Journal of Hydrology 534 (2016) 124–138

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review Paper

Implications of projected climate change for groundwater recharge in the western United States

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ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form 11 December 2015
Accepted 15 December 2015
Available online 4 January 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:
Groundwater recharge
Recharge mechanisms
Climate change
Western United States

SUMMARY

Existing studies on the impacts of climate change on groundwater recharge are either global or basin/location-specific. The global studies lack the specificity to inform decision making, while the local studies do little to clarify potential changes over large regions (major river basins, states, or groups of states), a scale often important in the development of water policy. An analysis of the potential impact of climate change on groundwater recharge across the western United States (west of 100° longitude) is presented synthesizing existing studies and applying current knowledge of recharge processes and amounts. Eight representative aquifers located across the region were evaluated. For each aquifer published recharge budget components were converted into four standard recharge mechanisms: diffuse, focused, irrigation, and mountain-systems recharge. Future changes in individual recharge mechanisms and total recharge were then estimated for each aquifer. Model-based studies of projected climate-change effects on recharge were available and utilized for half of the aquifers. For the remainder, forecasted changes in temperature and precipitation were logically propagated through each recharge mechanism producing qualitative estimates of direction of changes in recharge only (not magnitude). Several key patterns emerge from the analysis. First, the available estimates indicate average declines of 10–20% in total recharge across the southern aquifers, but with a wide range of uncertainty that includes no change. Second, the northern set of aquifers will likely incur little change to slight increases in total recharge. Third, mountain system recharge is expected to decline across much of the region due to decreased snowpack, with that impact lessening with higher elevation and latitude. Factors contributing the greatest uncertainty in the estimates include: (1) limited studies quantitatively coupling climate projections to recharge estimation methods using detailed, process-based numerical models; (2) a generally poor understanding of hydrologic flowpaths and processes in mountain systems; (3) difficulty predicting the response of focused recharge to potential changes in the frequency and intensity of extreme precipitation events; and (4) unconstrained feedbacks between climate, irrigation practices, and recharge in highly developed aquifer systems.

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http://dx.doi.org/10.1016/j.jhydrol.2015.12.027
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Contents

1. Introduction

Existing studies of the potential impact of climate change on groundwater are either global-level or basin specific analyses. The global-level studies consist of generalized considerations of potential future recharge trends, or some form of coupling of coarse resolution climate models with groundwater models (e.g., Green et al., 2011; Taylor et al., 2013; Döll and Fiedler, 2007). The basin/location-specific studies connect climate and groundwater-flow models for a particular aquifer system to understand the impacts of climate change on groundwater in that system (e.g., Serrat-Capdevila et al., 2007; Hanson et al., 2012). These two study types provide valuable insights, but between them a knowledge gap exists. The global studies lack the specificity to inform decision making, while the local studies do little to clarify potential changes over large regions (major river basins, states, or groups of states), a scale often important in the development of water policy. This gap has led to a lack of consideration of how the impacts of climate change on a specific recharge mechanism may vary within a given region. Depending on the recharge mechanisms operating in a given aquifer system there may be increased or decreased sensitivity to climate change, and varying response to climate change by different recharge mechanisms (Flint and Flint, 2014; Ng et al., 2010). This gap is particularly problematic for transboundary and multi-jurisdictional aquifers where existing agreements on use of groundwater generally assume a degree of stationarity (Cooley et al., 2011).

Groundwater represents 25% of fresh water withdrawals in the United States (U.S.) (Maupin et al., 2014). However, research efforts on the impacts of climate change on water resources in the U.S. have focused predominantly on surface-water systems (Overpeck and Udall, 2010; Seager et al., 2013; Vano et al., 2014). This paper assesses the impacts of projected climate change on groundwater recharge across the western U.S. (west of 100° longitude). The western U.S. was selected because of the importance of groundwater in the region and because the region spans the transition between humid conditions favorable to recharge and arid conditions with little or no recharge. This region thus includes aquifer systems with diverse recharge rates and mechanisms, and provides examples of recharge responses to climate change that could be useful to investigators in a variety of settings. The following questions guided this study: (1) What generalizations can be made about how total recharge will change across the western U.S. under projected climate change? (2) How do projected climate changes interact with individual recharge mechanisms? (3) What are the most significant knowledge gaps that limit our ability to predict future changes in recharge?

We conducted the assessment as follows. First, eight representative aquifers were selected that (a) have recharge estimates for the current climate, (b) are economically significant, and (c) capture a diverse set of climates, geologic settings, and recharge mechanisms. We converted published recharge budget components for these aquifers into four standard recharge mechanisms: diffuse, focused, mountain system, and irrigation. We analyzed available climate-change projections to determine likely changes in temperature and precipitation in the sub-regions containing the eight representative aquifers. Next, we predicted the direction of change for each recharge mechanism and for total recharge in each aquifer using either compiled prior model-based estimates (available for four of the eight aquifers) or careful consideration of how changes in temperature and precipitation will likely impact and propagate through specific processes controlling each mechanism. Finally, we assigned a confidence level (high, medium, or low) to predicted recharge changes. This structured approach provides a template for how large scale regional assessments of the response of groundwater recharge to climate change might be conducted in other regions. Our assessment represents a way in which the global scale process of climate change will modulate recharge processes in a specific region. While climate change is a global process, its impacts must be assessed in a specific place and time to understand how society may need to respond considering socio-economic factors.

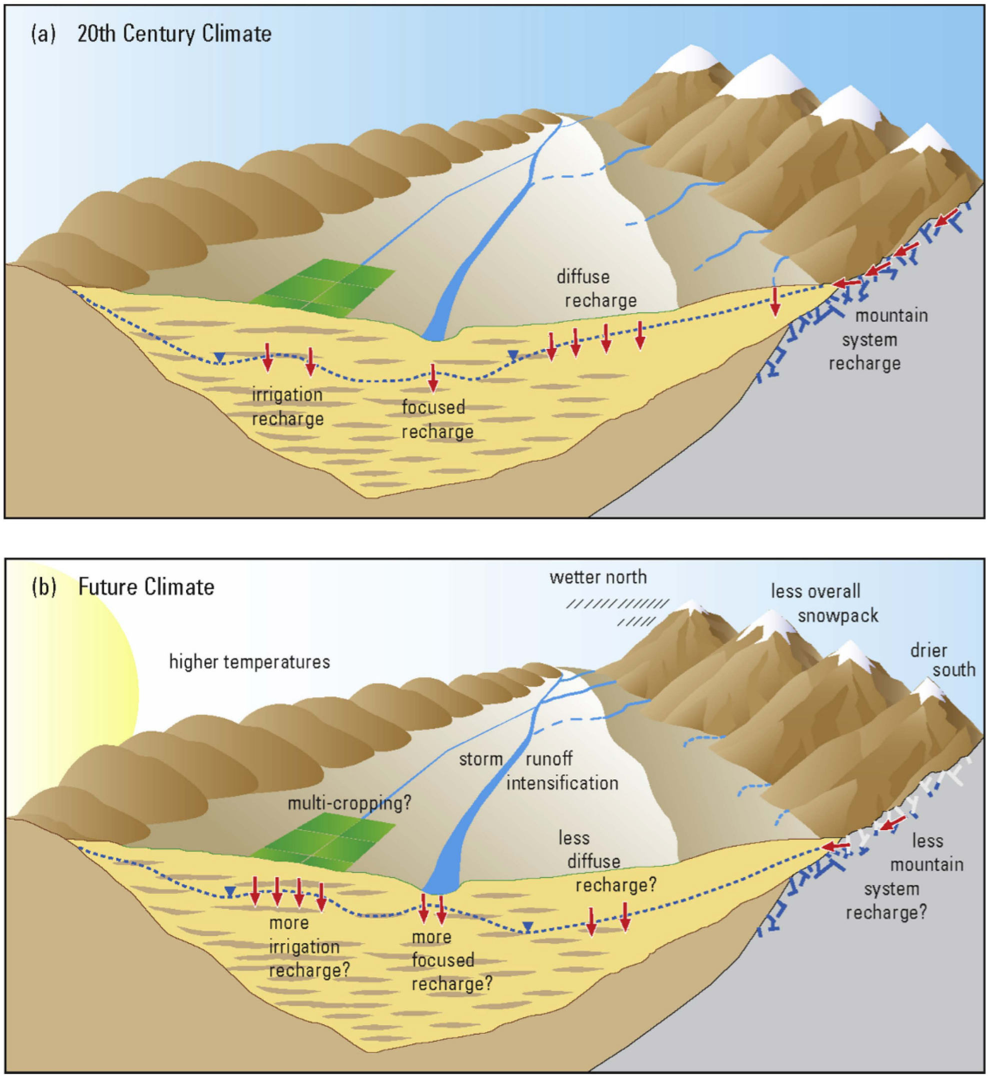

Fig. 1. Conceptual illustration of four different recharge mechanisms under 20th century climate (a) and future climate (b).

