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Climate change implications for irrigation and groundwater in the Republican River Basin, USA

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Abstract

This study investigates the influence of climate change on groundwater availability, and thereby, irrigation across political boundaries within the US High Plains aquifer. A regression model is developed to predict changes in irrigation according to predicted changes in precipitation and temperature from a downscaled dataset of 32 general circulation models (GCMs). Precipitation recharge changes are calculated with precipitation-recharge curves developed for prognostic representations of precipitation across the Nebraska-Colorado-Kansas area and within the Republican River Basin focal landscape. Irrigation-recharge changes are scaled with changes in irrigation. The groundwater responses to climate forcings are then simulated under new pumping and recharge rates using a MODFLOW groundwater flow model. Results show that groundwater pumping and recharge both will increase and that the effects of groundwater pumping will overshadow those from natural fluctuations. Groundwater levels will decline more in areas with irrigation-driven decreasing trends in the baseline. The methodologies and predictions of this study can inform long-term water planning and the design of management strategies that help avoid and resolve water-related conflicts, enabling irrigation sustainability.

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1 Introduction

Throughout the world, irrigation is the largest use of fresh water resources, and management of such infrastructure is central to the pursuit of more sustainable and integrated water, agricultural, and energy resources (Scanlon et al. 2017). According to 2010 estimated use of water in the USA, irrigation withdrawals are made up of 62% of total freshwater withdrawals (Maupin and Barber 2005). Although irrigation efficiency has increased with technological improvements, best management practices and shifts to less water-dependent crops, irrigated acreage continued to increase in the USA until 2010 (Donnelly and Cooley 2015). Under future climate projections, increasing atmospheric CO_2 concentrations will produce raising temperatures and more variable precipitation with more intense and frequent wet and dry spells, along with increased irrigation water demands (Fischer et al. 2007; McDonald and Girvetz 2013; Rehana and Mujumdar 2013). Thus, irrigated agriculture can be highly vulnerable to climate change, especially in arid and semi-arid areas with intensive irrigation demands.

Groundwater's high quality and accessibility typically make it the primary water supply in arid and semi-arid areas. However, climate change combined with land and water management can produce variability in groundwater demand and availability (Green et al. 2011). Most studies on the effects of climate change on groundwater focus on groundwater recharge because it is directly influenced by climate (Crosbie et al. 2011; Holman 2006; Jyrkama and Sykes 2007; Niraula et al. 2017). Some climate change studies estimate groundwater storage or groundwater budgets under projected climate scenarios (Allen et al. 2004; Goderniaux et al. 2011; Jackson et al. 2011). Comprehensive groundwater dynamics under climate change, provided in these studies, are more critical for water management as the system can shift to another balanced status. For example, Allen et al. (2004) found that groundwater balance can be significantly shifted temporally and spatially, even when groundwater levels are less sensitive to climate changes. The importance of using multiple general circulation models (GCM) projections has also been promoted as a way to account for uncertainty in projections (Allen et al. 2010; Crosbie et al. 2011). Nevertheless, the overall effects of climate change on irrigation and groundwater recharge have not yet been well addressed.

Recent studies indicate that climate change impacts on crop growth and irrigation demands can be positive or negative, depending on crop types and geographic locations (Fischer et al. 2007; Rehana and Mujumdar 2013; Shahid 2011). Maintaining the productive capacity of soils with irrigation increases evapotranspiration and near-surface humidity—eventually altering hydrologic cycles and even local or regional climate (Leng et al. 2013; Pokhrel et al. 2015; Vereecken et al. 2010). Groundwater availability is a constraint for irrigation, and when irrigation withdrawals exceed recharge, irrigation can decrease groundwater storage and even streamflow in areas where groundwater and surface water are connected (Eckhardt and Ulbrich 2003). This illustrates the need for integrated modeling of irrigation and hydrologic dynamics under climate change to better represent such systems.

The purpose of this study is to quantitatively evaluate climate change impacts on irrigation demands and regional water resources in the Republican River basin, an agricultural basin overlying the High Plains aquifer in the American Great Plains, where water management for irrigation across political boundaries has important implications for sustainability and the economy. Our objectives are to (1) predict changes in irrigation water requirements with a

regression model, according to projected temperature and precipitation; (2) feed predictions of groundwater pumping and recharge into a regional numerical groundwater flow model; (3) assess irrigation sustainability with respect to its impacts on groundwater in different seasons (irrigated and non-irrigated) across political boundaries; and (4) make adaptation recommendations for effectively planning with increasingly limited water resources in this region.

