RECLAMATION

Managing Water in the West

Technical Memorandum No. 86-68210-2016-11

A Case Study on Evaluating Impacts of Potential Climate Change on Groundwater Resources: Groundwater Recharge in the Upper Colorado River Basin

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

October 2016

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On the cover: Aerial view of the hairpin turn or "knife-edge" downstream from the confluence of the Yampa and Green Rivers near Vernal, Utah. Photo Credit: Bureau of Reclamation, Alex Stephens.

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A Case Study on Evaluating Impacts of Potential Climate Change on Groundwater Resources: Groundwater Recharge in the Upper Colorado River Basin

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ACRONYMS AND ABBREVIATIONS

AET	actual evapotranspiration
APWL	Accumulated Potential Water Loss
BCSD	bias-corrected spatially disaggregated
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project phase 5
DEM	digital-elevation model
ET	evapotranspiration
GCM	General Circulation Model
GRACE	Gravity Recovery and Climate Experiment
IPCC	Intergovernmental Panel on Climate Change
NRCS	Natural Resources Conservation Service
P	precipitation
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

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1. Introduction

More than 35 million people in the United States and 3 million people in Mexico depend on the Colorado River to supply their domestic and industrial water needs (Bureau of Reclamation 2011; Colorado River Basin Salinity Control Forum 2013). The Colorado River also supplies irrigation water for more than 4.5 million acres of land in the United States and Mexico, and generates about 12 billion kilowatt hours annually of hydroelectric power along the river and its tributaries (Colorado River Basin Salinity Control Forum 2011). Groundwater discharge to the stream system in the Upper Colorado River Basin (UCRB) supplies an important component of the available flow. Estimates of groundwater-supplied flow range from about 30 to 50% of total flow (Miller et al. 2014; Rumsey et al. 2015). Recently, a study by Castle et al. (2014) using remotely-sensed gravity observations from the NASA Gravity Recovery and Climate Experiment (GRACE) mission found that UCRB groundwater storage was depleted by more than 17 million acre-feet during the December 2004 to November 2013 time period of the investigation. Understanding groundwater-budget components, including groundwater recharge, is essential in being able to sustainably manage both groundwater and surface-water supplies in the UCRB.

The SECURE Water Act of 2009 instructs the Secretary of Interior to establish a climate change adaption program and coordinate with the U.S. Geological Survey (USGS) to "ensure that the Secretary has access to the best available scientific information with respect to presently observed and projected future impacts of global climate change on water resources" (Public Law 111-11, Subtitle F, Section 9503a). The Secure Water Act further requires the Secretary to "assess specific risks to the water supply of each major Reclamation river basin, including any risk relating to changes in groundwater recharge" (Public Law 111-11, Subtitle F, Section 9503b). In 2015, the Bureau of Reclamation (Reclamation) and the USGS began an investigation of potential changes in groundwater recharge in the UCRB resulting from climate change. This manuscript documents initial results from this investigation.

2. ACKNOWLEDGEMENTS

Investigation of groundwater recharge in the UCRB under climate change was supported by the 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 1 of this report) 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.

3. STUDY AREA

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 Lees Ferry, Arizona, a location 1 mile downstream of the mouth of the Paria River (Figure 1A, Figure 1B; Anderson 2004). The UCRB is defined for this study as the 113,406 square miles drainage area (HUC-2, Region 14) upstream of 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 10 inches in low elevation areas to more than 39 inches in high elevation areas in the Southern Rocky Mountains (Figure 1C; PRISM Climate Group 2012). The UCRB varies in elevation from about 3,100 feet near the Lees Ferry gage to over 14,000 feet in peaks in the Southern Rocky Mountains in the eastern part of the UCRB (Liebermann et al. 1989). UCRB land cover is predominately shrubland and evergreen forest (Fry et al. 2011), with few high-density population centers (Figure 1D).

