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Climate Change, Agriculture and Water Resources in the Southwestern United States

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Abstract: In February 2014 the USDA established regional climate hubs across the United States to assist farmers, ranchers and foresters in adapting to the effects of climate change. The Southwest (SW) region encompasses six states which provide highly diverse agricultural crops including cotton, stone fruit and grapes. Here we report on the hydrologic context within which SW working landowners operate, with focus on regional water resources and likely impacts of climate change. Water is a critical component of agricultural vulnerability in the SW, where high agricultural production can occur with sufficient irrigation. Since 1978, crop yield declines were reported on 11-21% of total irrigated acres, mostly due to surface water shortage. Southwestern agriculture relies on groundwater, using it to supply at least one-third of the agricultural water demand across the region since 1955. Regional groundwater use varies over time, with a decline in the agricultural groundwater fraction in Arizona, but an increase in the fraction in Nevada and Utah. Observed and predicted changes in the southwestern hydrologic cycle can impact regional agriculture. Observed records show an increase in the fraction of precipitation falling as rain, which is expected to continue with future warming, and decrease the natural high-mountain storage reservoir provided by snowpack. Warming causes the snowmelt to peak earlier in the season than observed in historical records, and can reduce water available to crops during the summer months without additional water storage. Observed records indicate streamflow has shifted earlier in the year, most notably in snow dominated watersheds. A continuation of this trend may challenge regional agriculture by further limiting water supplies.

Keywords: *climate change, agriculture, water resources, Southwest Climate Hub*

In February 2014 the U.S. Department of Agriculture (USDA) created seven regional hubs and three subsidiary hubs across the U.S. for climate change adaptation and mitigation (Figure 1). The overall goal of the regional hubs is to maintain and strengthen agricultural production and conservation of natural resources under increasing climate variability and environmental change.

The USDA Southwest Regional Climate Hub (SW Hub) works in six states: New Mexico, Arizona, Utah, Nevada, California and Hawaii (and the U.S. affiliated Pacific Islands west of Hawaii) (http://www.climatehubs.oce.usda.gov/southwest). There are major deserts in five of the six SW Hub states and irrigation water is essential in maintaining agricultural production and local economies of the region. Consequently, the SW Hub focuses on research activities related to limited water supplies, drought, climate change and agriculture in the arid SW. This article provides the operational context within which the SW Hub functions with regard to natural and man-made water storage, irrigation, and drought as well as the likely implications for water management in a changed climate. Southwestern agriculture is defined by availability of water for irrigation, which will generally decrease in the southwestern U.S. over time (Dettinger, Udall, and Georgakakos 2015).

Irrigation in the Southwest

When there is sufficient water for irrigation, the region can support plentiful agricultural production. California leads the U.S. in agricultural productivity

(USDA–ERS 2015) and depends heavily on irrigation in the Central Valley. California accounts for 66-70% of the total irrigated area in the region, with 7.5 to 9 M irrigated acres (Figure 2). While the total irrigated area in other states in the SW region is less than that of California, irrigation is vital to crop production in all states of the region. Since 1978, total irrigated acres have fluctuated somewhat in each state, with an apparent slight decline in Arizona, Hawaii and Nevada. Irrigated area in Utah has remained fairly constant since 1978.

Snowmelt produces a large portion of the water used for irrigation in the SW. In certain snowmelt mountain basins of the SW, snow is the source of up to 75% of the seasonal water supply (Serreze et al. 1999; Hamlet et al. 2005; Rango 2006). The snow cover in New Mexico, Arizona, Utah, Nevada, and California usually persists for up to six months or more, which acts as a natural reservoir releasing the snowmelt water gradually during the early part of the growing season (Serreze et al. 1999). Storage of water runoff from snow in artificial reservoirs then takes over in supplying irrigation water for the latter part of the growing season. Traditionally water is stored in surface reservoirs during times of excess. During drought conditions, reservoir supplies can be depleted, leading to low water levels associated with reservoir draw-down. As surface water supplies in streams and reservoirs decline, farmers rely upon supplemental groundwater supplies. Pumping of water from wells can be costly and result in declining water tables, further incurring pumping costs (Konikow 2013; Taylor et al. 2013). Such activities are essentially mining the groundwater, or removing groundwater in excess of the recharge rate of the aquifer.

Diminished Yields from Irrigation Interruption

The farm and ranch irrigation survey (FRIS), conducted every five years, collects information on irrigation across the U.S. (NASS 2015). The FRIS reports crops with diminished yields resulting from irrigation interruption by cause. Between 1978 and 2012, 11-21% of the total irrigated acreage in the SW region had crop yield declines due to irrigation interruption. The total diminished regional acreage ranged from 1.4 M acres (1982) to 2.4 M acres (2007). The potential causes included in the survey are shortage of surface water, shortage of groundwater, irrigation equipment failure, energy shortage, poor water quality, loss of water rights and other causes. Since 1978, the most reported cause of irrigation interruption and diminished crop yields in the SW is shortage of surface water (Figure 3). Over 70% of respondents indicated surface water shortage as the cause of irrigation interruption in the most recent surveys (2002, 2007, and 2012). Groundwater shortage was indicated for 3-30% of acreage with interrupted irrigation, with the highest percentage in the most recent surveys (2007, 2012). Shortage of surface water and groundwater appear to comprise a larger portion of the yield reduction cause in more recent years (1992, 2002, 2007 and 2012). Irrigation equipment failure caused crop yield reduction 9 to 42% of the time. Energy shortage was reported at 22% in 1978, but declined as a cause to 6% in 2012. Poor water quality, loss of water rights and water costs were less frequently reported causes of irrigation interruption and diminished crop yields.

These reductions in crop yield based upon unexpected irrigation interruptions reflect the current climate within which SW farmers operate. The hotter and drier conditions predicted in a changing climate represent a ‘new normal’ that could further exacerbate crop yield declines due to likely additional irrigation interruptions (Diffenbaugh, Swain, and Touma 2015). Irrigation serves as an important adaptive strategy to cope with higher temperatures (Haim, Shechter, and Berliner 2008), however shifts in relative profitability of irrigated production and declining water supplies may drive declining irrigated acreage in parts of the Southwest, mostly due to surface water constraints of a changing climate (Marshall et al. 2015).