2 Materials and methods

2.1 Study area

The Republican River originates in the State of Colorado (CO) and then generally flows east through Nebraska (NE) and Kansas (KS) (Fig. 1). The Republican River Basin (RRB), predominantly underlain by the High Plains Aquifer, extends across an area of 64,500 km^2 in CO, NE, and KS. The dominant land uses are grass/pasture and cropland, composing over 45% and 35% of the basin area, respectively, based on the 2008 National Cropland Data Layer. More than 95% of the water withdrawn from the High Plains Aquifer is used for irrigation, and CO, KS, and NE together account for more than 60% of the total withdrawals (Maupin and Barber 2005). In NE and KS, 98% and 85% of the total groundwater irrigation are from the High Plains Aquifer (Hutson et al. 2004).

To efficiently use and manage the water in RRB, the Republican River Compact Administration (RRCA) was formed in 1942 (United States Congress 1943). However, its crossing of multiple political boundaries resulted in conflicts over water access among CO, KS, and NE. Kansas filed a complaint against NE in 1998 and against CO and NE in 2010 for exceeding their water allocations. Recently, variably declining water tables throughout the RRB, a result of intensive irrigation, have been documented using the historical records of groundwater monitoring wells (McGuire 2017). Between 2002 and 2015, the maximum groundwater level decline reached 13.2 m in the RRB.
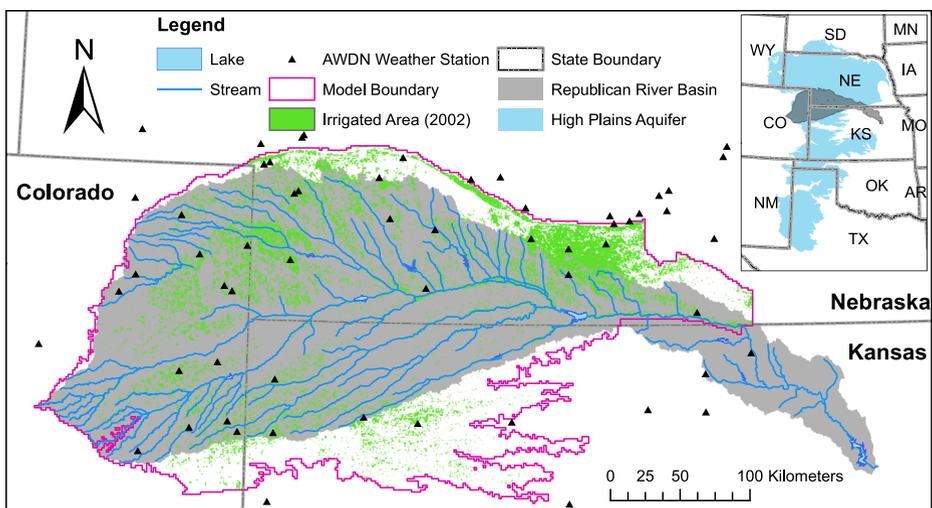
Fig. 1 Location of the Republican River Basin

2.2 The RRCA groundwater model

As a result of the Final Settlement Stipulation in the case of KS vs. NE and CO in 2002, a comprehensive groundwater flow model was developed using the MODFLOW code by technical experts from the three states, as appointed by the RRCA committee (RRCA 2003). The purpose of the RRCA model is "… to determine the amount, location, and timing of streamflow depletions to the Republican River caused by well pumping and to determine streamflow accretions from recharge of water imported from the Platte River Basin into the Republican River Basin …" (RRCA 2003). The RRCA model is discretized into a single-layer, uniform, 1-mi grid with 165 rows and 326 columns, of which 30,655 cells are active. Monthly stress period is implemented with two time steps per stress period. The stream package is used to simulate the stream-aquifer interaction and streamflow routing in the modeled area (Prudic 1989). Groundwater recharge and pumping are parameterized in the Recharge and Well packages, respectively. The model was calibrated with historical groundwater levels at monitoring wells and baseflows at stream gauges. The model has been being updated each year with new data. The model files can be downloaded at the RRCA website (http://www.republicanrivercompact.org/), and the simulation period ranges from 1918 to 2015 (accessed on June 8, 2017).

2.2.1 Estimation of irrigation withdrawal

Because observation of irrigation withdrawal was limited, the actual irrigation amount was estimated using other data sources, depending on data availability. In Nebraska, irrigation withdrawal can be estimated with electrical consumption for irrigation. For Kansas and Colorado, irrigation withdrawal is estimated based on irrigated acreages, net irrigation requirements, and application efficiencies (RRCA 2003). To account for the impact of climate variability on irrigation, an estimation of the monthly irrigation withdrawal can be unified as follows:

$$Q_p = (K_c ET_r - K_p P) A / E_f \tag{1}$$

where Q_p is the monthly irrigation withdrawal (m^3/mon), K_c is the crop coefficient, ET_r is the monthly reference ET (mm), P is the monthly precipitation (mm), K_p is the effective precipitation coefficient, A is the irrigated area (m^2), and E_f is the irrigation efficiency. ET_r is the sum of daily reference ET which is calculated through the Hargreaves equation:

