Changes in groundwater recharge under projected climate in the Upper Colorado River Basin

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Key Points:

- Flow in the Colorado River and tributaries is sustained by groundwater during low-flow periods
- Mean daily temperature and precipitation are both projected to increase in the UCRB
- Simulated groundwater recharge in the UCRB is projected to be mostly above the historical average through 2099

Abstract

Understanding groundwater-budget components, particularly groundwater recharge, is important to sustainably manage both groundwater and surface-water supplies in the Colorado River Basin now and in the future. This study quantifies projected changes in upper Colorado River basin (UCRB) groundwater recharge from recent historical (1950–2015) through future (2016–2099) time periods, using a distributed-parameter groundwater recharge model with downscaled climate data from 97 Coupled Model Intercomparison Project Phase 5 climate projections. Simulated future groundwater recharge in the UCRB is generally expected to be greater than the historical average in most decades. Increases in groundwater recharge in the UCRB are a consequence of projected increases in precipitation, offsetting reductions in recharge that would result from projected increased temperatures.

1 Introduction

From headwaters in the Rocky Mountains through seven states and Mexico, the Colorado River traverses more than 2200 km to discharge into the Gulf of California (Figure 1a). The Colorado River Basin drains parts of Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, California, and Mexico, and is divided into upper and lower basins at the compact point of Lee Ferry, Arizona, a location 1.6 km downstream of the mouth of the Paria River (*Anderson,* 2004; Figures 1a and 1b). The Colorado River provides water for more than 35 million people in the United States and 3 million people in Mexico (*Bureau of Reclamation,* 2011; *Colorado River Basin Salinity Control Forum,* 2013). The annual discharge of groundwater to rivers and streams (base flow) in the upper Colorado River basin (UCRB) has been estimated at 21–58% of streamflow, with higher percentages during low-flow conditions (*Miller et al.,* 2014). The UCRB is defined for this study as the 293,721 km^2 drainage area upstream of U.S. Geological Survey (USGS) streamflow-gaging station 09380000, Colorado River at Lees Ferry, Arizona (Figure 1b). Major tributaries to the Colorado River in the Upper Basin include the Dolores, Green, Gunnison, San Juan, White, and Yampa Rivers (Figure 1b). Average annual precipitation ranges from less than 250 mm in low-elevation areas to more than 1000 mm in high elevation areas in the Southern Rocky Mountains (*PRISM Climate Group,* 2012; Figure 1c). The UCRB varies in elevation from about 944 m near the Lees Ferry streamgage to more than 4260 m in peaks in the Southern Rocky Mountains in the eastern part of the UCRB (*Liebermann et al.,* 1989). UCRB land cover is predominately shrub/scrub and evergreen forest, with few high-density population centers (*Fry et al.,* 2011; Figure 1d).

Regional aquifers in the UCRB are composed of permeable, moderately to well-consolidated sedimentary rocks ranging in age from Cambrian to Tertiary (*Robson and Banta,* 1995), although groundwater in shallow alluvial deposits may be locally important in some locations in the Southern Rocky Mountains (*Apodaca and Bails,* 2000). At least three groups of regional, productive water-yielding geologic units have been identified in the UCRB (*Robson and Banta,* 1995; *Geldon,* 2003a,b; *Freethey and Cordy,* 1991). Tertiary aquifers of limited extent in the northern and southeastern parts of the basin overlie Mesozoic aquifers that also are present throughout most of the study area. Deeper Paleozoic aquifers are present throughout much of the UCRB and may rise to land surface in uplifted areas. Major aquifers are each partially separated by confining units, and groundwater flows between the aquifers in areas where confining units are missing. Interconnection of the aquifers creates the regional groundwater-flow system (*Geldon,* 2003a,b; *Freethey and Cordy,* 1991).

