

## Research Article

# Study on Water Storage Change and Its Consideration in Water Balance in the Mountain Regions over Arid Northwest China

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Changes in permafrost and glaciers influence water balance in mountain regions of arid northwest China. Terrestrial water storage change (TWSC) is an important factor in the water cycle. In this study, we used Gravity Recovery and Climate Experiment (GRACE) satellites data to retrieve the TWSC in Tien Shan and Qi Lian Mountains. Variation of seasonal TWSC was obvious. However, the seasonal and annual differences reflected the imbalance of water resource distribution in two mountains. The TWSC decreased in the Tien Shan Mountains but increased in the Qi Lian Mountains during 2003 to 2010. Permafrost and glaciers play an important role in the water cycle in arid mountain regions. Demands for water for agriculture need more groundwater extraction for irrigation and glacial melt feeding the rivers which leads to the state of loss of TWSC in Tien Shan Mountains. Increase and thickening of the active layer of permafrost could lead to more infiltration of surface water into the groundwater, which result in increasing water storage and changes in the regional water balance. According to water balance, precipitation and evaporation changed little in short time, and TWSC changed obviously, whereas runoff showed an increasing trend in the Tien Shan Mountains and a decreasing trend in the Qi Lian Mountains.

## 1. Introduction

Increasing vulnerability of the water resource systems threatens human well-being and the function of various eco-environmental systems in the arid Asian zone [1]. As precipitation predominantly occurs and glaciers (often called the “solid reservoir”) are distributed in mountain regions, water resources are mainly provided by mountainous areas in the arid region of northwest China [2].

Tien Shan Mountains and Qi Lian Mountains are two regions of headwaters in arid northwest China. As an important landform, Tien Shan Mountains are regarded as water tower for supplies of agricultural and human population in the Chinese province of Xinjiang. The volume of the glaciers is about 1011 km<sup>3</sup> in the Tien Shan Mountains, and runoff of the rivers originating from Tien Shan Mountains accounts for 50% of the total runoff at least in Xinjiang [3, 4]. The contribution of melting snow and glacier runoff accounting for the total river runoff ranged from 20% to 70% in the region [5, 6]. The volume of the glaciers is about 811.2 km<sup>3</sup> in

the Qi Lian Mountains, and the annual average runoff that flows from the mountains is about 71 km<sup>3</sup>, which irrigates about 7800 km<sup>2</sup> of farmland and supports more than 500 million people [7]. It is evident that the water resources of the Tien Shan and Qi Lian Mountains are the lifeblood of the ecosystems and human population in the arid lands of northwest China.

Changes of the water balance factors (precipitation, runoff, and evaporation) have become an important topic of research in the mountains of arid northwest China [8]. A significant increasing trend of temperature has also been observed in the mountains of northwest China [9, 10]. Climate change will undoubtedly influence surface process of runoff in arid and semiarid areas, especially on the scale of the basins [11]. Researches indicated that runoff, temperature, and precipitation had shown significant increasing trends from 1957 to 2007 in Manas, Jing, Tarim, Kaidu, and Urumqi river basins which were located in the Tien Shan Mountains [12–14]. During 1950–2000, precipitation showed an increasing trend in the Qian Lian Mountains, but runoff showed

a significant decreasing trend in the eastern region of the mountains (Shiyang River and Taolai River). Furthermore, the trend of runoff change was not obvious in central and western parts, although precipitation and temperature showed simultaneous rising trends (e.g., He River and Shule River) [15–18]. Evaporation also plays an important role in the water balance in northwest China. Some researchers have indicated that evaporation has shown a trend of decrease in the Tien Shan and Qi Lian Mountains [19, 20]. Changes of evaporation cause changes in other factors (e.g., precipitation, runoff, and terrestrial water storage change (TWSC) of the water balance). Most previous researches in the mountains of arid northwest China have focused on precipitation, runoff, and evaporation; however TWSC has been ignored. Therefore, systematic changes in the factors of the terrestrial water balance were still unknown in the arid mountains.

TWSC which is essential and important for understanding a wide range of hydrological, climatological, ecological processes and water resource management includes changes of surface water, snow and ice, soil moisture, and groundwater [21]. It is difficult to measure TWSC directly, especially in remote mountains. In tradition, satellites can be used to detect surface soil moisture in which the depth was only about ten centimeters. Besides, the spatial distribution of field stations for verification purposes is poor. However, the Gravity Recovery and Climate Experiment (GRACE) satellites can make up such disadvantages; it offers a new opportunity for quantitative studies of regional TWSC.

The GRACE detects the variation of the Earth's global gravity field which is mainly due to land TWSC, such as ice masses (e.g., polar ice sheets, alpine glaciers, and ice caps) and other geophysical signals (e.g., postglacial rebound and deformation caused by earthquakes) [22, 23]. Interference signals in the GRACE data caused by atmospheric and ocean-mass variations can be removed successfully using numerical simulations, and then TWSC was retrieved [24]. The GRACE satellites can monitor the water equivalent change about 0.9 cm and the precision can reach 1–1.5 cm when spatial scales are longer than 1300 km [25, 26]. Some researchers have compared the results between retrieved by GRACE and using global land-surface-process models. The two methods have shown similar results in most areas, although some discrepancies arose owing to difficulties in obtaining precise input data in models. TWSC retrieved by GRACE can provide the reference for improvements of the accuracies of global land-surface-process models [27–30]. Besides, GRACE data have also been applied to monitor soil moisture and groundwater depletion due to drought or irrigation [31–34] and extract flux information from the water balance equation, such as evapotranspiration [35, 36] or river discharge [37–40]. In addition, TWSC data retrieved by GRACE have been used in cryospheric-related research on permafrost activities in Alaska, Arctic, central Siberia regions, and Three-River Source Region of the Tibetan Plateau, indicating that changes in the permafrost active layer might be an important reason behind the variations of TWSC in these areas [41–44]. In China, researches have focused on large areas [5, 30, 45, 46]. Generally, the researches involved regional quantitative descriptions of TWSC which just reveal characteristics in