$$ET_{rd} = aR_a (T_{max} - T_{min})^{0.5} (T_{mean} + 17.8) + b \tag{2}$$

where ET_{rd} is the daily reference ET (mm day^{-1}); R_a is the net radiation (MJ m^{-2} day^{-1}); T_{min}, T_{max}, and T_{mean} are the daily minimum, maximum, and mean temperatures, respectively [°C]; and a and b are constants. The values of a and b are 0.0023 and 0 in the standard Hargreaves equation, respectively (Hargreaves and Allen 2003). To account for spatial variability, a and b are calibrated to match the results calculated with the Penman-Monteith (PM) Evapotranspiration equation (ASCE-EWRI 2005) at Automated Weather Data Network (AWDN) stations (Fig. 1) operated by High Plains Regional Climate Center (https://hprcc.unl.edu/). Data from AWDN stations are used because AWDN stations provide comprehensive weather information needed in the PM equation. After calibration, the values at the stations are interpolated over the

RRB domain through kriging. Supplementary Fig. S1 shows the distributions of the deviation of a and b relative to the standard values, respectively.

By combining the coefficients, Eq. (1) can be expressed as:

$$Q_p = \alpha ET_r - \beta P \qquad (3)$$

where $\alpha = K_c A/E_f$ and $\beta = K_p A/E_f$. In Eq. (1), K_c depends on the crop type and growth phase, while the values of A and K_p change with location. The values of α and β vary both in time and space. By neglecting the interannual variability in A, K_c and K_p, α and β become constants for different months in each grid cell. Thus, they can be estimated using historical pumping rates, precipitation, and temperature data in each irrigated cell. The best-fit values of α and β are found using the Limited-memory Broyden–Fletcher–Goldfarb–Shanno (L-BFGS) optimization algorithm (Byrd et al. 1995) with bounds of (0.0, 1.0). Individual α and β values were estimated for each irrigated cell and each month. The calibration period ranges from 1980 to 2009, while irrigation between 2010 and 2015 is used for verification (see Supplementary Materials for the model performance). Irrigation occurs primarily in the summer months and is negligible the rest of the year (Supplementary Table S1). As such, we defined June to September as the irrigation (IRRI) season and the rest months as the non-irrigation (NOIR) season.

2.2.2 Estimation of groundwater recharge

In the RRB, groundwater recharge originates primarily from precipitation and irrigation. Precipitation recharge is estimated with precipitation-recharge curves, while irrigation recharge is considered to be proportional to irrigation. Details follow.

Precipitation recharge Precipitation recharge is estimated with precipitation-recharge curves (PRCs), as shown in Supplementary Fig. S2. The PRCs, developed based on the results of a soil water balance model CropSim (Martin et al. 1984), transforms annual precipitation into annual precipitation recharge. CropSim is a water-driven point source model that uses weather data in combination with representative system characteristics (crop phenology, soils, management, and irrigation system) to model the daily crop growth and soil water balance. It was used to simulate soil hydrology and generate PRCs with the combinations of five soil types and irrigated and non-irrigated land use types (RRCA 2003).

In the RRCA model, precipitation data were retrieved at the AWDN weather stations in the study area. In order to calculate precipitation recharge, annual precipitation was interpolated to each cell based on the weather station data with the kriging interpolation method. Annual precipitation recharge is then calculated with the PRCs, according to the soil and irrigation types within each grid cell. The irrigated area within each cell is used to apportion the recharge between the irrigated and non-irrigated recharge curves. The annual precipitation recharge was distributed to months using a fixed monthly distribution defined by RRCA.

In this study, we implement two modifications to the precipitation recharge estimation method. First, in the baseline, the PRISM Climate dataset (Daly et al. 1994) is used to re-estimate precipitation recharge. Compared to the interpolation method, the PRISM dataset provides more accurate spatial distribution of precipitation. Meanwhile, the PRISM temperature data is used to estimate reference ET. Second, instead of a fixed monthly distribution of the annual precipitation, we use monthly precipitation from the PRISM dataset.

Irrigation recharge Irrigated water can be consumed by crops, become runoff, evaporate from the soil, or be stored in the soil, with the remainder recharging groundwater. Irrigation recharge is assumed to be proportional to the gross irrigation amount in the RRCA model (Dewandel et al. 2008). Therefore, changes in irrigation recharge are proportional to changes in gross irrigation withdrawals:

$$R_i = R_{i0} Q_p / Q_{p0} \tag{4}$$

where R_i and R_{i0} are the projected and baseline irrigation recharge rates, respectively, and Q_p and Q_{p0} are the projected and baseline irrigation withdrawal rates, respectively. The projected irrigation withdrawal rates are estimated using the regression model (Eq. 3) based on temperature and precipitation.