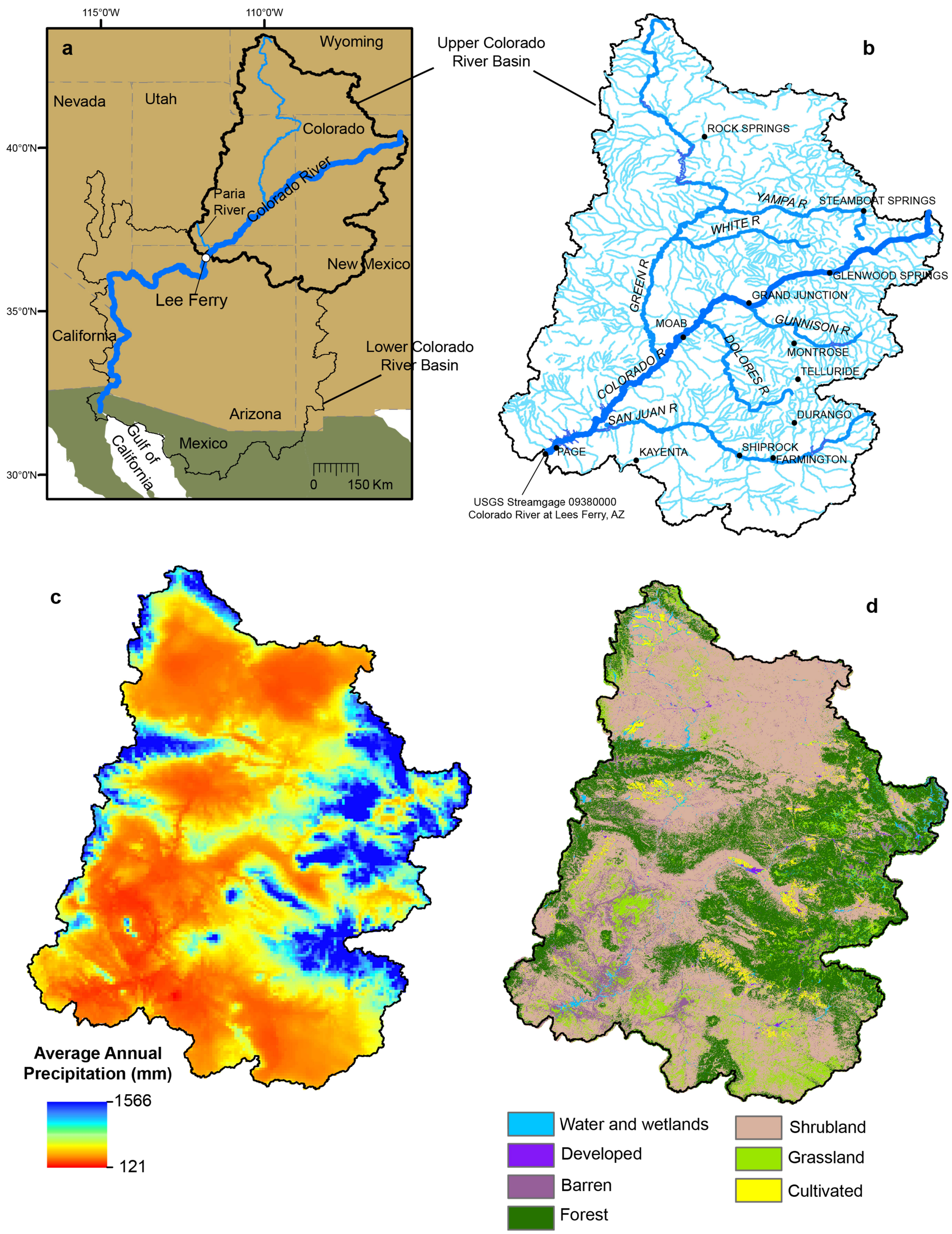

Figure 1. Location of the upper Colorado River basin study area within the southwestern United States (**a**), major tributaries to the Colorado River (**b**), average annual precipitation (**c**; *PRISM Climate Group,* 2012), and major land-cover classifications (**d**; *Fry et al.,* 2011).

Recently, simulations of future hydrologic conditions using downscaled climate data from one or more general circulation models (GCM) and multiple emission scenarios have become an important tool for evaluating potential changes in hydrologic systems (*Holman et al.,* 2012). Studies comparing simulated groundwater recharge in future climates projected by GCMs have been reported for basins in Germany (*Eckhardt and Ulbrich,* 2003), British Columbia (*Allen et al.,* 2010; *Scibeck and Allen,* 2006; *Toews and Allen,* 2009), Australia (*Crosbie et al.,* 2010; *Crosbie et al.,* 2011; *Crosbie et al.,* 2013; *McCallum et al.,* 2010), southern Canada (*Jyrkama and Sykes,* 2007), eastern Canada (*Kurylyk and MacQuarrie,* 2013), Africa (*Mileham et al.,* 2009; *Nyenje and Batelaan,* 2009), England (*Holman et al.,* 2009), and the western United States (*Meixner et al.,* 2016). For this study, the Soil-Water Balance (SWB) distributed-parameter groundwater recharge model (*Westenbroek et al.,* 2010) was used to simulate recharge in historical and future time periods.

