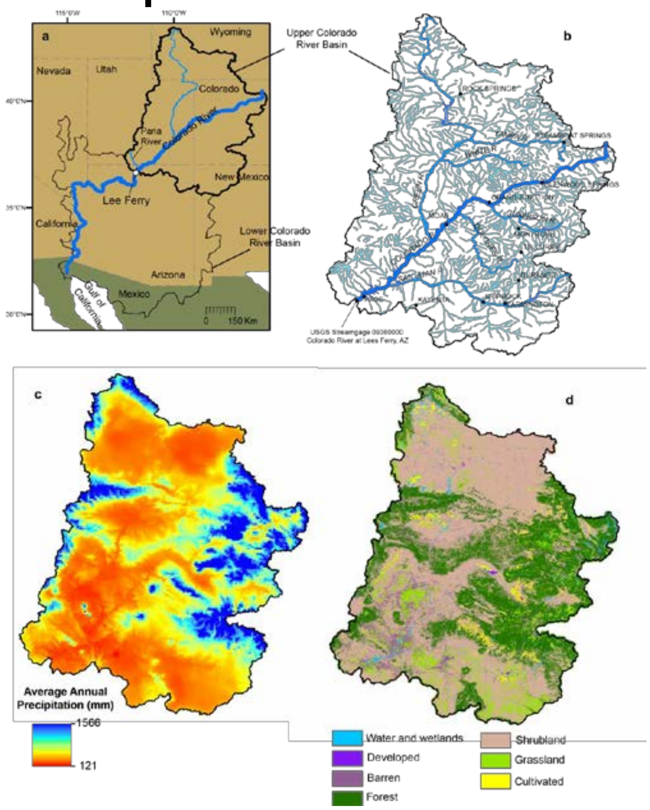
RECLAMATION

Managing Water in the West

Soil-Water-Balance Recharge Estimates for the Upper Colorado River Basin under Climate Change

Research and Development Office
Science and Technology Program
Final Report ST-2016-2005-01



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Figure on cover page: 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).

<table>
<tr><td colspan="3">REPORT DOCUMENTATION PAGE</td><td>Form Approved
OMB No. 0704-0188</td></tr>
<tr><td>T1. REPORT DATE
September 2016</td><td colspan="2">T2. REPORT TYPE
Research</td><td>T3. DATES COVERED
04/02/2015 – 09/30/2016</td></tr>
<tr><td colspan="3" rowspan="3">T4. TITLE AND SUBTITLE
Soil-Water-Balance Recharge Estimates for the Upper Colorado River Basin under Climate Change Final Report</td><td>5a. CONTRACT NUMBER:
R15PG00045</td></tr>
<tr><td>5b. GRANT NUMBER</td></tr>
<tr><td>5c. PROGRAM ELEMENT NUMBER
1541 (S&T)</td></tr>
<tr><td colspan="3" rowspan="3">6. AUTHOR(S)
Corresponding author: Fred Tillman (ftillman@usgs.gov).
Reclamation authors: Subhrendu Gangopadhyay and Tom Pruitt</td><td>5d. PROJECT NUMBER: 2005</td></tr>
<tr><td>5e. TASK NUMBER</td></tr>
<tr><td>5f. WORK UNIT NUMBER: 86-68210</td></tr>
<tr><td colspan="3">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Geological Survey, Arizona Water Science Center, 520 N. Park Ave, Suite 221 , Tucson, Arizona, 85719 USA
Reclamation, Technical Service Center, Water Resources Planning and Operations Support Group, Denver Federal Center, Building 67, Denver, Colorado, 80225 USA</td><td>8. PERFORMING ORGANIZATION REPORT NUMBER
NA</td></tr>
<tr><td colspan="3" rowspan="2">9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Research and Development Office
U.S. Department of the Interior, Bureau of Reclamation,
PO Box 25007, Denver Colorado, 80225-0007</td><td>10. SPONSOR/MONITOR'S ACRONYMS
R&D: Research and Development Office
BOR/USBR: Bureau of Reclamation
DOI: Department of the Interior</td></tr>
<tr><td>11. SPONSOR/MONITOR'S REPORT NUMBER: ST-2016-2005-01</td></tr>
<tr><td colspan="4">12. DISTRIBUTION / AVAILABILITY STATEMENT
Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/.</td></tr>
<tr><td colspan="4">13. SUPPLEMENTARY NOTES</td></tr>
<tr><td colspan="4">14. ABSTRACT
Groundwater recharge in the Upper Colorado River Basin was simulated to better understand potential changes in the groundwater system in response to projected climate change. Groundwater recharge is expected to be somewhat greater than in the recent past, as a result of projected increases in precipitation.</td></tr>
<tr><td colspan="4">15. SUBJECT TERMS: climate change, groundwater recharge, Upper Colorado River Basin, modeling</td></tr>
</table>

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<tr><td colspan="3">16. SECURITY CLASSIFICATION OF:</td><td rowspan="2">17. LIMITATION OF ABSTRACT
U</td><td rowspan="2">18. NUMBER OF PAGES:
43</td><td>19a. NAME OF RESPONSIBLE PERSON:
Subhrendu Gangopadhyay</td></tr>
<tr><td>a. REPORT
U</td><td>b. ABSTRACT
U</td><td>c. THIS PAGE
U</td><td>19b. TELEPHONE NUMBER
303-445-2465</td></tr>
</table>

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

Research and Development Office
Science and Technology Program

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name Soil-Water-Balance Recharge Estimates for the Upper Colorado River Basin under Climate Change WOID Z2005

Document Final Report

Document Author(s) Fred Tillman, Subhrendu Gangopadhyay, and Tom Pruitt Document date September, 2016

Peer Reviewer Multiple peer reviewers - USGS internal peer review, anonymous peer reviewers from the American Geophysical Union publication, Geophysical Research Letters.