2.3 Climate change projections

Projections of future temperature and precipitation are retrieved from the Locally Constructed Analogs (LOCA) statistical downscaled dataset developed by Pierce et al. (2014) for CMIP5 (Taylor et al. 2011). The dataset includes downscaled estimates of daily precipitation and minimum and maximum temperature at 1/16-degree resolution based on the simulation results of 32 GCMs (Supplementary Table S2). The climate data are re-projected to the 1-mi model grid using bilinear interpolation. Each GCM provides historical, RCP4.5, and RCP8.5 data. Changes in monthly precipitation and temperature are calculated between the RCP4.5 or RCP8.5 and mean historical values. A 90-year baseline simulation is constructed through repetition of the RRCA model simulation between 1980 and 2009. The final hydraulic head of a 30-year simulation is used as the initial head for the next 30-year simulation to propagate changes. In the present study, climate change impact is assessed through the comparison of the mean of the future ensemble simulation and the 90-year baseline simulation, in which the future climate impact is isolated from the current trend in the baseline.

3 Results and discussion

3.1 Future climate variability

Figure 2 shows the distribution of mean temperature changes in the IRRI and NOIR seasons of each year. Consistent trends can be identified from the plots in both the RCP4.5 and RCP8.5 scenarios; however, temperature increases are slightly different between states and seasons. In the RCP4.5 scenario, the mean temperature increases during the projection period are 2.07, 2.12, and 2.21 °C for CO, KS, and NE, respectively. Temperature increases in the IRRI seasons are significantly greater than those in the NOIR seasons based on the Welch's t test (Supplementary Table S4). The maximum temperature increases in CO, KS, and NE are 5.06, 5.13, and 5.28 °C, respectively, from 2070 to 2099 under the RCP8.5. As temperature increases intensify under the RCP8.5 scenario, differences between the states and the seasons are also enhanced. For example, in the irrigation season of RCP8.5, mean temperature increases are greater than the NOIR season by 0.36 °C.
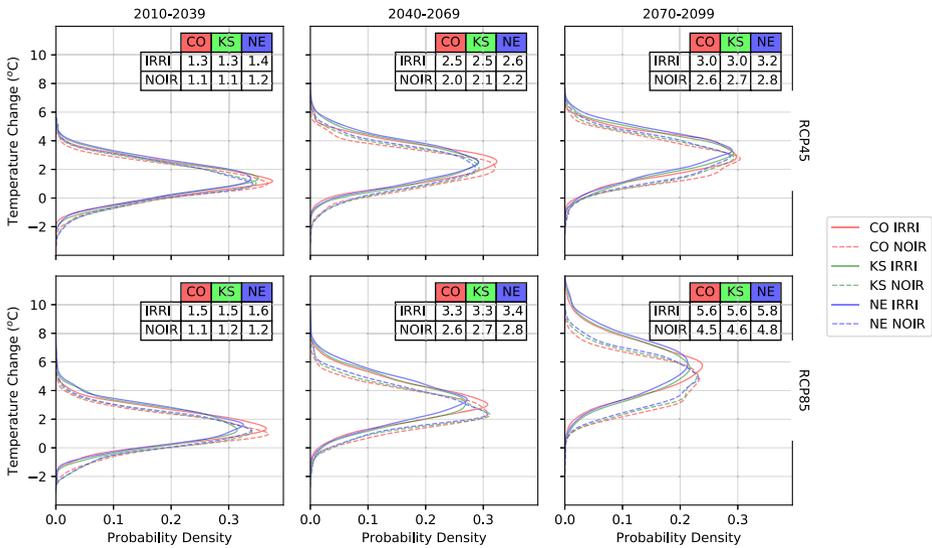
Fig. 2 Probability density functions of projected temperature changes for CO, KS, and NE in irrigation (IRRI) and non-irrigation (NOIR) seasons. The mean values are listed in the embedded tables

Figure 3 indicates that the overall changes in projected mean precipitation are small, but there was substantially greater variability in precipitation than temperature among coefficient of variation values, which were 0.70 °C and 20 mm for temperature and precipitation changes, respectively. Trends in precipitation changes are opposite between the IRRI and NOIR seasons (Supplementary Table S5). In the IRRI season, the mean precipitation changes are − 7.5 and − 14 mm under the RCP4.5 and RCP8.5 scenarios, respectively. In contrast, they are 17 and 20 mm, respectively, in the NOIR season. It is predicted that precipitation will decrease more in the irrigation seasons in Kansas and Nebraska than in Colorado. Combining the temperature and precipitation changes, it will become even drier in the irrigation season in the RRB.

