

Article

# Estimation of Actual Evapotranspiration in a Semiarid Region Based on GRACE Gravity Satellite Data—A Case Study in Loess Plateau

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**Abstract:** Jointly influenced by natural factors and artificial protection measures in recent years, the vegetation coverage of the Loess Plateau has significantly increased. However, extensive vegetation recovery can result in massive water consumption and a severe soil water deficit, which poses a great threat to the sustainable development of the regional ecological system. Maintaining the balance between precipitation and water consumption is an important foundation of ecological security in the Loess Plateau. Based on this, the present study used the GRACE (Gravity Recovery and Climate Experiment) gravity satellite data to simulate the annual actual water consumption from 2003 to 2014 and to analyze the temporal and spatial evolution of the regional precipitation and the actual evapotranspiration (AET). This study also applied the newly developed rainwater utilization potential index (IRUP) to quantify the sustainability of the water balance in the Loess Plateau. The spatial-temporal patterns of precipitation, potential evapotranspiration, and AET from 2003 to 2014 in the Loess Plateau were all analyzed in this study. Based on the results, the annual average precipitation (AAP) and AET in the entire Loess Plateau had significant increasing trends. The analysis of the spatial distribution reveals that the AET was decreasing from the southeast to the northwest in the Loess Plateau. However, the average values of potential evapotranspiration did not obviously change. Based on the estimated AET result, it was determined that the average IRUP had an increasing trend. The increase in the IRUP is due to an increased rate of precipitation that is statistically higher than that of the AET. Consequently, the Loess Plateau experienced a wetting trend during the period of 2003–2014, especially after the Grain for Green project was implemented. The results in this paper were proven by using three different depths of ERA-Interim (a global atmospheric reanalysis product created by the European Centre for Medium-Range Weather Forecasts) soil water content data from the same period and the observed runoff data from 18 different hydrological sites. Consequently, it seems that the vegetation could maintain a sustainable growth with the implementation of the Grain for Green Project.

**Keywords:** water balance; actual evapotranspiration; sustainability; Grain for Green Project; Loess Plateau

## 1. Introduction

The Loess Plateau is located in the middle and upper reaches of the Yellow River and has become one of the most vulnerable and most eroded areas, which is one of the worst environmental regions

in the world due to the erosion of loess and the impact of climate change (high-frequency torrential rains and extreme droughts) and human activities (overgrazing and mining) [1,2]. In order to reduce the increasingly serious soil erosion and improve the ecological environment of the Loess Plateau, since 1950, the Chinese government has carried out soil and water conservation measures vigorously, such as the Grain for Green Project, grassland reconstruction, and terrace and dam construction [3]. Among these efforts, the Grain for Green Project is an important project that was implemented by the Chinese government in 1999 to improve the ecological environment and the residents' quality of life and promote sustainable development.

According to the remote sensing monitoring, since the Grain for Green Project was implemented, the ecological environment of the Loess Plateau has undergone tremendous changes, and the average vegetation coverage has increased greatly. In 2013, it reached 59.6%, almost twice as much as before. As an example, the vegetation coverage of Ziwuling—a mountain which is located in the Loess Plateau hinterland—has reached 70–80% of the total area [4]. At the same time, the increase in regional vegetation coverage has effectively improved the soil structure and increased the storage capacity of soil reservoirs, and the river siltation in the region has decreased so significantly that the average value for 2000–2010 had decreased by 26% from the period of 1990–1999 [3,4]. Therefore, under the joint influence of climate change and human activities, the problems of serious soil erosion and ecological deterioration in the Loess Plateau seem to have been effectively alleviated and mitigated through a series of ecological restoration projects and natural restoration activities. Despite this success, there has been controversy over whether the vegetation water consumption in the Loess Plateau during these years is sustainable. The precipitation is the main source of water in the Loess Plateau. Added to the thick soil aeration zone, with an average depth of over 50 m, the groundwater level is relatively deep, which makes it difficult for vegetation to use groundwater [5]. Due to the scarce rainfall in the Loess Plateau, water resources are the biggest limiting factor to ecological sustainability [6].

In the arid and semi-arid Loess Plateau, the actual evapotranspiration (AET) is a primary important component of the water cycle, contributing to the conversion of energy and moisture between the soil, vegetation, and atmosphere, and the regulation of the local and regional climate. With the very limited precipitation in the Loess Plateau, the AET in this region is particularly important. Due to the uncertainties in the process of water transport and energy exchange in the soil–vegetation–atmosphere system, it is very difficult to estimate the AET of the land surface water cycle [7]. Based on this, results of quantitative research on the AET and the evaluation of the water shortage in the region have important guiding significance for vegetation construction practices in the Loess Plateau. At present, AET data are usually obtained by using two types of methods: the first is by direct measurement, and the other is by estimation and simulation. Among them, direct measurement methods mainly include the lysimeter method, Bowen ratio method [8], and eddy covariance method [9]. However, due to the high cost and heavy workload, it is impossible to distribute measuring spots at a large scale [10]. When the regional topography is undulating and the vegetation type is complex, the monitoring accuracy is greatly reduced, which limits the application of these methods to a large-scale monitoring area [11]. All three methods above are difficult to apply to large land areas with uneven geometric structure and non-uniform physical properties. In recent years, actual evapotranspiration estimation and simulation methods have gradually developed. At present, the hydrological model or hydrothermal coupling model are the approaches most applied to long-term AET estimation research. However, the hydrological model usually contains too many parameters, and the value range of the parameters are not clearly defined, which greatly increases the uncertainty of the output results of the model [12]. Another method is the remote sensing evapotranspiration model, which estimates the regional AET by monitoring the energy budget of the underlying surface [13]. However, the large uncertainties impede the calculation process, and the thickness of the estimated surface soil moisture can only reach a dozen centimeters [14–16].

