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Climate Change Made Major Contributions to Soil Water Storage Decline in the Southwestern US during 2003–2014

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Abstract: Soil water shortage is a critical issue for the Southwest US (SWUS), the typical arid region that has experienced severe droughts over the past decades, primarily caused by climate change. However, it is still not quantitatively understood how soil water storage in the SWUS is affected by climate change. We integrated the time-series data of water storage and evapotranspiration derived from satellite data, societal water consumption, and meteorological data to quantify soil water storage changes and their climate change impacts across the SWUS from 2003 to 2014. The water storage decline was found across the entire SWUS, with a significant reduction in 98.5% of the study area during the study period. The largest water storage decline occurred in the southeastern portion, while only a slight decline occurred in the western and southwestern portions of the SWUS. Net atmospheric water input could explain 38% of the interannual variation of water storage variation. The climate-change-induced decreases in net atmospheric water input predominately controlled the water storage decline in 60% of the SWUS (primarily in Texas, Eastern New Mexico, Eastern Arizona, and Oklahoma) and made a partial contribution in approximately 17% of the region (Central and Western SWUS). Climate change, primarily as precipitation reduction, made major contributions to the soil water storage decline in the SWUS. This study infers that water resource management must consider the climate change impacts over time and across space in the SWUS.

Keywords: atmospheric water input; climate change; drought; Southwest US; water storage

1. Introduction

Water is the most important life-supporting element on the planet [1]. The water storage in soil prolife is one fundamental resource for natural ecosystems and human society; therefore, understanding soil water storage variation and its controlling factors is essential for sustaining human society, which relies on water resources [2]. It was confirmed that a significant alteration in global water storage has occurred [3], and it has yielded dramatic impacts on natural ecosystems and human society [4–7]. Although the water resource dynamic and its impacts are intensively studied on a global scale [8,9], the regional-scale water resource variations and their controlling factors remain uncertain [10], particularly for the arid and semiarid regions that are experiencing water shortage and strong variations [11].

For arid or semiarid regions, water is a primary limiting resource for natural ecosystems, as well as for human society [3]. Therefore, the water availability is a critical issue for the sustainability of natural ecosystems and human society. Furthermore, the highly variable precipitation in semiarid regions [12] reinforces the negative consequences of water shortage. In addition, water stress becomes more and more severe across arid and semiarid regions due to climbing water demand [13] and climate change [14]. The Southwest United States (SWUS) is the hottest and driest location in North America [14,15]. As one of the fastest economy-growing regions in the United States, SWUS needs a large amount of water resources to support its accelerating industrial and agricultural activities, such as oil production, mineral production, crop productivity, and manufacturing industries [16]. The changing climate and growing demand for water from human society make water resources a critical issue in the SWUS [17].

A number of researchers have reported that water resources are expected to diminish as climate changes, which will critically influence human and ecological systems in the SWUS [14,18,19]. However, few studies to date have quantitatively examined the water storage change and its main dominant factors in the SWUS. To address this gap, we designed this study to (1) quantify the changes of soil water storage over the SWUS (Arizona, New Mexico, Oklahoma, and Texas) from 2003 to 2014 and (2) evaluate the role of climate change (particularly net atmospheric water input expressed as precipitation–evapotranspiration) on the water storage changes. It should be noted that this study focuses on soil water dynamics, excluding the water volume in inland reservoirs and lakes.

2. Materials and Methods

2.1. Research Domain

This study focuses on the SWUS, which encompasses Arizona, New Mexico, Oklahoma, and Texas, following the official boundary from the United States Geological Survey (https://www.fws.gov/southwest). The SWUS is a typical arid region in North America, and the water shortage is a severe environmental problem for sustaining the local community [20]. It is home to 40 million inhabitants, as well as a large amount of industrial activities, agricultural managements, and recreations [21]. Therefore, the soil water resources are a critical topic for the scientific and local communities.