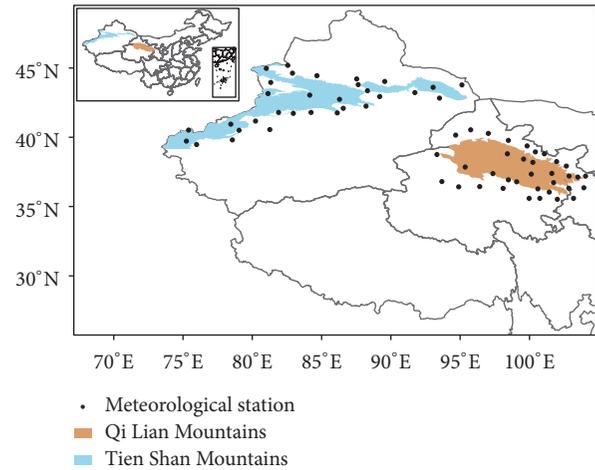


FIGURE 1: Locations of the Tien Shan Mountains and Qi Lian Mountains.

different area. However, a comprehensive study of WSC in the mountains of arid northwest China has not been reported previously.

In this study, gravity information retrieved from GRACE satellites was used to assess monthly TWSC during 2003 to 2010 in the Tien Shan and Qi Lian Mountains. This investigation focused on the influence of permafrost and glaciers on TWSC, changes in TWSC related to different mountains, and water balance changes in the study area. The purpose of this work is preliminary to reveal the basic law of water recycling and provide a baseline for water resource management in the arid northwest China.

## 2. Study Area

The study area encompassed the Tien Shan Mountains and Qi Lian Mountains, which are located in arid northwest China (Figure 1). The Tien Shan Mountains in the hinterland of Asia are located within 39–45.5°N and 73–96°E. They stretch 1700 km from east to west and cover an area of about  $27.1 \times 10^4 \text{ km}^2$ . There are 9035 glaciers with the area of about  $9225 \text{ km}^2$ , accounting for 3.41% of the total area. The area of permafrost is about  $6.3 \times 10^4 \text{ km}^2$ , which accounts for 23% of the total area [18]. The Tien Shan Mountains are located in an inland area affected by the mid-latitude westerlies, and thus the main source of water vapor is from the westerly circulation. The remaining water vapor (1/4–1/3) is brought by dry and cold Arctic air, and the impact of the Pacific and the Indian Ocean monsoons is small [47]. The Tien Shan Mountains constitute the main water source for the Chinese province of Xinjiang. Although the area of Tien Shan Mountains only accounts for 16.3% of the total area in the Chinese province of Xinjiang, they provide 40% of total water resources. The area of northern and southern slopes of Tien Shan Mountains is  $11.7 \times 10^4$  and  $15.4 \times 10^4 \text{ km}^2$ , respectively, which accounts for about 43% and 57% of the total area. Average annual precipitation on the northern and southern slopes is about 591 and 396 mm, respectively [48].

The Qi Lian Mountains are located in the northeastern edge of the Tibetan Plateau (36–40°N, 93.5–103.1°E) (Figure 1). The length of the Qi Lian Mountains is about 850 km, and the total area is about  $19.8 \times 10^4 \text{ km}^2$ . There are 2859 glaciers, whose area is  $1972.5 \text{ km}^2$ , and it accounts for 1% of the total area. The area of permafrost is about  $10 \times 10^4 \text{ km}^2$ , which accounts for about 50% of the total area [15]. Qi Lian Mountains are the most important water source for the inland rivers (Shiyang River, He River, Shule River, Datong River, and Qinghai lake) in Hexi Corridor, and thus they constitute an important factor for the regional population and socioeconomic development. The eastern Qi Lian Mountains are affected by the southwest and southeast summer monsoons. Because of the steep slopes, air rises vigorously and annual precipitation is more in this area. Middle and western parts of the Qi Lian Mountains are further from the ocean and consequently, annual precipitation is smaller than in the eastern part. Overall, the average annual temperature decreases gradually with increasing elevation, precipitation decreases from east to west, and the climate ranges from semihumid to semiarid and arid [48].

### 3. Data and Methods

**3.1. Method of TWSC Data Retrieval.** This study used GRACE Level-2 RL05 data from the University of Texas Centre for Space Research (<http://www.csr.utexas.edu/grace/asdp.html>), and the resolution of gridded data is  $1^\circ \times 1^\circ$ . As the reference frame used in the determination of GRACE satellites gravity field, gravity field coefficients of degree 1 in RL05 were processed as zero. However, the degree 1 information could have significant impact on the recovery of surface mass variations. To improve the accuracy and precision in deriving TWSC, the original gravitational coefficients of degree 1 were replaced by calculated values in RL05 [49]. RL05 data, with the same signals in RL04, has been improved with significant noise reduction. Given that the C20 coefficient which is measured by satellite laser ranging (SLR) is much better than in RL05, so C20 was replaced with SLR C20 in RL05 [50]. A decorrelation filter was applied to reduce the effects of noisy N–S stripes in the monthly time-variable coefficients. Correlated noises (N–S stripes) were removed from coefficients for orders ( $m$ ) greater than 15 which used a fifth-order polynomial, and it was fitted as a function for each odd or even set for a given order [49]. These processed spherical harmonic coefficients were transformed into gridded data with 1-arc-degree spatial resolution, indicating the Earth's surface mass variations, which were caused mainly by the redistribution of water on continents or in oceans. The global grids comprised 1-arc-degree water equivalent mass change complete to degree and order 40. The GRACE Level-2 RL05 data (300 km Gauss-smoothing kernel) land and ocean monthly grids during 2003 to 2010 were combined to provide global coverage [51]. Glacial isostatic adjustment (GIA) is ongoing movement of land, and the land once under and around the ice is still rising and falling in reaction to its ice-age burden (<http://oceanservice.noaa.gov/facts/glacial-adjustment.html>), and