Discontinued Irrigation in the Southwest

FRIS also reports discontinued irrigation statistics. Historically, the reason for discontinued irrigation is not consistently lack of water. For example, in 2003 most farmers cited sufficient soil moisture as the reason for discontinued irrigation, whereas shortage of surface and groundwater was the major reason in 2013. In 2013, 7,805 farms (470,404 acres) throughout the SW reported that they had discontinued irrigation since the previous census year; among the reasons for



Figure 1. United States Department of Agriculture Southwest Climate Hub Region.

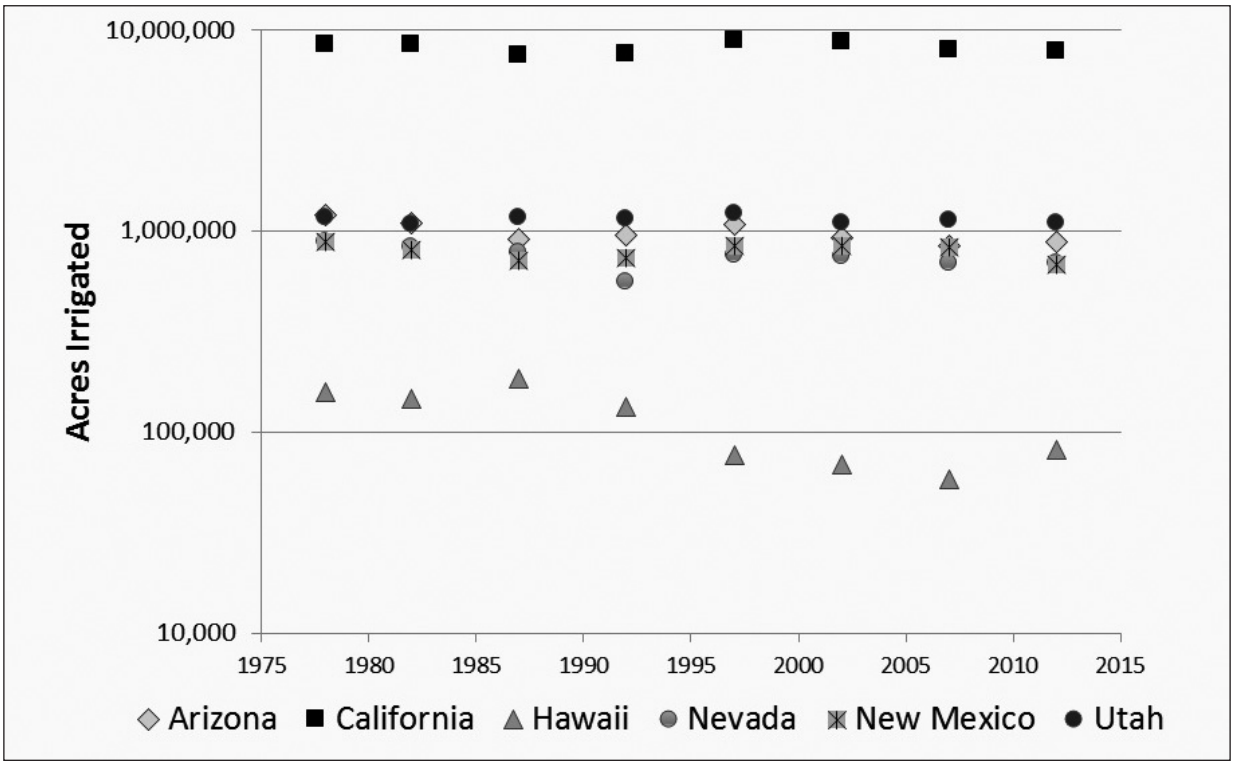

Figure 2. Acres irrigated by state in the Southwest Climate Hub region (NASS 2015).