2. Material and methods

2.1. Recharge mechanisms

We developed a uniform recharge mechanism classification scheme as part of this study because the available studies of current and projected recharge often had disparate classifications that made them difficult to use for comparative analysis. In this study the recharge mechanisms across aquifer systems were classified as: diffuse, focused, mountain system recharge (MSR), and irrigation (Fig. 1). Developing a common definition of different recharge mechanisms is important because studies of specific aquifer systems commonly provide site specific descriptions of recharge mechanisms that are not easily transferable to other places. Additionally, aquifer specific analyses often provide a large number of recharge mechanisms. The four mechanisms identified here are general enough to include the numerous types of recharge identified in prior studies, yet specific enough to maintain important distinctions between fundamentally different recharge processes and pathways. Thus, they can be used to make meaningful comparisons in climate induced changes across a diverse set of aquifers.

In this analysis, diffuse recharge is operationally defined as being sourced from precipitation and occurs as direct infiltration of precipitation followed by percolation to the water table. Focused recharge from ephemeral or perennial surface-water expressions occurs via concentration of precipitation and shallow interflow at the Earth's surface through runoff processes and subsequent infiltration, percolation, and recharge of runoff at specific locations on the landscape (e.g., ephemeral streams and playas). MSR includes recharge from stream loss at mountain fronts (MFR) (also a form a focused recharge, but herein grouped with MSR), along with subsurface transfer of groundwater from the mountain block to the adjacent alluvial aquifer (mountain-block recharge, or MBR). MFR and MBR were combined in our analysis because in most systems it is difficult to differentiate the source of recharge to the basin aquifer. Irrigation recharge is excess irrigation water that percolates to the water table (Scanlon et al., 2002; Sanford, 2002) and may be derived from both surface water and groundwater.

To illustrate the classification approach, a study of the High Plains aquifer system accounted for recharge as: precipitation sourced; groundwater-sourced irrigation-return flow; surface-water-sourced irrigation-return flow; canal leakage; and surface-water sourced recharge from natural landscape features (playas, lakes, and streams; Stanton et al., 2011). These recharge components were mapped to the four recharge components described above with the irrigation-return flow and canal leakage lumped together as irrigation recharge; precipitation sourced recharge classified as diffuse recharge; and surface water sourced recharge

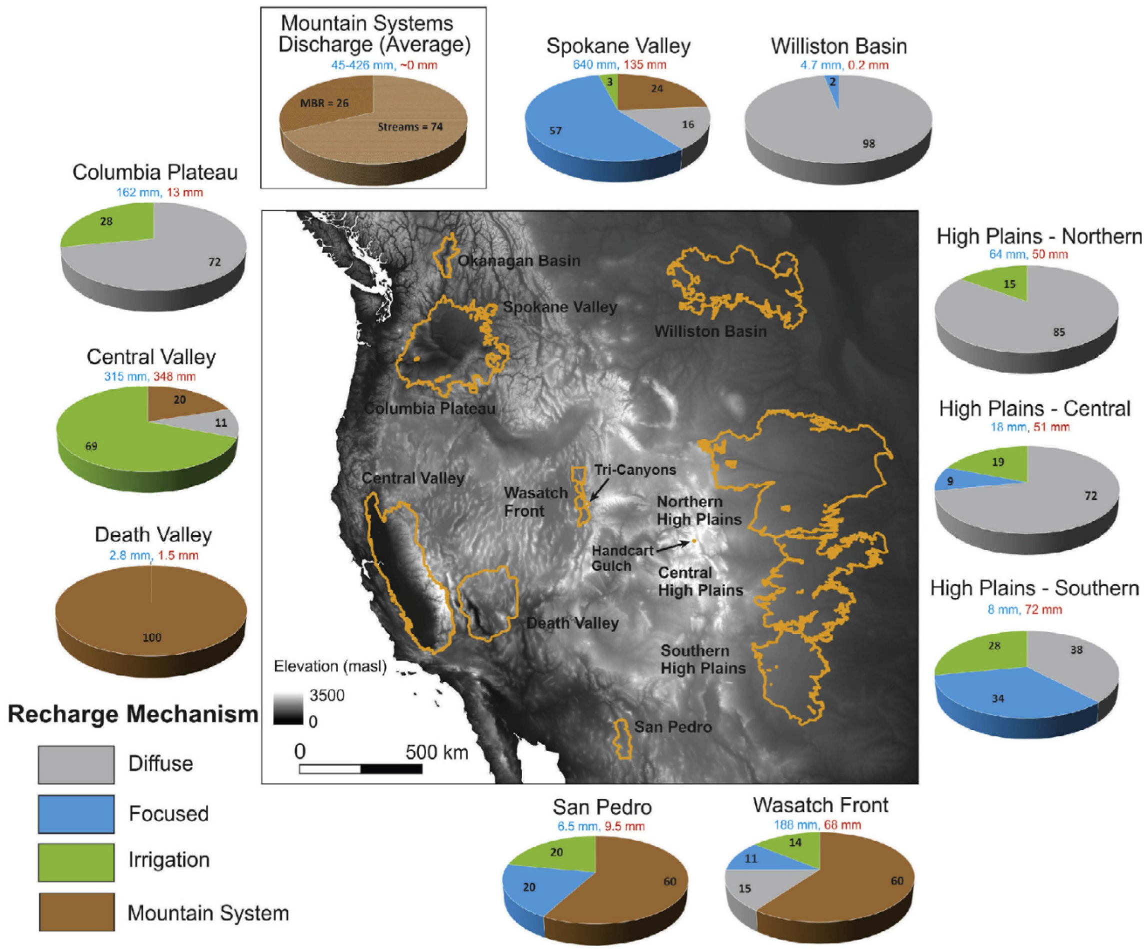

Fig. 2. Locations and recharge budgets of studied aquifers. For each aquifer, total estimated recharge is shown by numbers in blue and withdrawals shown by numbers in red; both values are reported in mm as depth to facilitate aquifer comparisons. Pie chart for each aquifer shows the contribution from each of the four recharge mechanisms as a percentage of total recharge. For mountain systems (top left pie chart), the average annual discharge budget is shown (blue numbers indicate range of estimated total discharge) because this discharge is a potential recharge source for neighboring lower-elevation basins; here "MBR" is water discharged as mountain-block recharge, and "Streams" is water discharged to mountain streams entering adjacent basins. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from natural features classified as focused recharge. MSR is not present as a recharge mechanism for the High Plains aquifer. Similarly, for the Wasatch Front, multiple recharge components were mapped to the four selected categories (Thiros et al., 2010). MSR combines MBR and infiltration of streamflow at mountain fronts. Diffuse recharge is distributed infiltration of precipitation on the valley floor. Focused recharge combines reservoir infiltration and stream loss on the valley floor away from the mountain front. Irrigation recharge combines infiltration from field irrigation, domestic watering, and canal seepage.

2.2. Aquifer selection

Eight aquifer systems in the western U.S. were selected to represent the broad range of climatological, geological, hydrological, and anthropogenic conditions affecting aquifers throughout the region (Fig. 2). Characteristics of these relatively well-studied aquifers, including estimates of current recharge, are summarized in Tables 1 and 2, and are described in greater detail in the Supplementary Materials. Though all selected aquifers are economically important, withdrawals vary greatly, both in absolute magnitude and relative to recharge rates (Fig. 3).

2.3. Projected climate change across the region

Climate varies widely across the western U.S (Fig. 4). The west coast has winter dominated precipitation characteristic of Mediterranean climates controlled mainly by synoptic-scale mid-latitude cyclones, with the precipitation season lengthening with increasing latitude. Areas further inland experience more continental-type climates, with a greater seasonal variation in temperatures and a predominance of warm-season convective precipitation. Mountainous areas are significantly cooler and wetter than low elevation regions. Such a diverse climate results in different recharge environments. Moreover, projected climate change varies considerably across the region and can be expected to result in regional differences in how recharge will change in the future.

