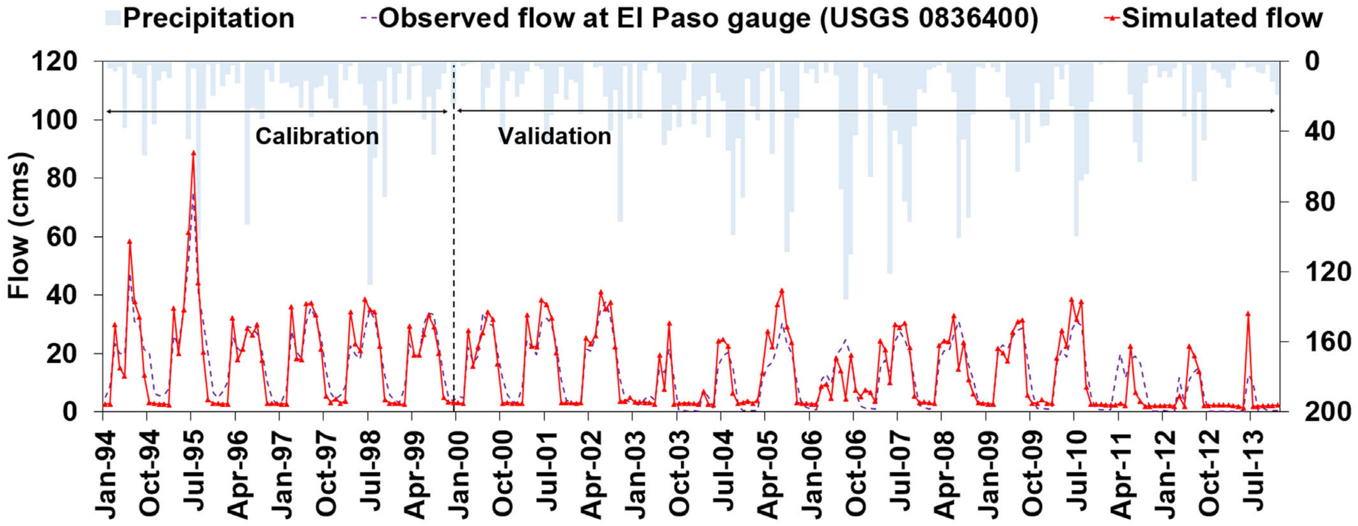

FIGURE 7. Comparison of observed streamflow with SWAT simulations.