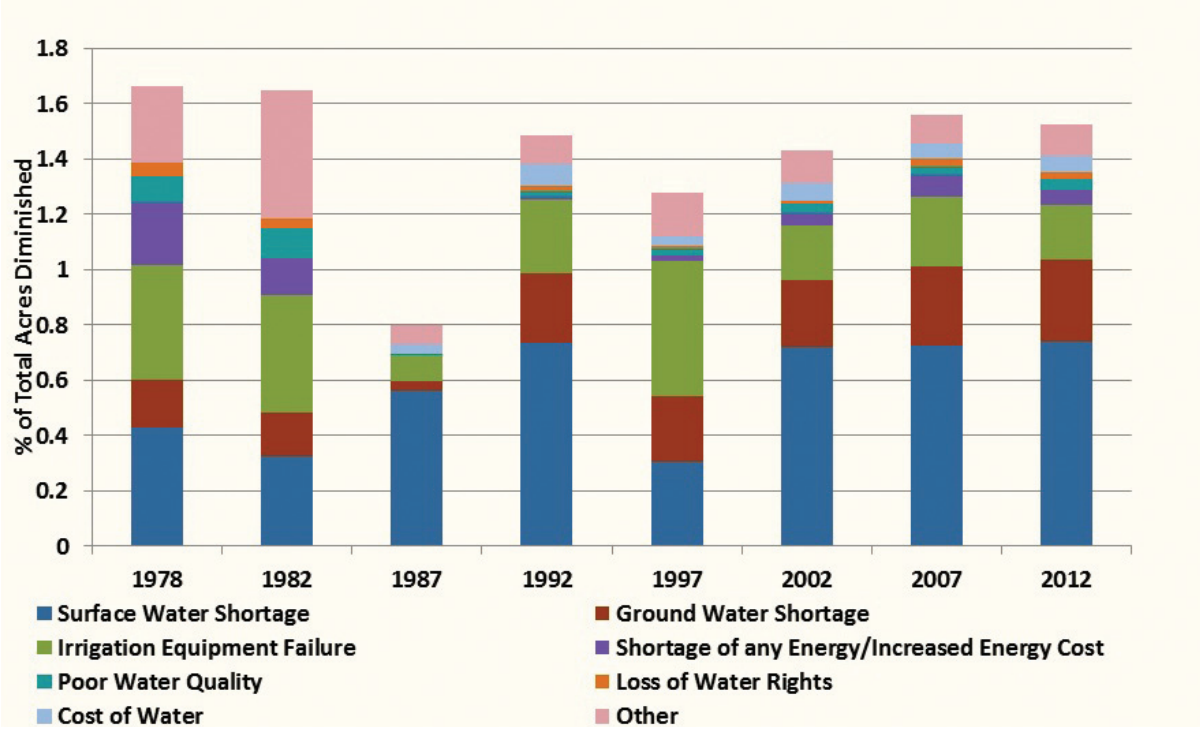

Figure 3. Diminished crop yields due to irrigation interruption by cause in the southwestern Hub states, 1978-2012 (NASS 2015). Note: total percentage can be larger than 100% because respondents could select multiple causes of irrigation interruption.

discontinuing irrigation were shortages of surface and groundwater and sufficient soil moisture. Sufficient soil moisture accounted for 8.4% of the discontinued irrigation acreage in 2013 (519 farms; 39,922 acres). Shortage of surface water accounted for 37% of the discontinued irrigation (1,704 farms; 173,674 acres) and groundwater shortage accounted for 22% of the discontinued irrigation in 2013 (698 farms; 102,486 acres). Interestingly, in 2013, 9% of farms and 4% of acreage (708 farms; 19,783 acres) reported the discontinued irrigation as permanent.

Southwestern Reliance on Groundwater

Water use data by state indicate changes in total and agricultural water use over a five year interval since 1955 (U.S. Geological Survey 2016). Between 1955 and 2010, groundwater has become a larger portion of the total agricultural water use in parts of the SW, primarily NV and UT, and a smaller portion of the total agricultural water use in other parts of the region, primarily AZ. Since 1955, total agricultural water use in the region ranged between 30,000 MGD and 54,000 MGD, with a general decline since 1980 (Table 1). The portion of total water use that is directed to agriculture for the SW region has declined from 92% in 1955 to 78% in 2005 and 2010. The overall fraction of agricultural water use supplied by groundwater in the region was between 44-46% in the early record (1955-1980), with a slight decline to 38-40% in the latter record (1985-2010) (Figure 4). Thus, southwestern agriculture consistently relies on groundwater to supply more than one-third of the agricultural water demand. As of 2010, AZ and CA groundwater fraction was slightly less than 40%, whereas NV and NM were slightly more than 40%. Utah represents a regional anomaly, with only 20% of the total agricultural water supplied by groundwater. In terms of total amount of groundwater use for agriculture, southwestern states are ranked CA (8,000 to 18,000 MGD) > AZ (1,900 to 5,000 MGD) > NM (900 to 1,600 MGD) > NV and UT.

Consistent with having the largest agricultural production in the region, California agriculture used between 60-69% of the total agricultural

Table 1. Agricultural water use for the contiguous Southwest Climate Hub Region and Southwestern states, 1955 to 2010 (U.S. Geological Survey 2016).

MGD		1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Southwest	Groundwater	16,696	13,001	17,057	21,986	23,603	24,451	15,294	15,774	15,538	17,112	13,671	13,259
	Total	38,637	29,560	39,243	48,777	51,704	54,232	46,288	43,164	43,374	45,796	38,504	36,617
	Fraction	0.43	0.44	0.43	0.45	0.46	0.45	0.33	0.37	0.36	0.37	0.36	0.36
Arizona	Groundwater	4,700	3,000	3,900	3,800	4,200	3,710	2,520	2,081	2,163	2,748	2,280	1,757
	Total	6,900	4,700	5,900	6,200	7,000	7,112	5,577	5,391	5,704	5,404	4,824	4,644
	Fraction	0.68	0.64	0.66	0.61	0.60	0.52	0.45	0.39	0.38	0.51	0.47	0.38
California	Groundwater	10,089	8,561	11,034	16,038	17,042	18,036	10,420	10,897	11,024	11,982	8,894	8,945
	Total	23,111	17,986	25,082	33,091	35,101	37,087	30,844	28,287	29,353	31,444	25,162	24,250
	Fraction	0.44	0.48	0.44	0.48	0.49	0.49	0.34	0.39	0.38	0.38	0.35	0.37
Nevada	Groundwater	213	274	462	382	534	534	755	872	642	567	693	669
	Total	1,918	1,777	1,967	2,985	3,142	3,143	3,373	2,828	1,650	2,107	1,522	1,629
	Fraction	0.11	0.15	0.23	0.13	0.17	0.17	0.22	0.31	0.39	0.27	0.46	0.41
New Mexico	Groundwater	1,416	921	1,233	1,312	1,313	1,610	1,183	1,389	1,308	1,229	1,319	1,289
	Total	2,520	1,845	2,765	2,844	2,944	3,620	2,871	3,033	3,026	2,862	2,891	2,756
	Fraction	0.56	0.50	0.45	0.46	0.45	0.44	0.41	0.46	0.43	0.43	0.46	0.47
Utah	Groundwater	278	245	428	454	514	561	415	535	401	586	485	599
	Total	4,188	3,252	3,529	3,657	3,517	3,270	3,623	3,625	3,641	3,979	4,105	3,338
	Fraction	0.07	0.08	0.12	0.12	0.15	0.17	0.11	0.15	0.11	0.15	0.12	0.18