3.2 Climate change impact on irrigation withdrawal

Irrigation withdrawal is likely to increase in all three states in the future (Fig. 4). The changes in irrigation withdrawal are closely related to the baseline pumping rate. Pumping increases more in the high pumping months (i.e., 1.23 mm in July and August and 0.56 mm in June and September) and more in Nebraska (1.88 mm) than in CO (0.73 mm) and KS (0.07 mm). The increase of pumping in KS is relatively small due to its low baseline pumping. The maximum pumping increase, occurring in NE for the RCP8.5 scenario, reaches 5.5 mm in July and August. The results suggest that irrigation water use will increase proportionally to the baseline and crop water stress will become more severe in dry years.

3.3 Changes in groundwater recharge

Groundwater recharge (including precipitation recharge) is one of the variables calibrated in the model to match the observed groundwater levels and baseflow during the model development (RRCA 2003). To validate the estimation of groundwater recharge, we compared the simulated recharge with the field measurements estimated through the ^{3}H profile at one
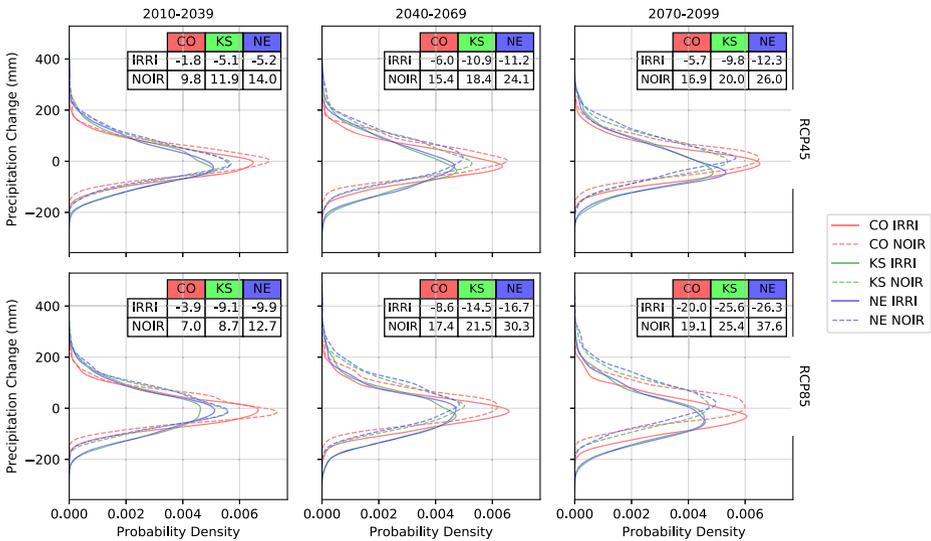
Fig. 3 Probability density functions of projected precipitation changes for CO, KS, and NE in irrigation (IRRI) and non-irrigation (NOIR) seasons. The mean values are listed in the embedded tables

rangeland site and two rainfed and irrigated agricultural sites in the basin (McMahon et al. 2006). The comparison (Supplementary Table S6) shows that the simulated recharge is the same as the measured (70 mm/year) at a rangeland site. At the irrigated sites, however, the modeled recharges are 15% and 23% smaller than the measured, respectively. This may be attributed to the fraction of non-irrigated areas in the same grid cell in the model. Recharge is smaller in the non-irrigated area than that in the irrigated area due to irrigation return flows. Therefore, the simulated mean recharge of a grid cell is lower than the measured recharge in the irrigated area.

For the future projection, groundwater recharge is predicted to increase generally (Fig. 5). Irrigation recharge is predicted to increase steadily due to the increase in pumping. Although
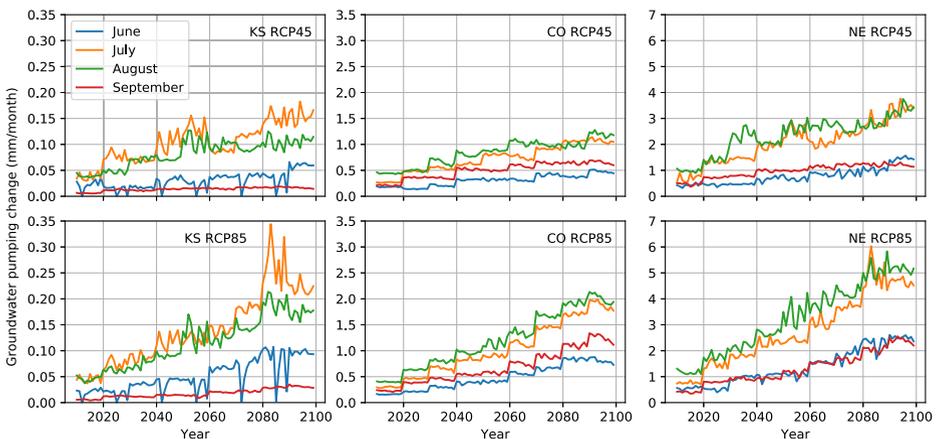
Fig. 4 Ensemble mean of groundwater pumping changes in KS, CO, and NE in different months of the irrigation season

annual precipitation recharge generally increases, in some cases, it decreases during the irrigation season, leading to decreased total recharge in the months with peak water demand. Due to the high variability of precipitation change, for example, precipitation recharge during the irrigation months decreases intermittently in the 2050s and 2090s in CO and 2050s in KS and NE under RCP4.5, and in the 2030s, 2080s, and 2090s in all three states under RCP8.5. Even with the intermittent reduction of precipitation recharge in the IRRI season, the total annual recharge increases because of increased precipitation recharge in the NOIR season. However, the region will face the greatest water stresses with reduced precipitation recharge and increased irrigation demands in the IRRI seasons of drought years.