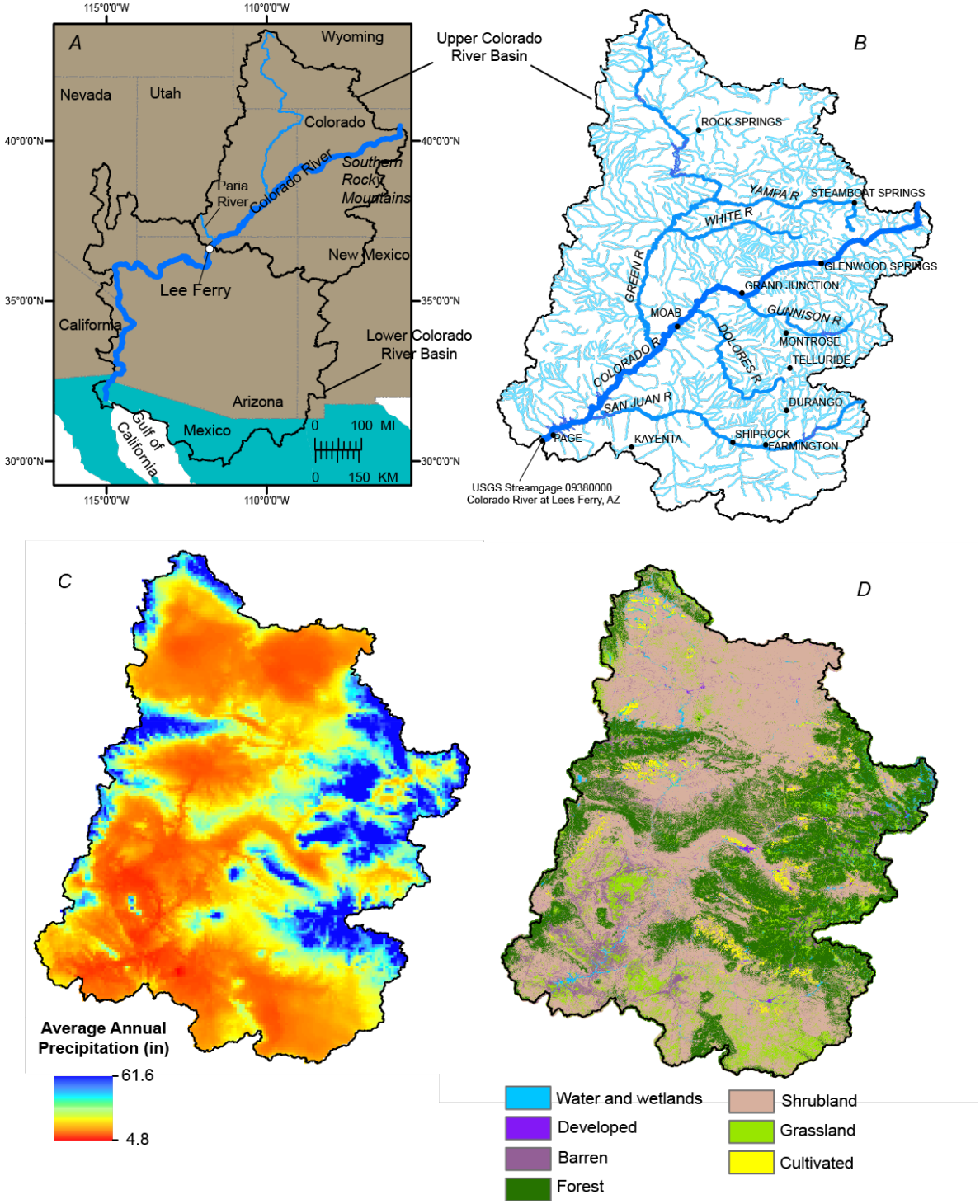

Figure 1. Maps of the Upper Colorado River Basin showing (A) its location, (B) major streams, (C) average annual precipitation (PRISM Climate Group 2012), and (D) major land-cover classifications (Fry et al. 2011).

Areas with the potential for recharge of groundwater supplies through infiltration of excess precipitation are present across most of the UCRB. Regional aquifers in the UCRB are composed of permeable, moderately to well-consolidated sedimentary rocks ranging in age from Permian 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 (Figure 2 and 3; 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 (Figure 2) overlie Mesozoic aquifers that also are present throughout most of the study area (Figure 3 and 4). Deeper Paleozoic aquifers are present throughout much of the UCRB and may rise to land surface in uplifted areas (Figure 3 and 5). 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 a regional groundwater-flow system (Geldon 2003a,b; Freethey and Cordy 1991).