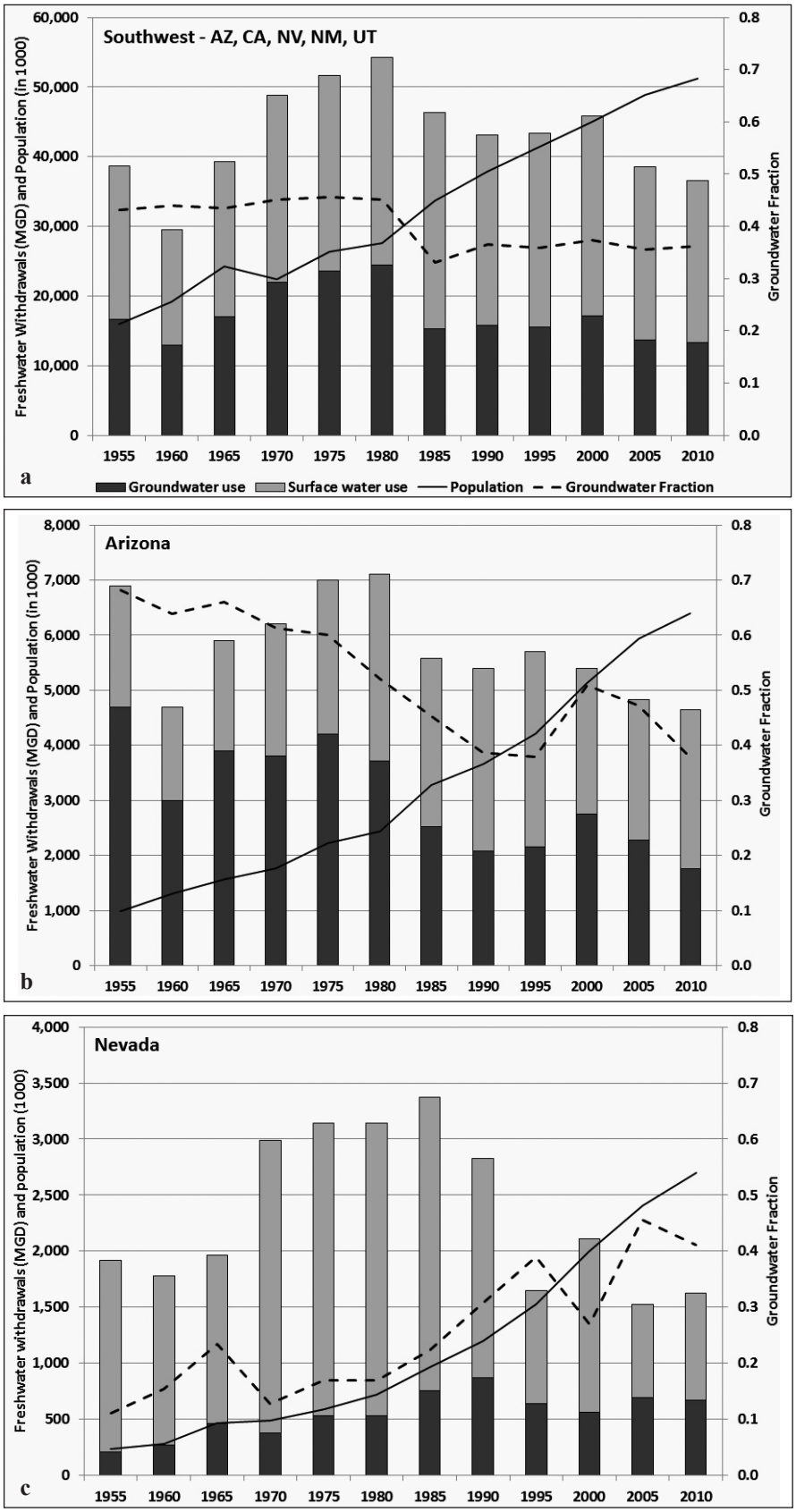

Figure 4. Total agricultural freshwater withdrawals, regional population change, and fraction of agricultural water use supplied by groundwater for a) southwestern states (AZ, CA, NM, NV, and UT), b) Arizona and, c) Nevada, 1955 to 2010 (U.S. Geological Survey 2016).

water in the region between 1955 and 2010, with around half the agricultural water of California supplied by groundwater. In 1955, Arizona agriculture used the largest percentage of groundwater to total agricultural water use or agricultural groundwater fraction (AGF) of any state/year, with 68% of the total agricultural water supplied by groundwater (Figure 4). Since 1955, there has been a gradual decline in groundwater use fraction in AZ for agriculture, with the 2010 AGF of 38%. A small increase in AGF in 2000 to 50% corresponds with the drought conditions of that year, with a statewide Palmer Drought Severity Index value of -2.53 (NOAA 2015). Arizona's Groundwater Management Act may be largely responsible for the decline in AGF in that State (Colby and Jacobs 2007).

Arizona's Groundwater Management Act was a result of the Central Arizona Project (CAP). Although the CAP, which diverts Colorado River water to central Arizona, was conceived in the 1940s, legal action, including decisions made by the Supreme Court on Colorado River water allocation hindered CAP construction until the Colorado River Basin Project Act of 1968. It took more than a decade to secure funds and political will for CAP construction and ultimately required Arizona to demonstrate a commitment to curtail groundwater overdrafting in the state, leading to the adoption of the Groundwater Management Act of 1980. The Act established active management areas where groundwater dependent development was discouraged, and irrigation nonexpansion areas. The CAP began supplying water in the early 1990's. The total amount of groundwater used in Arizona agriculture has generally declined since 1980 (Figure 4).

In September 2014, California approved the Sustainable Groundwater Management Act which empowers local agencies to adopt groundwater management plans and requires overdrafted basins to have a management plan by 2020 (State of California 2016). While California groundwater use for agriculture hovered around 10,000 MGD between 1985 and 2010, groundwater resources across agricultural regions of California have been more stressed during the 2012-2015 drought than at any other time in history in regard to depth to groundwater, groundwater demand and pumping costs increasing (Harter 2015). The Act aims at long-term preservation of groundwater resources for multiple uses, including agriculture.