Total groundwater recharge increased the most (30%) in the western portion of the study area in CO, which is mostly fallow or pasture land (Fig. 6). Therefore, the increase can be attributed primarily to increases in precipitation recharge. Elsewhere, groundwater recharge change is relatively small, except in irrigated areas where irrigation recharge results in an overall increase in annual recharge. Projected decreased recharge can be identified in parts of CO and NE under the RCP8.5 scenario. The overall results are consistent with a recent study that projects 5.3% and 11.8% increases in near and far future groundwater recharge, respectively, though under a different scenario, RCP6.5, in the Rockies and Northern Plains region (Niraula et al. 2017).

3.4 Change in groundwater levels

Groundwater level change represents the integrated response of the aquifer to changes in recharge as well as water management for irrigation. Spatial variability in baseline groundwater level changes and future accretional changes due to climate change are presented in Fig. 7. In the baseline simulation, the mean groundwater level declines in 2099 reach 10.7, 5.7, and 5.1 m in CO, KS, and NE, respectively. The maximum drawdown is over 39 m, occurring in CO. The distribution of the groundwater change of the baseline is in good agreement with the observation provided by McGuire (2017) (Supplementary Table S7). Spatial distribution of the
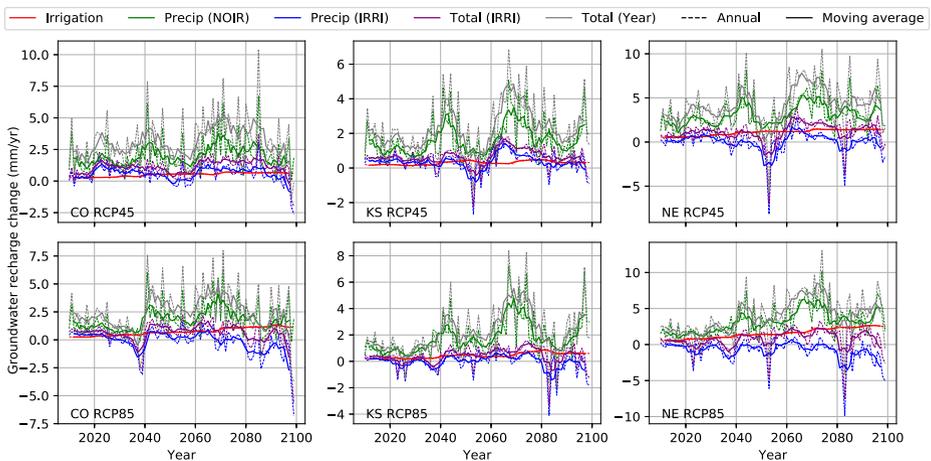
Fig. 5 Ensemble mean of groundwater recharge changes in CO, KS, and NE. The dash and solid lines represent annual values and moving average values, respectively. Irrigation recharge, Precip (NOIR) precipitation recharge in non-irrigation seasons, Precip (IRRI) precipitation recharge in irrigation seasons, Total (IRRI) total recharge in irrigation seasons, Total (Year) total annual recharge
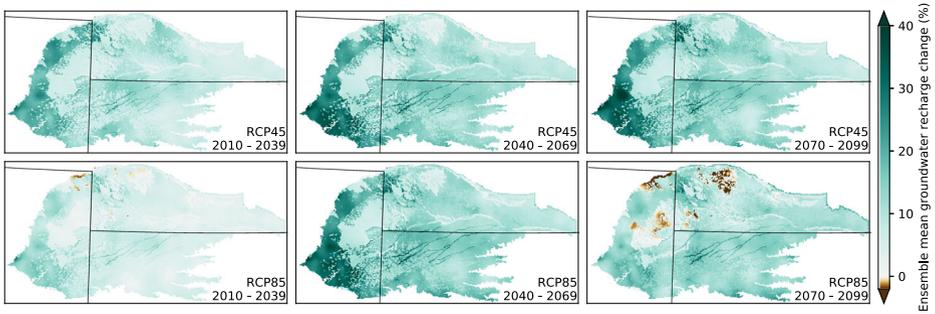
Fig. 6 Distribution of mean recharge changes in the RRB under RCP4.5 and RCP8.5

accretional groundwater level changes due to climate change is consistent with the baseline, and therefore, climate change will intensify groundwater declines in these vulnerable areas in the future. In the northeastern portion of the RRB, the accretional groundwater declines counter the increasing trend in the baseline. Based on the 2099 groundwater levels, climate change impacts counter the increasing trend in the baseline in 2% and 6% of the areas in which it occurs under RCP4.5 and RCP8.5, respectively.