Summary descriptions of anticipated climate changes in the western U.S. through the end of the 21st century are available in the most recent National Climate Change Assessment for the United States (Melillo et al., 2014) and supporting regional climate change assessment reports (e.g., Garfin et al., 2013). Temperatures are expected to increase throughout the region, with warming greatest in the southwest. Warmer temperatures during winter and early spring are expected to shift winter precipitation from snow to rain and increase the elevation of the rain-to-snow

Table 1
Physiographic, geologic, and climatic characteristics of selected aquifer systems.

Basin	Area (km^2)	Physiographic province[a]	Aquifer material	Dominant climate[b]	Min precip[c] ($mm\ yr^{-1}$)	Max precip[c] ($mm\ yr^{-1}$)	Avg precip[c] ($mm\ yr^{-1}$)	Precipitation notes	PET[c] ($mm\ yr^{-1}$)
High Plains	451,000	Great Plains	Unconsolidated, poorly-sorted clay, silt, sand and gravel underlain by bedrock	Arid cold steppe	330	845	535	Mainly summer rain, increases west to east	1940
Northern High Plains (NE, CO, WY, SD, KS)	250,000	Great Plains	Unconsolidated, poorly-sorted clay, silt, sand and gravel underlain by bedrock	Arid cold steppe	330	800	550	Mainly summer rain, increases west to east	1730
Central High Plains (KS,TX, OK, CO, NM)	125,000	Great Plains	Unconsolidated, poorly-sorted clay, silt, sand and gravel underlain by bedrock	Arid cold steppe	370	845	545	Mainly summer rain, increases west to east	2140
Southern High Plains (TX, NM)	76,000	Great Plains	Unconsolidated, poorly-sorted clay, silt, sand and gravel underlain by bedrock	Arid cold steppe	350	590	470	Mainly summer rain, increases west to east	2380
San Pedro (AZ, Sonora Mexico)	7560	Basin Ranges	Sand and gravel	Arid hot steppe	300	485	370	Mainly summer monsoon rain and mountain snow, increases with elevation	2540
Death Valley Regional Flow System (NV, CA)	45,300	Basin Ranges	Carbonate and volcanic rock, and alluvium	Arid hot desert	60	525	185	Increases with elevation	2430
Wasatch Front (UT)[e]	3020	Basin Ranges	Sand and gravel	Arid cold steppe with hot summer	345	1180	545	Increases with elevation, most falls as snow	1650
Central Valley (CA)	52,000	Pacific Mountains	Sand and gravel	Temperate steppe with hot dry summer	155	800	650	Increases from south to north, 85% falls November to April	2080
Columbia Plateau (WA, OR, ID)	114,000	Columbia Plateaus	Basalt, sand and gravel	Arid cold steppe and desert	175	1750	440	More precipitation in winter, increases with elevation	1590
Spokane Valley-Rathdrum Prairie Aquifer (WA)	2100	Columbia Plateaus	Sand and gravel	Cold steppe with warm dry summer	450	915	690	More precipitation in winter, increases with elevation	1410
Williston Basin (ND, MT, Saskatchewan Canada)	102,400	Great Plains/ Prairie Plains	Sand and gravel	Arid cold steppe	255	530	380	Increases west to east	1440

[a] Physiographic regions of Powell (1895).
[b] Köppen-Geiger classifications (after Peel et al., 2007).
[c] Spatial precipitation and potential evapotranspiration (PET) statistics; 30-yr normals (1981–2010); values from NLDAS[d] (Mitchell et al., 2004).
[d] National Land Data Assimilation System (NLDAS).
[e] Includes Salt Lake Valley and northern Utah Valley aquifers.

Table 2
Storage volumes and groundwater recharge components.

Basin	Volume[a] ($m^3 \times 10^6$)	Volume[b] (mm)	Recharge (mm yr^{-1})	Withdrawals (mm yr^{-1})	Diffuse recharge (mm yr^{-1}) (%)	Focused recharge (mm yr^{-1}) (%)	Mountain system recharge (mm yr^{-1}) (%)	Irrigation recharge (mm yr^{-1}) (%)
High Plains	3,680,000	8160	42	54	34 (82)	1 (2)	0	7 (16)
Northern High Plains	2,850,000	11,400	64	50	54 (85)	~0	0	10 (15)
Central High Plains	630,000	5000	18	51	13 (72)	1.6 (9)	0	3.4 (19)
Southern High Plains	180,000	2300	8	72	3 (38)	3 (34)	0	2 (28)
San Pedro	50,000	6600	6.5	9.5	~0	1.3 (20)	4 (60)	1.3 (20)
Death Valley Regional Flow System	2,200,000	48,600	2.8	1.5	~0	~0	2.8 (100)	~0
Wasatch Front[c]	34,400	11,400	188	68	28 (15)	20 (11)	113 (60)	26 (14)
Central Valley	500,000	9600	315	348	35 (11)	~0	62 (20)	217 (69)
Columbia Plateau	2,000,000	17,500	162	13	117 (72)	~0	~0	45 (28)
Spokane Valley-Rathdrum Prairie Aquifer	15,500	7,380	640	135	101 (16)	364 (57)	152 (24)	23 (3)
Williston Basin	850,000	8300	4.7	0.2	4.6 (98)	0.13 (2)	0	~0

[a] Volume of "extractable" water stored in aquifer, computed as specific yield times saturated thickness times areal extent.
[b] Volume of "extractable" water stored in aquifer, computed as specific yield times saturated thickness.
[c] Includes Salt Lake Valley and northern Utah Valley aquifers.

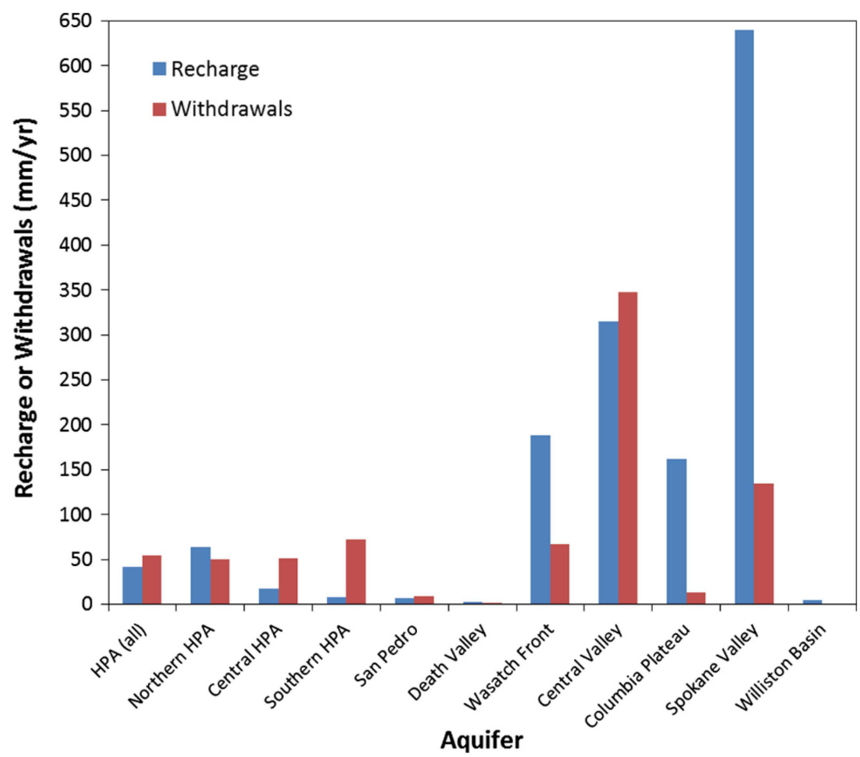

Fig. 3. Recharge and withdrawals (in mm yr^{-1}) from studied aquifers across western United States. HPA stands for High Plains Aquifer.

transition. Mean annual snowpack is expected to decrease further, continuing the observed pattern of decreasing snowpack across the West, though the effect lessens with increasing latitude and elevation (Gleick, 1987; Mote et al., 2005; Adam et al., 2009). Snowfall may increase at the highest elevations according to model projections that considered the headwaters region of the Colorado River (Rasmussen et al., 2011). Higher temperatures will almost certainly increase potential evapotranspiration (ET). With respect to precipitation, the most confident projections are for the cool season. The winter jet stream and storm track are expected to move northward, resulting in more precipitation north of approximately 40° latitude and less precipitation south of this latitude (Dominguez et al., 2012). The most dramatic precipitation decreases are projected to occur during spring and early summer in the southwest, and during late summer in the central and southern Plains. Increases in the intensity of cool season precipitation may occur as well (Rivera, 2014). Recent analyses of Coupled Model Intercomparison Project 5 (CMIP5) global climate model data suggest that precipitation during early summer in the southwest will decrease along with a delayed onset of the North American monsoon, but monsoon precipitation may increase in late summer (Cook and Seager, 2013). As in other parts of the world, climate in the western U.S. is projected to become more extreme, with more intense flooding and drought conditions (Karl and Knight, 1998; Meehl et al., 2000; Groisman et al., 2005; Min et al., 2011; Melillo et al., 2014).