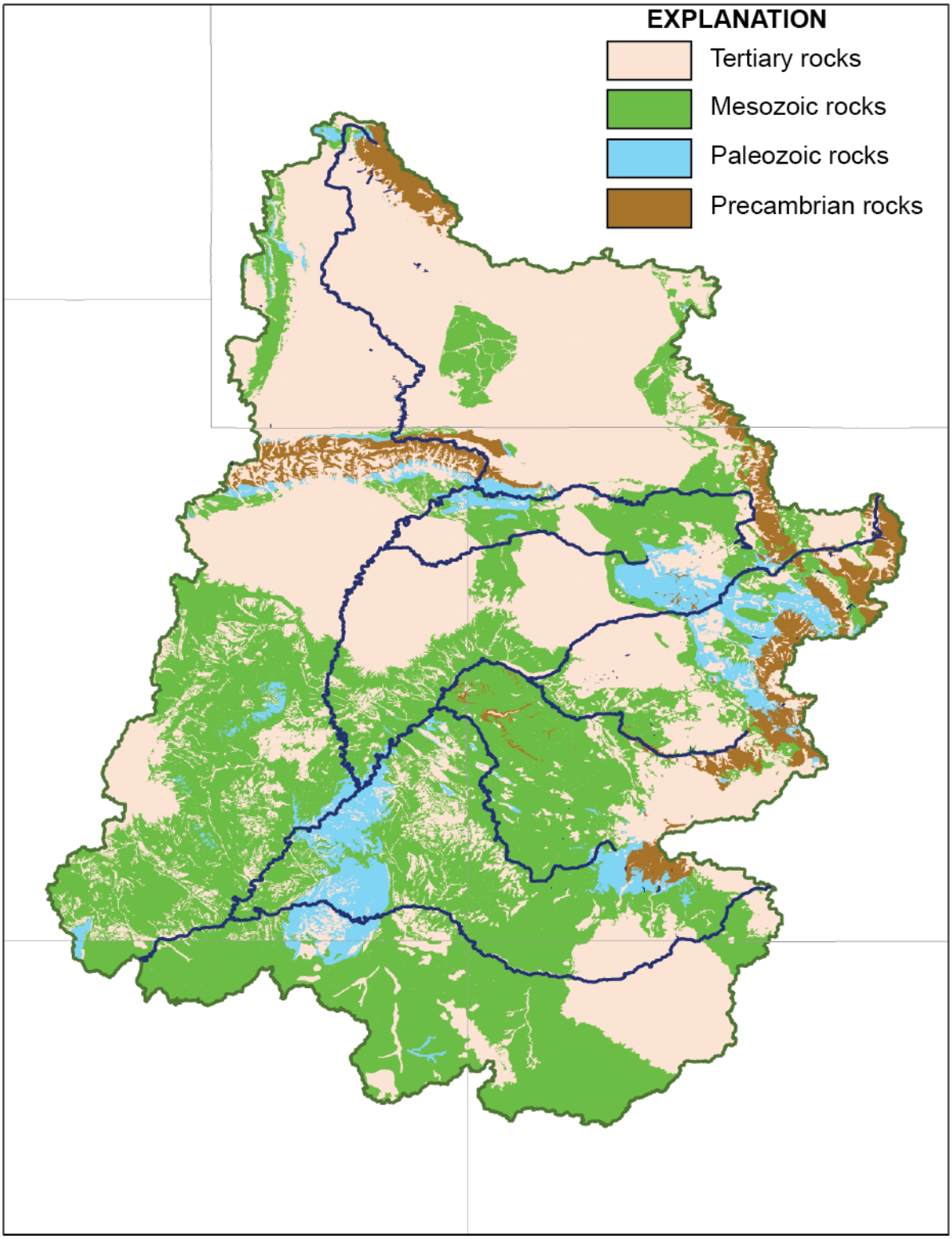

Figure 2. Generalized geology of the Upper Colorado River Basin. (Modified from Schruben et al. 1997).

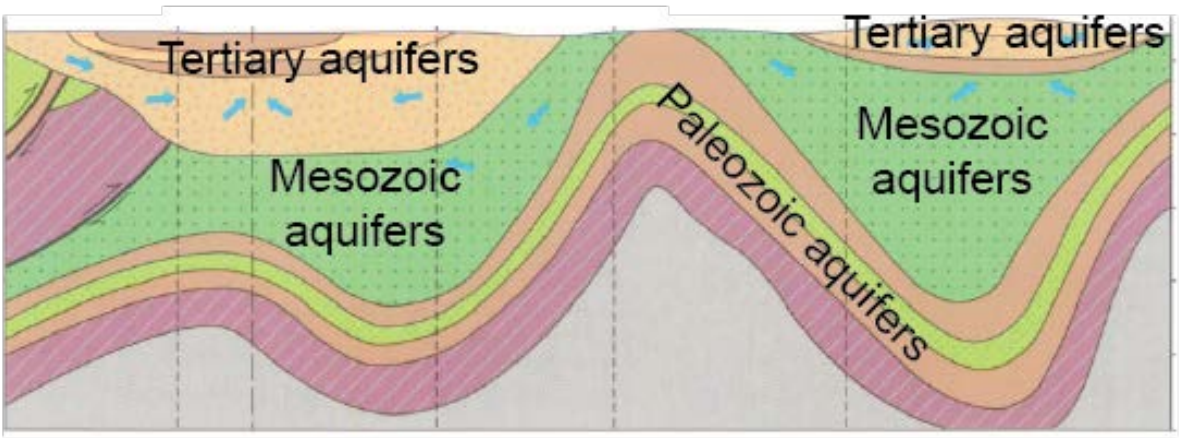

Figure 3. A diagrammatic east-to-west cross-section showing general stratigraphic and structural relation of major aquifer units in the Upper Colorado River Basin. (Modified from Whitehead 1996).