In contrast, the gravity satellites can overcome the shortcomings of remote sensing satellites, providing a new way to conduct quantitative research on changes in water reserves in large-scale

terrains. In recent years, the GRACE (Gravity Recovery and Climate Experiment) gravity satellite data have been widely applied to the study of regional groundwater reserve changes and the mass migration of rivers and glaciers. Since the GRACE gravity satellite data are equally sensitive to water reserves of various depths, Wang argued that the GRACE gravity satellite data can fully reflect the dominant factors that cause changes in water reserves [17]. Li et al. argued that the estimated changes in the total water reserves are in good agreement with the most complete global water reserve model on the inter-annual and seasonal scales [18]. Wang et al. used the GRACE data to analyze the changes in terrestrial water reserves in the Haihe River basin for 10 years, proving that it is highly applicable to long-term arid regions [19]. Ni et al. proved that the water reserve changes and precipitation in the Yangtze and Yellow River basins have good temporal and spatial consistency at different scales and frequency bands by comparing the changes in water reserves and precipitation in the basin [20]. However, there are few studies on the AET estimation using the GRACE gravity satellite data [21,22]. The AET estimation method based on the GRACE gravity satellite data could supply an innovative way to map the spatial and temporal characteristics of the water budget on a large scale. Therefore, this study attempts to use the GRACE gravity satellite data to estimate the AET of the study area from the perspective of water balance and provides a new solution for the simulation of the water cycle in the Loess Plateau.

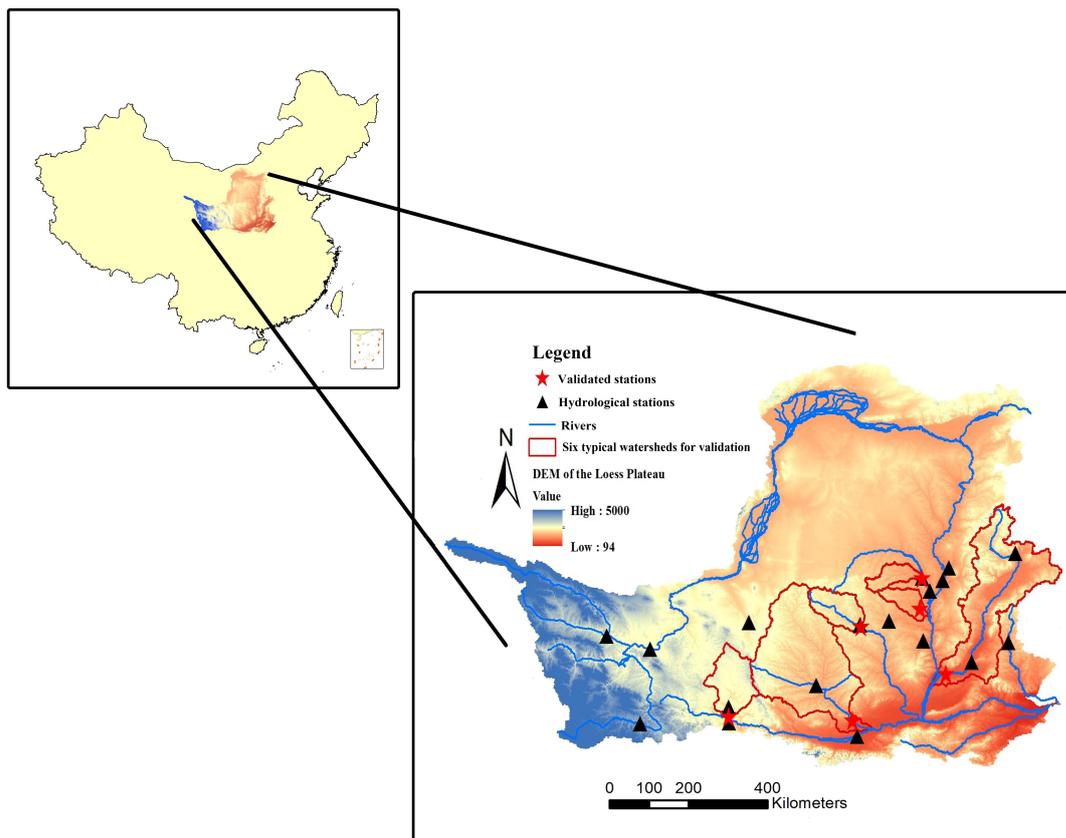
Based on this, this study aims to investigate the water balance in the condition of vegetation recovery through estimation of the AET using the GRACE gravity satellite data and evaluate the sustainability of vegetation growth in the future. The contents of this study can be summarized as follows: (1) The GRACE satellite-based estimation method will be introduced, and the AET from 2003 to 2014 will be simulated and validated; (2) The spatial and temporal characteristics of the AAP, potential evapotranspiration (PET) and AET in the whole study period (2003–2014) of the Loess Plateau will be analyzed; (3) the rainwater utilization potential index (IRUP) will be introduced to quantify the sustainability of the vegetation growth; (4) The changing trend of rainwater utilization potential will be proven using the ERA-Interim soil water content data, as well as the measured runoff data from 18 different hydrological sites. The above findings in this research may be an important reference for ecological restoration and vegetation recovery in the Loess Plateau.

## 2. Materials and Methods

### 2.1. Study Area

The research area of this study is the Loess Plateau, with a latitude between  $33^{\circ}43'$  and  $41^{\circ}16'N$  and a longitude between  $100^{\circ}54'$  and  $114^{\circ}33'E$ . It is the most concentrated and largest loess area in China but also in the world, with a total area of  $640,000\text{ km}^2$ . The average altitude is about 800–3000 m, decreasing successively from northwest to southeast. The topography of the region is complex and variable. Except for a few regions, most of the area is covered with thick loess. The thickness of the soil is about 50–80 m, and the maximum thickness is 150–180 m. The poor stickiness of the loess has caused serious soil erosion problems in this area. The specific topography and landform are shown in Figure 1.