2.4. Assessment of changes in groundwater recharge induced by climate change

For four of the aquifer systems, estimates of climate change impacts on groundwater recharge were available from published

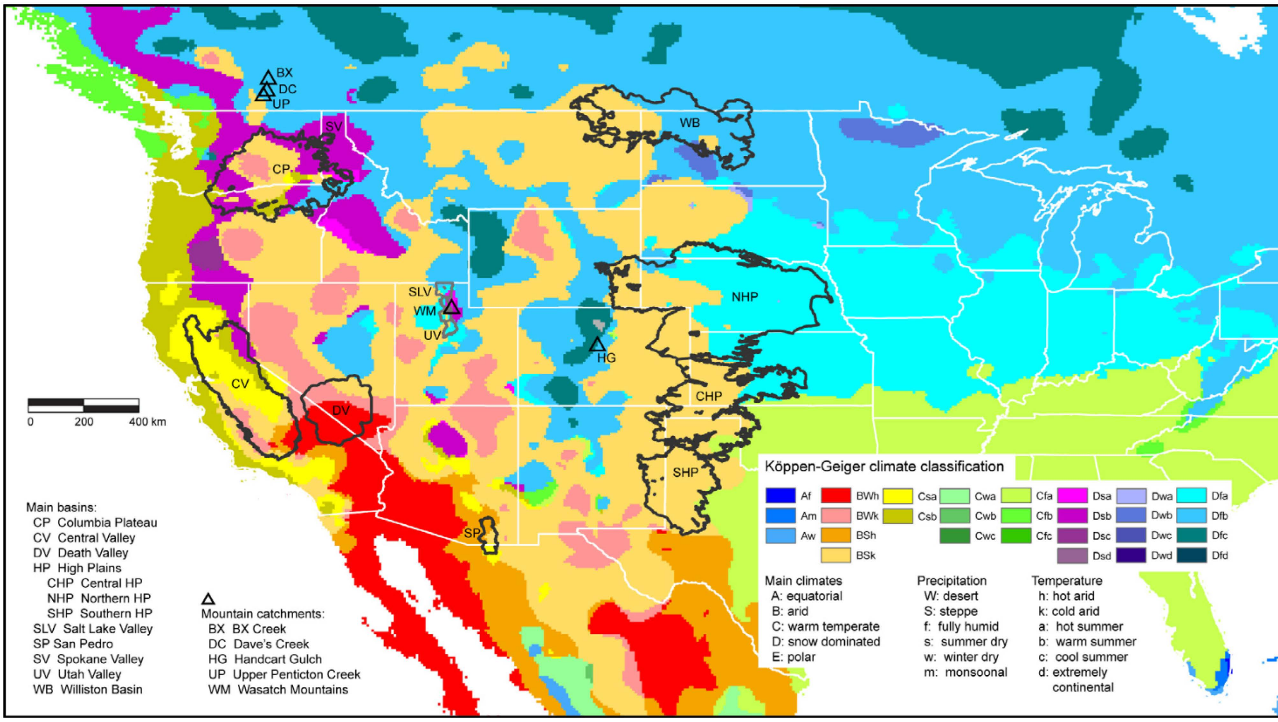

Fig. 4. Locations of main aquifer basins (outlines) and mountain catchments (triangles) for which recharge sensitivity to climate change was considered, in relation to current Köppen-Geiger climatic zones (Peel et al., 2007).

studies in which general circulation model (GCM) based climate projections were coupled with models of groundwater recharge (Fig. 5). In these studies, propagation of projected climate change into changes in groundwater recharge was accomplished by choosing a set of GCMs, selecting carbon dioxide emissions scenarios, downscaling GCM outputs (necessitated by the relatively coarse temporal and spatial resolutions of GCMs) (e.g., Teutschbein and Seibert, 2012; Hay et al., 2000), and using these to drive a hydrological model (e.g., Crosbie et al., 2013) that represents percolation through the unsaturated zone to the water table (i.e., recharge). When multiple model studies were available for a single aquifer, all were considered, and their results combined into a single range of estimates of future recharge change. The process of combining projections is described in the appropriate basin section of this paper. With the exception of the Columbia Plateau, available model-based studies were sufficiently comprehensive and robust to allow a quantitative estimate for the range of likely change in total recharge.

Climate projections vary depending on the chosen GCM and emissions scenario. The selected studies generally assumed a set of multiple GCMs and a range of multiple emissions scenarios in an attempt to bracket the range of future recharge (though two studies (Hanson et al., 2012; Ng et al., 2010) were based on a single emissions scenario) causing heterogeneity in estimated changes reflected in this analysis. The selected studies also varied in their downscaling approach, their bias correction methodology (or whether one was applied at all), and the recharge model applied. Evaluating the degree of variation in simulated future recharge potentially caused by these methodological differences is beyond the scope of this study. The authors of each basin study justify the usage of their particular climate model and downscaling approach as most suitable for their specific system (e.g., Crosbie et al., 2013; Flint and Flint, 2014).

For the other four aquifer systems, no published model-based future recharge estimates were available (nor for any other aquifers in the study region). For each of these aquifers, we used the available projections (Melillo et al., 2014; Garfin et al., 2013) for the end of the 21st century as the time frame for analysis. The direction of change of each recharge mechanism, as well as total recharge, was estimated using the basin-specific knowledge of the members of our research team who have investigated that recharge mechanism in the western U.S., and/or that particular aquifer. This exercise constituted a focused thought experiment in which changes in temperature and precipitation for that aquifer were logically propagated through the processes governing that recharge mechanism. For example, if precipitation was expected to decline and temperature to increase throughout a basin, diffuse recharge would likely decline as well as overall recharge. Countervailing factors might affect focused recharge where precipitation intensity plays an outsized role in determining recharge fluxes. With MSR, changes in precipitation and snowpack were assessed basin by basin to evaluate how recharge might change, taking into account potential changes at high versus low elevations. An underlying assumption was that a decline in snowpack in a given mountain area would lead to declines in MSR sourced from that area (Kundzewicz and Doell, 2009). Irrigation recharge, assessments of how recharge would change were based on an understanding of how water demand would change with climate change and how increased demand would propagate through the hydrologic system as currently configured and operated by agricultural irrigation users. For irrigation recharge, the response to climate change is likely to be complex and we have only approached the aspects here that address physical processes, not the ways managers and the social system might respond to climate change. Additionally, efforts to improve groundwater management and increase irrigation efficiency in the future were not addressed in this study. While the social response to climate change is important, the dynamics of water management changes and their relative magnitude were beyond the scope of this study.

Confidence levels (high, medium, and low) were assigned to estimated changes in individual recharge mechanisms based on the following criteria. A high confidence was assigned if estimates were based on published modeling studies, and model projections were consistent with each other and with the current understanding