2.2. Data Sources

The Gravity Recovery and Climate Experiment (GRACE) (http://www.csr.utexas.edu/grace/) [22,23] was used as a proxy for water storage in the SWUS; this method was widely used in previous studies for quantifying water balance on a regional scale [24–26]. The dataset for the time period of 2003–2014 was downloaded on 10 April, 2018, to be consistent with a new study for the GRACE dataset [27]. It should be noted that the GRACE data are not for absolute water storage, but for the relative changes of water storage compared to the baseline for the years 2004–2009. This was the key purpose of this satellite-derived dataset [28,29]. The six-hour precipitation and temperature data were obtained from the North American Regional Reanalysis (NARR) dataset of NOAA's National Climate Data Center (http://www.ncdc.noaa.gov/) on 15 March 2018. The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived terrestrial evapotranspiration (ET) data (MOD16) for the time period of 2003–2014 were downloaded on 25 April 2018; the dataset includes evaporation from wet and moist soil, from rainfall intercepted by the canopy before it reaches the ground, and the transpiration through stomata on plant leaves and stems. The MOD16 global ET data are at a spatial resolution of 1 km^2 and at a temporal resolution of month [30]. We collected the annual dataset of total water withdrawal for the Southwest from the U.S. Geological Survey (USGS), which maintains national databases of water-use information. The data were collected and compiled every five years for each county and state, and we estimated for other years between two five-year frameworks by using the linear interpolation approach.

2.3. Data Processing

We adjusted GRACE data by multiplying the scale factor correspondingly, since surface mass variations at small spatial scales tend to be attenuated [31,32]. The data were further aggregated from monthly to annual for analysis. The bilinear interpolation was used when resampling all data to a spatial resolution of 0.25 degree. Then, all data for the SWUS region were masked out from global datasets of GRACE, NARR, and MODIS.

The water balance equation is used (Equation (1)), and net atmospheric water input is defined as the difference between precipitation and evapotranspiration [24].

$$\frac{\partial S}{\partial t} = W_{net} - R - W_H = P - ET - R - W_H, \quad (1)$$

where the S represents land water storage, W_{net} net atmospheric water input, P annual precipitation, ET annual evapotranspiration, R total discharge or the net surface and ground water outflow, and W_H water consumption by human society. The calculation of net atmospheric water input is similar to the calculation used by Seager et al. [33]. The Pearson correlation was employed to quantify the association between any two variables; for example, net atmospheric water input and water storage variation. It is referred to as the correlation coefficient (r), which represents the strength of the correlation. The r is in the rage of $[-1, 1]$; negative r values indicate a negative linear relationship, while positive r values indicate a positive linear relationship between any two variables of interest.

Statistical analysis was performed based on annual data by considering the area of the corresponding region or state. Linear regression was employed to estimate the changing rates of water storage, annual precipitation, and ET over the study period. This approach is widely used for quantifying changing rates of water storage, carbon uptake, temperature change, etc. [34,35]. Based on these annual data, we analyzed the changing rates of all aggregated data with C++ computer language for net water input (precipitation minus evapotranspiration) and water storage. Significance is deemed if the p value is less than 0.05. The data conversion and aggregation were carried out with Python embedded in ArcGIS 10.1 (ESRI, Redlands, CA, USA).

3. Results and Discussions

3.1. Yearly Relative Water Storage in the SWUS during 2003–2014

There are large variations in relative water storage across the SWUS, at both spatial and temporal scales (Figure 1). There are substantial interannual variations in water storage across the SWUS; for example, the eastern portion of Texas showed a slight decline trend from 2003 to 2010, but the decline became a substantial drop from 2010 to 2011. This sharp decline in water storage from 2010 to 2011 was caused by a substantial drought in Texas in 2011 [36]. This signal is detectable in our regional data of precipitation (see Section 3.4). The relative change in water storage varied across the space; in the early period of 2003–2004, the relatively high water storage was observed in the western part of Arizona, and it quickly declined after 2011. The soil water decline was most apparent in the eastern part of Texas (Figure 1).