In contrast to the decline in AGF in Arizona, the AGF in Nevada increased from 11% in 1995 to 41% in 2010, with seven counties in southern and central NV reporting an AGF >80% in 2010. AGF also increased in Utah from 6% in 1955 to 18% in 2010, due to increased groundwater use in five counties of western UT. NM AGF ranged from 41-56%, indicating that roughly half of agricultural water use in NM has been supplied by groundwater since 1955. There are parts of the region that appear to have become less reliant on groundwater over time (AZ) whereas other parts of the region (NV and UT) seem to have become more reliant on groundwater to support agricultural production.

Greater depth to water increases pumping costs associated with groundwater use. Depth to water is consistently greater in AZ than other states, but has generally declined since 1984, possibly influenced by the observed shift away from agricultural groundwater use in that state. NV, which has been using more groundwater to support agriculture, also has an apparent increase in depth to water since 1974, possibly resulting from groundwater mining (Figure 5). The agricultural groundwater fraction within each state depicts areas of high groundwater reliance for production (Figure 6).

The projection of increased groundwater demand reinforces the need for novel methods to measure changes in total terrestrial water storage over large areas of the southwest. NASA's Gravity Recovery and Climate Experiment (GRACE) data have been used to detect changes in total water of a relatively large area (NASA 2015). GRACE consists of twin polar-orbiting satellites flying at a distance of ~220 km. Regional changes in terrestrial water storage affect the gravitational force exerted on the twin satellites causing minute changes in the speed of the satellites and the distance between them. GRACE data have been used in conjunction with other datasets to develop drought indicators (Houborg et al. 2012) and to estimate changes in regional and national water mass (Famiglietti and Rodell 2013). GRACE data were used to estimate groundwater loss in the Colorado Basin during the drought of 2004-2013 and researchers found a large freshwater loss in the region (Castle

et al. 2014). Another analysis relying on GRACE reported that total water storage decreased during the 2010-2013 drought, with most of the decline from surface reservoir and soil moisture storage in the upper basin and additional reductions in groundwater storage in the lower basin (Scanlon et al. 2015). As climate changes, traditional and novel ways of measuring available water may help ameliorate projected water scarcity.

Climate Change and Water Resources in the Southwestern United States

Climate change will affect the hydrologic cycle through various pathways including shifts in precipitation, potential evapotranspiration (ET) and snowmelt runoff timing and amount (Dettinger, Udall, and Georgakakos 2015). Thus, southwestern agriculture may suffer diminished water supplies in much of the region.

Changes in Precipitation

Annual average precipitation has decreased in parts of the Southwest (Walsh et al. 2014) and is projected to continue to decrease (Cayan et al. 2013). On a global scale, precipitation models are in complete agreement with decreased precipitation in the subtropics and increased precipitation at higher latitudes (Walsh et al. 2014). Since the U.S. is located in the transition zone between the two regions, projected changes in national precipitation range from small increases to small decreases leading to uncertain changes in overall future annual precipitation (Walsh et al. 2014). The annual average precipitation changes to expect in the SW U.S. are often quoted as being between plus or minus 10% and within the range of natural variability (Walsh et al. 2014). In general, the southern parts of the U.S. are expected to receive less precipitation in the future.

Snow is an important resource for several reasons. First, the snowpack is a natural reservoir that delays snowmelt until later in the season when irrigation water can efficiently be used to grow crops. But, temperatures will continue to rise throughout the 21st Century (Walsh et al. 2014). More often snow will be converted to rain as it falls in a basin. Even if the snow remains in the solid form as it reaches the ground, the high basin temperatures will quickly melt the snowpack, and the residence time for snow in the basin will be reduced.

The amount of snow that melts in a basin will occur earlier in time except in the highest elevation zones where below freezing temperatures persist. Low elevation snow course measurement stations show a strong decreasing trend in snow water equivalent (SWE) whereas there is little trend in stations higher than 2,500 meters above sea level (Regonda et al. 2005). Observed 1960–2002 snow course measurements show general decreasing trends in April 1 SWE across the western U.S. (Mote 2006). Warming trends will affect snowpack, even at higher elevations. Warming causes the snowmelt to peak earlier in the season making it unavailable to crops when needed later in the year. This facet of the changing snow hydrology is already leading to considerations of growing different crops, development of new water storage structures, or even leasing of water rights in order to continue efficiently using water when available.

The changes in solid to liquid precipitation can already be observed in current precipitation records. Observed records show an increase in the fraction of precipitation falling as rain, with considerable interannual variability causing changes at the local scale (Fritze, Stewart, and Pebesma 2011; Mankin and Diffenbaugh 2015). Some basins of the SW, particularly the Sierra Nevada mountains of California and parts of the Sangre de Cristo mountains of New Mexico, have shifted from mostly snowmelt dominated in the mid-1900s to mostly rain dominated in the early 21st century (Fritze, Stewart, and Pebesma 2011). When using observed data, one must be concerned with the snow catch deficit that is caused by wind. Most gauges do not have wind shields, and unfortunately the snow records are not corrected for this deficit issue, although correction factors are readily available (Sevruk 1985, 1989). Future research incorporating snow catch deficit correction is recommended. Beyond anticipated changes in precipitation amount, phase and regional snowpack, increased temperatures will impact other parts of the hydrologic cycle.

Changes in Evapotranspiration

Evapotranspiration (ET) is one of the largest components of the water cycle in the west,