Since the 1950s, large-scale ecological restoration projects have been carried out in the Loess Plateau region, notably the implementation of the Grain for Green Project that started at the end of 1999, which has significantly improved the vegetation conditions in the region and effectively prevented soil erosion. The paper published in Nature Geoscience points out that in the past 60 years, the sediment transport in the Yellow River basin has been greatly reduced. Engineering measures are the main reason for the decrease in sediment discharge from 1980 to 1999 [3]. Since the 1990s, the ecological environment has rapidly improved, and the role of vegetation has gradually become prominent.



**Figure 1.** Location of the Loess Plateau and the distribution of the 18 hydrological stations.

## 2.2. Data Source and Collection

Two types of data were used in this study: (1) the required parameters used to estimate AET, which include GRACE satellite gravity data, ERA-Interim data, and precipitation data. The GRACE satellite gravity data were provided by Release05 solutions by the Center for Space Research, University of Texas, Austin ([http://www2.csr.utexas.edu/GRACE/RL05\\_mascons.html](http://www2.csr.utexas.edu/GRACE/RL05_mascons.html)) and then converted to the variation in land water reserves through a series of data processing steps. The period analyzed was 2003–2014. The ERA-Interim data used were the third-generation reanalysis data developed by the European Centre for Medium-Range Weather Forecasts in 2006. Daily precipitation data came from 373 meteorological stations in the Loess Plateau region, provided by the Meteorological Bureau of Shaanxi Province, and were integrated with national precipitation grid data, which effectively improved the quality and accuracy of precipitation data in the research area. Before the precipitation data were released, the homogeneity and consistency test had been passed by the Meteorological Bureau based on a cumulative frequency curve method and Mann–Kendall test. To maintain the consistency of the data, the projected coordinate system used was WGS-84, with a resolution of  $1^\circ \times 1^\circ$ . The whole area was divided into 92 grids after resampling. (2) the required data used to validate the obtained AET included the observed runoff data collected from six typical watersheds, which were used to retrieve the actual evapotranspiration based on water balance analysis. We compared the estimated regional actual evapotranspiration with the AET results calculated by water balance to validate the reliability of the research findings. In this study, the runoff data for the six typical watersheds were obtained from six hydrological stations located in Yanchuan, Suide, Zhangjiashan, Qin'an, Hejin, and Liujiahe (the locations are shown in Figure 1) and are available from the National Data Sharing Infrastructure of Earth System Science (<http://www.geodata.cn/>). The homogeneity tests had been passed before release. As described in the discussion section, this study also collected ERA-Interim soil water content reanalysis data at three different depths (30, 100, and 300 cm) and

observed runoff data to verify the conclusions. The ERA-Interim data used in this study were the latest global atmospheric reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (<https://www.ecmwf.int/>). The runoff data were obtained from 18 hydrological stations (the locations are shown in Figure 1) and are available from the National Data Sharing Infrastructure of Earth System Science (<http://www.geodata.cn/>). The reliability, consistency, and representativeness of meteorological and hydrological data were validated before release.

### 2.3. Regional AET Estimation Using the Water Balance Equation

The Loess Plateau is located in the inland areas, where the ocean is very distant and the external water resources are very limited. Precipitation is the most important input source of water resources in the Loess Plateau. Meanwhile, the unsaturated zone is very deep in the Loess Plateau, ranging from 50 to 200 m over the entire area. Therefore, the groundwater resources are difficult to utilize [5]. To summarize, precipitation is the main water input, and evapotranspiration and runoff are the main water outputs in the Loess Plateau. Consequently, the water balance in the Loess Plateau can be estimated by the following equation:

$$\text{AET} = P - R - \Delta H \quad (1)$$

where P represents the average precipitation in a given time interval (a year), mm; R is the equivalent runoff depth in a given time interval (a year), mm; AET is the actual evapotranspiration in a given time interval (a year), mm; and  $\Delta H$  means the change in the soil water stored in the soil layer in a given time interval (a year), mm, which is measured because the unsaturated zone is very deep in the Loess Plateau, so the water flux between the groundwater system and the unsaturated zone is small enough to be neglected.

### 2.4. GRACE Gravity Satellite Data and TWSC (Terrestrial Water Storage Change)

The GRACE-derived terrestrial water storage (TWS) data were extracted to estimate the AET over the Loess Plateau. The  $1^\circ \times 1^\circ$  gridded monthly terrestrial water storage anomalies (TWSA) were obtained from each monthly TWS minus the mean TWS of the entire period. As GRACE monthly gravity models are often nonconsecutive, missing monthly data were interpolated from time series solutions. The TWSC was considered as the variation during a specific period. When estimating the AET using the method of Ramillien et al. [21], the TWSC for the  $i$ th month is,

$$\text{TWSC}(i) = \frac{\text{TWSA}(i+1) - \text{TWSA}(i-1)}{2} \quad (2)$$

When estimating AET using our method, the value of  $\Delta S$  is the TWSC derived from GRACE between two consecutive months, which can be written as:

$$\Delta S_{i,i+1} = \text{TWSA}(i+1) - \text{TWSA}(i) \quad (3)$$

### 2.5. The Definition of Rainwater Utilization Potential Index (IRUP)

The severe water shortage and the deep groundwater table make groundwater difficult to exploit; thus, rainwater has become the main water source for ecological construction. However, the distribution of precipitation within a year is uneven, and the loess layer is so thick that most of the aeration zones are thicker than 50 m. This peculiar climate condition and topographic feature mean that the groundwater cannot be supplied by short-duration precipitation [23]. To solve this problem, Wu et al. proposed the concept of the rainwater resource potential of the Loess Plateau, which is the amount of surface flow and increment in soil available water generated by precipitation within a period [24]. Regional rainwater resource potential is an efficient index of the available water resources of a region, and the larger the regional rainwater resource potential, the larger the available

water resource volume in the region. Seen from the perspective of water volume balance, the regional rainwater resource potential of the Loess Plateau can be reflected by precipitation minus the AET. On the basis of the concept of rainwater resource potential, this research proposes the rainwater utilization potential indicator (IRUP) to show the condition of the changes in wet and dry regions after the implementation of the Grain for Green Project; the IRUP can be calculated using Equation (4):

$$IRUP = 1 - \frac{AET}{AAP} \quad (4)$$

where, IRUP is the rainwater utilization potential, which is an important indicator to represent the dryness and wetness trends for the Loess Plateau. The higher the IRUP, the more water that is available for vegetation growth and ecological restoration on the Loess Plateau.