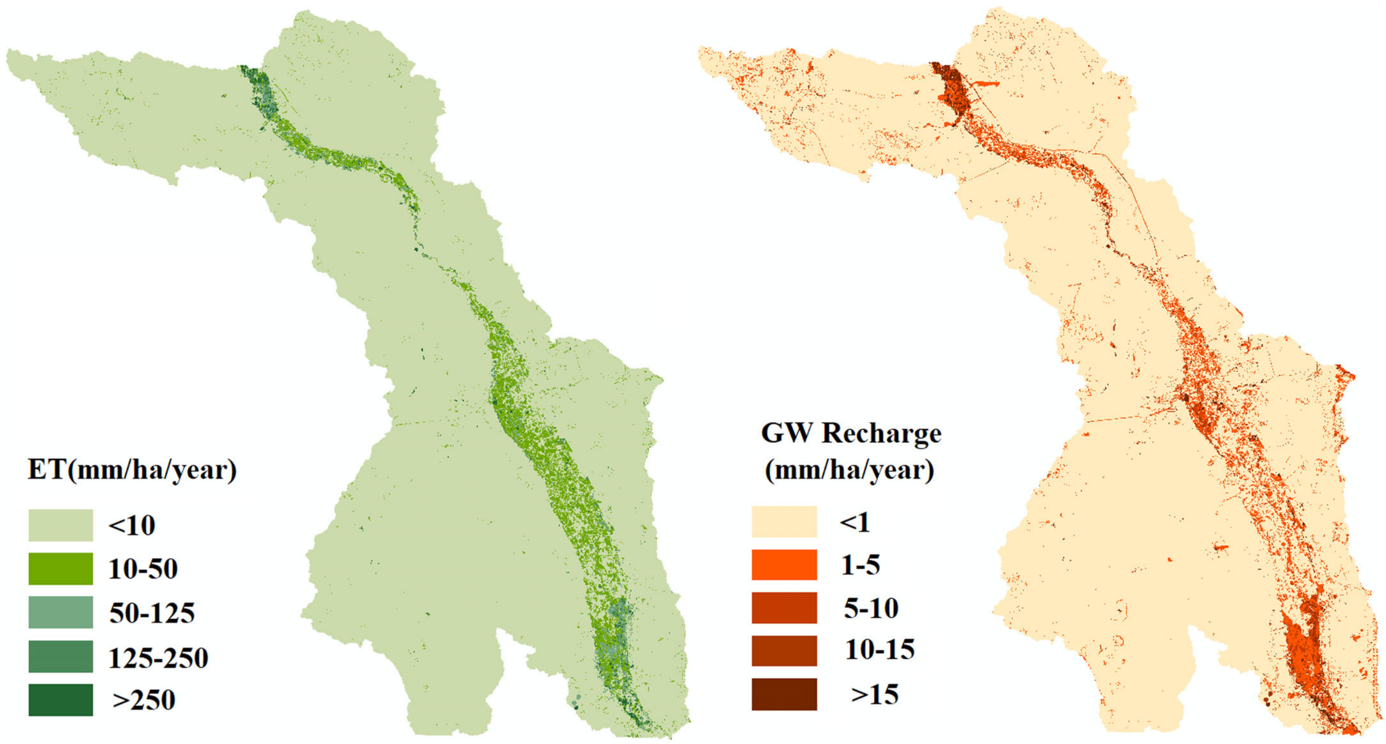

FIGURE 8. Spatial distribution of simulated ET and groundwater recharge in the study area.

water scarcity. However, the average annual irrigation is slightly smaller when only fresh groundwater is used to supplement river water (Table 3). The largest values of water budget components were obtained using the extreme wet (Wet 2) scenario, which is least expected based on historical hydroclimatic trends.

A drier future in the headwaters of the Rio Grande Basin in Colorado will increase the reliance of irrigated agriculture on good quality groundwater in the study area (Figure 11). This is because the dwindling surface water will make it difficult to provide full river water allocation in most years. Despite the wide range of available estimates, fresh groundwater storage is projected to deplete within the second half of the 21st Century, if current irrigated crop patterns and conjunctive use of river water and fresh groundwater persist. The exact time to depletion is difficult to predict and it will vary depending on the accuracy