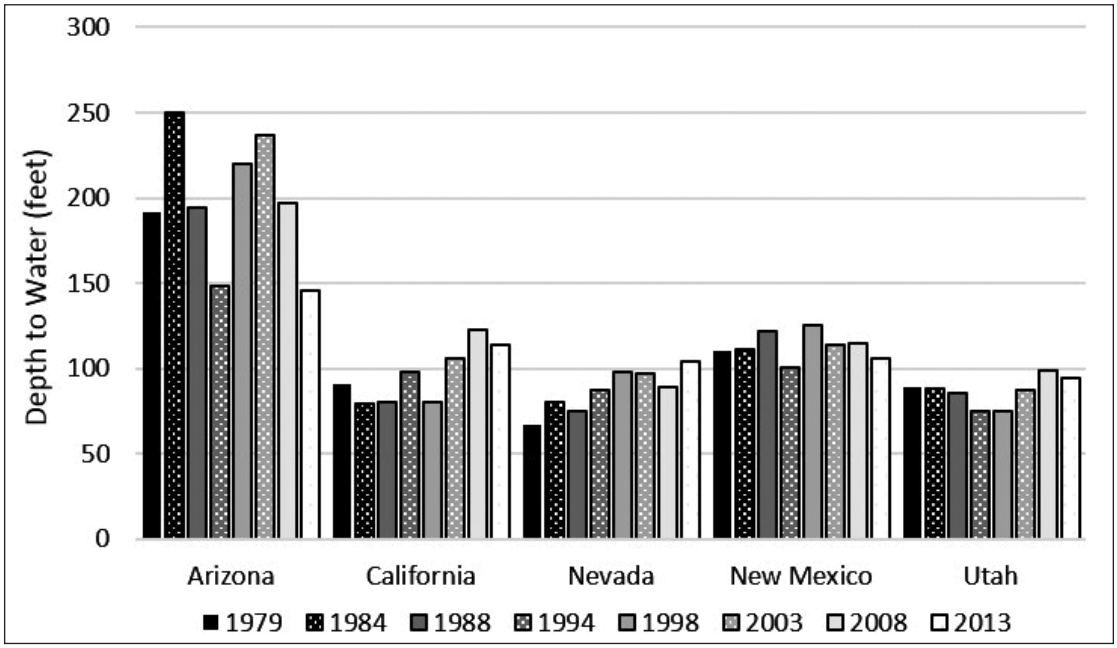

Figure 5. Depth to water (in feet) from irrigation wells used on farms by state, 1979 to 2013 (NASS 2015).

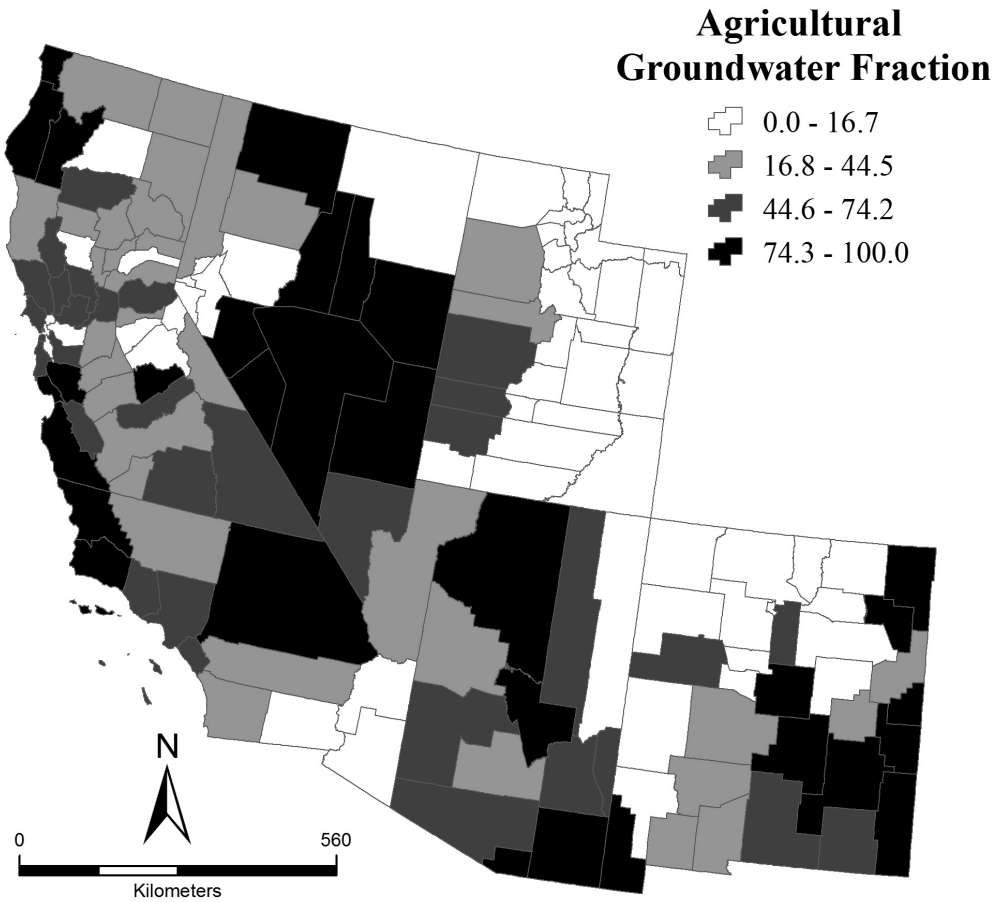

Figure 6. Agricultural groundwater fraction for the southwestern states in 2010. Fraction is groundwater used for irrigation/total water used for irrigation (U.S. Geological Survey 2016).

second to precipitation (Dettinger, Udall, and Georgakakos 2015). Global land ET estimates (derived from FLUXNET, meteorological observation, and remote sensing) suggest that the rate of ET increased from the early 1980s to the late 1990s (Jung et al. 2010). This trend of rising ET rates disappeared after the last major El Niño event in 1998, after which point global land ET rates began to decline. These trends are consistent with expected hydrologic cycle changes due to temperatures, radiative forcing, and evaporative demand (Jung et al. 2010).

Dettinger, Udall, and Georgakakos (2015) state that although projected actual ET rates vary by region, potential ET is expected to increase with warming across the Southwestern U.S. Potential ET is the maximum amount of water that would be evapotranspired if enough water were available, whereas actual ET is the amount of water actually evapotranspired and is limited by available water content. ET rates and totals are likely to be affected in the SW by changes in land use, vegetation, soil moisture, and changes in the lengths of growing and snow-covered seasons. Goulden and Bales (2014) found that warming projected for 2100 could increase ET in the Kings River basin in California's Sierra Nevada by 28%. Increased temperature, which can shift snowmelt timing and soil moisture, is also predicted to increase ET rates (Christensen and Lettenmaier 2007; Ficklin, Luedeling, and Zhang 2010; Hay, Markstrom, and Ward-Garrison 2011; Hoerling et al. 2012).