we deal with the GIA in study area by the method of Paulson et al. [52]. The process of retrieving is given by:

$$\Delta h(\phi, \lambda, t) = \frac{a_e \rho_e}{3\rho_w} \sum_{l=0}^{40} \sum_{m=0}^l \frac{(2l+1)}{1+k_l} W_l P_{lm} \sin(\phi) \cdot [\Delta C_{lm}(t) \cos(m\lambda) + \Delta S_{lm}(t) \sin(m\lambda)], \quad (1)$$

$$W_l = \exp \left[ \frac{(lr/a_e)^2}{4 \ln(2)} \right],$$

where  $P_{lm}$  is normalized Legendre polynomials,  $\Delta C_{lm}(t)$  and  $\Delta S_{lm}(t)$  are normalized time-varying Stokes spherical harmonic geopotential coefficients,  $a_e$  is Earth's mean radius,  $r$  is the spatial radius,  $k_l$  are Love numbers,  $\rho_e$  is Earth's mean density,  $\rho_w$  is water density,  $t$  is time, and  $\phi$  and  $\lambda$  are latitude and longitude, respectively.

**3.2. Precipitation Data and Spatial Interpolation Method.** Precipitation data were obtained from national meteorological stations within the study area during 2003 to 2010, and the data was corrected which considers the influence of wind [53]. Furthermore, to improve the continuous spatial extent of precipitation, the data were interpolated using Kriging with consideration of elevation [54]. This method uses precipitation and site elevation data to perform an initial linear regression. The spatial rasterized precipitation regressed by elevation  $P_r$  was calculated using the formula for linear regression, and the residuals (regressed precipitation minus measured precipitation) were interpolated using the Kriging spatial interpolation method, and then the values of the spatial  $P_r$  were added to the spatial residuals, providing the spatial distribution of precipitation:

$$P_{\text{result}} = P_r + P_{\text{residual}}, \quad (2)$$

where  $P_{\text{result}}$  is the spatial precipitation,  $P_r$  is the rasterized precipitation regressed by elevation, and  $P_{\text{residual}}$  is the spatial residual (units: mm).

**3.3. Change of Precipitation.** Precipitation is the main source of land surface water, and changes in precipitation affect evaporation, runoff, and TWSC. In this study, the change of precipitation was calculated using the following formula:

$$P_c = P_i - P_{i-1}, \quad (3)$$

where  $P_c$  is the change of precipitation,  $P_i$  is the precipitation in month  $i$ ,  $P_{i-1}$  is the precipitation in the preceding month, and  $i$  represents the month (1–12). And then we calculate the average annual change of precipitation from 2003 to 2010.

**3.4. Basin-Scale Water Balance.** The basic elements of water cycle include precipitation, runoff, evaporation, and water storage change in watershed. Runoff is relatively easy to obtain in scale of watershed. However, the total runoff of remote mountain region is more difficult to obtain. Actual evaporation ( $ET_a$ ) is an important factor in studies of hydrology, and it can be estimated indirectly using physical models