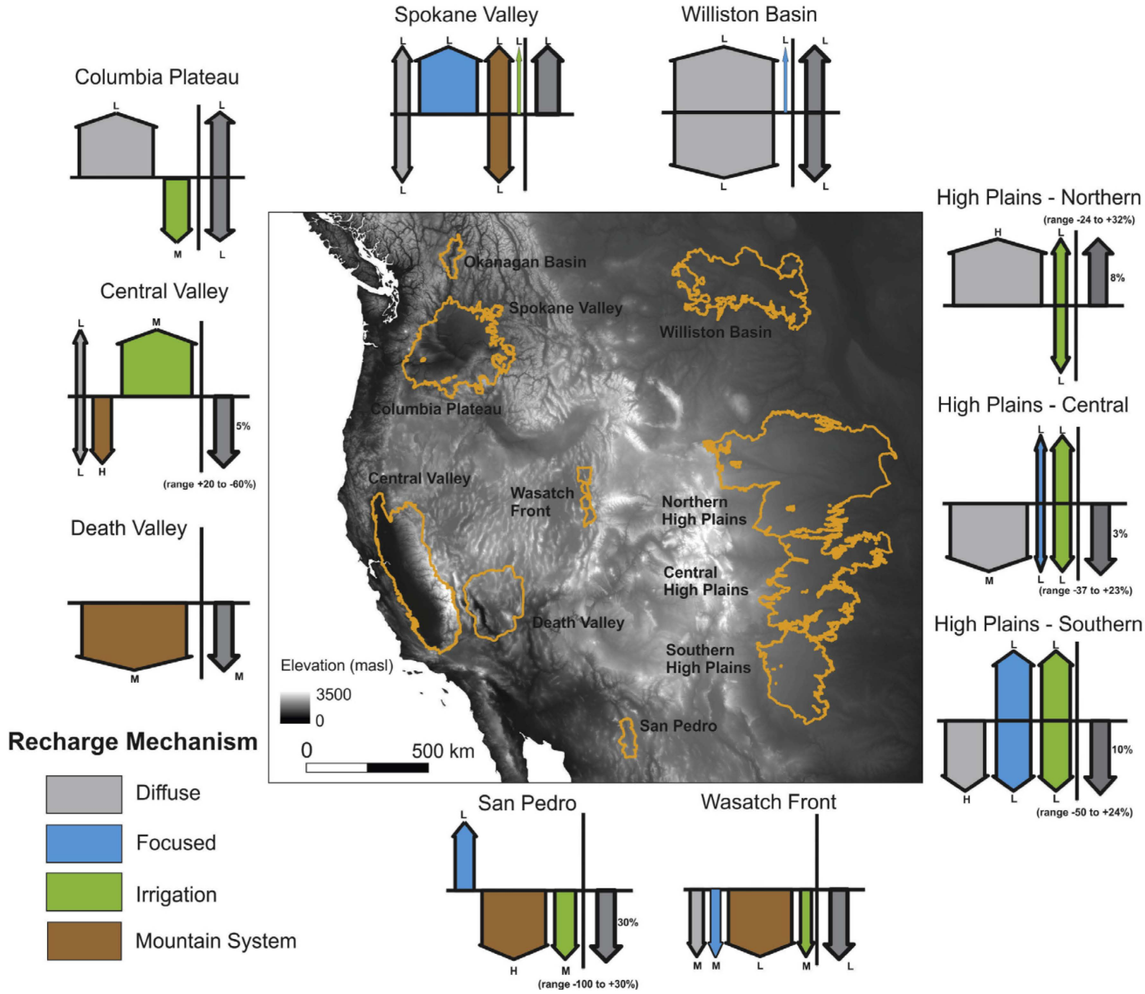

Fig. 5. Projected changes in recharge for the studied aquifers. For each aquifer, the change in each recharge mechanism is represented by an arrow with a width proportional to its fraction of total recharge based on the current climate and understanding. Total recharge is represented by dark grey arrow on far right. Arrow direction (up, down, or bidirectional) indicates the direction of change expected based on the analysis. Two arrows pointing opposite directions indicates an equal likelihood of positive and negative changes. The letters L (low), M (medium), and H (high) refer to confidence in the change indicated. Arrow lengths are all equal, and do not represent change magnitudes. Quantitative estimates of change magnitude are shown as percentages when available from existing studies.

of recharge in that aquifer system. A moderate confidence was assigned if either: (a) model-based projections exist, but are in disagreement; or (b) model-based projections do not exist, but current understanding is sufficient that the impact of climate change is relatively clear (e.g. declines in diffuse recharge due to decreased precipitation and increased temperatures). Low confidence was assigned in all other cases. For the four well studied aquifers, uncertainty in estimated changes in total recharge is reflected by the range of projected change indicated in Fig. 5 (in percent). For those aquifers where no range of projected changes in recharge was available, confidence levels similar to those for individual recharge mechanisms were also assigned to estimated changes in total recharge. These whole aquifer confidence levels were based on the confidence levels of associated individual recharge mechanisms.

2.5. Limitations of this study

As a synthesis of current understanding across a number of aquifer systems, there are limitations in study scope and interpretation. The analysis was limited by the available aquifer assessments and models across the region, the available climate simulations and their resolutions, the timing and timespan of previous investigations, and available knowledge of recharge. In particular, the time spans over which projections were made by the various studies range from 2050 to 2100 and include doubling of atmospheric CO_2 emissions. We provide the results from these underlying studies to enable a comparison across the region of how aquifers systems response might vary, but do not attempt to bring them into a common region-wide projection except for within individual aquifer projections where the results are used in a combined manner to estimate recharge response to climate change.

Additionally, these aquifers are often heavily impacted by human activity. Here the focus is primarily on natural recharge processes, which dominate in all the examined aquifers except the Central Valley (Fig. 2). Irrigation return flow is a major source of recharge in many arid and semi-arid aquifer systems (Jiménez-Martínez et al., 2010). While irrigation from groundwater pumping leads to a net reduction in aquifer storage (Stanton et al., 2011), surface water-sourced irrigation transfers water from streams to groundwater and augments natural recharge (Scanlon et al., 2007; Hanson et al., 2012). The efficiency of irrigation is particularly important, with more efficient technologies such as sprinkler and drip irrigation resulting in lower overall return flows (Scanlon et al., 2007; Dewandel et al., 2008; Kim et al., 2008), but the implementation and adoption of these techniques involves cultural and economic variables that are beyond the scope of this analysis (Steward et al., 2013). Therefore only changes in irrigation recharge that would ensue if current farming and irrigation methods remain unchanged (as reported in the studies synthesized) are considered. Irrigation recharge and the potential change in practice are a subset of larger landscape changes in land use and land cover that were not addressed by the underlying studies of this synthesis and thus not covered by this synthesis.

Finally, in most of the systems studied, vadose zone storage and the dynamic interaction of surface water flows with groundwater recharge was not included. An exception to this rule is Hanson et al. (2012), which includes a very robust representation of the how climate change will propagate through the hydrologic and water resource systems of California and how those shifts will impact groundwater recharge. The study of Shamir et al. (2015) similarly investigates surface–groundwater interactions and their impact on groundwater recharge in the micro-basin aquifer systems of the Upper Santa Cruz River system, but their study does not connect the micro-basin recharge to the larger regional aquifers system such as the eight aquifer systems included in our analysis.

3. Results – estimated future recharge conditions

3.1. High Plains aquifer

The High Plains aquifer (HPA) (also known as the Ogallala aquifer) is typically divided into northern, central and southern regions (Fig. 2). The majority of recharge is from diffuse (dominant in the north) and focused (dominant in the south) recharge processes enhanced in agricultural areas by surface water- and groundwater-sourced irrigation (Tables 1 and 2; Figs. 2 and 3; Stanton et al., 2011; Gurdak and Roe, 2010). Three published studies have estimated future changes in recharge within the HPA region over the next 50–100 years using model projections (Crosbie et al., 2013; Ng et al., 2010; Rosenberg et al., 1999). These studies suggest that the impact of climate change on recharge in the HPA will vary spatially, with moderate increases in recharge in the north, shifting to moderate decreases in the south (Fig. 5). This change would exacerbate existing water shortage in the south and increase recharge in the northern portions of the aquifer. These studies show that expected shifts in precipitation will cause an overall net decrease in diffuse recharge, but may increase diffuse recharge in the Sand Hills in the north. Changes in focused recharge in the central and southern HPA remain uncertain and it could increase or decrease (Crosbie et al., 2013) (Fig. 5). However, a potential increase in focused recharge is not expected to significantly offset the decrease in diffuse recharge. Crosbie et al. (2013) and Ng et al. (2010) indicated that predicted changes in recharge will be greater than the corresponding changes in precipitation (Table 3).

3.2. San Pedro aquifer

Recharge at the basin margins as a result of MSR dominates total annual recharge to the San Pedro aquifer, with additional contributions from focused recharge in ephemeral channels and irrigation recharge (Tables 1 and 2). Two published studies using the same empirical equation (Anderson et al., 1992) with different GCMs (Serrat-Capdevila et al., 2007; Ajami et al., 2012) support the projection that groundwater recharge will decrease in the San Pedro aquifer over the next 100 years (through 2100). Serrat-Capdevila et al. (2007) showed that groundwater recharge in the basin will decrease on average by 30% over the next 100 years.

Table 3
Groundwater recharge future scenario method details.