Changes in Runoff

In the early 1990s, researchers observed that the fraction of annual runoff occurring between April and July had been declining (Wahl 1991; Aguado et al. 1992), possibly related to a trend in decreasing snowmelt runoff (Roos 1991). The trend was most evident in mid-altitude basins where winter temperatures are near freezing and small temperature increases can result in less snow formation and earlier melt (Dettinger and Cayan 1995). The observed earlier snowmelt in California was related to trends toward warmer winters since the 1940s (Dettinger and Cayan 1995). These trends were evaluated over a broader area of the western U.S. using 302 stream gauges. Researchers observed earlier spring pulse onset and center of mass for annual flow for snowmelt dominated basins due, in part, to higher winter and spring temperatures (Stewart, Cayan, and Dettinger 2005). While temperature changes were partly controlled by decade scale Pacific climate mode (PDO), a springtime warming trend that spans the PDO phases was identified. Thus, a portion of the streamflow timing trend appears to be related to temperature increases consistent with observed increases in global temperature. More recent analyses of shifts in streamflow timing from1948 to 2008 indicate that streamflow has continued to shift earlier in the year, most notably in snow dominated watersheds (Fritze, Stewart, and Pebesma 2011). Researchers have observed that shading (Lundquist and Flint 2006) and dust on snow (Painter et al. 2007) have an important role in peak streamflow timing and snow cover depletion. Earlier snowmelt has also been observed using imagery from the Landsat program (Hall et al. 2015).

Observed changes in SWE, runoff timing and snowpack area are reflected in climate change simulations in the western U.S. Widespread warming caused decreasing trends in April 1 SWE across much of the Western United States (Hamlet et al. 2005) . Simulations of the impacts of temperature and precipitation changes using the Snowmelt Runoff Model (SRM) indicate advancement in runoff timing and reduced summer flow during the growing season of some crops (Rango and van Katwijk 1990; van Katwijk and Rango 1991; van Katwijk, Rango and Childress 1993; Rango and Martinec 1994, 1999, 2000; Rango, Martinec, and Roberts 2008; Elias et al. 2015; Elias et al. 2016). Measurement of impacts of climate change on snow covered area (SCA), streamflow timing and runoff volume of twenty-four sub-basins of the Upper Rio Grande, using four future climate conditions, reflect climate change simulation results in other western locations. Results indicate change in total annual volume with disparity between increased volume in wetter simulations (+7%) and decreased volume (-18%) in drier simulations. Peak flow is 14-24 days earlier in the future climates. Among the twenty-four sub-basins there was considerable range in mean melt season SCA, total volume change and runoff timing advancement, indicating that climate change is best evaluated at the sub-basin scale. The

timing of water supply will shift to earlier in the year and water management flexibility for current water users may decrease (Elias et al. 2015). These observed and simulated impacts to the hydrologic cycle are cumulative and serve to decrease surface water availability and likely increase reliance on groundwater resources to support agricultural production.

Changes in Drought

While some studies argue that a link between climate and drought cannot be made, there is recent scientific evidence clearly linking southwestern drought to the increased temperatures of climate change (Mann and Gleick 2015). The discrepancy in studies linking climate change and drought is due in part to the multiple definitions of drought, where studies considering only precipitation changes find little link to climate change, but metrics incorporating both incoming and outgoing moisture show increased drought risk in a future warmer climate. The SW climate might have already transitioned to a drier climate state leading to higher drought risk (Prein et al. 2016). Recent droughts in the upper Colorado River Basin have been amplified by warmer temperatures (Woodhouse et al. 2016). The recent California drought beginning in 2012 has similarly been linked to anthropogenic warming (Cook, Ault, and Smerdon 2015; Diffenbaugh, Swain, and Touma 2015; Mann and Gleick 2015). The California drought spanning 2012-2014 was the most severe drought in the past 1,200 years and was driven by reduced precipitation and record high temperatures (Griffin and Anchukaitis 2014). Griffin and Anchukaitis conducted their analysis prior to 2015. The 2015 water year in California was the hottest and driest on record, thereby exacerbating the drought severity reported in 2014. The hydrologic drought in the Southwest U.S. has been linked to observed and predicted increased aridity in the region, where the recent drought, the Dust Bowl and the 1950s droughts are projected to become the new climatology of the Southwest (Seager et al. 2007). Should drought conditions become the new 'normal' in the face of climate change, groundwater reserves would likely decline (Taylor et al. 2013). A study of the impacts of climate change on groundwater recharge indicates average declines of 10-20% in total aquifer recharge across southwestern aquifers, but with a wide range of uncertainty (Meixner et al. 2016).

Summary

Irrigation of cropland is critical in five of the six states of the SW region for continued high agricultural productivity across the region. The irrigation water supply comes primarily from snowmelt runoff, and this water supply is subject to the effects of climate change. If sufficient irrigation water supplies exist, agricultural production can be high in the SW. Since 1978, total irrigated acres have fluctuated somewhat in each state, with a slight decline in Arizona, Hawaii and Nevada. Between 1978 and 2012, 11-21% of the total irrigated acreage in the SW region had crop yield declines due to irrigation interruption. The most reported cause of irrigation interruption and diminished crop yields was surface water shortage. Shortage of surface water and groundwater appear to comprise a larger portion of the crop yield reduction in more recent years (2002, 2007, and 2012).

The portion of total water use that is directed to agriculture for the SW region has declined from 92% in 1955 to 77% in 2005 and 2010. At the state level, the overall fraction of agricultural water use supplied by groundwater was between 33-46% since 1955, with a slight decline in the latter half of the record (1985-2010). Southwestern agriculture relies consistently on groundwater, using it to supply more than one-third of the agricultural water demand across the region, with certain counties using groundwater to satisfy more than 80% of the agricultural water demand. In 2010, 40-50% of agricultural water use was supplied by groundwater in all SW states except UT.