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Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewed through USGS peer-rev

Reviewer Sharon K. Taylor
(Signature)

Date reviewed 9/8/16

Acknowledgements and Data

Investigation of groundwater recharge in the upper Colorado River basin under climate change was supported by the Bureau of Reclamation (Reclamation) Science and Technology Program and the U.S. Geological Survey Science (USGS) Groundwater Resources Program. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for the Coupled Model Intercomparison Project (CMIP), and we thank the climate modeling groups (listed in Table S1 in the supporting information of Tillman et al., 2016) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. Soil-water balance groundwater recharge modeling results for the upper Colorado River basin are available at the USGS ScienceBase web site (Tillman, 2016).

Acronyms and Abbreviations

AET	actual evapotranspiration
BCSD	Bias-Correction and Spatial Disaggregation
CMIP5	Coupled Model Intercomparison Project phase 5
ET	evapotranspiration
GCM	general circulation models
IPCC	Intergovernmental Panel on Climate Change
IQR	interquartile ranges
PET	potential evapotranspiration
RCP	Representative Concentration Pathway
Reclamation	Bureau of Reclamation
SWB	soil-water balance
UCRB	Upper Colorado River basin
USGS	U.S. Geological Survey

Executive Summary

Problem: Understanding groundwater-budget components, particularly groundwater recharge, is important to sustainably manage both groundwater and surface-water supplies in the upper Colorado River basin now and in the future.

Approach and Method: To better understand potential changes in the groundwater system in response to projected climate change, the Science and Technology Program research project simulated groundwater recharge in the upper Colorado River basin. This study quantifies projected changes in groundwater recharge from recent historical (1950– 2015) through future (2016–2099) time periods. The study used a distributed-parameter groundwater recharge model with downscaled climate data from 97 Coupled Model Intercomparison Project Phase 5 climate projections.

Results: Simulated future groundwater recharge in the upper Colorado River basin is generally expected to be slightly greater than the historical average in most decades. Increases in groundwater recharge in the upper Colorado River basin are a consequence of projected increases in precipitation, offsetting reductions in recharge that would result from projected increased temperatures.

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Main Report

Problem

The Colorado River traverses more than 2,200 kilometers from its Rocky Mountain headwaters through seven states and Mexico to discharge into the Gulf of California. The Colorado River and its tributaries are vital to the U.S. and to Mexico, generating billions of dollars a year in agricultural and economic benefits and provide habitat for a wide range of species.

The upper Colorado River basin is a drainage area of 293,721 square kilometers upstream of Lees Ferry, Arizona. The annual discharge of groundwater to rivers and streams (base flow) in the upper Colorado River basin has been estimated at 21–58% of the streamflow to the river, with higher percentages during low-flow conditions (Miller et al., 2014).

Understanding groundwater-budget components, particularly groundwater recharge, is important to sustainably manage both groundwater and surface-water supplies in the upper Colorado River basin now and in the future. 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).

Solution and Application

This Science and Technology Program research project quantified projected changes in groundwater recharge from recent historical (1950– 2015) through future (2016–2099) time periods in the upper Colorado River basin. To simulate recharge in historical and future time periods, the study used a soil-water balance distributed-parameter groundwater recharge model (Westenbroek et al., 2010) with downscaled climate data from 97 Coupled Model Intercomparison Project Phase 5 climate projections. The model used climate data, including daily precipitation, maximum daily temperature, and minimum daily temperature. These daily precipitation and temperature data for this study area were obtained from the downscaled climate and hydrology projections archive (Reclamation, 2013; http://gdo.dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html).

The soil-water balance groundwater recharge 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. 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.

Application and Results

Given the current understanding of projected climate in the upper Colorado River basin and the mechanics of the soil-water balance recharge model, study results indicate that groundwater recharge in future climates may in fact be somewhat greater than what has been experienced in the recent past and is not expected to be less. Increases in groundwater recharge in the upper Colorado River basin are a consequence of projected increases in precipitation, offsetting reductions in recharge that would 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 (Figure 1).

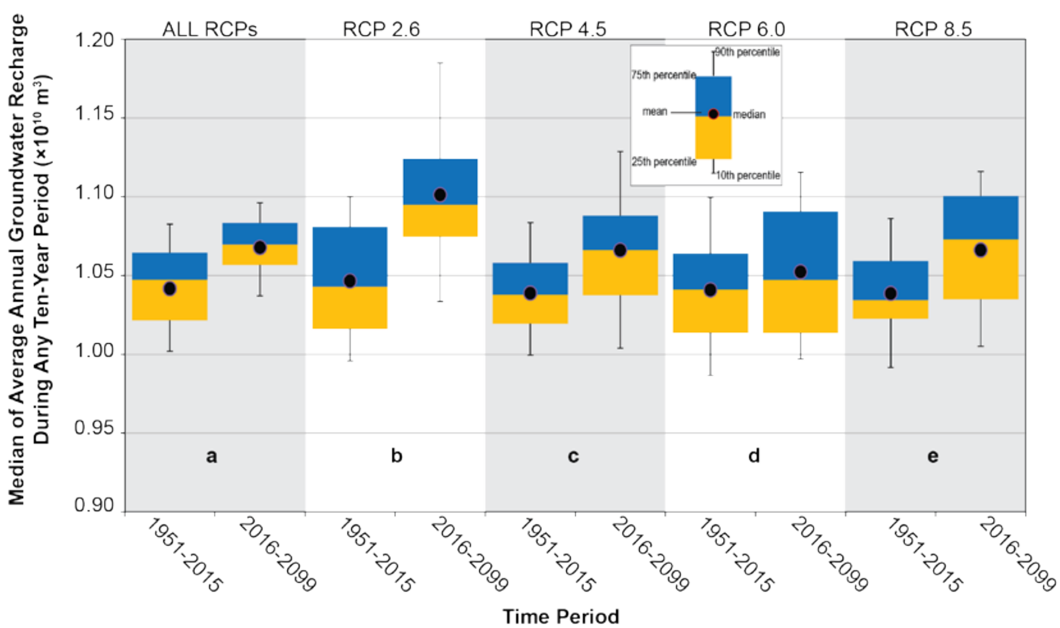

Figure 1.—Boxplots showing distribution of median of ten-year moving averages of simulated annual groundwater recharge in the Upper Colorado River basin from past (1951–2015) and future (2016–2099) time periods. Results presented for combined RCP simulations (a), and for separate RCP simulations (b-e).