Basin	Studies	GCM[a]	Emissions scenario	Nature of Climate Change Projections	Downscaling approach	Bias correction method	Recharge estimation approach
High Plains	Crosbie et al. (2013)	CMIP3 (16 total GCMs)[a]	Low, medium and high	Year – 2050	Delta change method	N/A[b]	WAVES model (Zhang and Dawes, 1998)
	Ng et al. (2010)	CMIP3 (3 total GCMs)	SRES A1B	Years – 2080–2099	Delta change method	N/A	SWAP model (van Dam et al., 2008)
Northern High Plains	Rosenberg et al. (1999)	GISS, UKTR, BMRC	Low, medium and high	Atm CO_2 of 365, 560 or 750 ppm	Delta change method	N/A	SWAT model (Arnold et al., 1998)
San Pedro	Serrat-Capdevila et al. (2007) and Ajami et al. (2012)	CMIP2 and CMIP3	A1, A2, B1, B2 and A1B	2050–2099 for both	Delta change method and CMIP3 GCM	BCSD[a]	Anderson et al. (1992)
Central Valley	Flint and Flint (2014)	CMIP3 and CMIP5	B1, A2, A1B and RCP 2.6–8.5	2070–2099	BCSD for 14 and constructed analogues for 4	BCSD	BCM (Flint and Flint, 2007)
	Hanson et al. (2012)	GFDL	A2	Present-2100	BCSD	BCSD	BCM (Flint and Flint, 2007) and MF-FMP2 (Schmid and Hanson, 2009)
Columbia Plateau	Vaccaro (1992)	Goddard, GFDL, OSU	Doubled CO_2	Non-specific Doubled CO_2	Transformed historic record using GCM output	N/A	DPM model (Bauer and Vaccaro, 1987)

[a] Global Circulation Models (GCMs); Community Modeling Integration Program, phase 3 (CMIP3); Bias Corrected Statistical Downscaling (BCSD).
[b] N/A, not applicable.

Future recharge varied from a 100% decline in recharge to a 30% increase in recharge across the GCMs used. Ajami et al. (2012) developed a partitioning index based on seasonal precipitation and ET (normalized seasonal wetness index) to conduct the dynamic partitioning of annual recharge. Results of recharge projections from Ajami et al. (2012) show that total aquifer recharge is significantly more sensitive to changes in winter precipitation than changes in summer precipitation. Overall, results of Ajami et al. (2012) indicate a 27% decrease in recharge (using ECHAM5) to no change (using HADCM3) in recharge. Given the agreement between the two available studies it is estimated that total recharge, and MSR in particular, will decrease in the future (Fig. 5). With less confidence it is expected that focused recharge in the San Pedro aquifer may increase due to increased precipitation intensity (Dominguez et al., 2012) (Table 3).

3.3. Death Valley regional flow system

Recharge to the Death Valley regional flow system (DVRFS) occurs almost entirely from infiltration of precipitation and runoff (particularly as snowmelt) in mountain systems and is low, reflecting the area's extreme aridity (Tables 1 and 2) (Hevesi et al., 2003; Stonestrom et al., 2003). Decreased groundwater recharge is anticipated in the DVRFS due to decreases in winter precipitation and snowpack (Garfin et al., 2013; Hevesi et al., 2003; Fig. 5). The projected warmer temperatures for the region, particularly in late spring and summer (Garfin et al., 2013), are expected to increase partitioning of soil moisture and shallow groundwater to ET, cause less extensive and shorter duration snowpacks, and thus less recharge (particularly MSR). Sources of uncertainty include potential increases in summer precipitation and winter precipitation intensity, which could lead to increased focused recharge. This source of recharge is currently so small that even large relative changes would result in negligible changes to total recharge (Hevesi et al., 2003; Stonestrom et al., 2003; Fig. 5).

3.4. Wasatch Front aquifers

A series of alluvial aquifers extends from the Utah-Idaho border southward approximately 200 km into central Utah, bounded to the east by the Wasatch Mountains (Tables 1 and 2; Fig. 2). The Wasatch Front aquifers (WFA) herein refers to the two best studied and populous of these basins, the Salt Lake Valley and Northern Utah Valley. The largest recharge component for the WFA is MSR, followed by diffuse, irrigation, and focused recharge. Projected climatic changes will likely produce an overall decrease in recharge to the WFA (Fig. 5). Diffuse valley-floor recharge will likely decrease due to higher ET rates associated with warmer temperatures and decreased spring precipitation. MSR will probably decrease due to an overall decrease in mountain recharge and mountain streamflow resulting from: (a) warmer temperatures leading to higher ET rates (including greater sublimation), particularly in spring time; (b) decreased spring precipitation leading to less total snowpack and snowmelt; and (c) a decrease in the snow fraction of precipitation and thus smaller snowpack depths, particularly at middle and lower elevations. However, decreasing MSR rates are far from certain, and could be offset by increases in high-elevation snowpack, more gradual snowpack melting, and other factors. Focused recharge in the valley away from mountain fronts will likely decrease, mainly because of anticipated declines in surface water flows. Irrigation recharge would also likely decrease due to growing urbanization (Thiros et al., 2010; Cederberg et al., 2009).

3.5. Central Valley aquifer system

Recharge to the Central Valley is dominated by irrigation recharge, with MSR and diffuse recharge playing subsidiary roles (Fig. 2; Faunt, 2009) (Tables 1 and 2). Modeled future recharge rates presented in Flint and Flint (2014) suggest that projected climate change is expected to decrease recharge by an average of 5% by 2100. These projections include a large range of uncertainty (upwards of ±25%) that includes no change in recharge. Flint and Flint (2014) employ output from 18 climate models to investigate recharge under future climate conditions under a variety of emissions scenarios. All 18 climate models predict that warming will reduce total winter snow water equivalent (SWE) in neighboring mountains, with the largest declines in the northern part of the Sierra Nevada. Ten of the 18 future climate scenarios show an increase in total precipitation, leading to an increase in diffuse recharge (Flint and Flint, 2014). Simulations forecasted increases in temperature which lead to an increase in irrigation, which also leads to increased recharge from irrigation return flow (Hanson et al., 2012). However, the large loss of MSR from declining mountain SWE outweighs these increases in diffuse and irrigation recharge, leading to a reduction in total recharge across the many scenarios studied (Flint and Flint, 2014).

Hanson et al. (2012) modeled future recharge conditions throughout the 21st century using a single GCM (General Fluid Dynamics Laboratory model) and emissions scenario (A2), and they coupled GCM output to a comprehensive numerical representation of the hydrological system that included groundwater flow, surface flow, and water delivery systems (in addition to recharge). Simulated future total recharge decreased, in general agreement with the finding of Flint and Flint (2014), but declines were larger, ranging from 25% to 60%. Although Hanson et al. (2012) employed a more robust representation of the entire hydrologic system, there is less confidence in their range of recharge outcomes due to their use of a single GCM and emissions scenario (they use the same recharge model as Flint and Flint, 2014). The mean total recharge change estimate of Flint and Flint (−5%) was thus adopted, but the negative uncertainty range was expanded to −60% to incorporate the findings of Hanson et al. (2012) (Table 3 and Fig. 5).

3.6. Columbia Plateau aquifer system

Diffuse recharge is the primary recharge mechanism for the Columbia Plateau aquifer system, with irrigation providing the balance of recharge (Fig. 2; Kahle et al., 2011; Burns et al., 2012). Vaccaro (1992) investigated future recharge to a highly-developed portion of the system (the 937 km^2 Ellensburg basin) using a deep-percolation water-balance model. Historical daily precipitation and temperature time series were adjusted by the projected temperature and precipitation shifts predicted by three GCMs under a doubling of atmospheric CO_2 levels compared to pre-industrial levels (Goddard, GFDL, OSU) (Table 3). Simulated future diffuse recharge increased, due to increased precipitation exceeding increased ET in the cool months, and irrigation recharge decreased, due to substantially increased ET during the growing season (Table 3 and Fig. 5). Simulated total recharge decreased because the decrease in irrigation recharge (−37 mm) was larger than the increase in diffuse recharge (+6 mm). Extrapolating this result to the entire Columbia Plateau is complicated by the fact that diffuse recharge comprises a considerably larger fraction of total recharge for the entire aquifer than for the agriculturally-intensive modeled area. Therefore, even a modest future increase in diffuse recharge could lead to an increase in total recharge across the whole plateau. Nevertheless, if the magnitude (relative or absolute) of modeled changes in diffuse and irrigation components are directly applied to the current estimated diffuse and irrigation components for the whole aquifer (Table 2), a small decrease in total recharge results. Recent non-model-based studies have suggested that diffuse recharge may actually decrease because future increases in precipitation may not be adequate to overcome future increases in ET (Kahle et al., 2011; Washington State Department of Ecology, 2011). Aquifer-wide changes in total recharge thus remain relatively uncertain, and may either increase or decrease (Fig. 5).