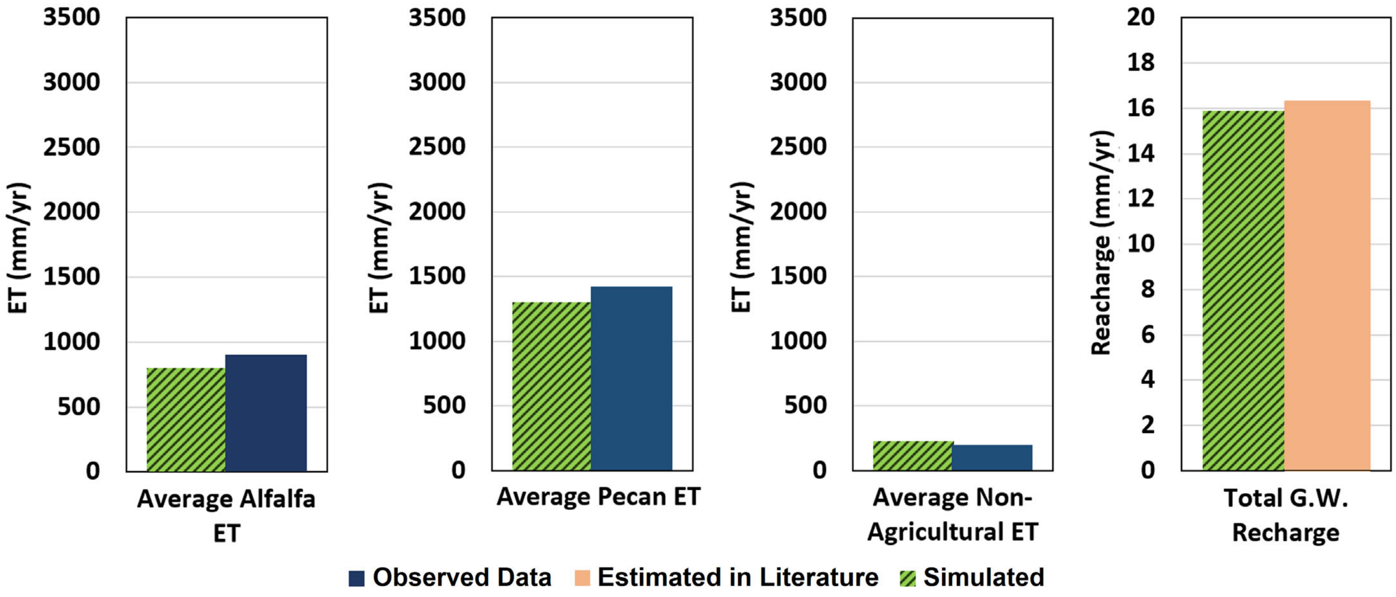

FIGURE 9. ET and groundwater recharge calibration compared with measured ET (Samani et al. 2004, 2013) and estimated recharge values in the Rincon Valley of Elephant Butte Irrigation District (Ahn et al. 2018).

of fresh groundwater storage estimates. Using the estimate by Hawley and Kennedy (2004), fresh groundwater depletion can occur as early as 2060, under the drier future scenarios. This resource can last up to 2080s under other more optimistic estimates of fresh groundwater storage (e.g., Balleau 1999). Likewise, fresh groundwater storage estimated by Hawley and Kennedy (2004) will last longer (e.g., up to 2080s) under a moderately wet scenario (Wet 1), whereas an extreme wet future (Wet 2) would prevent the depletion.

The reliability of meeting agricultural water demand declines in the second half of the 21st Century under all the simulated future water availability conditions (Table 4). The reliability declines more drastically when only fresh groundwater is used for irrigation during the 2022–2099 period. River water alone does not meet the agricultural water demand all the time even under Wet 2 scenario, indicating that agricultural water demand has significantly outgrown renewable water availability. In the absence of agricultural water management improvements to prolong fresh groundwater availability, agricultural producers should prepare to use marginal quality groundwater in a warm-dry future to mitigate potential impacts of fresh groundwater depletion. Although slightly saline groundwater storage will not run out by 2099, this storage will be severely depleted (i.e., by 52%). Groundwater withdrawal would significantly increase under a doomsday no release (NR) condition. At the aggregated watershed scale, it is theoretically possible to completely rely on groundwater for irrigation for a few decades, but this situation can lead to the depletion of fresh groundwater resources before 2040. A NR scenario will also accelerate the depletion of slightly saline water, creating a need to tap into moderately saline groundwater (TDS > 3,000 mg/L) before the end of 21st Century.

Figure 12 illustrates average annual agricultural ET as an indicator of crop production. Baseline ET is included to provide a basis for comparing the variability and magnitude of ET under Dry 1 and Wet 2 scenarios. The dry-scenario ET results are shown for two cases, namely (1) when only river water and fresh groundwater (FGW) are used for irrigation, that is, Dry1 (River+FGW), and (2) when river water is used in conjunction with fresh to slightly saline groundwater, that is, Dry 1 (River+GW). The significant drop in ET in Dry1 (River+FGW) in the late 2050s demonstrates the severe vulnerability of irrigated agriculture when fresh groundwater is depleted. If fresh to slightly saline groundwater can be used effectively for irrigation, it will be possible to maintain full water allocation reliability at about 50%.

The results should be interpreted considering a few caveats and uncertainties related to future streamflow, fresh groundwater storage, groundwater withdrawal, SWAT model parametrization, and dynamic natural and anthropogenic watershed attributes (e.g., land use). The wide range of managed streamflow projections developed based on 97 downscaled bias-corrected GCM products indicates significant uncertainty in future water availability in the region. It is essential to account for upstream impacts on flows as a primary input for assessing potential impacts of future climate conditions in heavily regulated arid/semiarid basins (e.g., Townsend and