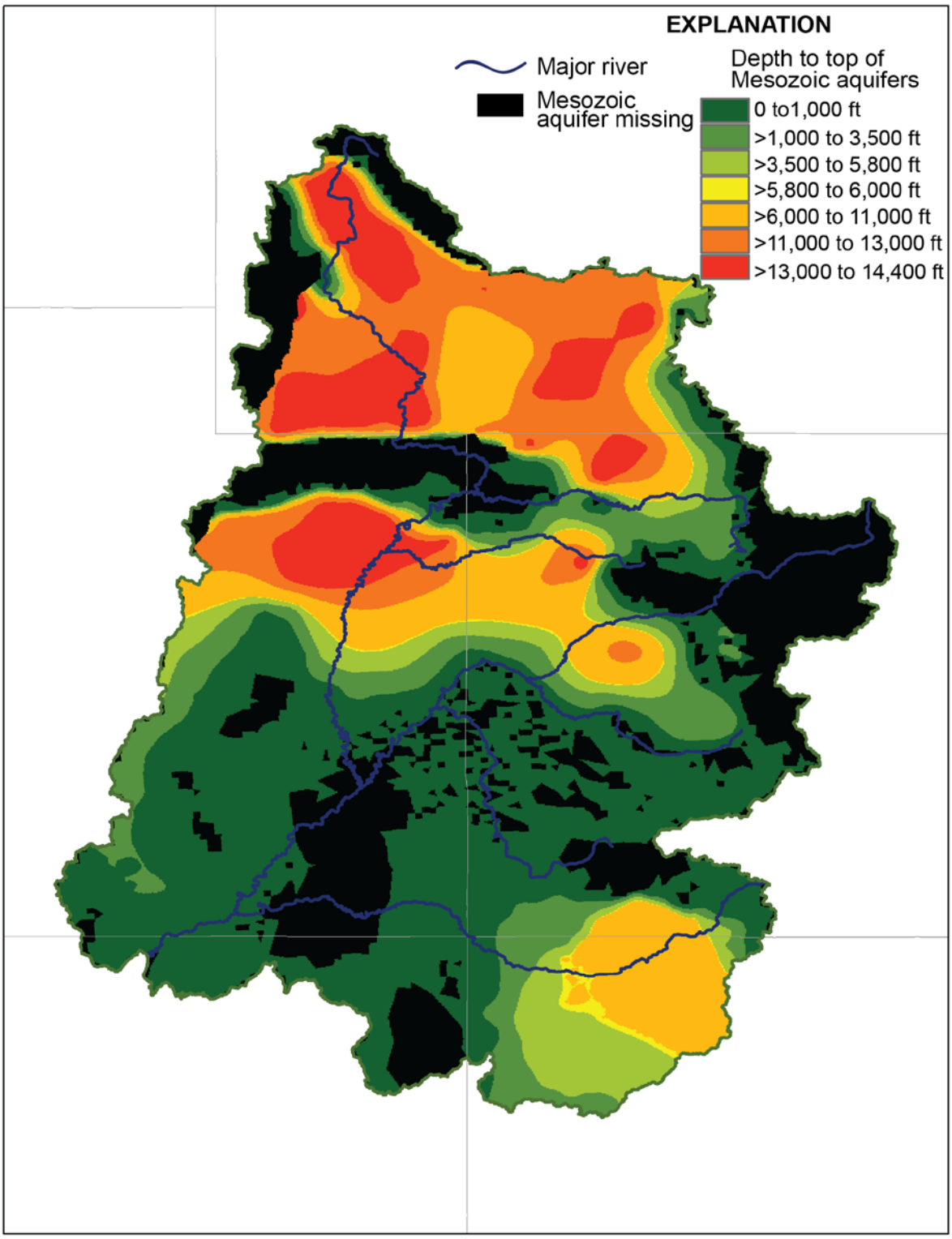

Figure 4. Depth to top of UCRB Mesozoic-rock aquifers, except the Mesa Verde unit which has a small water budget compared with the Dakota sandstone and deeper units. (Modified from Geldon 2003a,b; Freethey and Cordy 1991).