2 Methods and Data

2.1 The soil-water balance groundwater recharge model

The SWB model estimates groundwater recharge by direct infiltration by calculating water-balance components at daily time steps for each model cell using a modified version of the Thornthwaite-Mather (*Thornthwaite,* 1948; *Thornthwaite and Mather,* 1957) soil-water-balance approach (see Text S1 in supporting information for model details and limitations). Sources of water in the model include rainfall, snowmelt, and inflow from other model cells. Sinks of water in the model include interception, outflow to other model cells, and evapotranspiration (ET). Groundwater recharge is calculated on a daily basis as the difference between sources and sinks of water, and the change in soil moisture. The SWB groundwater recharge model has been used in several completed and ongoing regional groundwater studies in the U.S. including the High Plains Aquifer (*Stanton et al.,* 2011), the Lake Michigan Basin (*Feinstein et al.,* 2010), basins in Wisconsin (*Dripps and Bradbury,* 2009) and Minnesota (*Smith and Westenbroek,* 2015), and the Northern Atlantic Coastal Plain Aquifer System (*Masterson et al.,* 2013).

2.2 Climate data

Climate data required by the SWB model include daily precipitation, maximum daily temperature, and minimum daily temperature. For UCRB groundwater recharge simulations, simulated climate datasets were available for 97 climate projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model archive (Table S1 in the supporting information). Each of the 97 ensemble members were derived from a General Circulation Model (GCM) run using a given future-emission scenario, known as a Representative Concentration Pathway (RCP), with a unique initial condition. The four RCPs, developed at the request of the Intergovernmental Panel on Climate Change (IPCC), are for radiative forcing levels of 8.5, 6, 4.5, and 2.6 W/m^2 by the end of the century (*Van Vuuren,* 2011). The four RCPs include one very high baseline (no climate policy) emission scenario (RCP8.5), two medium stabilization scenarios (RCP4.5 and RCP6), and one very low forcing level (RCP2.6; *Van Vuuren,* 2011). Since GCMs are typically run at coarse spatial resolutions (e.g., ~100-200 km on a grid side) and at time scales of 100-years or longer, there is a need to post-process GCM-derived variables such as precipitation and temperature to finer spatial scales in order to conduct climate impact assessments. This post-processing step is commonly referred to as downscaling, and there is a continuum of downscaling methods ranging from statistical approaches to physically-based modeling. The 97 projections used in this study were developed using a statistical downscaling method referred to as BCSD (Bias-Correction and Spatial Disaggregation; *Wood et al.,* 2004). The BCSD method was used to develop monthly precipitation and temperature fields at 1/8° × 1/8° (latitude × longitude) spatial resolution from the GCM native-scales. The monthly precipitation and temperature fields were subsequently disaggregated to daily values using a historical resampling and scaling technique (*Wood et al.,* 2002). These daily precipitation and temperature data for the UCRB study area were obtained from the downscaled climate and hydrology projections archive (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html; *Bureau of Reclamation,* 2013).

3 Projected Groundwater Recharge Results

Daily simulated groundwater recharge for the 1950–2099 time period for the UCRB was aggregated into water years (October–September) that were subsequently averaged over 10-year periods, moving every year. The ten-year moving average balances the need to smooth out variability in recharge from individual years, whose effects are integrated over time in groundwater systems (*Green et al.,* 2011), with a desire to provide useful information to water managers over a reasonably short time frame in order to allow for corrective management action. Moving the ten-year average through time by one year eliminates the subjectivity of picking decade start and stop years that may encompass anomalously wet or dry periods. Comparing future and past recharge results over ten-year moving averages addresses the question "how might recharge conditions in any future decade differ from conditions experienced in decades since 1950?"

Simulation results indicate that average annual UCRB groundwater recharge in future decades is more likely to be greater than the 1951–2015 historical average than less than the historical average (Figure 2). The trend of increased recharge in more future time periods than the past is observed in pooled simulation results from all RCP climate data where all scenarios are considered equally likely (Figure 2a), as well as from simulation results that are separated by RCPs (Figures 2b-e) from low future emissions scenarios (RCP2.6) to high (RCP8.5). Comparing median values of simulated annual 10-year averages (Figure 2a), in only 14 out of 75 (19%) future decades of combined-RCP results is recharge expected to be less than the median of historical averages. Results from separate-RCP simulations range from a low of 56% (RCP6.0) to a high of 88% (RCP2.6) of future decades with greater recharge than the historical average (Figures 2b-e). Comparing medians of all future decades with medians of all past decades (Figure 3), the median of future recharge is significantly greater than that of the past for all RCP combinations except RCP6.0 simulations (Mann-Whitney test of medians, one tail, $p<4\times10^{-4}$ for all groups). Moreover, the median of average annual groundwater recharge in 59% of future decades in combined-RCP results exceeds recharge in the 75th percentile of historical decades (Figures 2a and 3a). Even under the maximum emissions scenario (RCP8.5), median average annual recharge in 60% of future decades exceeds the 75th percentile of historical recharge (Figures 2e and 3e). For all decadal results from combined or separate RCP simulations, in only 15 out of 375 (4%) possible future decades is the median of average annual groundwater recharge projected to be less than the 10th percentile of the median of average annual recharge in the historical time period.