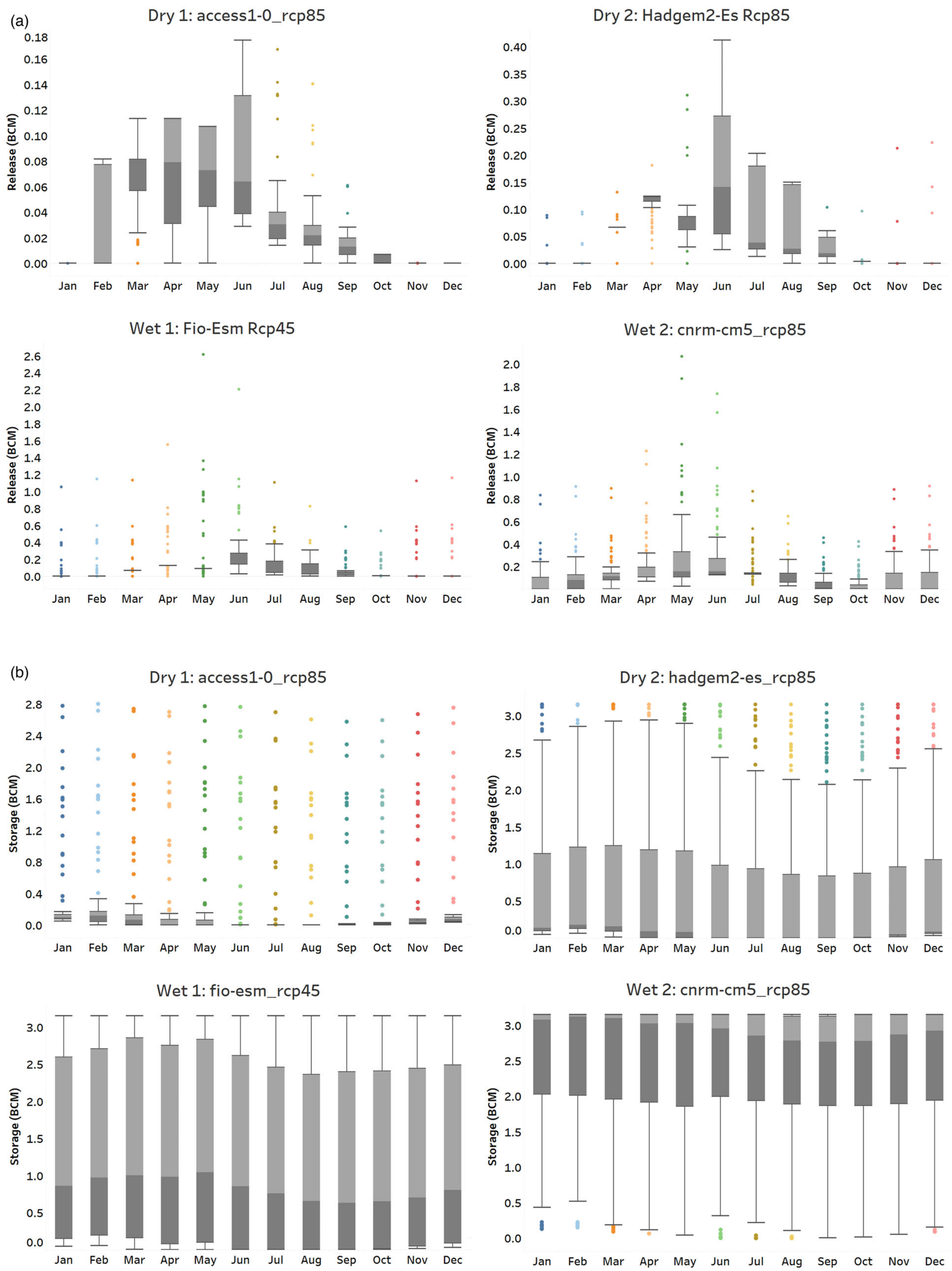

FIGURE 10. Ranges of Elephant Butte-Caballo reservoir system release (a) and storage (b) under selected climate-based flow scenarios through year 2099.

TABLE 3. Simulated average annual values of major water budget components for different projected scenarios (2022–2099).