Future Plans

This research method and results will help to inform future research activities with Reclamation, USGS, and other partners and stakeholders in the upper Colorado River basin. Improvements in climate modeling and downscaling techniques could help reduce uncertainty and refine projections for groundwater at smaller time-scales and locations.

Investigations of temporal sub-basin results are needed to further understand the relationship between magnitude and timing of changing climate parameters. For example, increasing temperatures during already dry times of the year would not further reduce groundwater recharge in the soil-water balance model. Location also is important. Increasing temperatures in already dry areas of the basin coupled with increasing precipitation in areas that are not expected to experience higher temperatures would result in an overall increase in basin recharge.

Further investigations to reduce uncertainty stemming from the substantial variability in projected impacts of climate change on groundwater systems are also recommended. Substantial variability is evident in the 97 climate data projections, mostly in projected precipitation—but also somewhat in projected temperature. This variability in input data is compounded in recharge simulation results. 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.

Further Information

See accepted journal paper, cited as:

Tillman, F. D, S. Gangopadhyay, and T. Pruitt, 2016. Changes in groundwater recharge under projected climate in the upper Colorado River basin. Geophysical Research Letters, 43, 6968–6974, doi:10.1002/2016GL069714.

Author submitted copy to the journal Geophysical Research Letters is attached as Appendix A per S&T Closeout Requirement element 5b. For all copyright questions related to this report and paper, please contact the Reclamation Research and Development Office, and American Geophysical Union (AGU) Publications.

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Westenbroek, S.M., V.A. Kelson, R.J. Hunt, and K.R. Bradbury (2010), SWB – A modified Thornthwaite-Mather soil-water balance code for estimating groundwater recharge, U.S. Geol. Surv. Techniques and Methods 6–A31, 60 p., http://pubs.usgs.gov/tm/tm6- a31/.

Data Sets that Support the Final Report

This USGS Data Release represents Soil-Water Balance (SWB) groundwater recharge modeling results for the Upper Colorado River Basin (UCRB). The data release was produced in compliance with 'open data' requirements as way to make the scientific products associated with USGS research efforts and publications available to the public. There are three separate datasets associated with this Data Release:

1. SWB model results from simulations run using observed climate data, summarized by water year from 1951 through 2010.
2. SWB model results from simulations run using projected climate data, summarized by month and UCRB sub-basin from 1950 through 2099.
3. SWB model results from simulations run using projected climate data, summarized by water year from 1951 through 2099.

Contacts

Originator : Fred D Tillman, U.S. Geological Survey, Arizona Water Science Center

Publisher : U.S. Geological Survey– ScienceBase, https://www.sciencebase.gov/catalog/

Tillman, F.D., 2016, Soil-Water Balance Groundwater Recharge Model Results for the Upper Colorado River Basin: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7ST7MX7.

Appendix A

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

Soil-Water-Balance Recharge Estimates for the Upper Colorado River Basin under Climate Change

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).