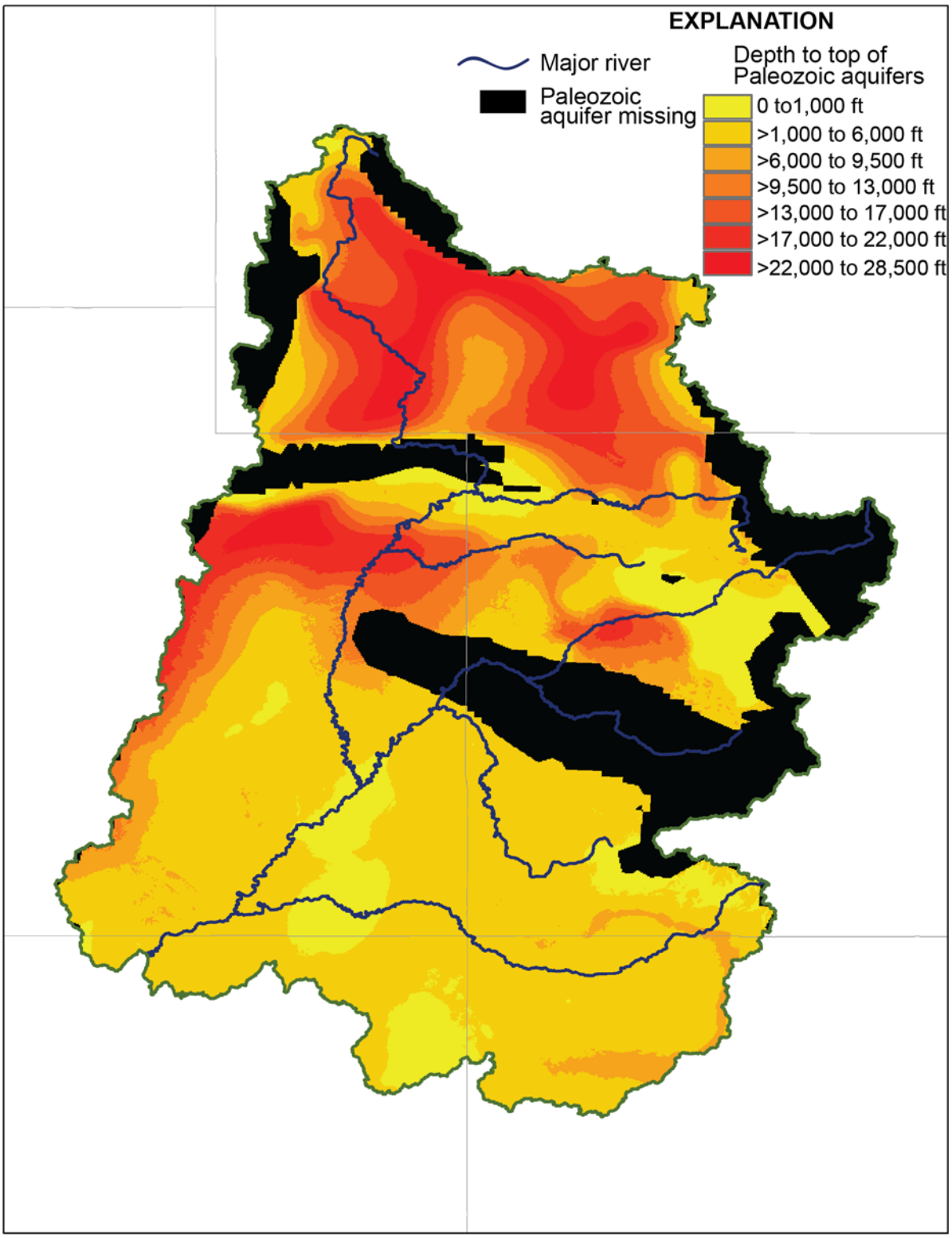

Figure 5. Depth to top of UCRB Paleozoic-rock aquifers. (Modified from Geldon 2003a,b; Freethey and Cordy 1991).

4. METHODOLOGY

UCRB groundwater recharge was estimated using the Soil-Water-Balance (SWB) model with historical and projected climate data. The 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 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), the Northern Atlantic Coastal Plain Aquifer System (Masterson et al. 2013), the Ozark Plateau Groundwater Availability Study (see http://ar.water.usgs.gov/ozarks/waterbud.html), and the Appalachian Plateaus Groundwater Availability Study (see http://va.water.usgs.gov/appalachianplateaus/waterbud.html). SWB follows a modified Thornthwaite-Mather SWB 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:

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

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 Natural 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 then computed for use in equation 1. For these simulations, the Hargreaves and Samani (1985) method was used as it produces spatially variable estimates of potential ET from spatially varying minimum and maximum temperature data for each daily time step.

The computation of soil moisture 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 APWL value in the Thornthwaite-Mather relation that describes the nonlinear

relation between soil moisture and APWL. AET is then equal to only the amount of water that can be extracted from the soil (i.e., the change in soil moisture). 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 found by adding (P – PET) directly to the previous soil-moisture value. If the new soil moisture value is below the maximum water-holding capacity of the soil (calculated as the product of the available soil water capacity and the root-zone depth), 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. For details on the SWB recharge model, see Westenbroek et al. (2010), and for details on UCRB SWB input datasets, see Tillman (2015).