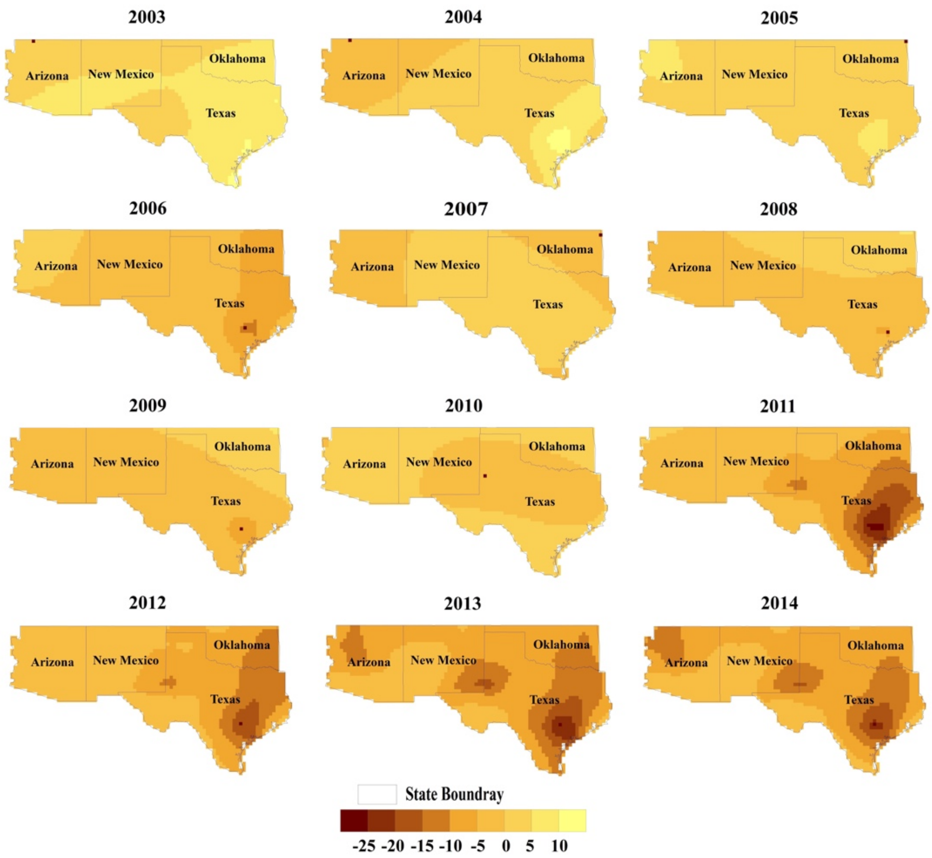

Figure 1. Annual average for water storage across the Southwest United States (SWUS) from 2003 to 2014.

3.2. Water Storage Decline from 2003 to 2014

GRACE provides a valuable tool to monitor water storage depletion, linking meteorological and hydrological droughts [27,31,37]. The 12-year averaged water storage anomaly ranges from –1 to −70 mm across the entire SWUS from 2003 to 2014, with a mean of −20 mm (Figure 2A). The lowest water storage anomaly was located in the southeastern part of the SWUS, primarily in Texas, ranging from −70 to −30 mm, and Oklahoma, ranging from −30 to −20 mm; another region with a low water storage anomaly was the central SWUS, on the border of Texas and New Mexico, which was approximately −40 mm. The substantial water storage decline in the southeastern part of the SWUS is consistent with a recent study which reported a large water depletion and severe drought in Texas [31].

A significant decline in water storage was observed across the entire SWUS from 2003 to 2014; spatially, 98.5% of the area experienced significant decreases (Figure 2B). The highest declining rate was −28.8 mm/year, and the lowest was −0.5 mm/year. There was a gradient of water storage decline, decreasing from the southeast to the west in the study domain. The highest water decline was observed in the southeastern part of Texas, and the lowest water storage decline was observed in the southern part of Arizona and the southwestern part of New Mexico. At the state level, the decrease in water storage was highest in Texas (−12.3 mm/year), followed by Oklahoma (−9.6 mm/year), Arizona (−6.0 mm/year), and New Mexico (−5.4 mm/year); these averaged to a region-wide decreasing rate of −8.9 mm/year (Table S3). A significant spatial correlation (r = 0.8500) between the water thickness and water storage declining rate was observed across the entire SWUS; that is to say, the region with larger water thickness anomaly was experiencing higher water loss. The high spatial consistency between water resource availability and water loss rate suggests a trend of region-wide water resource declining [33,38]. Similar to this research, a number of studies used GRACE data to quantify the water loss and its association with climate variability and change [28,39,40].