Scenario	Reservoir storage (% of time) <50% full	Reservoir storage (% of time) <10% full	Water source	Average flow (m^3/s) In	Average flow (m^3/s) Out	Deep GW recharge (mm)	Lateral flow (mm)	Irrigation (mm)	ET (mm)	Soil moisture (mm)
Baseline (1994–2013)	100	38	River+FGW	25	13.3	78	16.4	539	635	10.5
Dry1	98	87	River+GW	25.2	12.3	68.8	12	589	626	11.2
			River+FGW	19	9.3	62.7	10	505	561	11.3
Dry2	78	69	River+GW	25.2	12.3	68.8	12	589	626	11.2
			River+FGW	23.5	13.2	64	11	525	577	11
Wet1	62	36	River+GW	51	38	72.3	14	605	635	11.2
			River+FGW	48	36	69.4	13	574	612	11
Wet2	21	8	River+GW	68	53	80.3	19	639	653.5	11.1
			River+FGW	66	52.6	79.6	18	633	649	12

Note: FGW = fresh groundwater (total dissolved solids [TDS] < 1,000 mg/L). GW = fresh to slightly saline groundwater (TDS < 3,000 mg/L) and moderately saline groundwater (TDS > 3,000 mg/L).

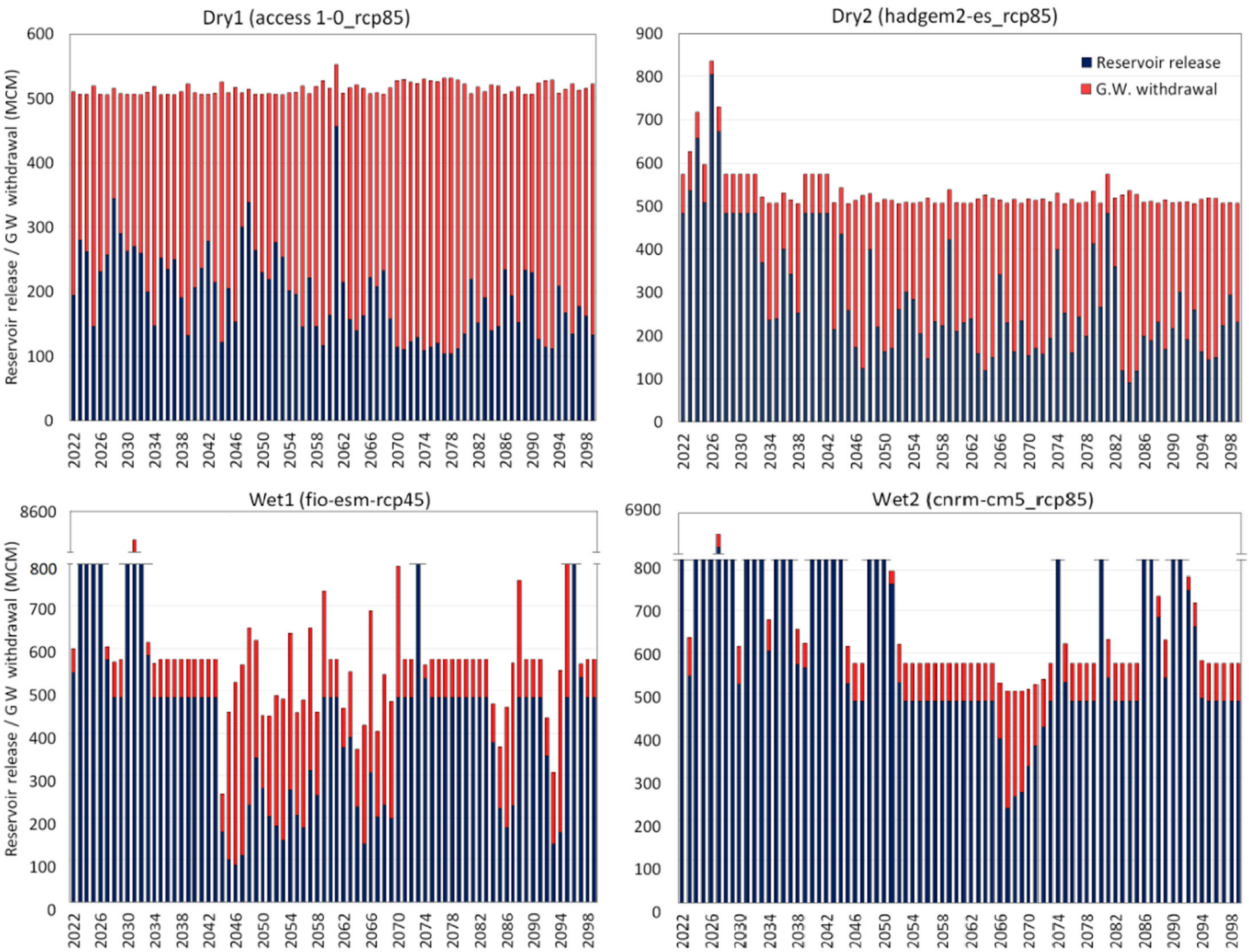

FIGURE 11. Conjunctive use of surface water and groundwater for the selected scenarios.