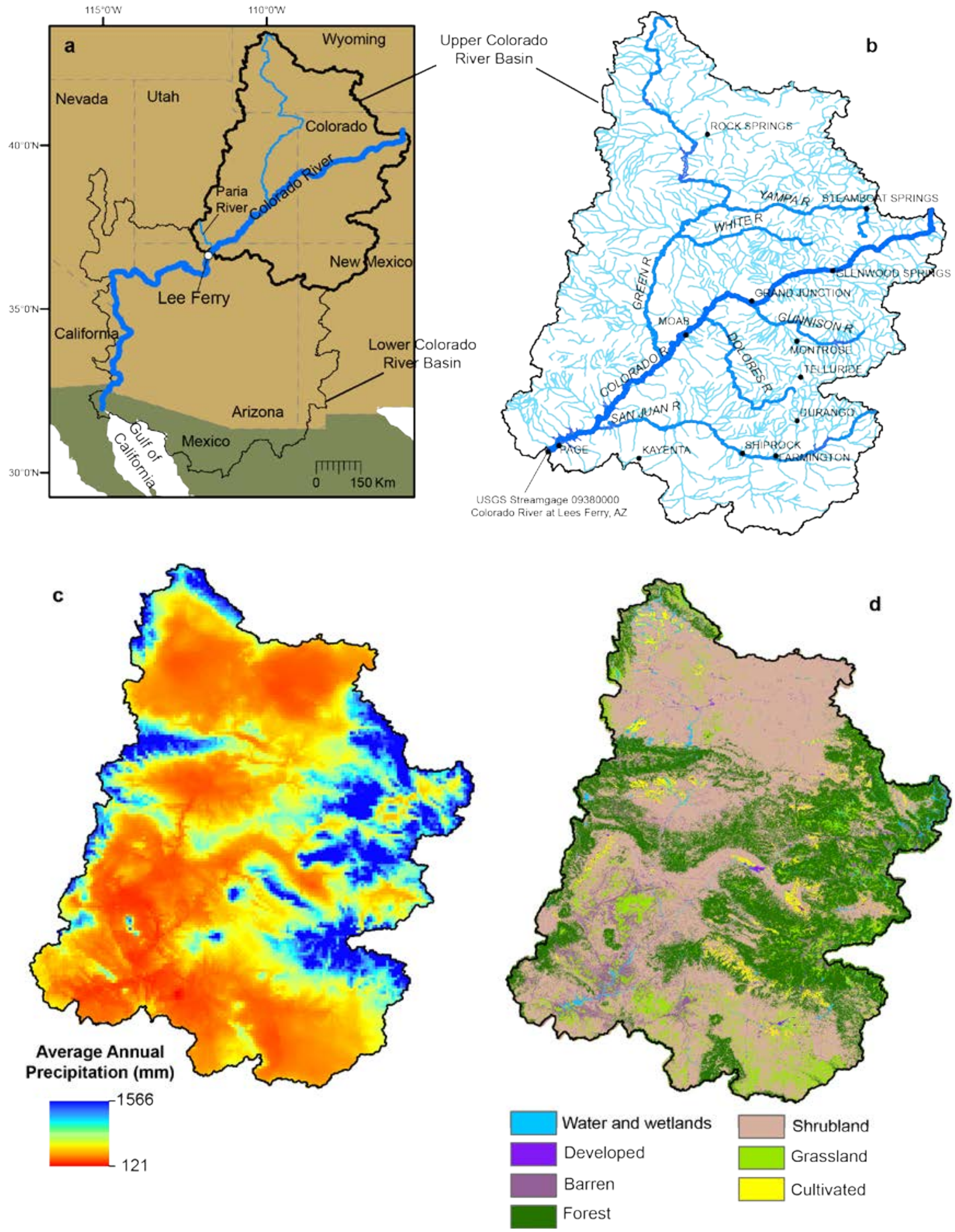

Figure 1. Location of the upper Colorado River basin study area within the southwestern United States (**a**), major tributaries to the Colorado River (**b**), average annual precipitation (**c**; *PRISM Climate Group*, 2012), and major land-cover classifications (**d**; *Fry et al.*, 2011).

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.

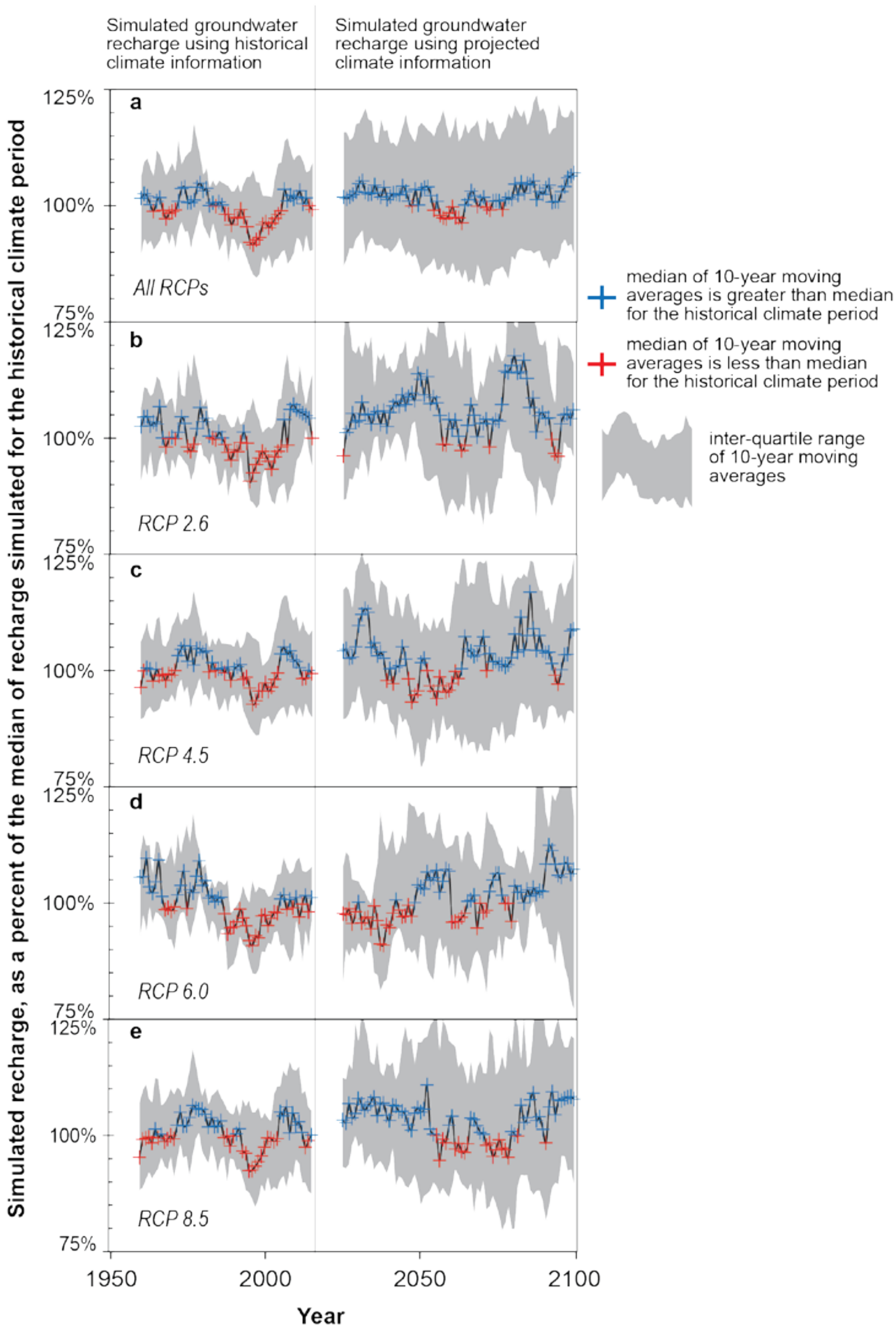

Figure 2. Median of ten-year moving averages of simulated annual groundwater recharge in the upper Colorado River basin for (a) combined RCP recharge results, and (b-e) results grouped by individual RCP. Symbols are placed at the end of the ten-year averaging period.