### 2.6. Spatial Interpolation Method

Since the meteorological data from 373 meteorological stations are point-scale data, it is necessary to change the "point" data to the "region" data through the spatial interpolation. Spatial interpolation of the meteorological data is divided into two steps. Firstly, the 373 stations are divided into two groups, one group includes 369 stations for interpolation and another group includes four stations (Yuzhong, Hequ, Linfen, and Pingliang stations) for validation. Then, we separately used three methods (IDW, Kriging, and Natural Neighbor) using the ArcGIS platform, to interpolate the point-scale data to regional data using the observed values of the 369 stations. After we obtained the regional interpolation results of the precipitation, we used the four stations to validate the interpolation results. The interpolation results of the three different interpolation methods are shown in Table 1.

**Table 1.** Error comparison among three different spatial interpolation methods.

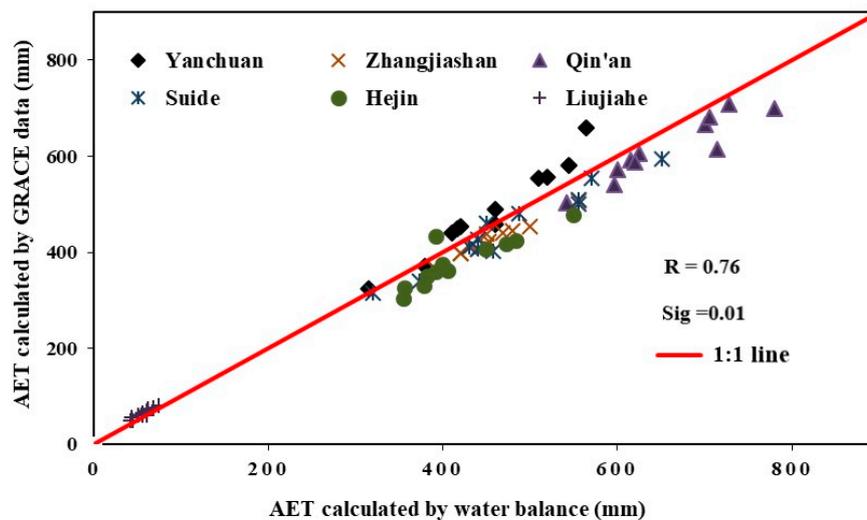
Validated Stations	Measured Value (mm)	Interpolation Results(mm)			Absolute Error (%)		
		IDW	Kriging	Natural Neighbor	IDW	Kriging	Natural Neighbor
Yuzhong	382.04	343.7	176.5	524.84	10.03	53.79	37.38
Hequ	377.89	341.4	155.3	530.46	9.65	58.88	40.37
Linfen	440.09	365.3	294.3	614.88	16.98	33.12	39.72
Pingliang	485.89	453.5	207.6	673.25	6.66	57.27	38.56
Mean Value					10.83	50.76	39.01

As shown in the above table, the absolute error of the interpolation results by the IDW method is the lowest. Therefore, in this study, we used the IDW method to interpolate the precipitation data to reduce the uncertainty.

## 3. Results

### 3.1. Validation of the Estimated AET

Based on the runoff data collected from the six hydrological stations (Yanchuan, Suide, Zhangjiashan, Qin'an, Hejin, and Liujiahe) from 2003 to 2014, the annual AET in the corresponding watersheds can be calculated using Equation (1). For a complete hydrological year, there is almost no change in the soil water stored in the soil layer. During the validation process, we compared the AET results calculated by water balance with the AET estimated using the GRACE gravity data for the six typical watersheds. The comparison charts are shown in Figure 2.

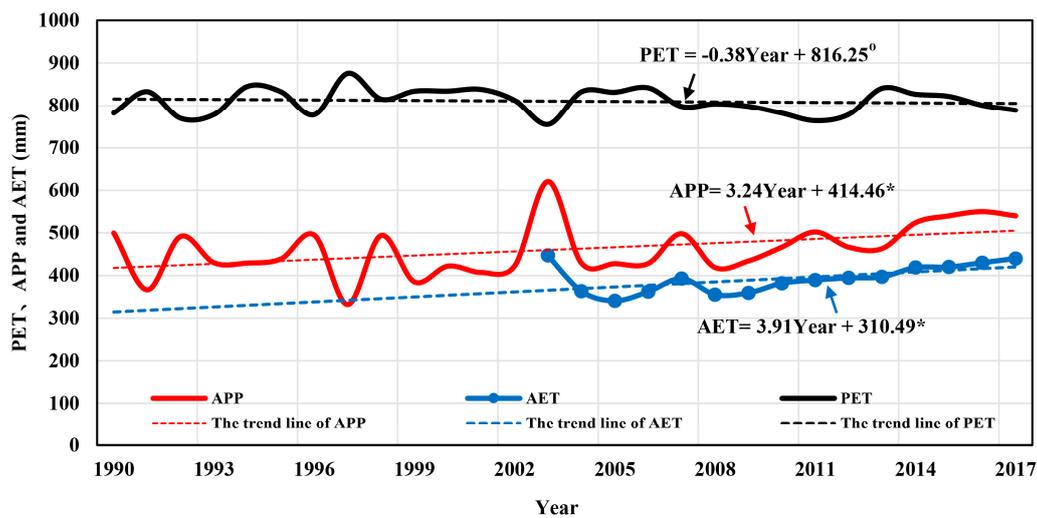


**Figure 2.** Comparison between the actual evapotranspiration (AET) calculated by water balance and the estimated annual AET based on GRACE data from 2003 to 2014.