In 1955, Arizona agriculture used the largest agricultural groundwater fraction (AGF) of any state/year, with 68% of the total agricultural water supplied by groundwater. Since that time, there has been a gradual decline in groundwater use fraction in AZ for agriculture, with the 2010 AGF of 38%. This decline may be related to the enactment of the Arizona Groundwater Management Code in 1980. In contrast, the AGF in Nevada and Utah increased since 1955. Depth to water is consistently largest in AZ, but has been recovering since a peak in 1984,

possibly influenced by the observed shift towards less agricultural groundwater use in that state. NV, which has been using more groundwater to support agriculture, has an observed increase in depth to water since 1974.

Observed and predicted changes in the southwestern hydrologic cycle will impact regional agriculture. Observed records show an increase in the fraction of precipitation falling as rain, which is expected to continue with future warming. Potential ET is expected to increase with warming across the Southwestern U.S., with projections in parts of the region of an increase in ET of 28% by 2100. Annual average precipitation has decreased in parts of the SW and is projected to continue to decrease. Snowpack functions as a natural reservoir, but warming causes the snowmelt to peak earlier in the season and reduces water available to crops during the summer months. Observed records indicate streamflow has continued to shift earlier in the year, most notably in snow dominated watersheds. This facet of the changing snow hydrology is already leading to considerations by agricultural producers of changing to different crops, development of new water storage structures, or leasing water rights in order to continue efficiently using water when available.

The observed shifts in streamflow timing will likely continue into the future with the increasing temperatures of a changing climate, first at lower elevations and then progressively into higher elevations as temperatures increase. The storage reserves of high mountain snowpack will decline. Should irrigated agriculture continue at a similar footprint, then reliance on groundwater to support production will likely increase, with concurrent economic and environmental consequences. Climate change affects water resources of the SW to a degree that is probably unmatched anywhere in the U.S. SW agriculture, which relies heavily on available water for production, is particularly vulnerable to the reduced water availability stemming from current and predicted climate changes.

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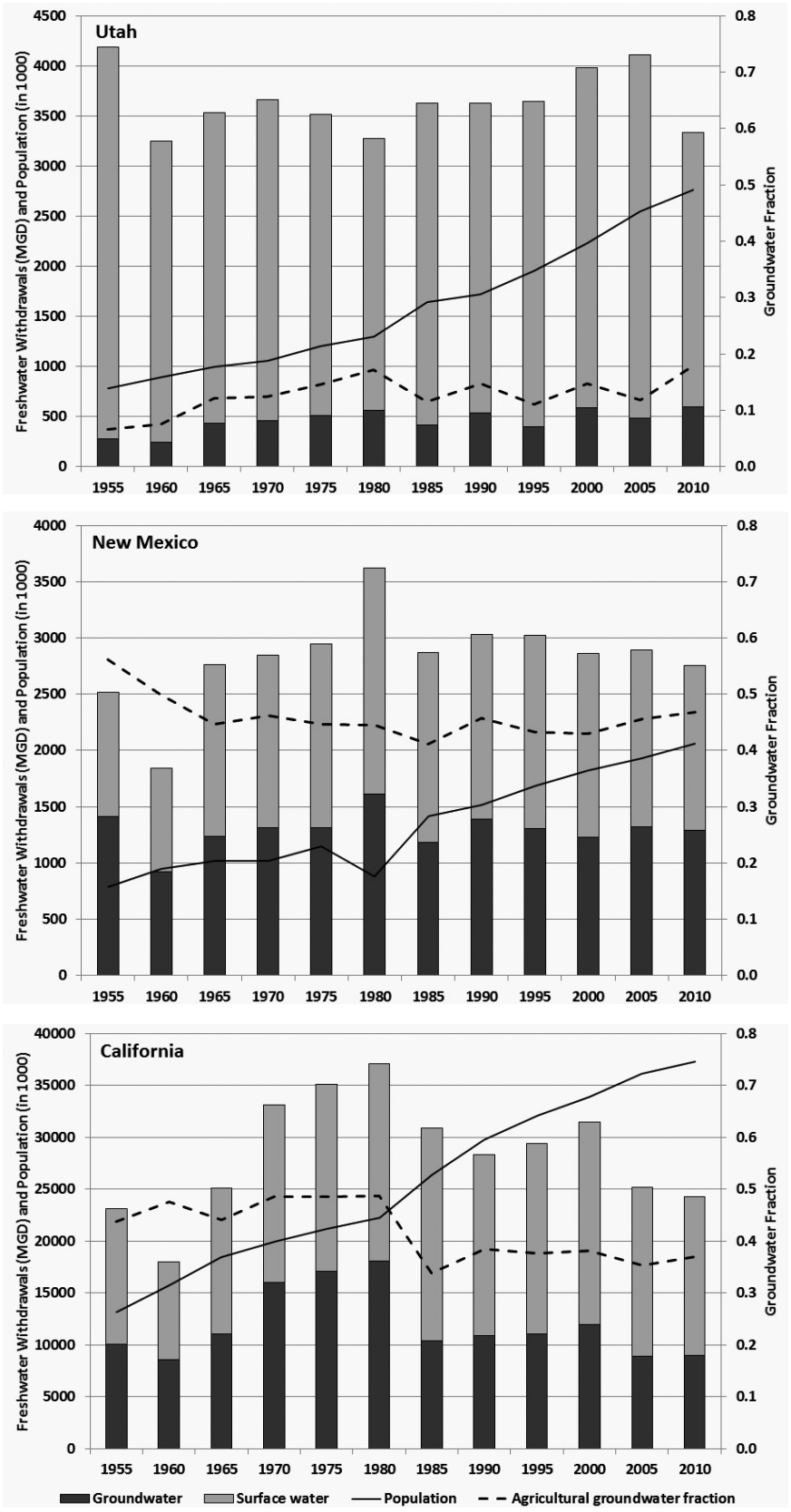
Appendix

Agricultural water use, groundwater fraction and population change in California, New Mexico and Utah, 1955 to present.



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