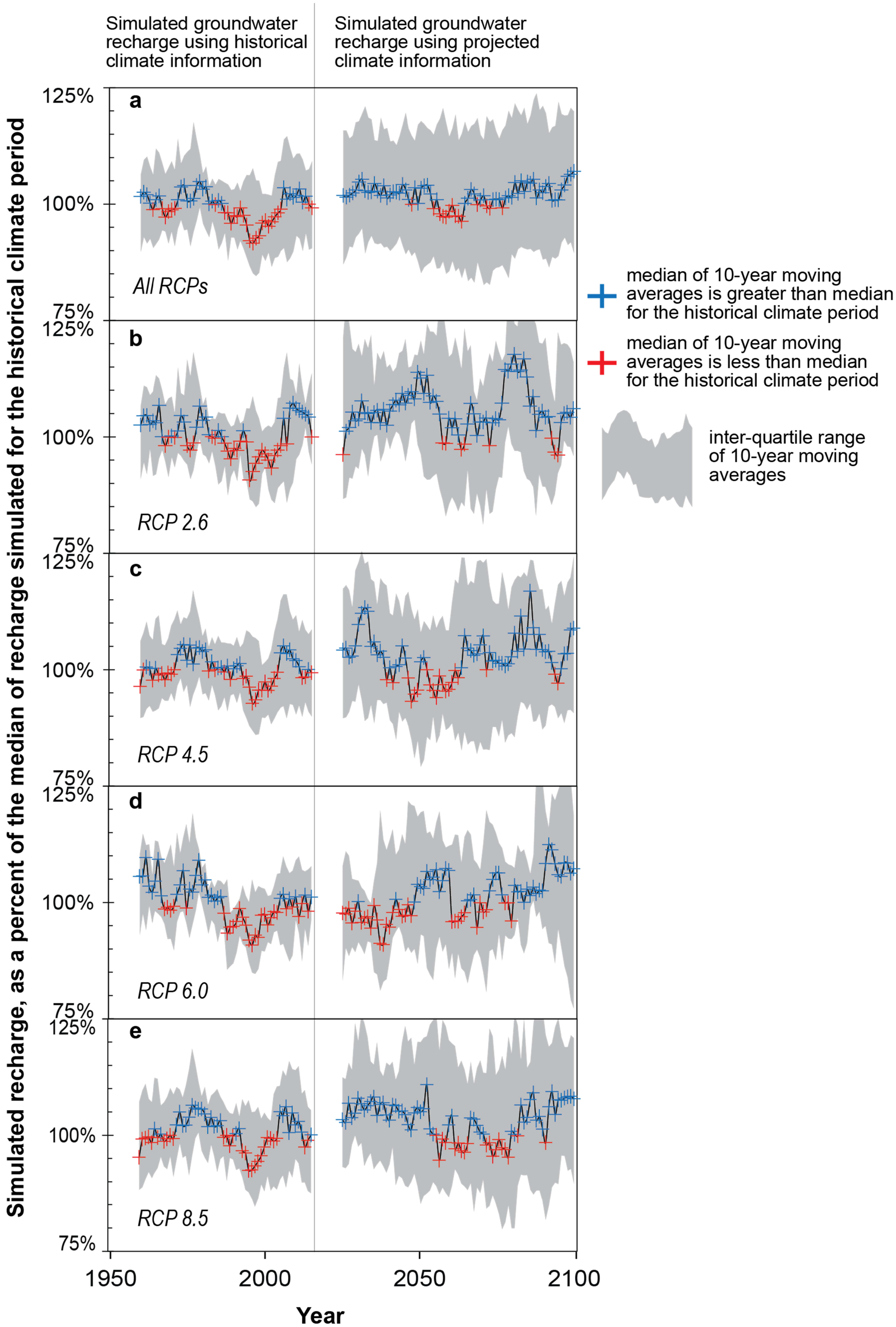

Figure 2. Median of ten-year moving averages of simulated annual groundwater recharge in the upper Colorado River basin for (a) combined RCP recharge results, and (b-e) results grouped by individual RCP. Symbols are placed at the end of the ten-year averaging period.