The x-axis represents the AET calculated by water balance while the Y-axis represents the AET simulation results calculated using the GRACE data, valid for the period from 2003 to 2014, and the points represent the annual AET from 2003 to 2014 in the six watersheds. The verification results show that the estimates are in good agreement with the AET results calculated by water balance since these points are basically distributed along a straight line. To further expand on the verification results, the correlation coefficient ( $R$ ) and the confidence level ( $Sig$ ) were determined to quantitatively describe the consistency between the AET results calculated by water balance and the estimation results. As shown in Figure 2, the  $R$  value is 0.76 and the  $Sig$  value is below 0.05. Based on the above analysis, it is credible and acceptable to estimate the AET of the region using the GRACE gravity satellite data.

### 3.2. Trend Analysis of the Temporal Characteristics of Water Balance

It can be seen from Figure 3 that the AAP in the Loess Plateau showed a significant upward trend from 1990 to 2014, with a significance level of 90%, a multiyear average of 451.6 mm, and a slope of 1.91 mm/a. The AET of the Loess Plateau in 2003–2014 also shows an upward trend with an increasing rate of 1.66 mm/a and a multiyear average of 383.37 mm/a in the study area. The precipitation over the years has a positive correlation with the AET. The AET is mainly affected by the supply of precipitation because the Loess Plateau is located in arid and semiarid areas, and the underlying surface is not saturated. The potential evapotranspiration shows a slight upward trend during the study period; however, it did not pass the significance test and is not statistically significant at the 95% confidence level. In summary, the precipitation and AET of the entire Loess Plateau shows an upward trend occurred over the period of 2003–2014, during which the water cycle accelerated and the AET increased slowly compared to the precipitation.

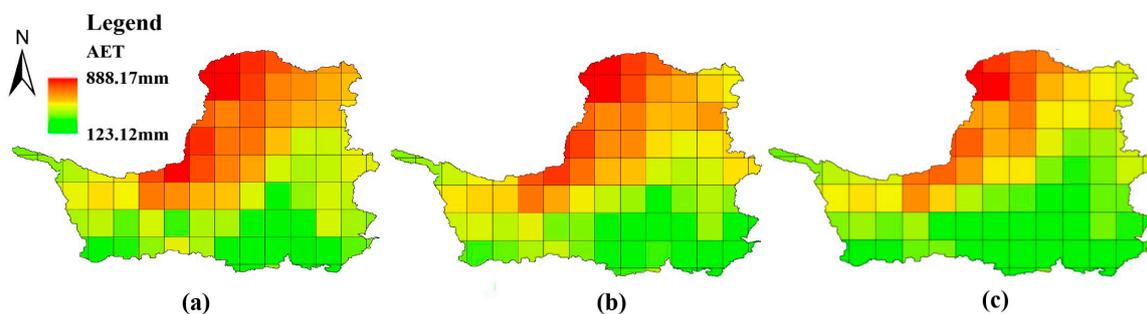


**Figure 3.** The temporal changing trend of the annual average precipitation (AAP) and regional potential evapotranspiration (PET) and AET (“\*” means the changing trend is statistically significant at a 95% confidence level, and “<sup>o</sup>” means the changing trend is not statistically significant.).

### 3.3. Trend Analysis of the Spatial Characteristics of Water Balance

#### 3.3.1. Characteristics of the Spatial Distribution of AAP

The spatial distribution of precipitation in the Loess Plateau during the three study periods between 2003 and 2014 is shown in Figure 4.

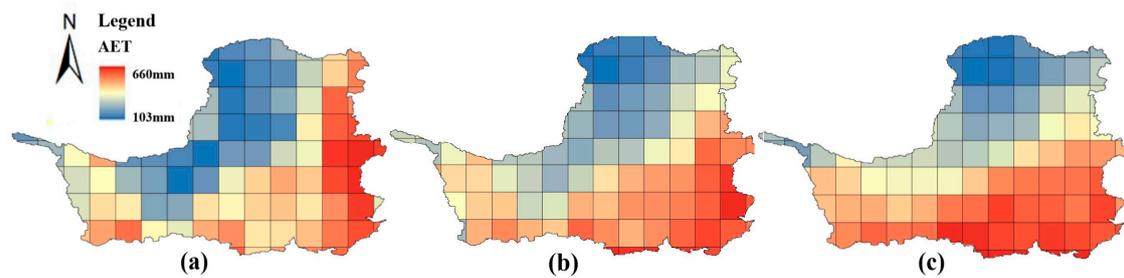


**Figure 4.** The spatial distribution of the AAP in three stages: (a) the spatial distribution of AAP in the initial stage after the Grain for Green Project launched (2003–2006), (b) the spatial distribution of the AAP in the middle stage after the Grain for Green Project launched (2007–2010), and (c) the spatial distribution of the AAP in the late stage after the Grain for Green Project launched (2011–2014).

Due to the influence of topography and monsoons, the precipitation for the whole area shows a decreasing trend from southeast to northwest. The low precipitation areas are concentrated in the northwest, and the high precipitation areas are concentrated in the southeast of the Loess Plateau. With the progress of the Grain for Green Project, the low-value area decreased gradually while the high-value area increased. The results showed that the humidity for the whole area of the Loess Plateau increased, and most areas reached the  $\alpha = 0.05$  significance level. The AAP increased from 450.86 to 480.13 mm—an increase of 30 mm from 2003 to 2014. Most of the regional precipitation was in the range of 400–500 mm.

#### 3.3.2. Spatial-temporal Analysis of AET

Figure 5 plots the changes in AET in the Loess Plateau during the three periods of conversion during the Grain for Green Project.