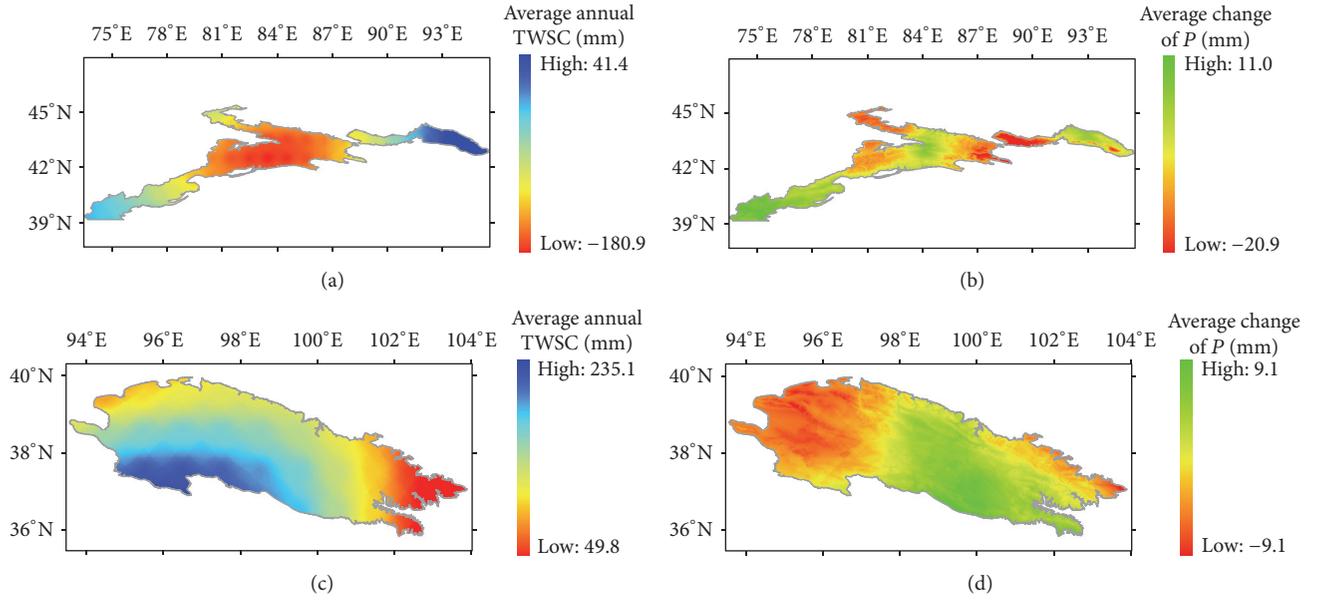


FIGURE 2: Spatial distribution of mean annual terrestrial water storage change (TWSC) and mean annual change of precipitation ( $P$ ) over the Tien Shan Mountains (a, b) and Qi Lian Mountains (c, d) during 2003 to 2010.

(e.g., the Penman–Monteith equation). Based on the river-basin-scale terrestrial water balance, changes of regional runoff can be estimated by TWSC, precipitation, and  $ET_a$ . In the equation of water balance, the TWSC can be retrieved by GRACE, the precipitation can be measured by rain gauge, and  $ET_a$  was calculated by Penman–Monteith equation. Within a closed area, changes in the various elements of the water cycle determine the regional water cycle characteristics. The water balance equation was used to calculate  $\Delta R$ , and it can be expressed as

$$\Delta R = \Delta P - \Delta ET_a \pm \Delta W, \quad (4)$$

where  $\Delta R$  is the change of runoff,  $\Delta P$  is the change of precipitation,  $\Delta ET_a$  is the change of actual evaporation, and  $\Delta W$  is the TWSC of the watershed, which can be retrieved by GRACE.

**3.5. Trend of TWSC.** The trend represents the spatial variation of slope. A positive slope indicates TWSC increased and a negative slope indicates that TWSC decreased. We calculated the interannual slope for the Tien Shan and Qi Lian Mountains using the following equation [55]:

$$\text{slp} = \frac{8 \times \sum_{i=1}^8 i \times \text{GRACE}_i - \left(\sum_{i=1}^8 i\right) \left(\sum_{i=1}^8 \text{GRACE}_i\right)}{8 \times \sum_{i=1}^8 i^2 - \left(\sum_{i=1}^8 i\right)^2}, \quad (5)$$

where slp is the spatial variation of slope and  $\text{GRACE}_i$  is the TWSC in year  $i$ ; for example, 2003 is the first year, 2004 is the second year, and so on.

## 4. Results and Discussion

**4.1. Temporal and Spatial Patterns of TWSC and Precipitation over the Tien Shan and Qi Lian Mountains.** The TWSC was retrieved from GRACE satellites data during 2003 to 2010 in the Tien Shan and Qi Lian Mountains. The spatial distributions of the average annual TWSC and change of precipitation calculated using (2) and (3) are shown in Figure 2. The average annual TWSC of the Tien Shan Mountains is in a state of gain in the west and east, but in a state of loss in central parts. The magnitude of TWSC in the west and east of the Tien Shan Mountains is smaller than in central parts. The ranges of TWSC and precipitation changes are from  $-180.9$  mm to  $41.4$  mm and  $-20.9$  mm to  $11.0$  mm during 2003 to 2010, respectively. The spatial distributions of TWSC are consistent with precipitation, which indicates that the spatial distribution of TWSC is influenced by precipitation in the western and eastern Tien Shan Mountains and even in some central parts. However, they also show opposite distributions in central and some eastern areas (Figures 2(a) and 2(b)), which is mainly because of the more demands for water for agricultural use from these area, and more groundwater extraction for irrigation leads to the state of loss of TWSC. Even though the change of precipitation is positive in these areas, rising temperatures accelerated glacial melt, which fed the rivers, and thus the TWSC remained in a state of loss. Research has indicated that the average loss of mass balance was about 267 mm in number 1 glacier in Urumqi river over the Tien Shan during 1959 to 2009 [56, 57], and the TWSC of the Tien Shan Mountains might reflect the partial loss of the glaciers.

The TWSC was in a state of gain throughout the Qi Lian Mountains during 2003 to 2010 (Figures 2(c) and 2(d)), but the spatial distribution of TWSC shows significant differences; that is, it is more in the west than in east, and