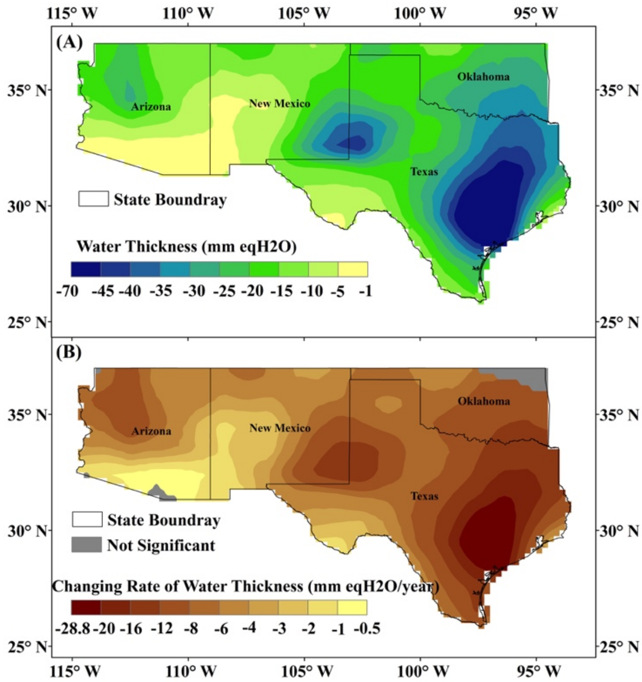

Figure 2. (**A**) Mean relative water thickness and its (**B**) changing rates across the Southwest US from 2003 to 2014

The changing rate of net atmospheric water input (precipitation minus evapotranspiration or $P-ET$) was positive for portions of Arizona and New Mexico and was negative for the majority of the SWUS (Figures S1 and S2). The highest declining rate was −48 mm/year for the SWUS, with most noticeable changes in Texas and Oklahoma (Figure 2A), which is consistent with the water storage declining pattern (Figure 2B). A slight increase was found in the majority of Arizona and New Mexico, which explains the modest decline rate of water storage in the southwestern part of the SWUS (Table 1). The remaining area in Arizona and New Mexico represented a modest decreasing trend of net atmospheric water input. In summary, the interannual variation in soil water storage and $P-ET$ is highly positively correlated at state level and across the entire SWUS region (Table 1).

Table 1. Annual water storage, precipitation minus evapotranspiration in SWUS from 2003 to 2014 (S: water storage estimated from GRACE; $P-ET$: precipitation minus evapotranspiration estimated from NARR and MODIS data) (unit for S is mm/m^2 and unit for $P-ET$ is mm/m^2/a).

Year	SWUS		AZ		NM		OK		TX	
	S	$P-ET$	S	$P-ET$	S	$P-ET$	S	$P-ET$	S	$P-ET$
2003	7.2	348.8	−3.1	125.5	−1	78.6	8.9	606.1	15.7	509.3
2004	17.7	595.3	−9.6	197	2.5	208.1	19.2	896.7	38	875.8
2005	24.4	393.4	35.1	209.7	17.4	195.1	12.1	625.3	27.6	508.1
2006	−27.3	393.2	3.8	145.1	−10	234.4	−53.5	586.3	−44.2	525.5
2007	2.9	599.1	−5.4	203.4	4.1	210.8	−8.8	1047.2	9.4	839.7
2008	−4.8	458.9	−2.6	227	−0.4	211.4	10.9	885.7	−12.4	566.7
2009	−13	331.6	−21.2	59.4	−13.6	104.7	20.2	676.1	−18.4	463.5
2010	0.9	354.5	2.9	203.9	−0.9	130.5	6.5	550	−0.6	470
2011	−58.2	185.5	−9.5	118.3	−30.3	86.6	−61.8	387.4	−95.6	209.1
2012	−60.1	250.7	−21.2	103.3	−36	35.5	−90.9	400.5	−84.3	378.1
2013	−83.5	328.3	−61	241.5	−62.1	183.2	−98.1	531.7	−106.5	377.1
2014	−73.3	347.4	−60	247.6	−57.7	270.4	−80.7	415.1	−88.7	408.8

3.3. Water Consumption across the SWUS from 2003 to 2014

The large spatial variation in water consumption was observed for the study period (Figure 3 and Table S1). The average water usage remained approximately 35 mm/year for the whole SWUS from 2002 through 2010, and to 2014. Texas showed the highest water usage among the four states making up the SWUS, with approximately 50 mm of water usage each year. The average water usage was about 27 and 15 mm per year for Arizona and New Mexico, respectively, and there exists an increasing rate of water usage for Oklahoma. The large interannual variation was observed for all four states and the entire study region (Table S1). Over the 12 years, a slight declining trend was observed for the majority of the SWUS, except for a portion of Oklahoma.