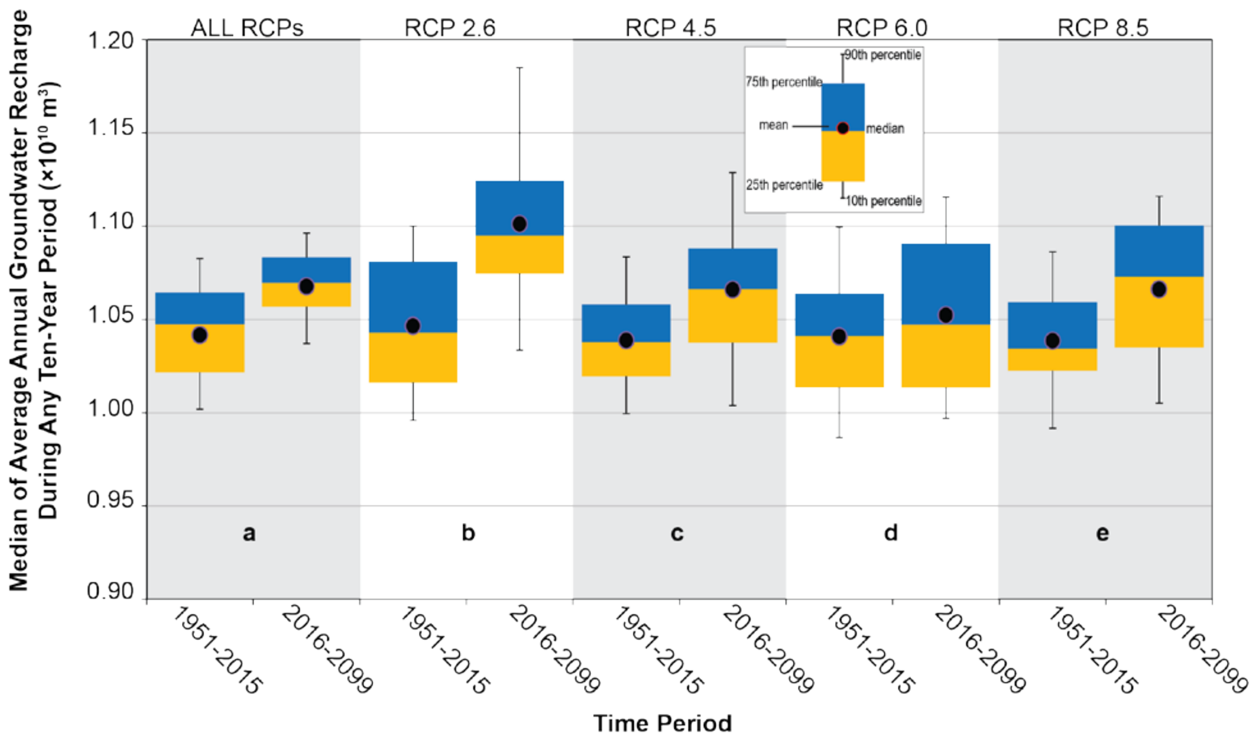

Figure 3. Boxplots showing distribution of median of ten-year moving averages of simulated annual groundwater recharge in the upper Colorado River basin from past (1951–2015) and future (2016–2099) time periods. Results presented for combined RCP simulations (a), and for separate RCP simulations (b-e).

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

Investigation of groundwater recharge in the upper Colorado River basin under climate change was supported by the Bureau of Reclamation Science and Technology Program and the USGS Groundwater Resources Program. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for the Coupled Model Intercomparison Project (CMIP), and we thank the climate modeling groups (listed in Table S1 in

the supporting information) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. SWB groundwater recharge modeling results for the UCRB are available at the USGS ScienceBase web site (*Tillman,* 2016).

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Supporting Information for

Changes in groundwater recharge under projected climate in the upper Colorado River basin

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Contents of this file

Introduction

The following supporting information includes computational details on the Soil-Water Balance (SWB) groundwater recharge model (Text S1); additional SWB output from upper Colorado River basin simulations including precipitation (Figure S1), potential evapotranspiration (Figure S2), and actual evapotranspiration (Figure S3); and a table of multi-model ensembles and institutions providing model output used in this investigation (Table S1).

Text S1.

The Soil-Water-Balance (SWB) computer code (*Westenbroek et al.*, 2010) estimates spatial and temporal variations in groundwater recharge by calculating water balance components at daily time steps. SWB follows a modified Thornthwaite-Mather soil-water-balance accounting approach (*Thornthwaite,* 1948; *Thornthwaite and Mather,* 1957) and recharge is estimated separately for each grid cell within the model domain. Sources and sinks of water within each grid cell are estimated based on climate data and landscape characteristics, and recharge is then estimated as the difference between the change in soil moisture and these sources and sinks:

$$\underbrace{(\text{rainfall} + \text{snowmelt} + \text{inflow})}_{\text{water sources}} - \underbrace{(\text{interception} + \text{outflow} + \text{AET})}_{\text{water sinks}} - \Delta\ \text{soil moisture} = \text{RECHARGE} \qquad (1)$$

Spatially gridded datasets required for SWB simulations include land cover, overland flow direction, hydrologic soil group, available soil-water capacity, daily precipitation, daily maximum temperature, and daily minimum temperature. Tabular information required by SWB include runoff curve numbers, vegetation rooting depths, interception values, and maximum daily recharge values for each combination of hydrologic soil group and land-cover type. Inflow to a cell is surface flow from adjacent cells, calculated using the National Resources Conservation Service (NRCS) curve number rainfall-runoff relation. The direction of runoff from cell to cell is determined using a flow-direction grid derived from a digital-elevation model (DEM). Interception is a user-specified amount of precipitation that is trapped and used by vegetation. Outflow from a cell is calculated in the same manner as inflow to the cell. There are several methods available for estimating potential evapotranspiration (PET) in the SWB model, from which actual evapotranspiration (AET) is calculated. For the UCRB simulations, the Hargreaves-Samani (*Hargreaves and Samani*, 1985) method is used as it produces spatially variable estimates of potential ET (PET) from spatially varying minimum and maximum air temperature data for each daily time step:

$$\text{PET} = 0.0135 \times \text{RS} \times (\text{T}+17.8) \ \text{ with RS} = \text{KRS} \times \text{RA} \times \text{TD}^{0.5} \qquad (2)$$

where PET is potential ET, RS is incoming solar radiation, T is mean air temperature in °C, KRS is a calibration coefficient, RA is extraterrestrial radiation, and TD is the measured air temperature range (*Hargreaves and Samani,* 1985). Extraterrestrial radiation is estimated as a function of the day of year and latitude (*Allen et al.,* 1998). The computation of soil moisture in equation 1 requires several intermediary values. First, PET is subtracted from precipitation (P) for all grid cells. If P – PET is negative (i.e., if $P < PET$), then there is a potential deficiency of water. Accumulated Potential Water Loss (APWL) is computed as the running sum of daily P – PET values during times when $P < PET$. Soil moisture is estimated using the current AWPL value in the Thornthwaite-Mather relation that describes the nonlinear relation between soil moisture and APWL. Actual ET (AET) is then equal to only the amount of water that can be extracted from the soil. If P – PET is positive (i.e., if $P > PET$), a potential surplus of water exists and AET is equal to PET. Soil moisture is calculated by adding P – PET directly to the previous day's soil-moisture value. If the new soil moisture value is less than the maximum water-holding capacity of the soil (calculated as the product of the available soil water capacity and the root-zone depth), then the Thornthwaite-Mather relation is used to back-calculate a reduced APWL. If the new soil moisture value is greater than the maximum water-holding capacity of the soil, then soil moisture is capped at the maximum water-holding capacity, excess soil-moisture becomes recharge, and AWPL is set to zero.