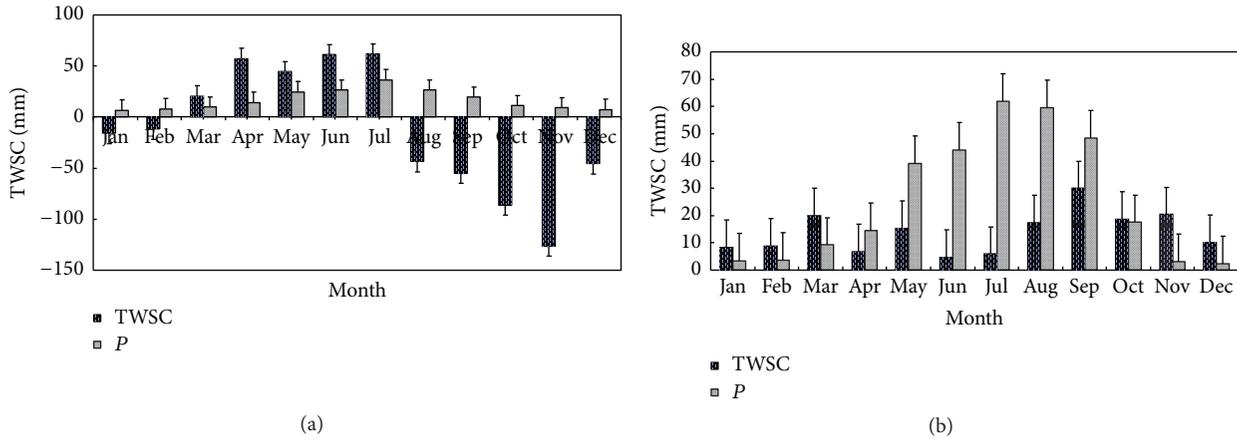


FIGURE 3: Annual distributions of terrestrial water storage change (TWSC) and precipitation during 2003 to 2010: (a) Tien Shan Mountains and (b) Qi Lian Mountains.

more in the south than in the north. The maximum value is in the south and the minimum value in the east. Precipitation changed little during 2003 to 2010, and it decreased in western areas and decreased slightly in the northeast but increased in most central parts (Figure 2(d)). The ranges of TWSC and precipitation changes are from 49.8 mm to 235.1 mm and -9.1 mm to 9.1 mm during 2003 to 2010, respectively. There are differences between the spatial distributions of TWSC and precipitation change, which indicate that the distribution of TWSC is not only influenced by precipitation but also by the underlying surface. The maximum value appears on the southern slopes of central parts, because the TWSC is controlled by the presence or absence of permafrost and the thickness of the active layer of permafrost in this region. Here, surface water was recruited for subsurface groundwater storage and increasing groundwater residence time led to the increase of the TWSC, as it has been similarly confirmed in the Arctic [58–60].

TWSC and precipitation have obviously seasonal variations in the Tien Shan and Qi Lian Mountains, and the distribution of TWSC exhibits different characteristics (Figures 3(a) and 3(b)). The study areas are located in different parts of northwest China where the sources of water vapor depend mainly on the zonal westerly circulation (Tien Shan and Qi Lian) and the East Asian monsoon (Qi Lian) [61, 62]. Rainfall is concentrated mainly from May to October in study area. The peak values of TWSC and precipitation appear at the same time (July) in the Tien Shan Mountains. The gain of TWSC is concentrated mainly during March to July in the Tien Shan Mountains, the end of which is the period of maximum precipitation (maximum value of average monthly TWSC is 61.7 mm in July) during 2003 to 2010. The value of TWSC in the Tien Shan Mountains is larger than precipitation from March to July. Conversely, the TWSC in the Tien Shan Mountains is in a state of loss during the other months; for example, the minimum value is -126.3 mm in November during 2003 to 2010. There are two peaks of TWSC in the Qi Lian Mountains (March and September). In spring, because of the thawing and refreezing

of permafrost, precipitation is stored in the mountains, which leads to the peak in the TWSC in the Qi Lian Mountains. However, over time, runoff is generated and the WSC decreases. With the arrival of the rainy season, the second peak appears, although the process of TWSC has a certain lag compared with the process of precipitation, which indicates that permafrost might play a decisive role in the formation of cold groundwater transport processes and the pattern of distribution of groundwater and its pathways in the Qi Lian Mountains. The TWSC is in a state of gain during January to December in the Qi Lian Mountains, and the maximum value is in September (20.4 mm) and the minimum value is in June (6.7 mm).

The process of TWSC is consistent with the process of precipitation during 2003 to 2010 in the Tien Shan Mountains (Figure 4(a)). The variation of TWSC ranged from -98.4 mm to 41.5 mm during 2003 to 2010 in Tien Shan Mountains. This means that the maximum increase in water was about 41.5 mm equivalent water height and the minimum value was -98.4 mm equivalent water height. Monthly precipitation ranges from 2.8 to 53.7 mm, although there is little variation in the annual precipitation during 2003 to 2010 (Figure 4(a)). The characteristics of the variation in precipitation have the dominant effect on TWSC in the time series, especially in 2008 and 2009 (i.e., less precipitation and lower TWSC). TWSC shows a significant decreasing trend during 2003 to 2010, which means that the difference between the water flowing into and out of the region fell (Table 1).

The process of TWSC is more complicated in the Qi Lian Mountains, although there is little variation in the annual precipitation in the Qi Lian Mountains during 2003 to 2010 (Figure 4(b)). The variation of TWSC ranges from -59.3 mm to 96.3 mm and variation of precipitation ranges from 0.9 mm to 72.2 mm in Qi Lian Mountains during 2003 to 2010. The minimum and maximum values in the Qi Lian Mountains are all larger than in the Tien Shan Mountains, which means the distribution of water resource is uneven in the Qi Lian Mountains and that water resources in the Tien Shan Mountains are even scarcer. The TWSC shows a