Precipitation and temperature climate data are used in SWB simulations in both source and sink terms in equation (1). Precipitation and snow melt are sources of water in SWB simulations (equation 1). Snow accumulates or melts in the SWB model on a daily basis based on air temperature. The Hargreaves and Samani (1985) method of estimating ET (a sink in equation 1), requires spatially varying minimum and maximum temperature data for each daily time step. 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) as downscaled 1/8th degree bias-corrected spatially disaggregated (BCSD) climate projection datasets (Bureau of Reclamation 2013). Climate datasets were available for 97 climate projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model archive (Table 1). Each of the 97 ensembles is a General Circulation Model (GCM) run using a given future-climate scenario known as a Representative Concentration Pathway (RCP; see Table 1). 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/m2 by the end of the century (VanVuuren 2011). Daily climate data were available from 1950 through 2099. All spatially gridded input datasets were resampled to the same cell size and geographic coordinate system as the BCSD climate data (for details on the source, manipulation, and resampling of datasets, see Tillman 2015).

Table 1. CMIP5 multi-model ensembles and institutions providing model output used in the UCRB groundwater recharge investigation.

Modeling Center or Group[1]	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)	✓	✓	✓	✓

[1]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

5. RESULTS

SWB simulations were run on a daily time step for the 1950 through 2099 time period for the 97 downscaled CMIP5 multi-model climate projections. The only input datasets that changed through time were climate data (precipitation, maximum and minimum temperatures). Other input data that may be affected by changing climate (e.g., land cover) were held constant throughout the simulations. Daily SWB model output was compiled into monthly and then water year (October to September) time periods for analysis. For this study, all CMIP5 projections were considered to be equally likely and results for all climate input datasets are grouped together without regard for Representative Concentration Pathway (RCP).

Changes in simulated UCRB groundwater recharge through time, and changes in the climate-affected parameters of precipitation and actual ET (see equation 1), were computed for water year 1951 through water year 2099 (Figure 6). All GCM/RCP climate projection combinations and subsequent impacts on precipitation, AET, and groundwater recharge are considered equally likely and results were grouped together by water year. The central tendency of water-year model results from all simulation runs is reflected in median values, with 5th and 95th percentiles providing information on result variability (Figure 6). Compared with water-years 1951-1999, the mean annual 50th percentile of precipitation for 2000-2049 is about 4% larger, the mean annual 95th percentile is about 6% larger, while the mean annual 5th percentile is almost unchanged (Figure 6, Table 2). Water years 2050-2099 experience about 7% and 10% more precipitation for the mean annual 50th and 95th percentiles compared with 1951-1999, while the mean annual 5th percentile during this time period is only 0.4% greater than 1951-1999 values (Table 2). From the perspective of groundwater recharge, the increase in precipitation in the 50th and 95th percentiles is somewhat offset by increases in actual ET (AET; Figure 6, middle panel; Table 2). The mean annual 50th and 95th percentiles for AET in 2000-2049 compared with 1951-1999 are about 2% and 4% higher, respectively. The 2050-2099 time period has even higher AET, with increases of mean annual 50th and 95th percentiles for AET of about 3% and 7%, respectively, relative to 1951-1999 (Table 2). Future 5th percentile AET values decline somewhat relative to 1951-1999, with mean annual 5th percentile values about 2% and 5% lower for 2000-2049 and 2050-2099, respectively (Figure 6; Table 2). Resulting groundwater recharge (Figure 6, lower panel; Table 2) increases about 4% (50th percentile) and 8% (95th percentile) in the 2000-2049 time period, and about 4% (50th percentile) and 12% (95th percentile) in the 2050-2099 time period, relative to mean annual values in 1950-1999. Future 5th percentile recharge values decline about 7% (2000-2049) and 17% (2050-2099), relative to 1950-1999 (Table 2).