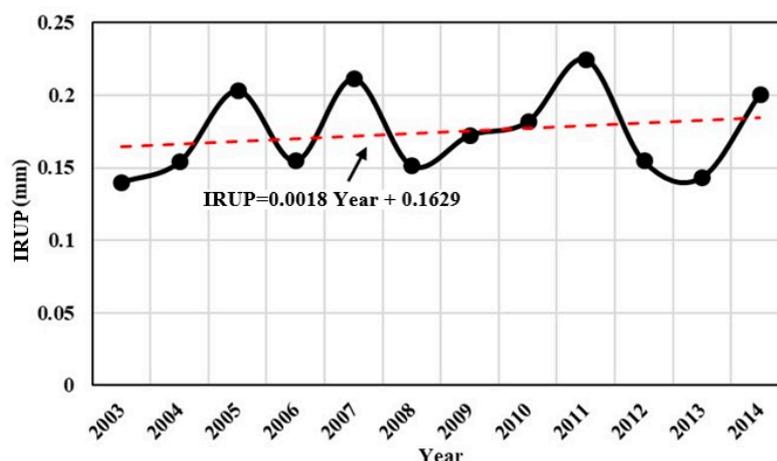


**Figure 5.** The spatial distribution of the estimated annual AET in the three stages: (a) the spatial distribution of AET in the initial stage after the Grain for Green Project launched (2003–2006), (b) the spatial distribution of the AET in the middle stage after the Grain for Green Project launched (2007–2010), and (c) the spatial distribution of the AET in the late stage after the Grain for Green Project launched (2011–2014).

Due to the complicated climate type and underlying surface type in the study area, the hydrological cycle response to climate change shows significant regional differences. The AET in the northwestern part of the Loess Plateau was significantly lower than that in the southeast during the study period. As with the increasing AAP trend, the AET in the study area of the Loess Plateau had an upward trend. The regional average AET increased from 374.26 to 396.14 mm, indicating that the AET increased significantly with the implementation of the Grain for Green Project. The AET for all regions of the Loess Plateau was around 400 mm.

### 3.3.3. Analysis of Water Consumption of Vegetation under Current Conditions

The above results reveal that both the AAP and AET had upward trends in 2003–2014, but the impact of vegetation cover on the regional water balance is currently controversial. Therefore, this study introduces the Rainfall Utilization Potential Index (IRUP) to quantitatively evaluate the water consumption of vegetation under the current conditions of the Loess Plateau. The inter-annual variation curve of the IRUP in the Loess Plateau is shown in Figure 6.

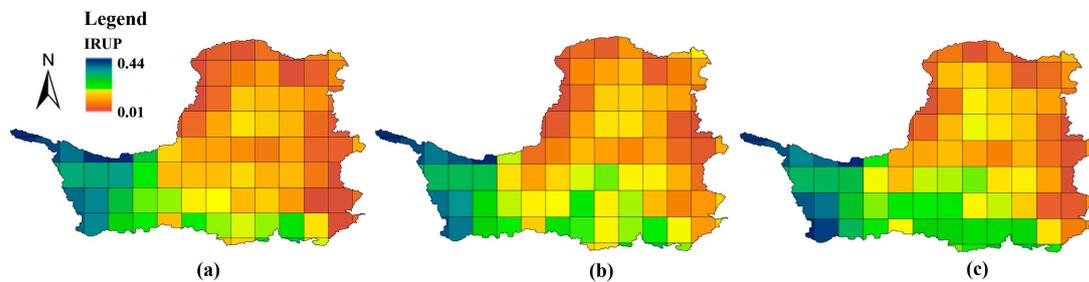


**Figure 6.** The changing trend of the average rainwater utilization potential index (IRUP) in the Loess Plateau.

It can be determined from Figure 6 that the IRUP has a multiyear average of 0.17, showing a slow upward trend. The previous analysis shows that both regional precipitation and AET had upward trends. However, the IRUP also shows an upward trend, which is mainly due to the fact that the increasing rate of the AET is less than that of precipitation, indicating that the proportion of water used for ecological construction and vegetation restoration during the study period increased. To a

certain extent, this can be interpreted as an optimistic outcome of the implementation of the Grain for Green Project in the entire Loess Plateau under the current vegetation conditions.

The spatial distribution of the IRUP in the Loess Plateau during the three study periods between 2003 and 2014 is shown in Figure 7.



**Figure 7.** The spatial distribution of the IRUP in three stages: (a) the spatial distribution of the estimated annual IRUP in the middle stage after the Grain for Green Project launched (2003–2009) and (b) the spatial distribution of the estimated annual IRUP in the late stage after the Grain for Green Project launched (2010–2014).

The IRUP for the whole region shows a decreasing trend from southwest to northeast. The high-IRUP areas appeared in the western area of the Loess Plateau, while the low-IRUP areas appeared in the eastern and northern areas of the region. The annual average IRUP of the whole region increased from 0.17 to 0.18, showing a slight upward trend. Among the areas, the IRUP in the south part of Loess Plateau increased the most, indicating that there is greater water supply in the south part for vegetation restoration. The change in area with different annual average IRUP values for three stages is shown in Figure 7.