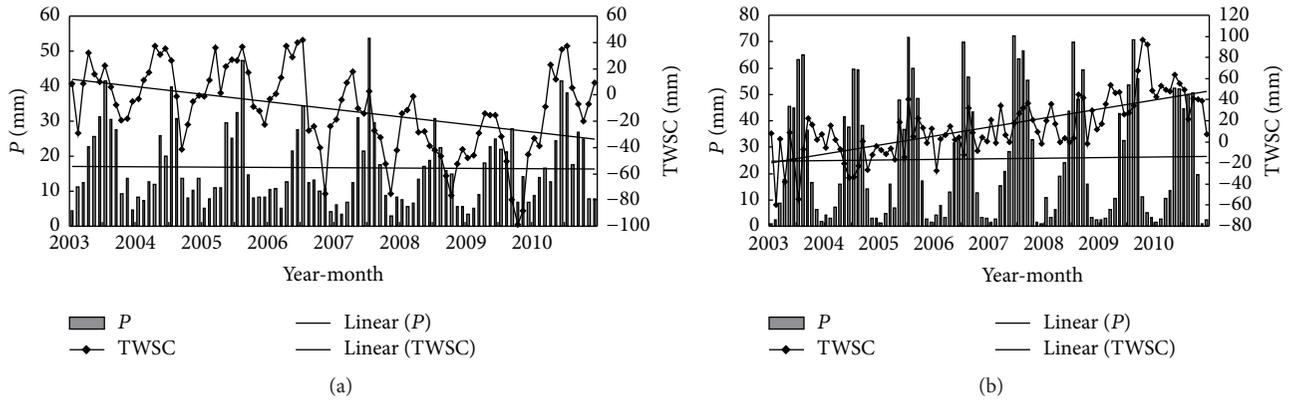


FIGURE 4: Time series of terrestrial water storage change (TWSC) and precipitation ( $P$ ) during 2003 to 2010: (a) Tien Shan Mountains and (b) Qi Lian Mountains.

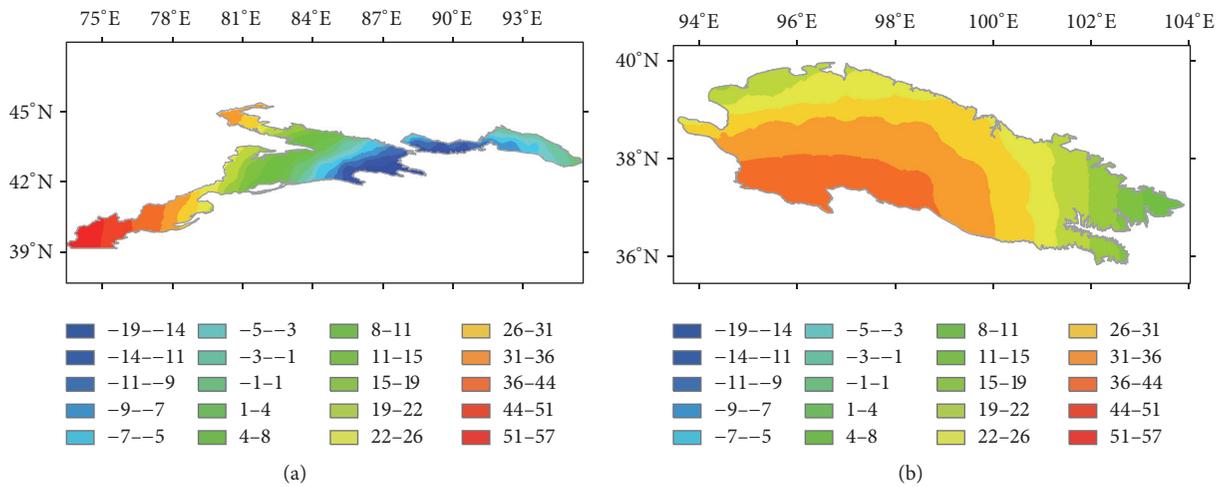


FIGURE 5: Spatial trends of terrestrial water storage change (TWSC) during 2003 to 2010: (a) Tien Shan Mountains and (b) Qi Lian Mountains.

TABLE 1: Amount of terrestrial water storage change (TWSC) in the Tien Shan Mountains and Qi Lian Mountains during 2003 to 2010.

Region	Rate of change (mm/year) ( $p < 0.05$ )	2003–2010 TWSC ( $\text{km}^3$ )
Tien Shan Mts.	$-5.8 \pm 1.1$	$-12.5 \pm 2.3$
Qi Lian Mts.	$8.6 \pm 0.8$	$13.6 \pm 1.3$

significant increasing trend during 2003 to 2010, which means that more water is stored in the Qi Lian Mountains (Table 1).

**4.2. Spatial Trends and Cycles of TWSC over the Tien Shan and Qi Lian Mountains.** The spatial trends of TWSC during 2003 to 2010 in the Tien Shan and Qi Lian Mountains were calculated using (5) and are illustrated in Figures 5(a) and 5(b), respectively. There is a positive trend in the west and a negative trend from central parts to the east in the Tien Shan Mountains. The minimum value of the trend appears in central parts of the Tien Shan Mountains (Figure 5(a)). The spatial trends of TWSC during 2003 to 2010 in the Qi Lian Mountains are all positive (Figure 5(b)), and the maximum

value appears on the southern slopes and the minimum value is in the east. A comparison of the two regions shows uneven distribution of TWSC in the Tien Shan Mountains and more abundant water resource in the Qi Lian Mountains (Figures 5(a) and 5(b)). The TWSC retrieved by GRACE are in line with normal patterns (Figure (4)). The change of water storage change in the Tien Shan Mountains has greater complexity and uncertainty. For one thing, water storage change is more scarce and needs more time to supplement. And although the TWSC of the area has increased overall, a greater quantity of water is stored in the Qi Lian Mountains.