3.5 Change in overall groundwater budgets

Groundwater budget changes are calculated as the budget difference between the simulations of the baseline and RCP4.5 or RCP8.5 (Table 1). Future groundwater budget changes are dominated by consistently increasing groundwater recharge and pumping. Total groundwater recharge is projected to increase. Still, increasing irrigation demands amplify stress on groundwater availability when changes in pumping are greater than changes in recharge. Thus, groundwater storage is reduced, with the exception of 2010–2069 in CO and 2010–2039 in KS and NE under RCP4.5, in which groundwater storage slightly increases. Changes
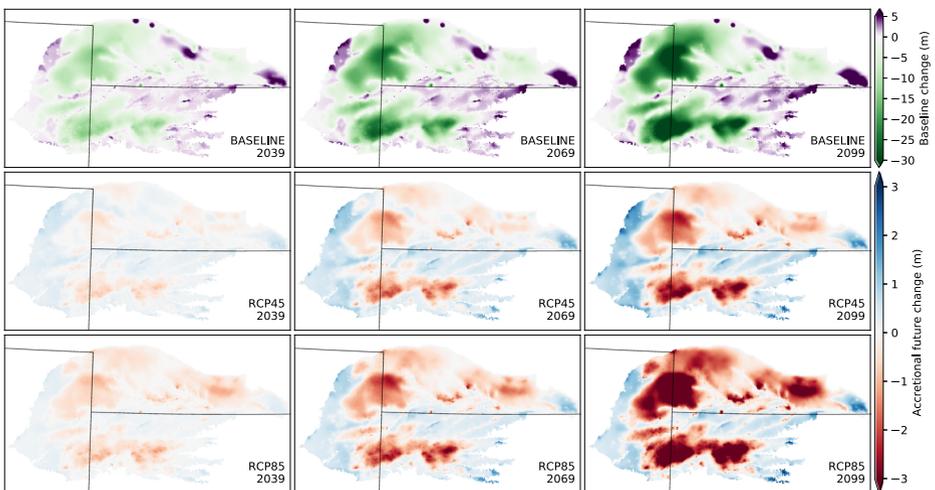
Fig. 7 Ensemble mean of groundwater level changes. Each column represents the end of 2039 (left), 2069 (middle), and 2099 (right). The rows represent the baseline (upper), RCP4.5 (middle), and RCP8.5 (lower)

in other variables in the budget are negligible compared to recharge and pumping, except for the constant-head boundary in NE, which represents the streambed leakage of the Platte River at the north and east model boundary (RRCA 2003). Streambed leakage of the Platte River will partly compensate for the pumping increase in Nebraska. While groundwater ET will increase in CO and KS, it will decrease in NE except for 2010–2039 under RCP4.5. Except for 2010–2039 in NE and 2070–2099 in CO under RCP8.5, baseflows are projected to increase under both the RCP4.5 and RCP8.5 scenarios as a result of groundwater recharge increases in the Republican River Valley. However, increased irrigation withdrawals will reduce baseflows in irrigation seasons. The exchange of groundwater flows among the three states will barely be altered by climate change, suggesting that climate change will not enhance water conflicts between the states. The sensitivity of the groundwater budget shifts among different periods and different scenarios. Investigation of a single variable in isolation may overlook other important impacts. This, again, highlights the importance of investigating the comprehensive water budget instead of a single variable influenced by climate change.

3.6 Adaptation strategies

Our study suggests that groundwater pumping, indirectly influenced by climate, will continue to play a key role for groundwater sustainability under climate change in this region. Despite the increased recharge, groundwater level declines will be exacerbated by climate change. To comply with streamflow obligations, two important augmentation projects, the Colorado Compact Compliance Pipeline (http://www.republicanriver.com/Pipeline/tabid/101/Default.aspx) and Nebraska Cooperative Republican Platte Enhancement (http://www.ncorpe.org/), are currently being implemented. In the future, however, these projects may become less cost-effective or even nonproductive due to the lower groundwater levels. The distribution of

Table 1 Mean annual groundwater budget changes. *STO* groundwater storage, *RCH* recharge, *WEL* groundwater pumping, *EVT* groundwater evapotranspiration, *STR* baseflow, *CHD* constant head, *DRN* drains, *FIN* inflow from adjacent aquifers, *FOT* outflow to adjacent aquifers