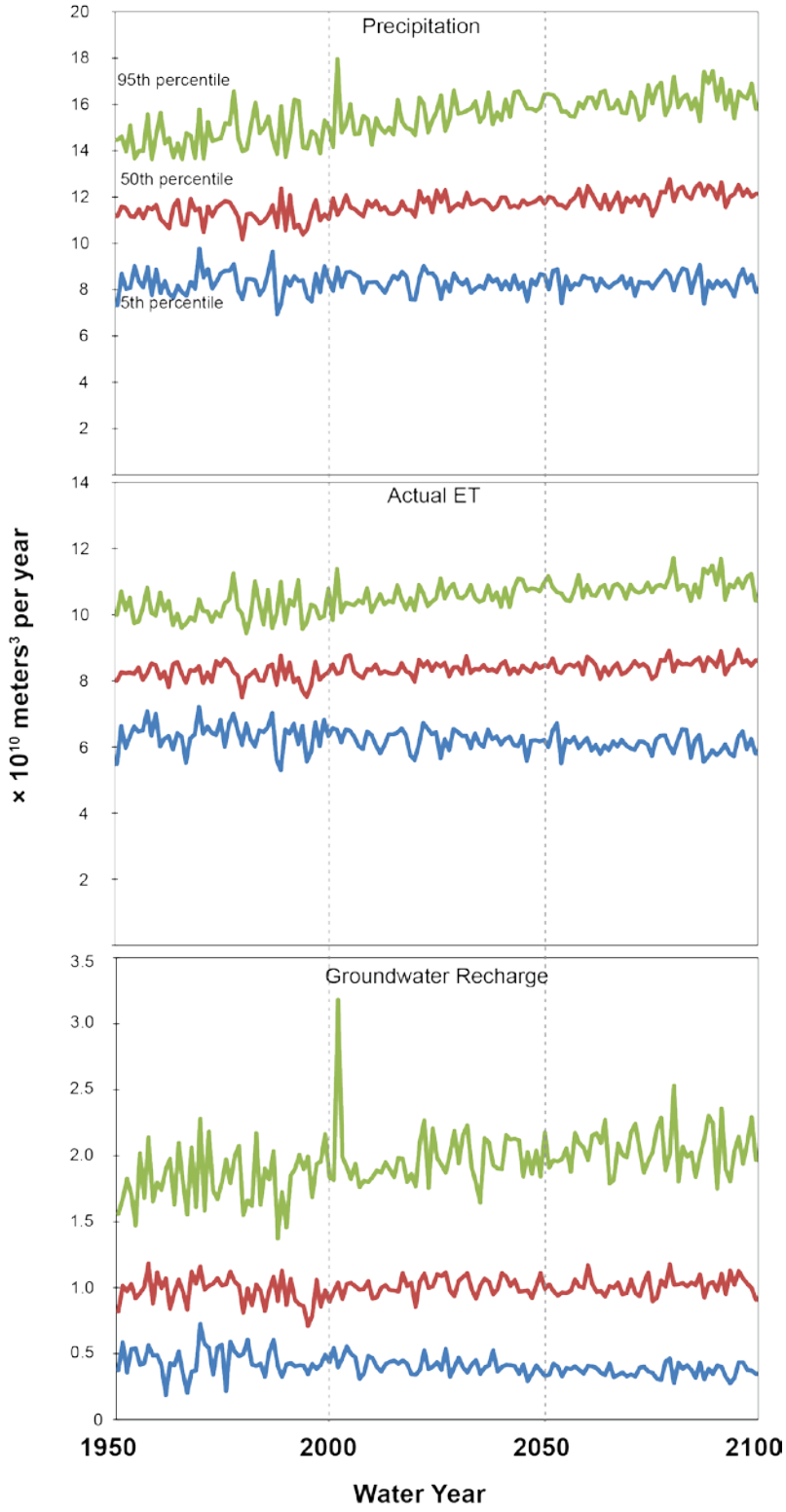

Figure 6. Temporal changes in 95th, median, and 5th percentiles for precipitation, actual evapotranspiration (ET), and groundwater recharge in the Upper Colorado River Basin from Soil-Water Balance simulations using 97 CMIP5 model-ensemble climate datasets.

Table 2. Percentage change of mean precipitation, actual ET, and groundwater recharge for the Upper Colorado River Basin from water-year time period indicated compared with mean from water year 1951-1999 time period.

Parameter	Water year time period	5th percentile	50th percentile	95th percentile
Precipitation	2000-2049	0.2%	3.7%	5.8%
	2050-2099	0.4%	6.7%	10.4%
Actual ET	2000-2049	-2.1%	1.9%	4.0%
	2050-2099	-4.6%	3.3%	6.9%
Groundwater recharge	2000-2049	-6.6%	3.6%	8.2%
	2050-2099	-16.9%	3.8%	12.5%

The change in spatial distribution of groundwater recharge in response to potential climate change is evaluated by comparing mean annual recharge for the decades 2020s (water years 2020-2029), 2050s (water years 2050-2059), and 2070s (water years 2070-2079), with mean annual recharge from the 1990s (water years 1990-1999). Mean annual recharge for each of the decades listed was computed for each model cell for each of the 97 model simulations, separately. Percentage difference (difference divided by the mean) was then computed for each cell in each of the 97 model simulations between the three future decadal averages and the 1990s average. Finally, the 25th, 50th, and 75th percentiles of the percentage differences were computed for each model cell from all 97 model simulations (Figure 7). Mean annual recharge values of less than 0.01 inch were considered to be zero in the percentage change analyses. Results indicate general increases in groundwater recharge throughout most of the UCRB at both the 50th and 75th percentile levels for all future decades relative to the 1990s (Figure 7). Percentage differences at the 25th percentile level appear to show decreases for all future decades relative to the 1990s throughout most of the UCRB (Figure 7).