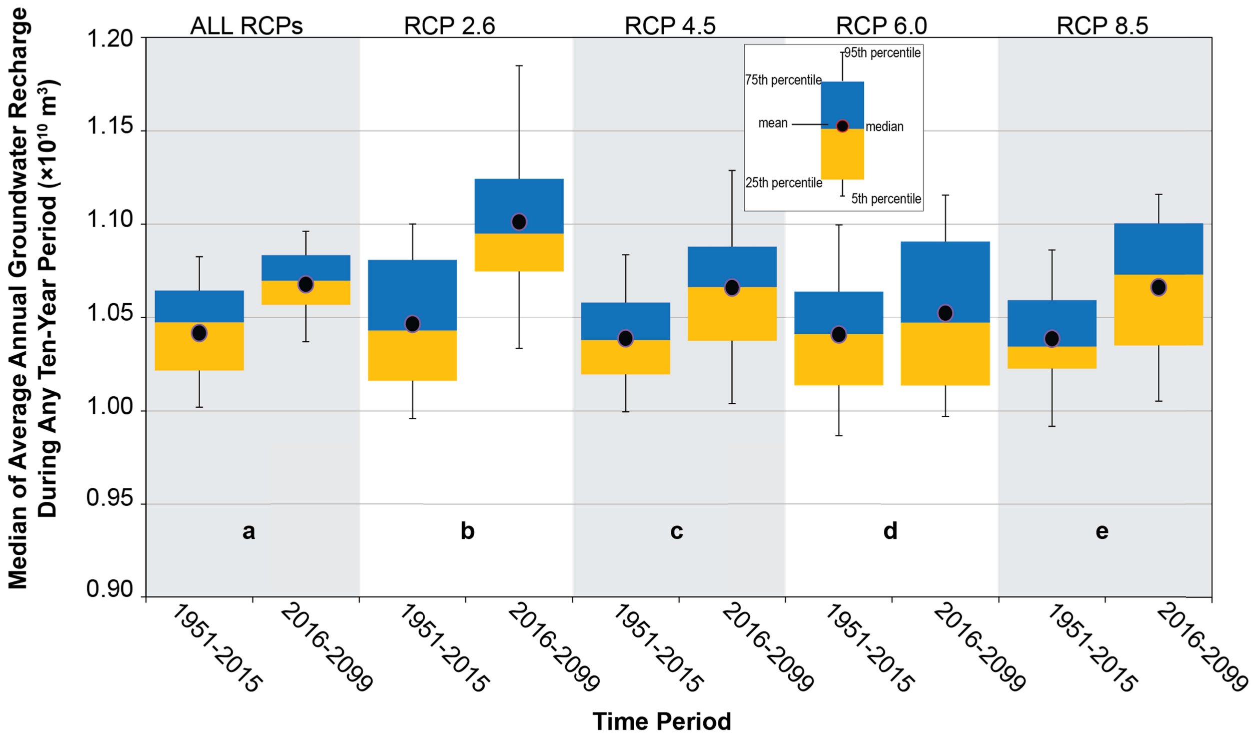

Figure 3. Boxplots showing distribution of median of ten-year moving averages of simulated annual groundwater recharge in the upper Colorado River basin from past (1951–2015) and future (2016–2099) time periods. Results presented for combined RCP simulations (a), and for separate RCP simulations (b-e).

Climate change impacts both the sources and sinks of water in the SWB groundwater recharge equation (see model details in Text S1 in the supporting information). Increasing precipitation, seen in all future decades in the UCRB (Figure S1 in the supporting information) adds additional water to the source term in the SWB water budget, and would result in increased recharge for a given amount of evapotranspiration (ET). Increasing temperatures will result in increasing evapotranspiration (a sink term), which, for a given amount of precipitation, would result in decreased groundwater recharge. The Hargreaves-Samani (*Hargreaves and Samani,* 1985) estimation of potential evapotranspiration (PET), which is used in this study to estimate actual evapotranspiration (AET), is directly related to temperature, and shows substantial increases in future decades in the UCRB for both combined and individual RCP results (Figure S2 in the supporting information). Actual ET (AET; Figure S3 in the supporting information) is the amount of PET that can be satisfied by existing soil moisture, which in the SWB model is a result of today's infiltrating precipitation and yesterday's soil moisture. The limiting role of precipitation and soil moisture on AET can result in increases in temperature (and PET) having a muted impact on groundwater recharge. For example, increasing temperatures during already dry times of the year would not further reduce groundwater recharge in the SWB model. In addition to the magnitude and timing of changing climate parameters, the location also is important. Increasing temperatures in already dry areas of the basin along with increasing precipitation in areas that are not expected to experience higher temperatures would result in an overall increase in basin recharge. Further investigations of temporal sub-basin results are needed to elucidate this process for the UCRB.