All spatially gridded input datasets were resampled to the same cell size and geographic coordinate system as the 1/8th degree CMIP5 climate data. Detailed descriptions of the sources, manipulation, and resampling of SWB model inputs for UCRB recharge simulations are provided in *Tillman* (2015).

Climate changes are expressed in SWB simulated recharge results (equation 1) through the computation of AET (mean temperature) and through precipitation input. The SWB model does not include changes in land use over time or simulate changes in stomatal conductance or leaf area in a CO_2 enriched atmosphere (*Holman et al.,* 2015; *Eckhardt and Ulbrich,* 2003). Only direct impacts of climate change are evaluated in SWB recharge results.

While the SWB model has been shown to provide reasonable basin-scale estimates of groundwater recharge, SWB limitations and assumptions should be considered when evaluating simulation results (*Westenbroek et al.*, 2010). The daily time step of the SWB model allows short-term surpluses of water to become recharge, but also necessitates that overland-flow routing of runoff either infiltrate in cells downslope or be routed out of the model domain on the same day in which it originated. Depth to the top of the aquifer surface also is not considered in SWB, and there may be significant time of travel through the unsaturated zone. Use of the NRCS curve number method to estimate runoff in SWB introduces limitations, including that the method was developed to evaluate floods and was not designed to simulate daily flows of ordinary magnitude, and studies that show that the curve number is not constant but may vary from event to event (*Westenbroek et al.,* 2010). Finally, there are numerous methods for estimating groundwater discharge by evapotranspiration, each with its own benefits, limitations, uncertainties, and data requirements. This study uses the Hargreaves-Samani (*Hargreaves and Samani,* 1985) method for PET, in which climate changes are reflected only in the daily air temperature range. More complex ET relations require additional data including relative humidity, wind speed, and percentage of actual to possible daily sunshine hours, among others (*Westenbroek et al.,* 2010).

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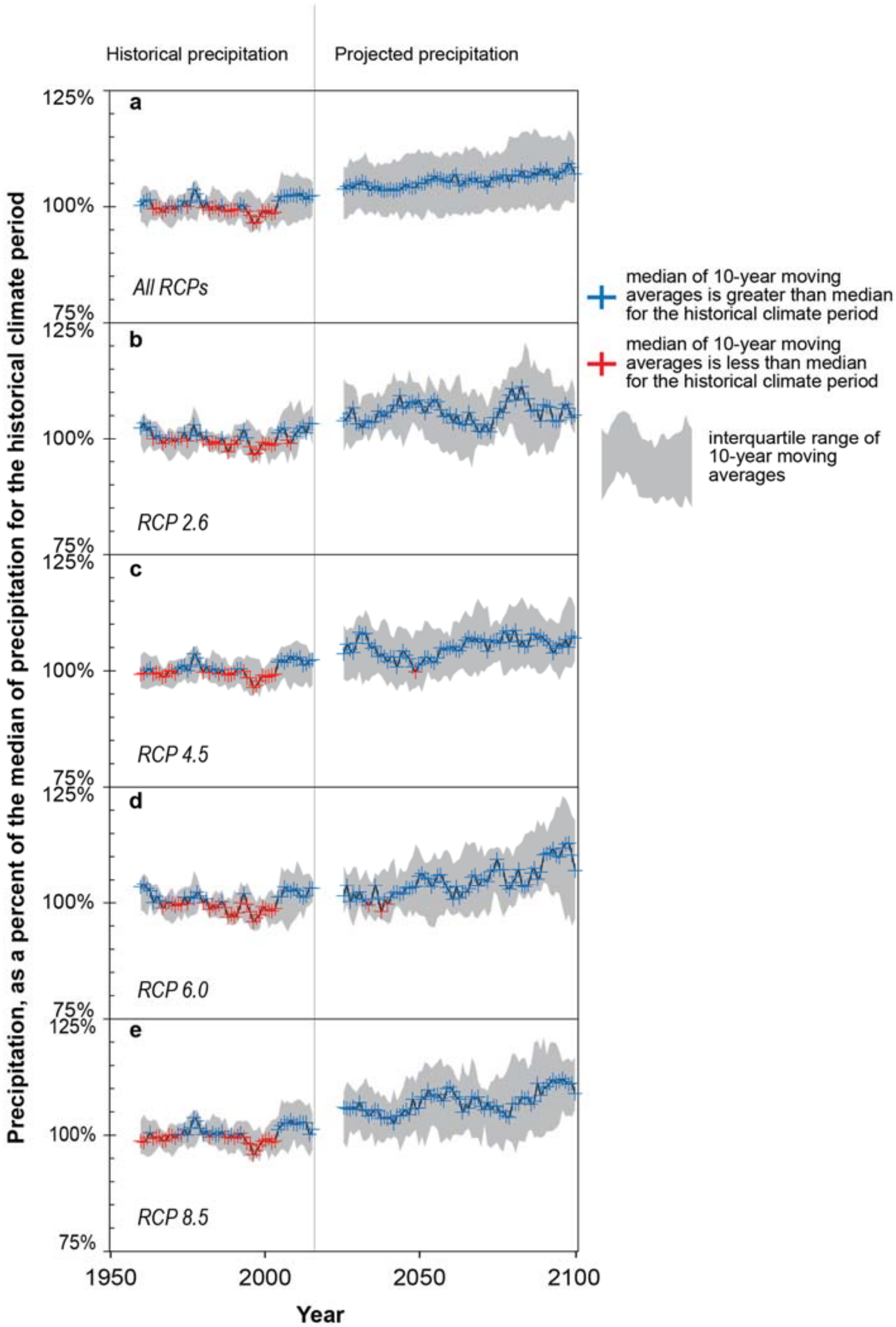

Figure S1. Median of ten-year moving averages of annual precipitation in the upper Colorado River basin for (a) combined RCP results, and (b-e) results grouped by individual RCP. Symbols are placed at the end of the ten-year averaging period.