## 4. Discussion

### 4.1. The Advantages and Limitations of the GRACE Satellite-based Estimation Method

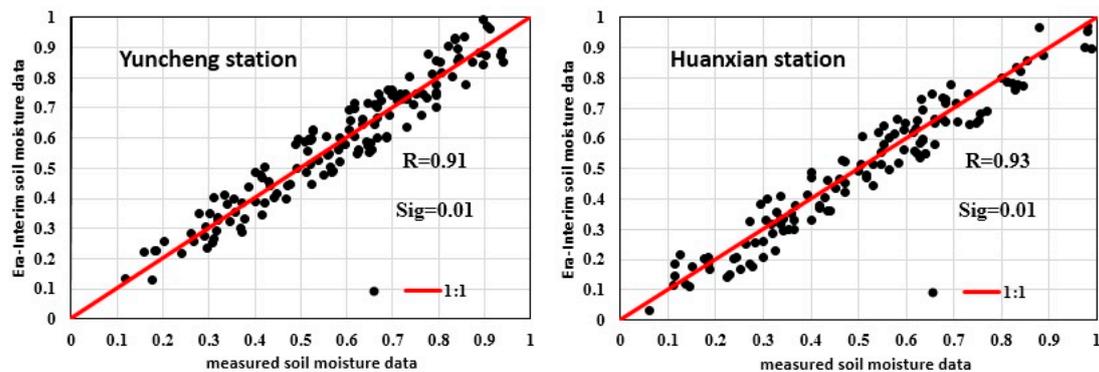
The GRACE satellite-based estimation method has been introduced in this paper. With the launch of the GRACE satellites in March 2002, the terrestrial water mass variations (which contribute significantly to the observed water storage change) could be reasonably inferred over sufficiently large regions [25,26]. Moreover, the influences of natural processes (e.g., glaciers, snow, and frozen soil moisture) and anthropogenic interferences such as reservoir operations and inter-basin water transfers could also be reflected in GRACE-retrieved TWSA. Using GRACE gravity satellite data to estimate the AET over a large-scale region can effectively avoid the error caused by parameter calculation and greatly improve the accuracy of the results. However, the temporal coverage of GRACE data is relatively short (2002 onward) for the validation of historical ET products and its spatial resolution only reached  $1^\circ \times 1^\circ$ , which is about  $111 \times 111 \text{ km}^2$ . If compared with other satellite data, the resolution is relatively low, which leads to a difficulty to apply to the research of hydrological processes in small watersheds.

### 4.2. Reliability Analysis of the IRUP Results

The above results show that, with the increase in the vegetation [4], the proportion of the water resources that can be used for vegetation growth and recovery is also increasing. This shows that the vegetation water use is still optimistic for most areas under the current vegetation conditions. In order to verify the conclusions, this study collected ERA-Interim soil water content reanalysis data at three different depths (30, 100, and 300 cm) and observed runoff data from 18 hydrological stations for reliability analysis of the conclusions.

#### 4.2.1. Validation of the ERA-Interim Soil Moisture Data

Relevant studies have shown that the ERA-Interim soil water content reanalysis data could well reflect the inter-annual changes in China's observed values of soil water content (the reported correlation has been as high as 0.955–0.995 [27–30]). This study collected soil water data from Huanxian and Yuncheng stations for the period from 1990 to 2014 and analyzed the reliability of ERA-Interim soil moisture data in the Loess Plateau. The comparison results are shown in Figure 8 below:

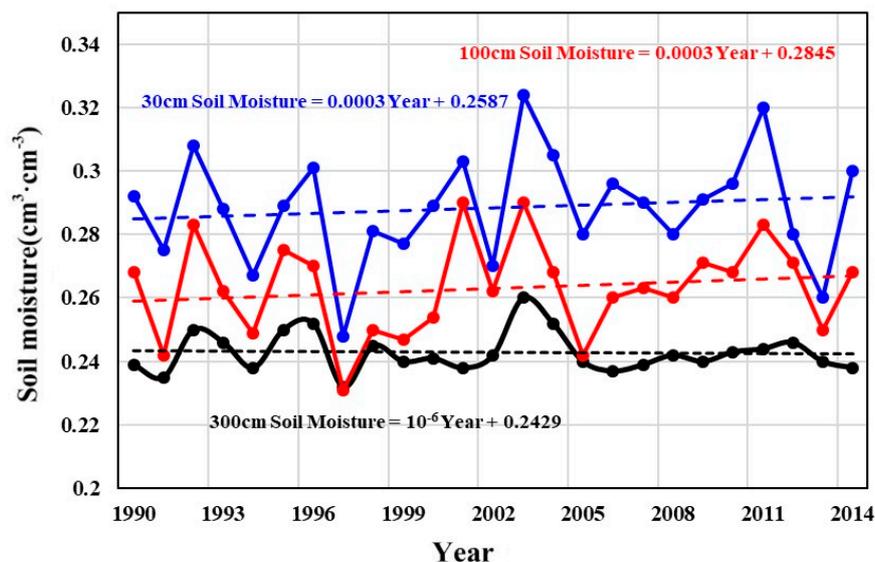


**Figure 8.** Comparison between the ERA-Interim soil moisture data and observed soil moisture data from 1990 to 2014: The x-axis represents the measured soil moisture data, while the Y-axis represents the ERA-Interim soil moisture data, valid for the period from 1990 to 2014.

The verification results show that the estimates are in good agreement with the observed data since these points are basically distributed along a straight line. As is shown, the R values are both above 0.9 and the Sig values are below 0.05. Based on the above analysis, the ERA-Interim soil moisture data are credible and acceptable to use for verifying the conclusions.

#### 4.2.2. Temporal Trend of Soil Moisture and Runoff Data

The conclusions of this paper were verified using soil moisture and runoff data. The temporal changing trend of soil water content at different soil depths of the Loess Plateau is shown in Figure 9.



**Figure 9.** The temporal changing trend of soil water content in different soil depths of the Loess Plateau.

The results show that there was no significant change in soil water content at the three different soil depths (30, 100, and 300 cm) from 1990 to 2014. The differences did not pass the significance test,

indicating that the growth of vegetation did not lead to over-consumption of soil water. This conclusion is consistent with previous study results [31–33]. According to the results of this study, if there is no significant change in the soil water, the regional runoff should show an upward trend. The annual runoff trends from 18 hydrological sites from 2002 to 2012 are shown in Figure 10.