Median values of ten-year moving averages were used in this study to indicate the central tendency of projected climate data and groundwater recharge simulation results, with interquartile ranges (IQR) presented to highlight data and simulation variability. Substantial variability is evident in the 97 climate data projections, mostly in projected precipitation (Figure S1 in the supporting information) but also somewhat in projected temperature (Figure S2). This variability in input data is compounded in recharge simulation results (Figure 2). While recharge simulations from a majority of the projected climate datasets result in increased recharge in the UCRB during most future decades, a number of projected climate datasets result in decreased future recharge relative to the historical climate period. Improvements in climate modeling and downscaling techniques will help reduce this uncertainty in projected impacts of climate change on groundwater systems.

4 Conclusions

Increases in future groundwater recharge in the UCRB are a consequence of projected increases in precipitation in future climates offsetting reductions in recharge that result from projected increased temperatures. Median simulated groundwater recharge in future moving ten-year annual averages is projected to be greater than the median of historical averages in 81% of combined RCP simulations, and 88%, 73%, 56%, and 75% of RCP2.6, RCP4.5, RCP6.0, and RCP8.5 simulations, respectively. These results indicate that, given the current understanding of projected climate in the UCRB and the mechanics of the SWB model, groundwater recharge in future climates is not expected to be less than what has been experienced in the recent past and may in fact be somewhat greater.

Acknowledgments and Data

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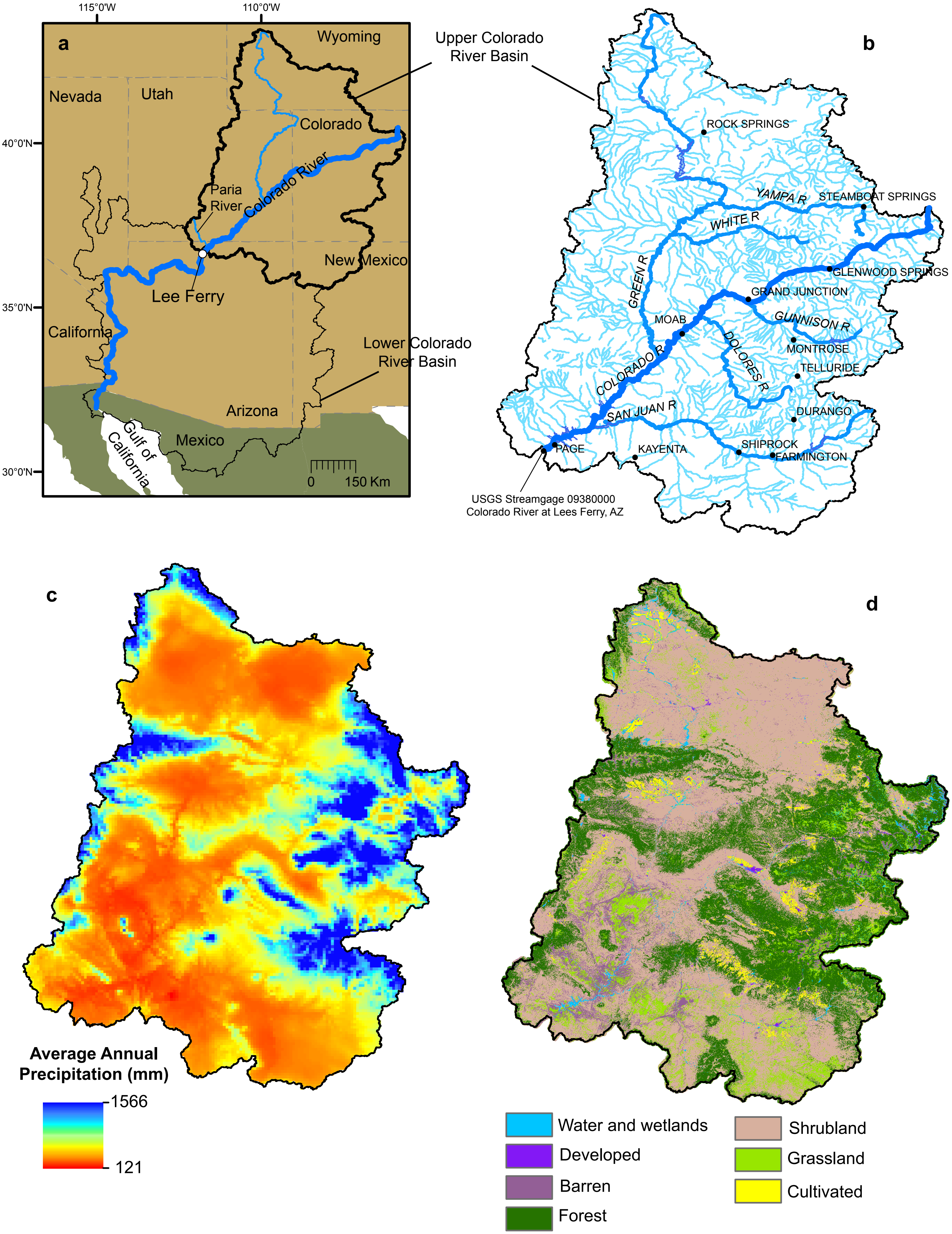
Figure 1. Figure