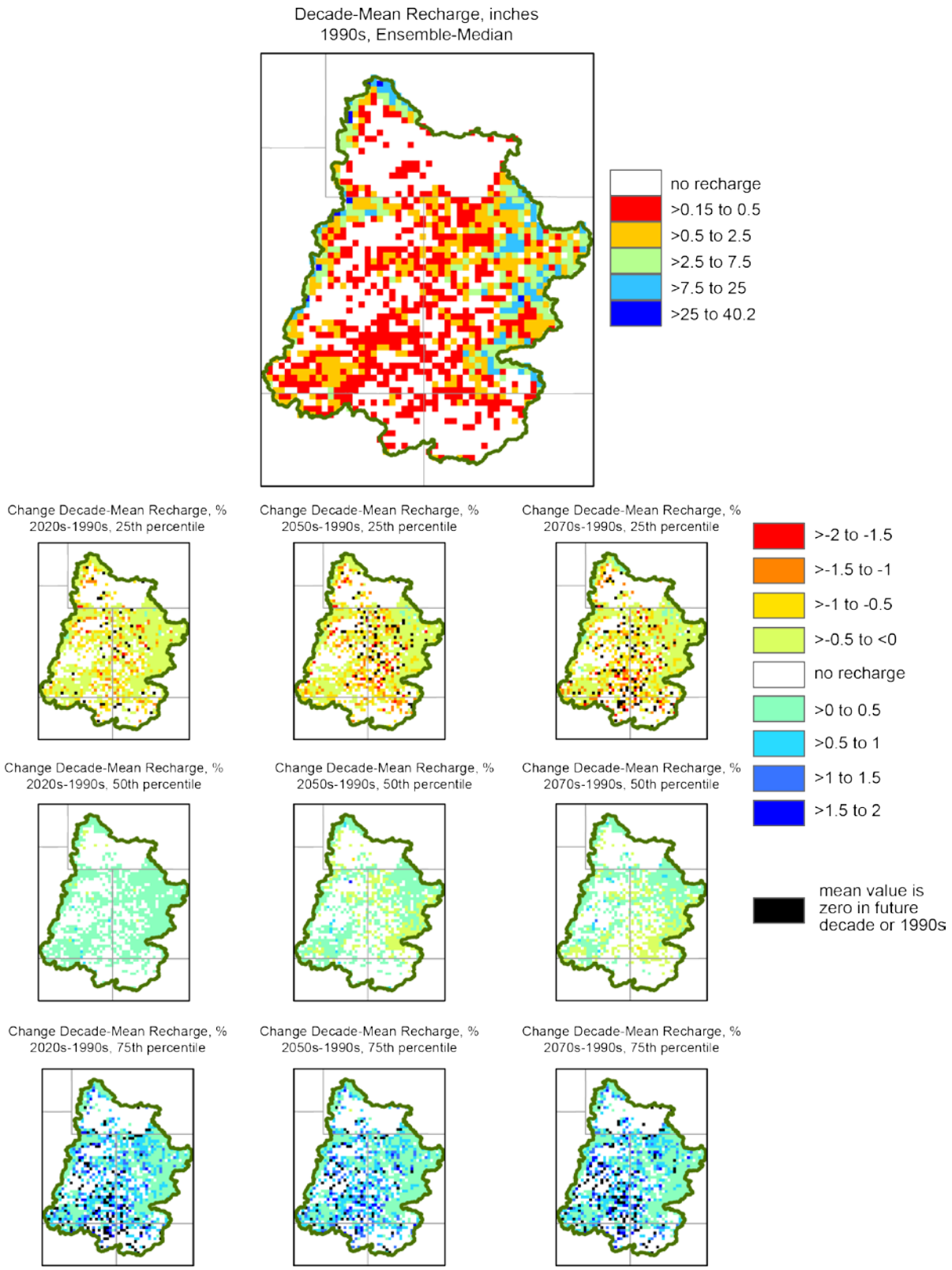

Figure 7. Spatial distribution of mean recharge for the 1990s (top) and 25th, median, and 75th percentiles of changes in decadal mean recharge from the 1990s to select future decades (bottom grid).

6. CONCLUSIONS

An investigation of the change in groundwater recharge in response to potential climate change was performed for the UCRB using the SWB groundwater recharge model and downscaled climate data from the CMIP5 multi-model dataset. Climate projections from 97 downscaled CMIP5 datasets were assumed to be equally likely and recharge simulation results were combined. Results for the UCRB suggest that projected increases in actual ET from higher temperatures may be offset by increases in precipitation, resulting in increased groundwater recharge for many areas in the basin in future time periods.

While the SWB model may provide reasonable annual or monthly basin-scale estimates of groundwater recharge model, SWB limitations and assumptions should be considered when evaluating 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 of the model domain on the same day in which it originated. Depth to the top of the aquifer surface is also 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 also 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).

Future analyses of the UCRB SWB results will group model results by RCP to better understand the role of different scenarios on future recharge estimates. Results also will be analyzed on a subbasin scale. Analyses such as those presented in this report may be valuable in understanding potential climate-change impacts on groundwater resources in other Reclamation-managed river basins.

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