RCP	Period	State	Groundwater budget (10^6 m^3)								
			STO	RCH	WEL	EVT	STR	CHD	DRN	FIN	FOT
RCP45	2010–2039	CO	17.2	57.6	38.5	0.5	1.3	0.0	− 0.1	0.0	0.1
		KS	3.8	39.5	28.5	1.6	4.1	− 0.1	− 1.5	0.1	0.1
		NE	1.5	100.4	94.2	1.1	5.5	1.6	0.1	0.2	0.1
	2040–2069	CO	3.3	72.2	66.6	0.6	1.2	0.0	− 0.2	0.0	0.4
		KS	− 2.7	62.2	53.0	1.6	6.9	− 0.1	− 3.2	0.2	0.2
		NE	− 18.8	138.7	164.7	− 1.7	6.0	10.7	0.4	0.6	0.2
	2070–2099	CO	− 6.2	77.5	81.4	1.0	0.4	0.0	− 0.4	0.0	0.6
		KS	− 16.6	61.8	61.9	2.3	8.3	− 0.1	− 5.6	0.3	0.5
		NE	− 34.5	156.2	200.2	− 3.0	8.1	13.3	0.4	1.0	0.2
RCP85	2010–2039	CO	− 13.0	31.2	43.5	0.0	0.6	0.0	− 0.1	0.0	0.1
		KS	− 13.5	24.6	35.1	0.2	1.8	0.0	− 0.9	0.1	0.1
		NE	− 42.7	56.1	111.9	− 3.4	− 0.4	8.9	0.3	0.1	0.0
	2040–2069	CO	− 6.8	78.7	85.0	0.0	0.2	0.0	− 0.2	0.0	0.2
		KS	− 8.0	68.9	66.8	0.8	6.0	− 0.1	− 3.2	0.2	0.2
		NE	− 27.2	156.5	210.5	− 7.2	1.6	20.0	0.6	0.4	0.2
	2070–2099	CO	− 89.2	49.0	140.6	− 1.3	− 1.8	0.1	− 0.2	0.1	0.6
		KS	− 58.1	66.1	110.9	− 0.2	7.3	− 0.1	− 5.9	0.3	0.5
		NE	− 130.3	156.1	341.0	− 17.5	3.1	38.2	1.2	1.1	0.3

groundwater level declines is concentrated in irrigated areas. To mitigate this climate change impact, irrigation water use can be reduced through improved irrigation efficiency. Retiring irrigated acres is also an effective means of reducing water demands, which in fact is the driver of the current shift in irrigated acreage from drier western states to water-abundant southeastern states (National Agricultural Statistics Service 2014). Groundwater recharge is projected to increase consistently in non-irrigation seasons. Banking the winter recharge may help alleviate the water stress in the irrigation seasons (Karimov et al. 2010). Finally, with advancement in genetics, the continued development and adoption of drought-tolerant crops may also help reduce total irrigation demands (Yang et al. 2010).

3.7 Assumptions and limitations

Climate change can impact groundwater via multiple pathways. In this study, we focus on the effects contributed by precipitation and temperature changes. The precipitation-recharge relationship is represented by a number of calibrated curves based on the land use and soil types. It ignores the vadose zone processes and soil water regime—which plays an important role in the land energy and water balances (Seneviratne et al. 2010). Management and farming practices are assumed unchanged so that the irrigation efficiency remains constant in the simulation. Future improved irrigation technologies and practices may increase irrigation efficiency, but those impacts are not incorporated in this study. The effects of precipitation and temperature on crop growth are embedded in the irrigation regression model; however, other consequences of climate change are not considered. For example, heat stress can reduce crop yields (Hawkins et al. 2013). Alternatively, increased CO_2 concentrations may reduce stomatal conductance and increase photosynthesis (Eckhardt and Ulbrich 2003).

4 Conclusions

We investigate the impacts of future climate change on groundwater resources in the RRB, an important agricultural region overlying the High Plains Aquifer. Future precipitation and temperature changes, retrieved from the LOCA downscaled dataset for CMIP5, are used to calculate changes in groundwater pumping and recharge. Projected pumping and recharge are then used in a groundwater flow model to simulate the groundwater responses. The simulation results suggest that in response to climate change: (1) Water stress in the irrigation season will be exaggerated due to increased irrigation water demands; (2) recharge will increase in the non-irrigation season; (3) groundwater levels will decline more in areas with declining trends in the baseline; and (4) baseflow will increase because of increased groundwater recharge in the Republican River Valley. The methodologies and predictions of this study may inform proactive planning and management that increase sustainability and help avoid and resolve conflicts in the RRP and surrounding Great Plains landscapes. Limitations of this study include the lack of representation of the soil water regime and crop physiological responses to other climatic variables. These limitations can be overcome with a physically based model that integrates parameterization of these processes. The improvement of irrigation technology and management practice can also be incorporated into future analyses.

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