Gutzler 2020), and select flow projections that are regionally relevant based on the realities of how flow conditions have changed historically. The historical Rio Grande flows in the study area (i.e., San Marcial and El Paso gauges) display an overall declining trend related to a combination of climate conditions

TABLE 4. Reliability of water resources in different time-periods under future scenarios.

Scenario	Water source	Reliability[1] (%) 2020–2060	Reliability[1] (%) 2060–2099
Dry1	Surface water and fresh groundwater	49	17
	Surface water and fresh to slightly saline groundwater	49	50
Dry2	Surface water and fresh groundwater	54	18
	Surface water and fresh to slightly saline groundwater	54	50
Wet1	Surface water and fresh groundwater	62	38
	Surface water and fresh to slightly saline groundwater	62	57
Wet2	Surface water and fresh groundwater	75	63
	Surface water and fresh to slightly saline groundwater	75	63

[1]Reliability is defined as the probability that water demands are fully met (McMahon et al. 2006).

and upstream management practices (Figure 13). The declining trend underscores the importance of preparing for scenarios of reduced surface water availability under hotter and drier conditions in the future. This is particularly important for evaluating long-term availability of fresh groundwater and sustainability of irrigated agriculture.

There are uncertainties associated with the modeling component of the climate impact assessment framework (see Figure S5). There is a critical need to update the estimates of fresh and slightly saline groundwater storages based on hydrogeological assessments to develop robust models of the aquifer while accounting for mixing of fresh and saline groundwater because of increased pumping. Calibration of highly managed water systems using hydrologic parameters is generally challenging, especially when detailed management operations data are unavailable (Abbaspour 2013). Alternative model parametrizations can lead to similar streamflow simulations, known as equifinality or parameter nonuniqueness (Khatami et al. 2019). Furthermore, a good streamflow calibration does not necessarily translate into equally good results for other managed components (e.g., ET and groundwater recharge) of the water budget in arid irrigated areas. Thus, the hard-soft streamflow-ET-recharge calibration strategy applied in the current analysis was necessary to provide a realistic characterization of the water budget components in the region to inform adaptive management of regional water resources. Other caveats include limited capability for detailed simulation of pecan trees such as impacts of irrigation water shortage in different time-periods on plant survival and productivity. A static crop mix and acreage was assumed in the model based on recent land use maps (NLCD 2011), which does not capture dynamic land use change in response to water availability during wet and dry periods and crop market value. Thus, the reported implications of future climate conditions are conservative in that they are based on water