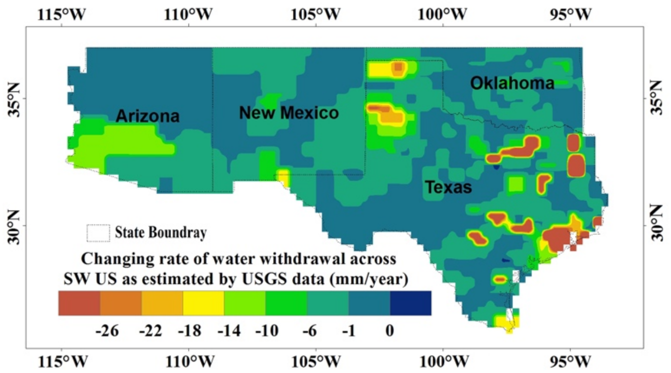

Figure 3. Changing rate of water withdrawal for human society from 2003 to 2010.

3.4. Association between Net Atmospheric Water Input and Water Thickness Anomalies

We further analyzed the temporal and spatial correlations between water storage and annual net atmospheric water input to quantify the input control on water balance variations, according to the Equation (1). The net annual atmospheric water input varied from the lowest of 186 mm in 2011 to the highest of 599 mm in 2007 across the entire SWUS (Table S1). As a major input to the water pool in the land surface, the net atmospheric water input played an important role in the interannual variation of net water storage (Equation (1)). There was a strong association between the interannual fluctuation of net water input and the water storage anomalies for this region (r = 0.6171) (Figure 4A), indicating that 38% of the temporal variation of water storage could be explained by net atmospheric water input.

The decreasing rates are −8.9 mm/year for water storage and −18.6 mm/year for net atmospheric water input across the entire SWUS. The twice-decreasing rate of net atmospheric water input than that for water storage (Figure 4A) implies two aspects: first, net atmospheric water input played a dominant role in decreasing water storage [29]; second, there are other mechanisms which contributed to the water storage increase, which could be surface runoff and ground discharge [41]. The strong positive correlation between water storage and net atmospheric water input was also observed across the eastern part of the SWUS (Eastern New Mexico, Oklahoma, and Texas), while a weak correlation, or even a negative correlation, was observed for the western part of the SWUS (Western New Mexico and Arizona) (Figure 4B). The net atmospheric water input had a positive influence on water storage in 74% of the study area (Figure 4B).

Specifically, we found that net atmospheric water input made a strong contribution to water storage variation in a large portion of the SWUS, with positive relationships ranging from around 0.1 to 0.6 between net water input and water storage from 2003 to 2014, especially for Texas and Oklahoma, with a correlation coefficient even greater than 0.6 (Figure 4B). There was no obvious influence in approximately half of Arizona and New Mexico because of the negative correlation coefficient. There existed a weaker impact of net water input on water storage variation with positive relationships for the remaining area of Arizona around 0.1 to 0.3. For the remaining area in New

Mexico, the association varied between net water input and water storage variation, with the coefficient varying from approximately 0.1 to 0.6.