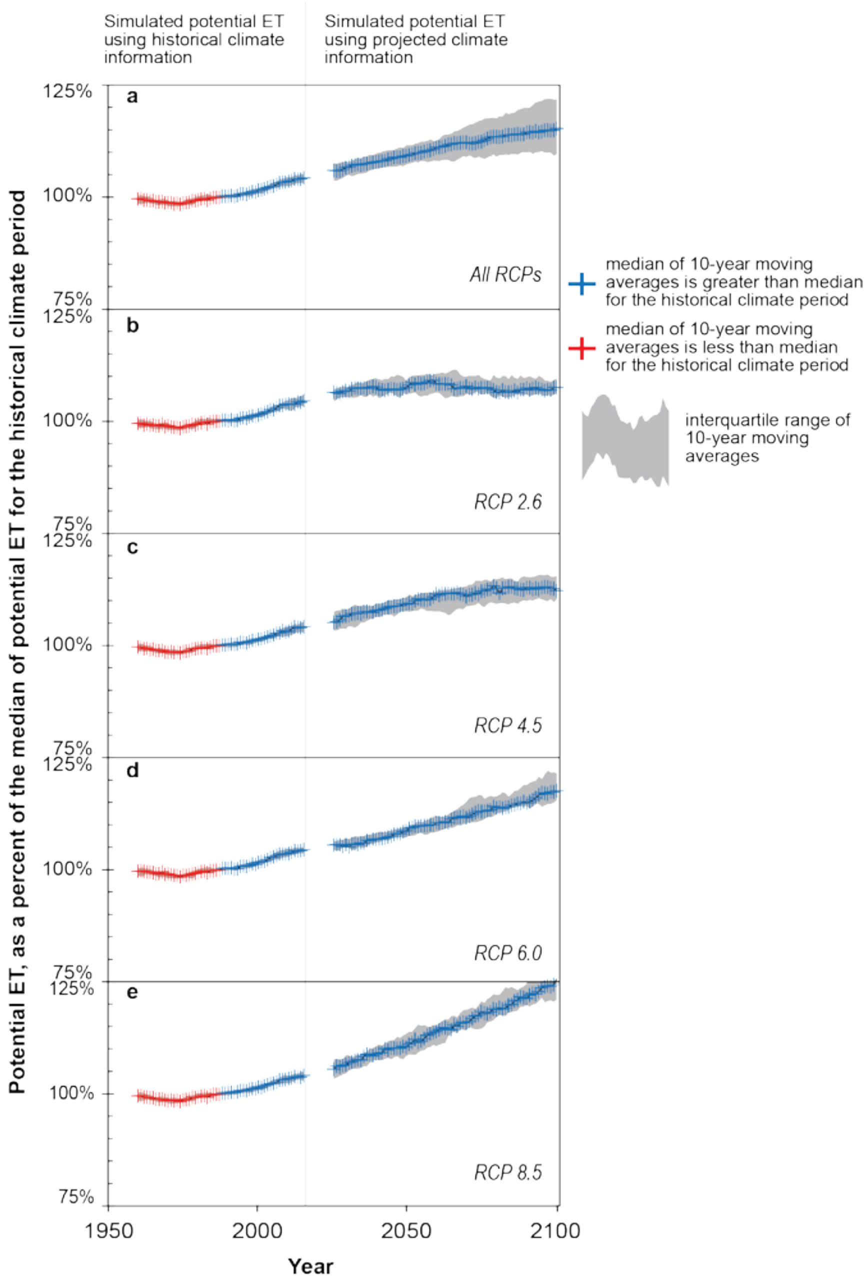

Figure S2. Median of ten-year moving averages of annual potential evapotranspiration (PET) in the upper Colorado River basin for (a) combined RCP results, and (b-e) results grouped by individual RCP. Symbols are placed at the end of the ten-year averaging period**.**