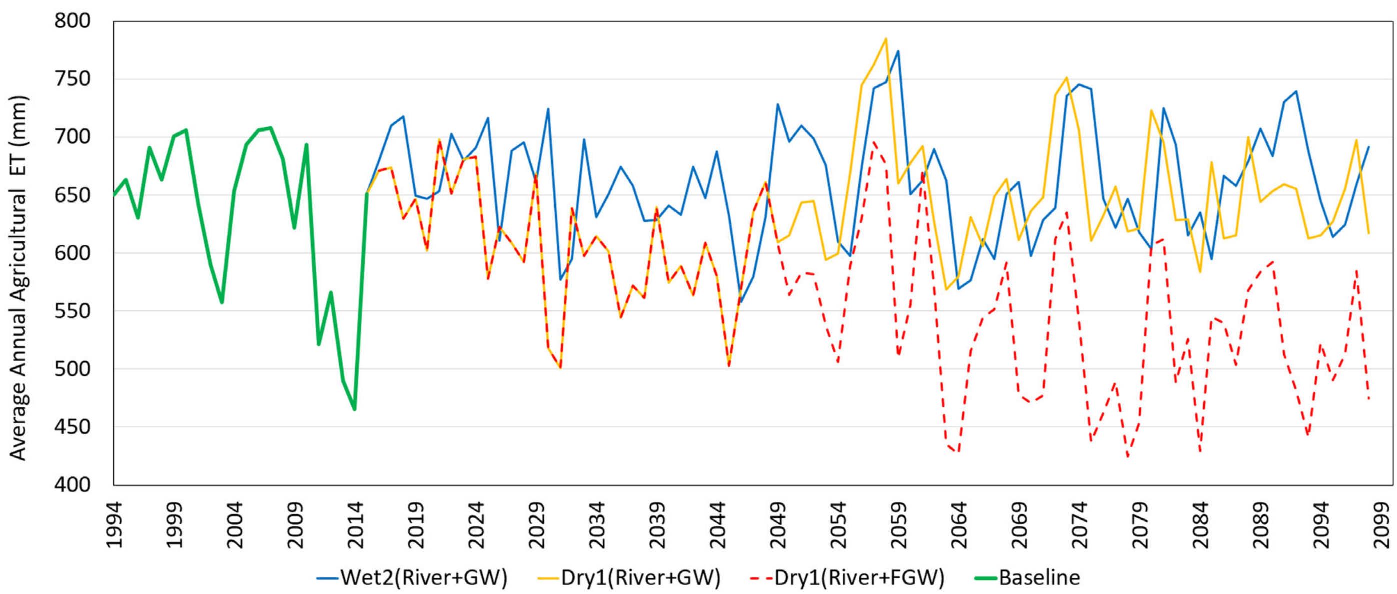

FIGURE 12. Simulated evapotranspiration for baseline, Wet2 and Dry 1 with all available water resources (River+GW) and Dry1 with surface water and fresh groundwater only (River+FGW).

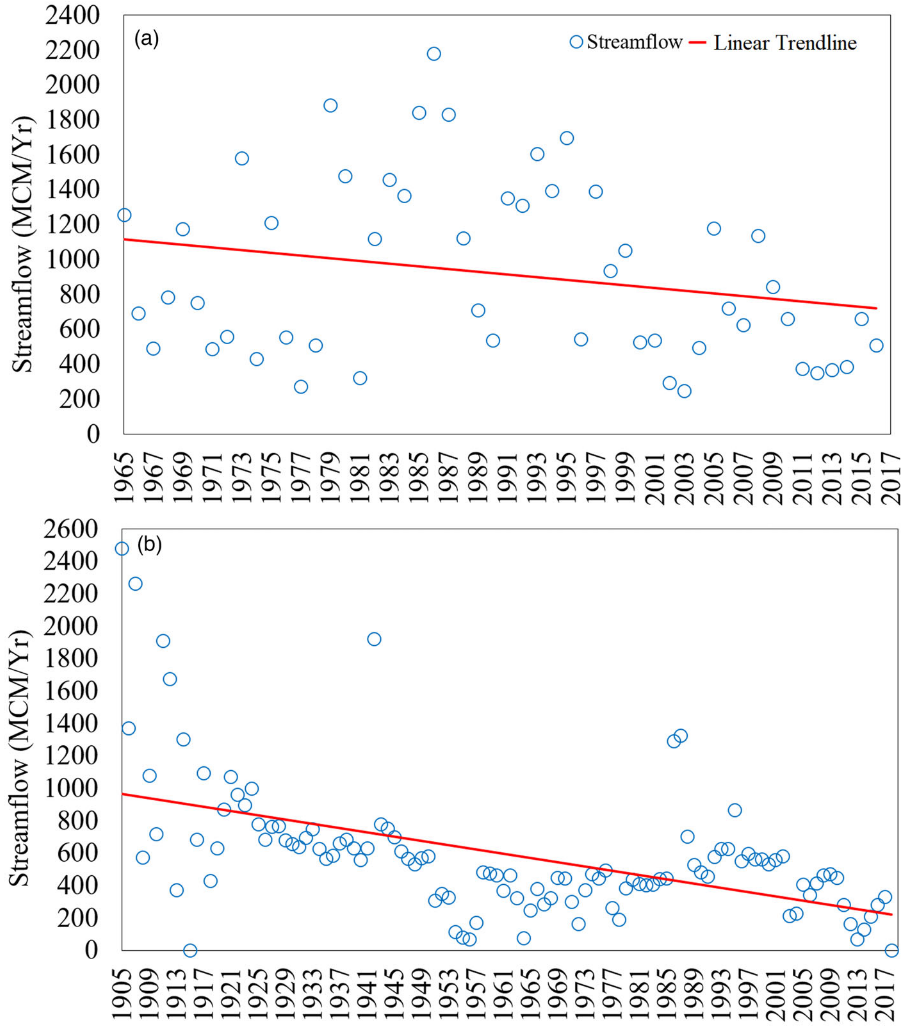

FIGURE 13. Historical annual variability of Rio Grande flow at (a) San Marcial gauge (USGS 08358300) immediately upstream of the watershed, and (b) watershed outlet at El Paso gauge (USGS 08364000).

demands corresponding to agricultural lands during the exceptional drought in 2011. Due to higher agricultural activity in average and wetter than average years, which requires more irrigation, the impacts of diminished river flow in the future may be even more severe.