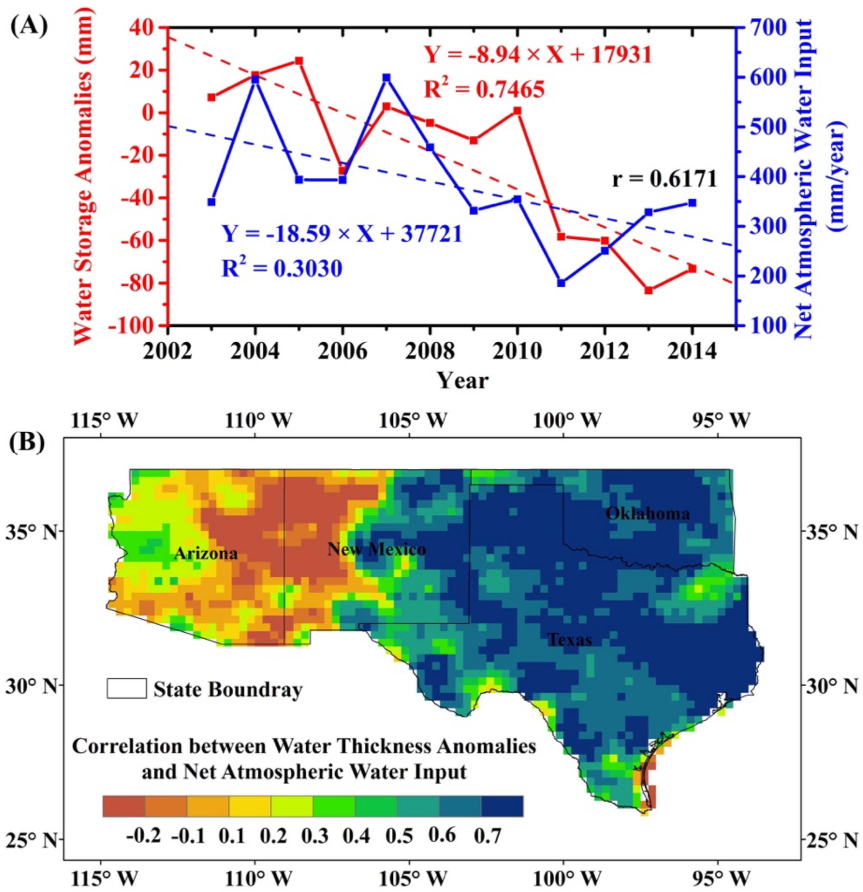

Figure 4. Temporal correlation between annual net atmospheric water input and annual water thickness over the SWUS from 2003 to 2014 ((**A**) temporal correlation of average across entire SWUS; (**B**) spatial distribution of the temporal correlation).

The decreasing net atmospheric water input was caused by a combination of water withdrawal, precipitation, evapotranspiration, and runoff and discharge. The western part of the SWUS experienced growing water withdrawal (Figure 3), as well as small increases in precipitation and evapotranspiration (Figures S1 and S2), while the eastern SWUS experienced decreases in precipitation (Figure S1) and evapotranspiration (Figure S2), as well as small changes in water withdrawal (Figure 3).

3.5. Climate Contribution to Declined Water Storage

We further used attribution analysis to quantify the climate contribution to the observed water storage decline (Figure 5). The dominant role of net atmospheric water input in water storage changes across the entire region was confirmed in the previous section; we are interested in the spatial distribution of climate control in the study region. Net atmospheric water input made a partial contribution for approximately 17% of the SWUS (254,407 km^2); it made a 20% to 40% contribution, covering 2.9% of the region, a 40% to 60% contribution in 4.0% of the area (Table 2), a 60% to 80% contribution in 3.3% of the region, and a 80% to 100% contribution in 4.4% of the area. Precipitation changes dominated the water-storage changes for approximately 60% of the region (Figure 5). The remaining 20% of the SWUS showed no significant effect on water storage from precipitation. The changing contribution pattern was consistent with that of the correlation framework for net water input and water storage variation (Figure 4B).

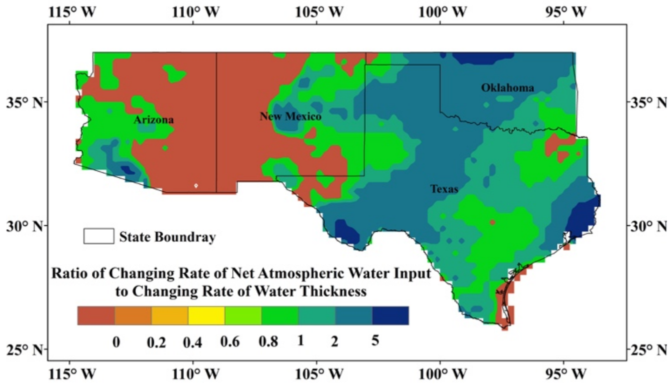

Figure 5. Contribution of net atmospheric water input to water storage decline across the SWUS from 2003 to 2014.

Table 2. Contribution of net atmospheric water input to water storage change (ratio = (decreasing rate of net atmospheric water input)/(decreasing rate of water thickness)).