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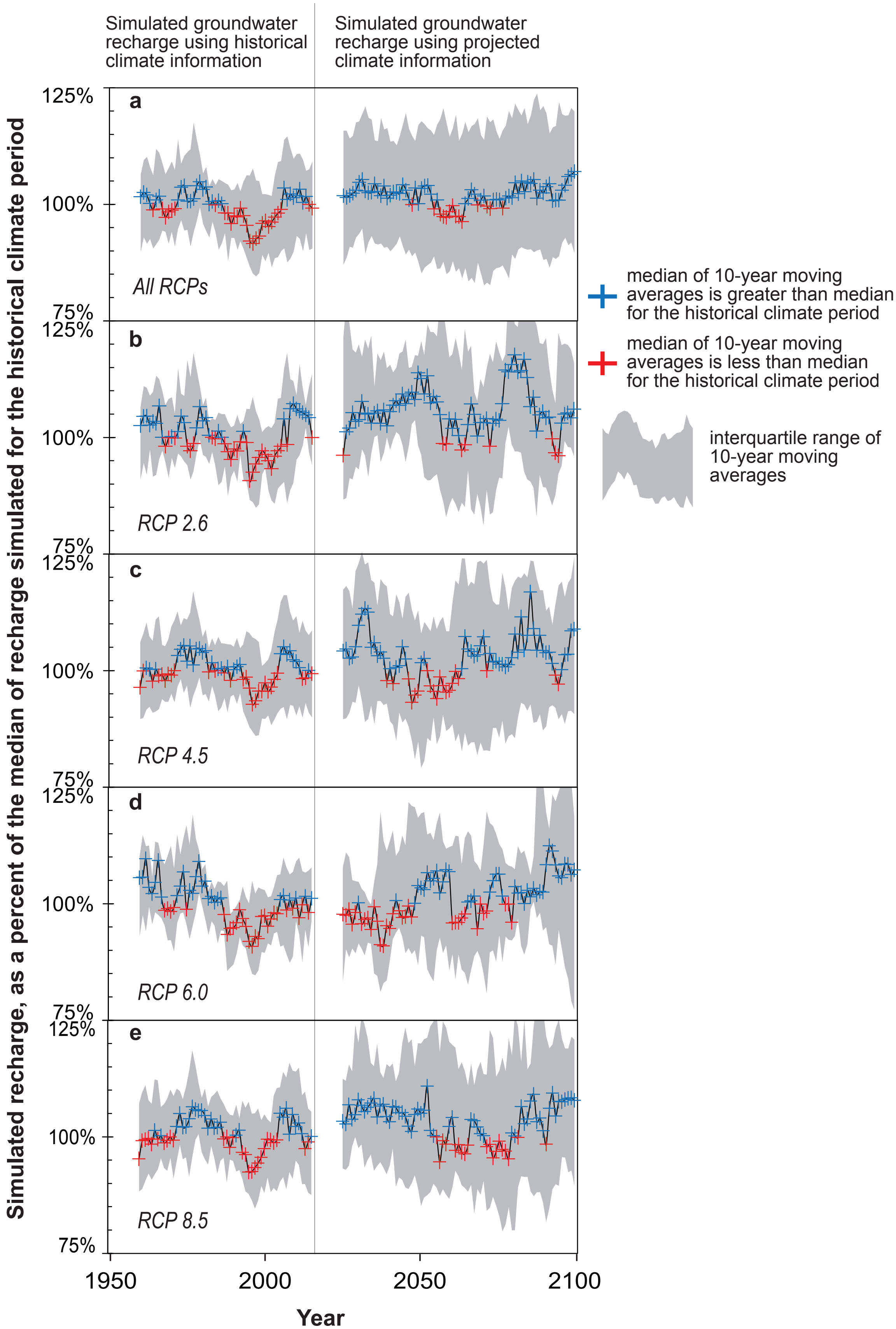
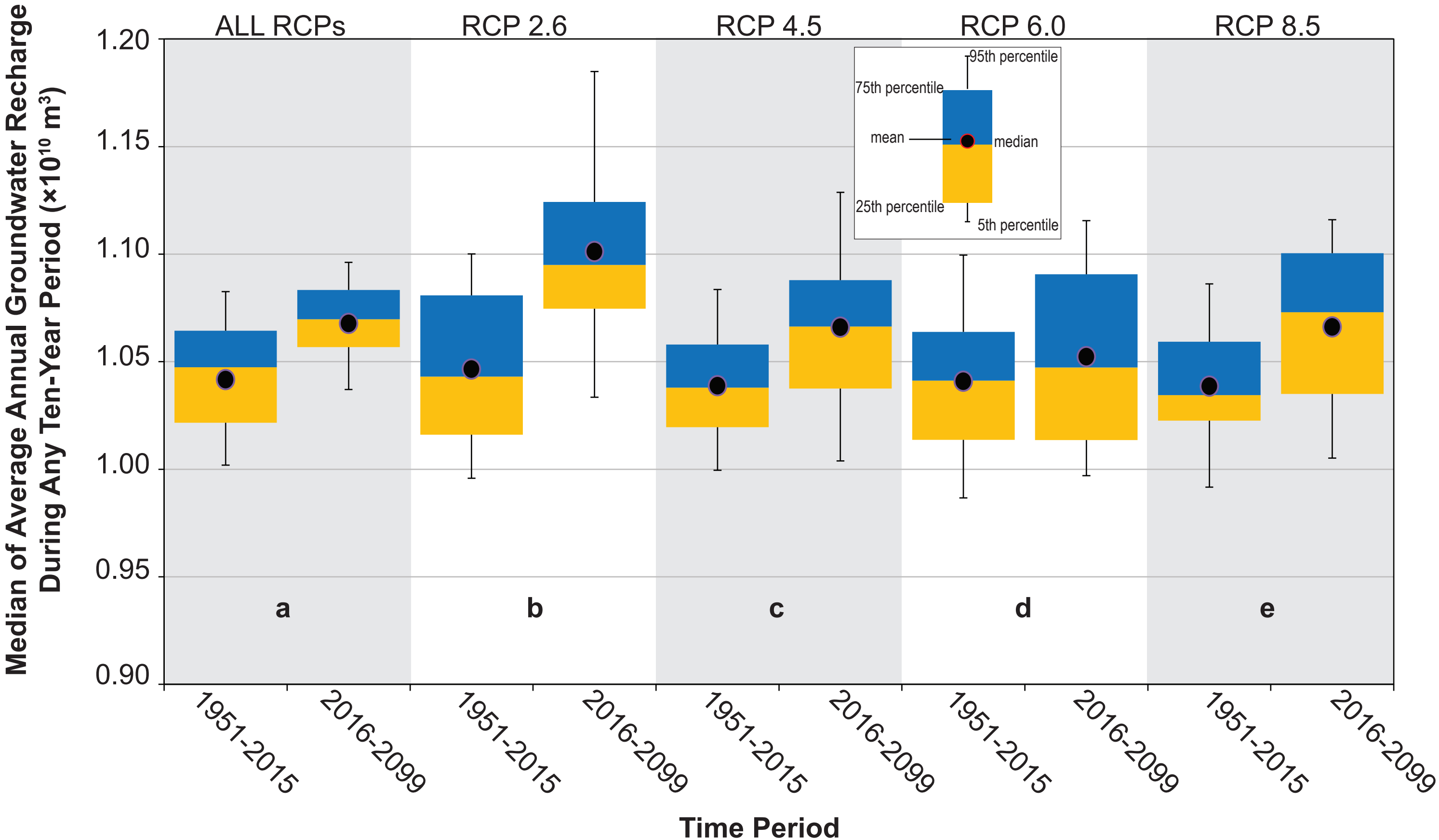
USGS Streamgage 09380000
Colorado River at Lees Ferry, AZ
c
Average Annual Precipitation (mm)
1566
121
d
Water and wetlands
Developed
Barren
Forest
Shrubland
Grassland
Cultivated

Figure 2. Figure



Simulated groundwater recharge using historical climate information
Simulated groundwater recharge using projected climate information
Simulated recharge, as a percent of the median of recharge simulated for the historical climate period
125%
100%
75%
a
All RCPs
b
RCP 2.6
c
RCP 4.5
d
RCP 6.0
e
RCP 8.5
1950
2000
2050
2100
Year
median of 10-year moving averages is greater than median for the historical climate period
median of 10-year moving averages is less than median for the historical climate period
interquartile range of 10-year moving averages

Figure 3. Figure



Median of Average Annual Groundwater Recharge During Any Ten-Year Period (×10^10 m^3)
ALL RCPs
RCP 2.6
RCP 4.5
RCP 6.0
RCP 8.5
1.20
1.15
1.10
1.05
1.00
0.95
0.90
95th percentile
75th percentile
mean
median
25th percentile
5th percentile
a
b
c
d
e
1951-2015
2016-2099
Time Period