**4.3. The Influences of Permafrost and Glaciers on TWSC in the Tien Shan and Qi Lian Mountains.** As shown in Figure 6, precipitation in the two mountain areas does not change much during 2003 to 2010, but the pattern of TWSC is very different. During 2003 to 2005 and in 2010, TWSC is in a state of gain in the Tien Shan Mountains (maximum value appears in 2005: 132.2 mm), and during 2006 to 2009, TWSC is in a state of loss (minimum value appears in 2009:  $-561.5$  mm). In the Qi Lian Mountains, WSC is only in a state of loss in 2003 and 2004, and it is in a state of gain in other years

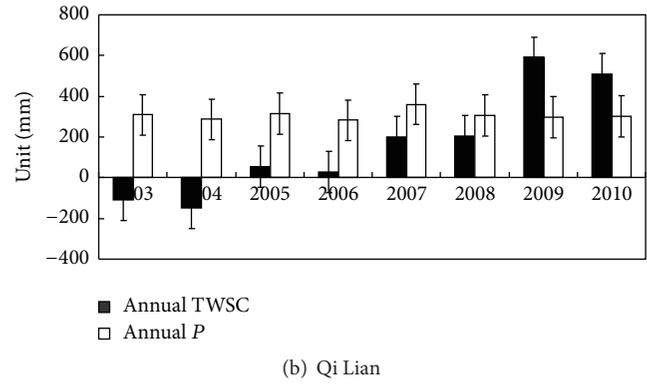
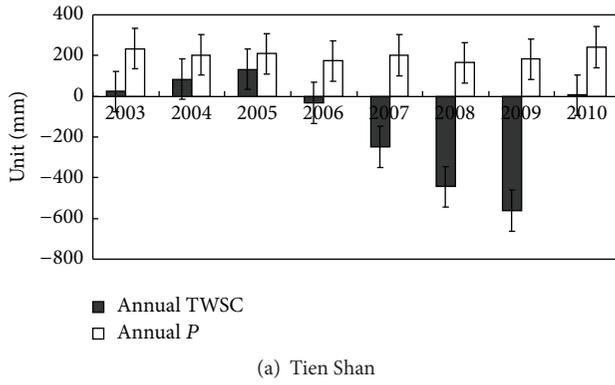


FIGURE 6: Annual terrestrial water storage change (TWSC) and precipitation ( $P$ ) in the Tien Shan and Qi Lian Mountains.

(maximum and minimum values are 591.7 mm (2009) and 22.9 mm (2003), resp.). The distributions of glaciers, permafrost, and talik (a layer of ground that remains unfrozen year-round) affect the characteristics of surface drainage and groundwater storage changes in northwest China [39]. The dynamics of permafrost, talik, and the active layer exert significant influence on the surface and groundwater hydrology and geomorphology in the Qi Lian Mountains. The Qi Lian Mountains is the region of numerous and quite large thermokarst thaw ponds, lakes, and drained thaw-lake basins [63, 64]. The increase and thickening of the active layer can lead to greater infiltration of surface water into the groundwater, which results in increased water storage. The GRACE monthly water equivalent changes capture the changes of the base flow from groundwater and surface water into the permafrost area.

In related research, GRACE-derived TWSC has been found to increase in the watershed of the Lena and Yenisei rivers [65]. These watersheds encompass large areas of both continuous and discontinuous permafrost zones and talik. Glacier mass loss has occurred across the QL and Tien Shan Mountains [66]; however, since the early 2000s, the trend of precipitation has not changed much. In contrast, TWSC has exhibited large differences (Figure 6). TWSC decreased in Tien Shan Mountains, but it increased in Qi Lian Mountains. The total area of the Tien Shan Mountains is  $27.1 \times 10^4 \text{ km}^2$ , and the area of glaciers is approximately  $9225 \text{ km}^2$  which accounts for 3.41% of the total area. The area of permafrost is about  $6.3 \times 10^4 \text{ km}^2$  which accounts for 23% of the total area. The area of the Qi Lian Mountains is  $19.8 \times 10^4 \text{ km}^2$ , and the area of glaciers is approximately  $1931 \text{ km}^2$ , which accounts for about 1% of the total area. The area of permafrost is about  $10 \times 10^4 \text{ km}^2$ , which accounts for 50% of the total area. In the Tien Shan and Qi Lian Mountains, meltwater is the primary supplement to runoff. However, the TWSC is in a state of loss in the Tien Shan Mountains, which shows that glacial meltwater flows out of this area and less surface water infiltrates into the groundwater. The Qi Lian Mountains have a greater distribution of permafrost than the Tien Shan Mountains, and thus the thickened active layer, as well the greater number of ponds, might store additional water that causes the increase of WSC (Figure 7).

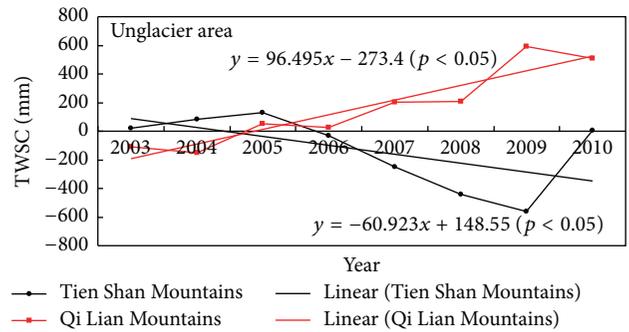


FIGURE 7: Terrestrial water storage change (TWSC) of nonglaciered areas of the Tien Shan and Qi Lian Mountains.

TABLE 2: Average rates of water balance parameter change in the Tien Shan Mountains and Qi Lian Mountains during 2003 to 2010.

Region	$\Delta P$ (mm/year)	$\Delta E$ (mm/year)	$\Delta W$ (TWSC) (mm/year)	$\Delta R$ (mm/year)
Tien Shan Mts.	-0.1	-2.5 [20]	-5.8	+8.5
Qi Lian Mts.	+0.2	-1.7 [19]	+8.6	-6.7

TABLE 3: Changes of water balance parameter in the Tien Shan Mountains and Qi Lian Mountains during 2003 to 2010.