3.7. Spokane Valley-Rathdrum Prairie aquifer

The three predominant sources of recharge to the Spokane Valley-Rathdrum Prairie (SVRP) aquifer are focused recharge from the Spokane River and two major reservoirs, MSR from tributary upland basins, and diffuse infiltration of precipitation (Fig. 2). With projected warmer temperatures and slight precipitation increases, changes in recharge will hinge primarily on whether the effects of warming (greater ET) outweigh the effects of increased precipitation (Mote et al., 2008; Mote and Salathé, 2010; Reclamation, 2011; Robson and Banta, 1995). Due to a lack of relevant studies, it is currently not possible to estimate whether diffuse recharge will increase or decrease, and both scenarios appear equally likely (Fig. 5). Similarly, increasing and decreasing MSR appear equally likely; both MBR and surface water flow from upland tributary basins could decrease due to increasing mountain ET and smaller snowpacks (particularly at lower elevations). However, this effect could be compensated by increasing precipitation, particularly greater snowfall at higher elevations (Lundquist et al., 2009). Focused recharge from the Spokane River and associated reservoirs is expected to increase slightly given the close link between precipitation, river flows, and seepage loss (Hsieh et al., 2007), and the expected precipitation increases in this system.

3.8. Williston Basin aquifer system

Recharge to the Williston Basin consists almost entirely of diffuse recharge, with a small amount of focused recharge through streambeds (Fig. 2; Long et al., 2014). Changes in total recharge will thus depend upon changes in diffuse recharge. As in the SVRP, changes in diffuse recharge will depend upon the net effect of two competing factors, a temperature increase (and thus increased ET) and a precipitation increase (Reclamation, 2011). Because surface soils in the Williston Basin generally have low permeability (Long et al., 2014), it is likely that modest increases in shallow soil moisture resulting from precipitation increases would be lost to ET. Mean annual soil water storage is projected to generally decline across the Williston Basin area through the 21st century according to the U.S. Geological Survey's National Climate Change Viewer (http://www.usgs.gov/climate_landuse/clu_rd/apps/nccv_viewer.asp). These considerations suggest that diffuse recharge to the Williston Basin may decline. However, model-based projections in multiple studies of future recharge to the northern HPA, located directly south of the Williston Basin, indicate that diffuse recharge will increase. Given these inconsistent outlooks, uncertainty in future diffuse recharge is high (Fig. 5). Higher intensity rainfall is projected for the Williston Basin area (Gutowski et al., 2008; Lundquist et al., 2009). This change in rainfall may increase focused recharge, but the impact on total recharge would not be significant as focused recharge currently contributes a small fraction of total recharge.

3.9. Mountain aquifers

Mountain aquifers are individually small compared to the eight major aquifer systems considered above, and they directly support only small communities. However, mountain aquifers were included in this analysis due to their essential role in storing and transmitting groundwater that becomes mountain system recharge to adjacent aquifer systems. Changes in recharge in the mountains due to climate change will translate into changes in mountain aquifer storage and discharge, which in turn will directly influence MBR and MFR and thus MSR. Studies of mountain aquifers, while few, do provide sufficient knowledge of mountain recharge and flow processes to guide inferences regarding potential changes under future climate conditions. Between 61% and 93% of diffuse mountain catchment recharge becomes streamflow (available for basin aquifer recharge by stream loss), and between 7% and 39% becomes MBR (Table S1; Fig. 2).

Snowmelt likely contributes the majority of recharge in most mountain regions of the western U.S., either because snow comprises the majority of precipitation, or snowmelt more effectively infiltrates below the root zone than rainwater (Earman et al., 2006). Snowmelt can comprise a disproportionately large fraction of recharge because a substantial amount of water is released from the snowpack over a prolonged period in early spring, when ET is low (Ajami et al., 2012; Earman et al., 2006; Eckhardt and Ulbrich, 2003; Winograd et al., 1998). Mountain recharge is therefore sensitive to climatic shifts that result in changes in snowpack snow water equivalent (SWE). Warmer temperatures projected for the entire region will likely produce a decrease in maximum annual SWE due to a smaller fraction of precipitation falling as snow and more winter melting events (Mote et al., 2005). Warming will also likely increase ET (including snowpack sublimation), which should impact both rain-dominated and snow-dominated systems. These factors are likely to cause a general decrease in mountain recharge, particularly in the south where warming will be greatest and probably accompanied by a decrease in spring precipitation. However, other factors could buffer this decrease, or even produce an increase in mountain recharge. First, SWE (and winter rain in coastal mountains) could increase in the north and at the highest elevations in the south due to a possible increase in winter precipitation, accompanied by more atmospheric river events (Rasmussen et al., 2011; Dominguez et al., 2012; Rivera et al. 2014). Second, recharge in many mountain areas is permeability-limited rather than recharge-limited due to thin soils overlying low-permeability crystalline bedrock (Flint et al., 2008). A decrease in maximum annual SWE in these areas may decrease spring streamflow (overland flow of snowmelt to streams) but have little influence on recharge because spring snowmelt substantially exceeds the unsaturated zone storage capacity (Blankinship et al., 2014). Recharge could also increase in these areas as a result of a more gradual release of water from the snowpack due to enhanced winter melting (Byrne et al., 2014).

The difficulty of predicting changes to MSR is compounded by the fact that MSR depends on not only the total amount of mountain recharge, but also the spatial distribution and timing of mountain recharge and streamflow generation. For example, although recharge could increase at the highest elevations in the south, MBR may still decrease because the majority of MBR can be sourced from watersheds adjacent to the mountain front that have lower mean elevations (Manning and Solomon, 2005; Welch and Allen, 2012). Predicting MSR changes requires forecasts of changes in the each of the two different MSR components, which in turn requires knowledge of groundwater routing within mountain systems that is generally unavailable. In short, MSR appears likely to decrease in the south, but changes in MSR remain uncertain throughout the region given limited understanding of mountain recharge processes and groundwater flow in mountain blocks.

4. Discussion

4.1. General changes in groundwater recharge across the western United States

Several key observations can be synthesized from these existing studies. The largest declines in recharge are expected for the aquifer systems in the southwestern U.S., including the San Pedro aquifer, the southern HPA, the southern sections of the Central Valley, and the DVRFS (Fig. 5; Serrat-Capdevila et al., 2007; Crosbie et al., 2013; Hanson et al., 2012). Farther north, expected decreases in recharge are more moderate or nonexistent. This pattern is clearly illustrated in the HPA: the southern HPA is expected to receive 10% less recharge, the central HPA 3% less, and the northern HPA 8% more through the year 2050 (Crosbie et al., 2013). Similarly, in the Central Valley larger reductions in recharge are projected for the southern portion of the valley (Hanson et al., 2012). Whether or not this spatial pattern holds throughout the Basin and Range Province is unclear, as only the San Pedro basin has had coupled GCM-groundwater-recharge studies completed. Across the northern set of aquifers (Columbia Plateau, SVRP, and Williston Basin) projections remain uncertain. Nevertheless, available information suggests that, in contrast to the southwestern aquifers, modest increases in recharge are as likely as declines in recharge (Fig. 5).

Together these results show that the wet areas will get wetter and the dry areas will get drier (Trenberth, 2011). In particular, because recharge is a threshold process, as dry places get drier, recharge will decrease more sharply than precipitation declines as shown in several studies (Serrat-Capdevila et al., 2007; Ajami et al., 2012; Crosbie et al., 2013; Ng et al., 2010). Importantly, the southern extents of the Central Valley, the southern HPA and the San Pedro aquifer are all locations of significant groundwater overdraft under current climate conditions (Konikow, 2013) (Table 2). The results of available studies indicate that this overdraft will become more severe as recharge declines and pressure to increase groundwater pumping grows (Loáiciga, 2003). In contrast, there is a potential for increased recharge across the northern set of aquifers, though confidence in the expected changes is low.

4.2. Changes in recharge mechanisms

Similar to overall recharge, there are discernible trends in the geographic patterns of change in individual recharge mechanisms. MSR is expected to decrease in all of the systems investigated where MSR is a significant recharge component (Figs. 2 and 4). The strongest evidence for this decline is the modeled changes in both the Central Valley (Hanson et al., 2012) and the San Pedro aquifer (Serrat-Capdevila et al., 2007). In these systems, the change in MSR is driven by both decreased winter precipitation and a decline in the fraction of winter precipitation arriving as snow (increasing rain/snow ratio). Similar mechanisms are expected to cause a decline in MSR in the DVRFS and WFA. However, confidence in declining MSR rates decreases substantially toward the east and north where total precipitation will decrease less (Garfin et al., 2013; Melillo et al., 2014) (or may increase), meaning that changes in MSR would be driven primarily by increasing rain/snow ratios. The effect of increasing rain/snow ratios on MSR, particularly the MBR component, is difficult to predict given the current limited understanding of recharge processes in snow-dominated mountain settings (Viviroli et al., 2007).