Ratio	Area (km^2)	Percentage (%)
Ratio ≤ 0	309,579	22.29
0 < Ratio ≤ 0.2	40,270	2.75
0.2 < Ratio ≤ 0.4	42,440	2.90
0.4 < Ratio ≤ 0.6	58,587	4.00
0.6 < Ratio ≤ 0.8	48,532	3.31
0.8 < Ratio ≤ 1	64,578	4.41
1 < Ratio ≤ 2	331,546	22.63
2 < Ratio ≤ 5	509,941	34.81
Ratio > 5	42,400	2.89
Total	1,447,873	100

The average net water atmospheric inputs for Oklahoma and Texas were obviously larger than those for Arizona and New Mexico, with higher variations of water storage (Table S3); this explained the remarkable changing rate of water storage anomalies in this area (Figure 1B). This suggests that climate change influences the water resources available for human beings [42,43]. Associated with rising temperatures, the projected declining net precipitation seems likely to increase the region's aridity in the years to come [19,44,45]. The annual average temperature stayed relatively stable over this study period, at around 17 °C for the whole Southwest (Table S2). It varied widely across the whole region for latitudinal variations partially and elevation mostly [46]; for example, the annual mean temperature was approximately 13 °C in New Mexico and 19 °C in Texas during 2002–2014 (Table S2). Therefore, water storage decline in the SWUS was associated with both the rising temperature and decreasing precipitation [47], with a higher contribution from declining precipitation and a weaker contribution from the rising air temperature.

3.6. The Way Forward

This study integrated the time-series satellite data, societal water consumption, and meteorological data and found that climate change made the dominant contribution to the water storage decline across the SWUS from 2003 to 2014. A few issues need special attention when interpreting the results. First, recent studies have revealed the potential uncertainties associated with the GRACE dataset [22,48]; although it is a systems error that has trivial impacts on our regional analysis, it should be acknowledged for all studies based on the GRACE dataset. Second, the differences among climate datasets might have caused bias in analysis of precipitation [49] and evapotranspiration; the CRUNCEP dataset used in this study is one of the best meteorological datasets for the United States [49]. Third, the societal water consumption data was based on county, which is in a relatively coarse spatial resolution. Further data development should bring high accuracy to the analysis, like this study.

4. Conclusions

Given the severe droughts, decreasing water storage, and projected changing climate, it is expected that the extreme rainfall events will have significant impacts on both ecosystems and the human community in the SWUS. We quantified the climate change impacts on water storage in the SWUS from 2003 to 2014. Precipitation made a partial contribution to the water storage decline for approximately 17% of the study area, dominated the variability of water storage for 60% of the whole region, and showed no influence in the remaining. The spatial analysis is spatially consistent for both water storage change and net atmospheric water input, which confirms the dominant contribution of climate change on water resources.

The shortage of water resources will likely become more severe, since water usage is expected to increase across the entire SWUS, given the projected population increase of 68% by 2050 [50]. Furthermore, water supplies are constrained under current climate change, as shown in our study; water storage decline and decreasing precipitation indicate drier future conditions for the arid SWUS. Decreasing precipitation translates to less water being available for storage in the network of reservoirs. This will definitely increase the chances of the region experiencing more severe and prolonged droughts [51]. The entire SWUS region will likely face a rising demand and decreasing supply of water resources under the changing climate, which poses a serious challenge for water resource management.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/9/1947/s1:

Figure S1. Changing rate of annual precipitation from 2003 to 2014;
Figure S2. Changing rate of evapotranspiration during 2003–2014;
Figure S3. Changing rate of net atmospheric water input ($P-ET$) from 2003 to 2014;
Figure S4. Changing rate of air temperature from 2003 to 2014;
Table S1. Average water consumption (mm/m^2/year) for each state and entire SWUS region during 2003–2010;
Table S2. Annual temperature (°C) at state and regional level in SWUS during 2003–2014.

Author Contributions: Conceptualization, X.X.; methodology, X.X. and L.G.; software, J.L. and L.G.; validation, J.L. and L.G.; formal analysis, J.L. and L.G.; investigation, J.L., L.G., and F.Y.; resources, X.X. and Y.G.; data curation, L.G.; writing—original-draft preparation, L.G. and J.L.; writing—review and editing, X.X.; visualization, X.X. and J.L.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.G. and X.X.

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Conflicts of Interest: The authors declare no conflicts of interest.

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