Region	$\Delta P$ ( $\text{km}^3$ )	$\Delta E$ ( $\text{km}^3$ )	$\Delta W$ (TWSC) ( $\text{km}^3$ )	$\Delta R$ ( $\text{km}^3$ )
Tien Shan Mts.	-0.2	-5.4	-12.5	+17.7
Qi Lian Mts.	+0.4	-2.7	+13.6	-10.6

4.4. Changes of Water Balance in the Tien Shan and Qi Lian Mountains. Changes of the water balance were analyzed in the Tien Shan and Qi Lian Mountains during 2003 to 2010 and the results are presented in Tables 2 and 3. Precipitation in the study area shows different trends. The rate of decrease is  $-0.1 \text{ mm/year}$  in the Tien Shan Mountains, which is equivalent to a water volume of  $-0.2 \text{ km}^3$  during 2003 to 2010. The rate of increase in the Qi Lian Mountains is  $0.2 \text{ mm/year}$ . Evaporation shows the same trend. Evaporation in the Tien

Shan and Qi Lian Mountains shows decreasing trends in recent decades which is  $-2.5$  mm/year and  $-1.7$  mm/year, respectively, and they are equivalent to water volumes of  $-5.4$  km<sup>3</sup> and  $-2.7$  km<sup>3</sup> during 2003 to 2010, respectively. The changes of water balance in the two mountain regions can be calculated using (4). The rates and volumes of  $\Delta P$ ,  $\Delta E$ ,  $\Delta W$ , and  $\Delta R$  within the study area are given in Tables 2 and 3. The trend of  $\Delta R$ , although of similar magnitude, is opposite sign (decrease) relative to the trend determined using GRACE (increase). The increase of  $\Delta R$  in the Tien Shan Mountains is  $8.5$  mm/year ( $17.7$  km<sup>3</sup>) and the decrease of  $\Delta R$  in the Qi Lian Mountains is  $-6.7$  mm/year ( $-10.6$  km<sup>3</sup>) during 2003 to 2010. In all cases, the precipitation trends are clearly lower than those derived from GRACE. This indicates that precipitation is not the dominant component of short-term TWSC in the Tien Shan and Qi Lian Mountains. Changes in the water balance of the study area were mainly related to changes of TWSC and runoff, which were influenced by the distributions of glaciers and permafrost as discussed above.

## 5. Conclusions

The TWSC was retrieved using GRACE data during 2003 to 2010 in the Tien Shan and Qi Lian Mountains. The spatial distribution of WSC was more influenced by precipitation in the Tien Shan Mountains than in the Qi Lian Mountains. Permafrost and glaciers of mountains play an important role in the water cycle of arid land, and the increase and thickening of the active layer can lead to more infiltration of surface water into the groundwater, which can result in increased water storage and changes in the regional water balance.

In the Tien Shan Mountains, the TWSC decreased obviously during 2003 to 2010 with an average rate of decrease of about  $-5.8 \pm 1.1$  mm/year ( $p < 0.05$ ) (a total decrease of  $-12.5 \pm 2.3$  km<sup>3</sup>). In the Qi Lian Mountains, the TWSC increased during 2003 to 2010 with an average rate of increase of about  $8.6 \pm 0.8$  mm/year ( $p < 0.05$ ) (a total increase of  $13.6 \pm 0.8$  km<sup>3</sup>). We try a new method to estimate runoff based on water balance. Runoff increased in the Tien Shan Mountains during 2003 to 2010 at a rate  $8.5$  mm/year, which is  $17.7$  km<sup>3</sup>, but it decreased in the Qi Lian Mountains at a rate of  $-6.7$  mm/year, which is  $-10.6$  km<sup>3</sup>. In cases of little changes in precipitation and evaporation in short time, the increase (decrease) of WSC was significant, which caused a decrease (increase) in runoff from the mountains of northwest China.

GRACE can reveal trend of water storage change in large and middle scale area, and it is the complement for elements of water cycle in monitoring techniques which have existed (e.g., dig wells and remote sensing technology). With the improvement of retrieved method and implementing a follow-on satellite gravity exploration program, spatial resolution and accuracy of global and regional water storage changes will be further enhanced. The GRACE data was assimilated with surface ecological environmental multisources, multiscale observations which can reveal the

variation of hydrological cycle and its response to climate change.

## Competing Interests

The author declares that they have no competing interests.

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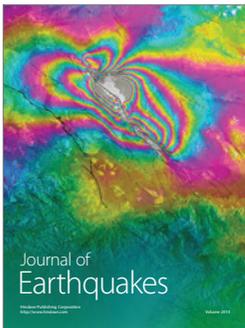
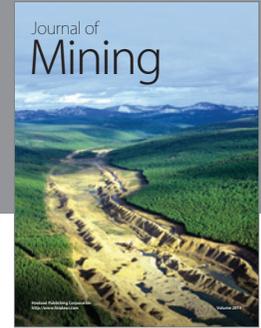
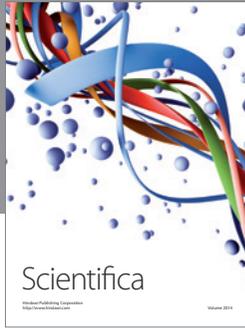
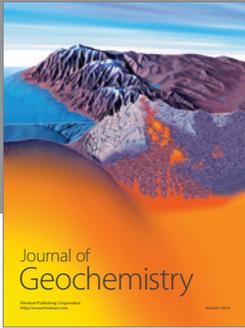
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