The pattern of changes in diffuse recharge is more complex. There is high confidence that several systems (central HPA, southern HPA, and WFA) will experience a reduction in diffuse recharge as a result of the combined effects of increasing temperature and decreasing precipitation. However, changes in diffuse recharge are considerably more uncertain in more northern systems where precipitation will increase. In some cases (e.g., Columbia Plateau and the Northern HPA) increases in precipitation are expected to be large enough to counteract increases in ET driven by warmer temperatures (Vaccaro, 1992). In other cases (e.g., Williston Basin), the net effect of increases in both ET and precipitation remains uncertain (Rosenberg et al., 1999). The increased plant water-use efficiency through improved stomatal conductance at higher CO_2 concentrations has not been extensively studied especially at the basin scale, and its effect on deep percolation is uncertain. Nevertheless, Rosenberg et al. (1999) found that temperature increases were sufficient to overcome the effect of CO_2 fertilization in the High Plains system.

Focused recharge is expected to increase in several of the aquifers studied. The reason for this expected increase is that precipitation intensity will likely increase in a warmer climate due to the greater water vapor holding capacity of the atmosphere (Dominguez et al., 2012). While expected increases in precipitation intensity might increase focused recharge, the magnitude of this change is challenging to quantify due to: (a) the relative uncertainty of projected changes in precipitation intensity, particularly associated with convection during the warm season; (b) a lack of understanding of how to use coarse-resolution climate, land-surface, and hydrologic model outputs to effectively predict the fine-resolution process of focused recharge (Ng et al., 2010; Pulido-Velazquez et al., 2015); and (c) the relatively short lived peak flows that induce focused recharge might not greatly impact overall recharge fluxes. A recent example of an analysis of the interaction of climate change with focused recharge is provided by Shamir et al. (2015), which evaluated focused recharge to small micro-basin aquifers along the Upper Santa Cruz River in southern Arizona. While their study did not connect to regional aquifers like those investigated in this synthesis, the methods utilized are applicable to investigating these larger scale regional systems.

Irrigation recharge is expected to increase in environments where surface water irrigation is used (e.g., Central Valley, northern HPA) (Hanson et al., 2012; Crosbie et al., 2013). While irrigation recharge may also increase in areas dependent on groundwater for irrigation (southern HPA, central HPA), the net effect of more irrigation with groundwater is net loss in groundwater storage (Stanton et al., 2011). While increased irrigation is a high-confidence prediction for a warmer world (Loáiciga, 2003), the effect of such a change on recharge is more difficult to forecast due to the variety of ways the human system can adapt to climate change (e.g., increased efficiency, change in crop type, alterations in irrigation practices).

4.3. Gaps in knowledge

Several gaps in knowledge about the impact of climate change on groundwater recharge across this region became evident as this study was conducted. First, only four aquifer systems in the western U.S. had been studied using GCM model results to drive recharge estimates. Basin-specific knowledge of recharge mechanisms and climate projections and their implied impact on recharge is useful and gives a general indication of how recharge might change in the future, but subtleties in the response of the water balance to changes in precipitation and ET cannot be teased apart without numerical simulation of feedbacks between processes (e.g., Crosbie et al., 2013). Given the potentially countervailing impacts of precipitation changes, temperature and ET increases, and the effects of increased CO_2 on plant water use efficiency, coupled modeling studies offer a way forward for understanding how groundwater recharge might change in a particular area. Such coupling should ideally take place within the context of atmospheric modeling where (1) the dominant physical mechanisms of precipitation generation in the western U.S. are explicitly resolved (principally warm season convective thunderstorms and cool season synoptically and orographically-forced rain and snow) (e.g., Flint and Flint, 2014; Ng et al., 2010), and (2) surface energy and water exchanges incorporate more dynamic treatments of ecosystems (especially vegetation) and groundwater (e.g., Hanson et al., 2012; Markstrom et al., 2008). Such applications are nontrivial due to computational demands and the lack of data to robustly parametrize earth surface and vegetational processes. In addition, throughout most studies synthesized, higher temperatures were assumed to lead to higher actual ET, an assumption that is far from settled (Roderick et al., 2015; see also Greve and Seneviratne, 2015).

Second, the response of mountain systems to climate change represents a key knowledge gap due to a lack of process level understanding. It is often assumed that decreased snowpack will lead to decreased groundwater recharge (Taylor et al., 2013; Tague and Grant, 2009). However, the actual net effect of changes in temperature and precipitation on mountain stream flows and MBR remains uncertain due to the generally poor understanding of mountain aquifers (Viviroli et al., 2007). Detailed study of infiltration and recharge processes, aquifer characteristics (structure, permeability, and storage), and flow pathways needs to be a focus of future research in order to predict how MSR will respond to warmer temperatures and elevation-dependent changes in precipitation patterns.

Third, the integrated agro-ecosystem response to changes in climate and the resulting farming and irrigation practices may have large implications for groundwater recharge in agricultural areas (Green et al., 2011; Taylor et al., 2013). This review found only two published estimates of future recharge in the western U.S. that considered potential changes in farming and irrigation (Hanson et al., 2012; Flint and Flint, 2014). Variations in climate will undoubtedly change the quantity and timing of groundwater pumping and irrigation application (Loáiciga, 2003; Hanson et al., 2012). A robust analysis of agronomic systems is needed to understand how these systems might respond on an integrated basis to climate change.

5. Conclusions

This investigation synthesized the current state of knowledge about how aquifers in the western U.S. might respond to projected climate change. Regions in Asia, Africa and South America have similar recharge environments and the knowledge gained in this study about how to assess the impact of climate change on groundwater recharge at the regional scale may be of interest to investigators in these and other regions (Trenberth, 2011; Döll and Fiedler, 2007).

The key outcome is that existing information supports a "wet gets wetter, dry gets drier" scenario. Southern portions of the western U.S. are likely to experience declines in recharge of varying magnitudes. Northern portions of the western U.S. may experience slight increases to modest declines. In the relatively unstudied aquifers of the northern half of the western U.S. (e.g., Spokane Valley-Rathdrum Prairie and Williston Basin), a lack of coupled GCM groundwater modeling makes it difficult to predict the direction and magnitude of changes with confidence.

Anticipated changes in recharge mechanisms display definite regional patterns in magnitude and confidence. Mountain System Recharge (MSR) is expected to decrease with high certainty in the southern and western portions of the region and with lower certainty in the northern and eastern portions. This gradient in confidence results from decreases in precipitation being responsible for decreased MSR in the south, whereas change in the form of precipitation (from snow to rain) underlies the expected change in the north. A lack of robust knowledge of mountain system processes means that the impacts of snow-to-rain transitions are relatively uncertain. Also, declines in MSR due to expected snow-rain shifts may be offset in the north by increased precipitation amounts. The pattern of decreased diffuse recharge in the south to little change or slight increases in the north is fairly robust and certain. Forecasted increases in precipitation intensity are highly uncertain but if realized should increase focused recharge in most aquifer systems. Finally, future irrigation recharge is highly uncertain due to interactions among markets, climate, and agricultural practices across the west.

Patterns of expected recharge change (in total recharge and recharge mechanism) inherit all of the uncertainties of the underlying GCMs and downscaled average climatologies. These uncertainties are compounded by projected increases in variance (intensifications) that while expected on solid physical grounds are poorly resolved in current climate projections. Uncertainties regarding the impacts of future climate change on MSR, focused recharge, and irrigation recharge present the greatest opportunities for improvement through process level studies. The need for integrated modeling that links future changes in climate to recharge mechanisms and flow paths to realistically propagate the changes through aquifer systems across broad regions like the western U.S. is the main conclusion of this synthesis.

Acknowledgments

The synthesis work reported in this paper is the result of a John Wesley Powell Center group "Potential Impacts of Prospective Climate Change on Groundwater Recharge in the Western United States". The work received support from the USGS and also from the NSF through a concurrent award (EAR-1328505). Additional support to several authors was provided by the USGS National Research Program and the USGS Office of Groundwater. We also wish to thank Jill Baron and the staff of the Powell Center for their assistance in meeting arrangements and their professional attitude and pleasant demeanor.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2015.12.027.

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