It is necessary to improve agricultural water management with the goal of reducing net water consumption in the region. While water storage in the upstream reservoirs and increasing groundwater withdrawal can mitigate the negative impacts of future droughts, the dominant agricultural water management approach for high-value crops is unsustainable. The transition to using marginal quality groundwater for irrigation will create a set of new challenges that were not accounted for in the present assessment. Irrigating pecan trees with water with TDS > 700–1,000 mg/L could result in shrinkage of leaves and nuts. Once the soil salinity exceeds 6–8 dS/m (TDS = 4,800–6,400 mg/L) pecan trees start to die-back. Accumulation of Na+ in soil profile due to irrigating with saline water might cause soil sodicity, affecting soil structure stability, erosion, and nutrition balance (Rengasamy and Olsson 1991; Qadir and Schubert 2002). Saline soils require more water for leaching the salt out of the root zone, while other methods such as adding gypsum may help the plant to tolerate the salinity to some extent (Miyamoto, et al. 1985; Miyamoto 2006; Fipps 2021). Increasing energy cost of pumping may weaken the economic attractiveness of irrigated agriculture in the region.

The future availability of irrigation water in the middle section of the Rio Grande will depend on the cooperation of all users to develop an integrated regional water plan to manage the declining resources. Water conservation practices such as deficit irrigation, changing the crop pattern by reducing perennial crops like alfalfa in the crop mix can increase water availability for high-value crops. Growing drought tolerant crops like pistachio and pomegranate, which are compatible with the regional climate, and modern irrigation methods like drip irrigation could increase the agricultural resiliency to future severe drought conditions. There are also different alternatives to augment agricultural fresh water supply, including groundwater desalination and importation from other regions, which are more expensive sources of water as compared to the status quo. Selecting the optimum water management plan for the region requires field experiments and detailed modeling of individual or portfolio of intervention options.

CONCLUSIONS

We applied a climate impact assessment framework consisting of projected monthly Rio Grande flows at San Marcial gauge, a semidistributed watershed hydrology model, and a simple model of conjunctive management of surface water and groundwater to support irrigated agriculture. The calibrated and validated SWAT model reproduced the major components of the water balance budget (e.g., streamflow, ET, and groundwater recharge) in the arid/semiarid agricultural watershed with a heavily managed river system to support irrigation. The results indicate that the EB-Caballo reservoir system will become a much less reliable water source in the future. Consequently, the region will likely become more groundwater-dependent. It is highly likely that maintaining the region's agricultural production will lead to fresh groundwater depletion within the 21st Century. This calls for building consensus about possible agricultural water management improvements to prolong fresh groundwater availability while also preparing to use marginal quality groundwater for irrigation in the middle section of the Rio Grande.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Supporting Information document includes five figures and one note.

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AUTHOR CONTRIBUTIONS

Maryam Samimi: Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing — original draft. **Ali Mirchi:** Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation; Visualization; Writing — review & editing. **Nolan Townsend:** Data curation; Investigation. **David Gutzler:** Investigation; Methodology; Supervision; Writing — review & editing. **Subhash Daggubati:** Data curation; Visualization. **Sora Ahn:** Investigation; Software; Writing — review & editing. **Zhuping Sheng:** Investigation; Methodology; Supervision; Writing — review & editing. **Daniel Moriasi:** Investigation; Methodology; Supervision; Writing — review & editing. **Alfredo Granados-Olivas:** Investigation; Methodology; Writing — review & editing. **Sara Alian:** Investigation; Supervision; Visualization; Writing — review & editing. **Alex Mayer:** Investigation; Methodology; Writing — review & editing. **William Hargrove:** Conceptualization; Investigation; Methodology; Project administration; Writing — review & editing.

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