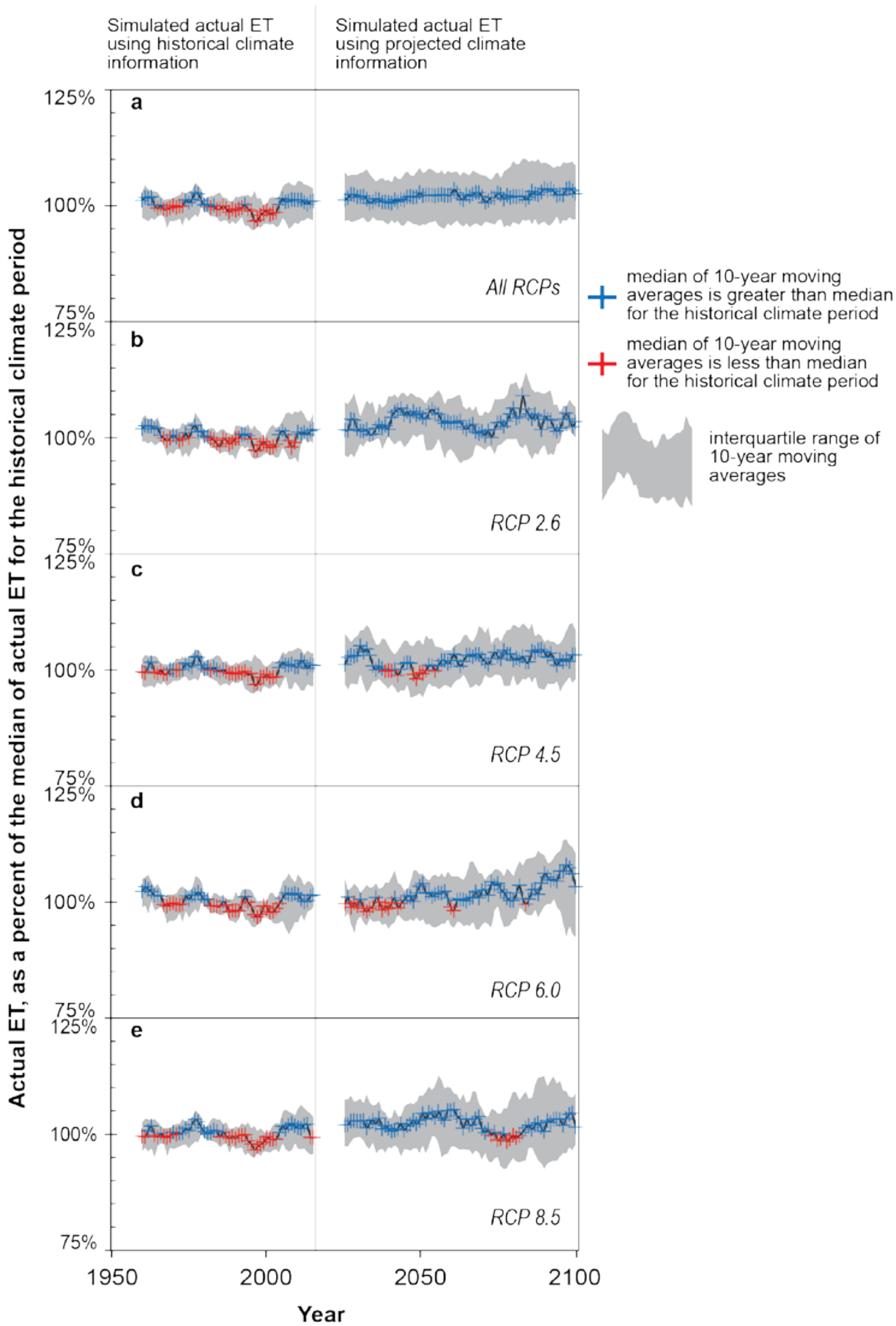

Figure S3. Median of ten-year moving averages of annual actual evapotranspiration (AET) in the upper Colorado River basin for (a) combined RCP results, and (b-e) results grouped by individual RCP. Symbols are placed at the end of the ten-year averaging period**.**

Table S1. CMIP5 multi-model ensembles and institutions providing model output used in the upper Colorado River basin groundwater recharge investigation.

Modeling Center or Group[a]	Model Name	Representative Concentration Pathway			
		2.6	4.5	6.0	8.5
BCC	BCC-CSM 1.1	✓	✓	✓	✓
BCC	BCC-CSM 1.1(m)		✓		✓
CCCMA	CanESM2	✓	✓		✓
CMCC	CMCC-CM		✓		✓
CNRM-CERFACS	CNRM-CM5		✓		✓
CSIRO-BOM	Access 1.0		✓		✓
CSIRO-QCCCE	CSIRO-mk3.6.0	✓	✓	✓	✓
FIO	FIO-ESM	✓	✓	✓	✓
INM	INM-CM4		✓		✓
IPSL	IPSL-CM5A-MR	✓	✓	✓	✓
IPSL	IPSL-CM5B-LR		✓		✓
LASG-CESS	FGOALS-g2	✓	✓		✓
MIROC	MIROC5	✓	✓	✓	✓
MIROC(2)	MIROC-ESM	✓	✓	✓	✓
MIROC(2)	MIROC-ESM-CHEM	✓	✓	✓	✓
MOHC	HadGEM2-CC		✓		✓
MOHC	HadGEM2-ES	✓	✓	✓	✓
MPI-M	MPI-ESM-LR	✓	✓		✓
MPI-M	MPI-ESM-MR	✓	✓		✓
MRI	MRI-CGCM3	✓	✓		✓
NASA GISS	GISS-E2-H-CC		✓		
NASA GISS	GISS-E2-R	✓	✓	✓	✓
NASA GISS	GISS-E2-R-CC		✓		
NCC	NorESM1-M	✓	✓	✓	✓
NIMR/KMA	HadGEM2-AO	✓	✓	✓	✓
NOAA GFDL	GFDL-CM3	✓	✓	✓	✓
NOAA GFDL	GFDL-ESM2G	✓	✓	✓	✓
NOAA GFDL	GFDL-ESM2M	✓	✓	✓	✓
NSF-DOE-NCAR	CESM1(BGC)	✓	✓		✓
NSF-DOE-NCAR	CESM1(CAM5)		✓	✓	✓
RSMAS	CCSM4(RSMAS)	✓	✓	✓	✓

[a]BCC = Beijing Climate Center, China Meteorological Administration; CCCMA = Canadian Centre for Climate Modelling and Analysis; CMCC = Centro Euro-Mediterraneo per I Cambiamenti Climatici; CNRM-CERFACS = Centre National de Recherches Météorologiques /Centre Européen de Recherche et Formation Avancée en Calcul Scientifique; CSIRO-BOM = Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia; CSIRO-QCCCE = Commonwealth Scientific and Industrial Research

Organization in collaboration with Queensland Climate Change Centre of Excellence; FIO = The First Institute of Oceanography, SOA, China; INM = Institute for Numerical Mathematics; IPSL = Institut Pierre-Simon Laplace; LASG-CESS = LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University; MICROC = Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology; MIROC(2) = Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies; MOHC = Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais); MPI-M = Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology); MRI = Meteorological Research Institute; NASA GISS = NASA Goddard Institute for Space Studies; NCC = Norwegian Climate Centre; NIMR/KMA = National Institute of Meteorological Research/Korea Meteorological Administration; NOAA GFDL = NOAA Geophysical Fluid Dynamics Laboratory; NSF-DOE-NCAR = Community Earth System Model Contributors; RSMAS = University of Miami – RSMAS