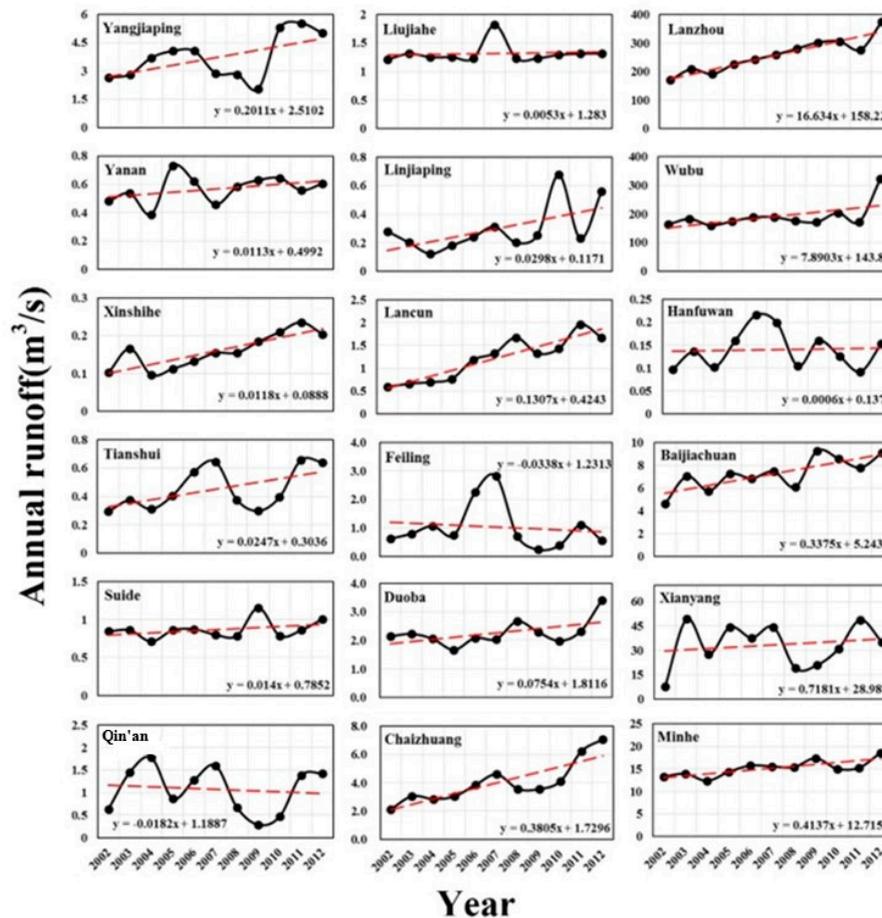


Figure 10. The temporal changing trend of runoff from 2002 to 2012 in the Loess Plateau.

The statistical results showed that the observed runoff data of only two stations (Qin'an and Feiling) decreased slightly, the changing trend of four stations was not obvious, and the observed runoff data of the remaining 12 stations showed a significant upward trend from 2002 to 2012, which verified the conclusion of this study.

According to the statistical data [34], the upper and middle reaches of the Yellow River (most of the areas are the Loess Plateau) had an average annual runoff of  $4.55 \times 10^{10} \text{ m}^3$  and an AAP of 432 mm in 1960–1969. From 1990 to 1995, the annual observed runoff decreased to  $2.43 \times 10^{10} \text{ m}^3$ , and the AAP was 389 mm. In comparison, from 2000 to 2010, the runoff continued to decrease to  $2.09 \times 10^{10} \text{ m}^3$  with an AAP of 391 mm. Based on the above analysis, the runoff coefficients in the three stages are 15.5%, 9.2%, and 7.8%, respectively. These data show that the observed runoff in the Loess Plateau region does decrease in stages and some studies have speculated that large-scale afforestation and vegetation restoration may have contributed to the decrease in runoff [3,4,35]. Based on the results, however, large-scale afforestation and ecological restoration are unlikely to be the main reason for the decrease in the runoff in the Loess Plateau. The main stage of vegetation restoration in the Loess Plateau region is from 2000 to now (the Grain for Green Project was launched in 1999). Before 2000, the regional vegetation didn't change significantly, while the observed runoff showed an upward trend in 2002–2012, which reflects the function of vegetation in water conservation. In addition, with the

development of economy and society, an increasing amount of water is blocked by reservoirs and dams and flows to urban and industrial households, which could be the root cause of the runoff decrease.

## 5. Conclusion

Maintaining the balance between precipitation and water consumption is an important foundation of ecological security in the Loess Plateau. This study used the GRACE gravity satellite data to analyze the variation in the water input and output balance characteristics of the Loess Plateau. In addition, it also introduced the rainwater utilization potential index (IRUP) to study the current situation of vegetation water consumption. The main conclusions of this study can be summarized as follows:

(1) The GRACE gravity satellite data were used to analyze the water input and output balance characteristics of the Loess Plateau for the period from 1990 to 2014. The results show that the AAP was 452 mm from 1990 to 2014, and it was increasing by 1.91 mm/a. The annual average AET was 383 mm, also showing a significant upward trend, with an increased rate of 1.66 mm/a. From the perspective of spatial distribution, the AET decreased from southeast to northwest. At the same time, the high-value region (AET > 400 mm) also increased from 39% (1990) to 73% (2014). However, there was no significant change in potential evapotranspiration during the study period.

(2) In order to explore the effect of the Grain for Green Project on the regional AET, the rainwater utilization potential index (IRUP) was introduced in this study to evaluate the sustainability of vegetation water use during the vegetation restoration process in the Loess Plateau. The results show that the IRUP experienced a significant increasing trend in the Loess Plateau region. In the three stages of 2003–2014, the averaged IRUP values increased from 0.15 to 0.17, respectively. Therefore, the sustainability of vegetation water consumption has increased slightly with the ecological restoration of the Loess Plateau.

(3) By analyzing the soil water content at different depths (30, 100, and 300 cm) using ERA-Interim data and the observed runoff data from 18 hydrological stations, this study found that there was no significant change in soil water in the Loess Plateau during the study period, while the annual runoff at most hydrological sites in 2002–2012 had an upward trend. Previous studies showed that the average annual runoff from 2000 to 2010 had a decreasing trend compared to that from 1960 to 1969 and from 1990 to 1995. However, since the initiation of vegetation restoration efforts in the Loess Plateau in 2000, the statistical results of the observed runoff data for the 2002–2012 period show no signs that drought is worsening in the region; therefore, large-scale afforestation and ecological restoration are not likely to be the main reason for the reduced runoff. On the contrary, vegetation should function as a means of water conservation, and the decrease in the observed runoff at different stages is likely attributed to the influence of other human activities, such as the construction of silted dams and reservoirs.

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