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Influence of Grain on Green Patterns and Their Underlying Surface Characteristics on Water Conservation: A Case Study in a Semiarid Area

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Abstract: Water-conservation enhancement is a crucial objective of regional ecological restoration projects in arid and semiarid areas, and it is significantly influenced by land use/cover change (LUCC). The Grain for Green Project (GFGP) is a common strategy for ecological restoration. However, insufficient attention has been paid to the impact of reforestation patterns and the underlying surface characteristics on the effectiveness of GFGP in enhancing water conservation. In this study, a Soil and Water Assessment Tool (SWAT) scenario-based simulation was conducted to assess changes in water-conservation depth (WCD) in the Zhangjiakou section of the Guanting Reservoir basin. Redundancy analysis (RDA) and a mixed linear model were employed to determine the effects of different reforestation patterns and their underlying slope gradient and soil-type characteristics on WCD variation. The results showed that there were differences in the effect characteristics of reforestation patterns and different vegetation types on WCD changes; the effectiveness of increased water conservation is associated with the adaptation of reforestation plants to underlying characteristics. Returning farmland to evergreen forests was the most effective approach, leading to a relative increase in WCD that was 2.6 times greater than the relative increase in total WCD. WCD decreased with the slope gradient, with WCD decreasing by 0.2 mm for every 1° increase in slope. Converting grassland to evergreen forests on slopes greater than 16.19° and converting deciduous forests to grassland on slopes less than 16.19° would further increase WCD, promoting the synergistic development of ecosystem services. This study provides insights into the development of more efficient reforestation strategies to enhance water conservation in a complex terrain area.

Keywords: GFGP; water conservation; underlying surface characteristics

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1. Introduction

With the growth of climate anomalies and irrational land-use configuration, drought will become increasingly severe worldwide [1,2]. Arid and semiarid climatic areas are water stressed and suffer from ecological problems, such as desertification and severe soil erosion [3–5]. The decline in water conservation would inhibit the water-regulation capacity of ecosystems, thus exacerbating drought. Regional land use and landcover change (LUCC) is the most direct and efficient approach for enhancing the ecological situation in arid and semiarid regions.

Water conservation is defined as the process of intercepting, infiltrating, storing, and evaporating precipitation through the interaction of the ecosystems due to their unique structure. This is an essential regulating ecosystem service that effectively alleviates regional water scarcity. The rich vertical structure of forest ecosystems reallocates precipitation [6] and alters the physical structure of the subsoil through the root system to achieve water-storage functions [7], thus providing water conservation, soil retention, climate regulation, and pollution control services, etc. [8]. Therefore, the water-conservation function of the forest ecosystem has received a lot of attention, and increasing the forest cover area is a practical approach to improving water-conservation capacity. In the context of climate change stresses on the water-holding capacity of the forest [9,10], it is an interesting question to discuss how land-use patterns can be optimized to efficiently utilize the water-conservation capacity of forests.

Recent advances in remote-sensing technology and hydroecological modeling have led to an increasing number of studies examining and evaluating ecosystem services on larger scales through the utilization of hydrological models [11–13]. The Soil and Water Assessment Tool (SWAT), which is widely applied in water-related ecosystem-service projects [14], enables the quantification of water in a horizontal direction. Researchers have employed the SWAT model in ecosystem-service assessments to analyze the spatial and temporal variability of multiple ecosystem services [15,16]. They have also determined ecosystem-service values for specific agricultural management patterns and GFGP projects [17,18], as well as identified relationships between these ecosystem services [19,20] and the elements that influence changes in ecosystem services and their relationships [21,22]. Presently, the majority of studies employing the SWAT model to analyze the effects of variation on water-related ecosystem services concentrate on landcover change and meteorological factors [23,24]. Insufficient attention has been paid to the effects of slope and soil on changes in water-related ecosystem services. Ecological restoration studies have increasingly explored the influence of underlying surface characteristics, such as slope, on water conservation [25,26]. However, few researchers have investigated the combined effects of surface-vegetation changes and their underlying slope and soil types on water conservation.

The Zhangjiakou section of the Guanting Reservoir basin is situated in the upper region of the Beijing–Tianjin–Hebei synergistic development area (BTH). It serves as a significant water source for BTH [11], and the quality and quantity of its water have a significant impact on the development of downstream urban areas. The distribution of different slopes and soil types in the region is complex, and the contribution of afforestation patterns to ecosystem services varies under different landforms and soil conditions [27,28], which will have an impact on the enhancement of regional water conservation [25], and unreasonable land use planning will limit the synergistic development of ecosystem service in BTH. Landcover optimization patterns that promote the enhancement of water conservation need to be urgently proposed.

Almost all of the studies determine which landcover is the most beneficial for water-conservation enhancement by comparing the amount of water conservation on different landcovers in different scenarios [29]; such an approach clarifies only the contribution of land cover/use to ecosystem services, but the reality is that landcover always changes from one to the other. Dynamic variation in ecosystem services due to land use/cover change (LUCC) was obscured. To fill the aforementioned gaps, the SWAT model was employed to quantify the water-cycle process, with the Zhangjiakou section of the Guanting Reservoir being considered an ideal study area. The study innovatively summarized the effects of different reforestation patterns on water conservation and identified the contribution of underlying heterogeneity to water conservation in different reforestation patterns. The study attempted to answer three research questions: (1) what are the impact characteristics of LUCC and its underlying soil type and slope characteristics on changes in water conservation? (2) Is there a consistency between the contribution of land use/cover changes to water conservation and the impact characteristics of LUCC, which includes land use/cover, on changes in water conservation? (3) How can these features be utilized to inform the development of future afforestation strategies in regions with similar environmental conditions, in order to promote further enhancement of water conservation? The results of the study will complement the missing impacts of LUCC on ecosystem services and inform the development of future landcover allocation optimization strategies.

2. Material and Methods

2.1. Study Area

The Guanting Reservoir is located in the Guanting village of Huailai county, Hebei Province, about 90 km northwest of Beijing, which is an important water source for Beijing and its downstream areas. Zhangjiakou (113°50′–116°30′ E, 39°30′–42°10′ N) is adjacent to Beijing to the southeast and has two rivers, the Sangan River and the Yanghe River, within the administrative area. The region has an East Asian continental monsoon climate, with an average annual temperature of 7.6 °C and an annual precipitation of 330–400 mm. The region is semiarid, and agricultural management techniques are primitive, leading to the overirrigation of farmland [30]. This, in turn, contributes to inadequate water conservation, threatening the water security of the region and its downstream areas.

As part of GFGP, large-scale vegetation restoration projects have been implemented in Zhangjiakou since 1999. These projects have greatly changed the regional landcover type, where the major afforestation forest types are *Pinus tabuliformis* Carr., *Platycladus orientalis*, *Populus* L., *Betula* L., *Quercus mongolica*, *Prunus triloba*, *Hippophae Fructus*, *Caragana Korshinskii* Kom., etc. [31]. We simulated the hydrological processes in the whole Guanting Reservoir basin by the SWAT model and took all subbasins in the Zhangjiakou section, where ecological projects were highly concentrated and landcover changed dramatically, as the study area, with a total study area of 2,143,342.82 ha (Figure 1).

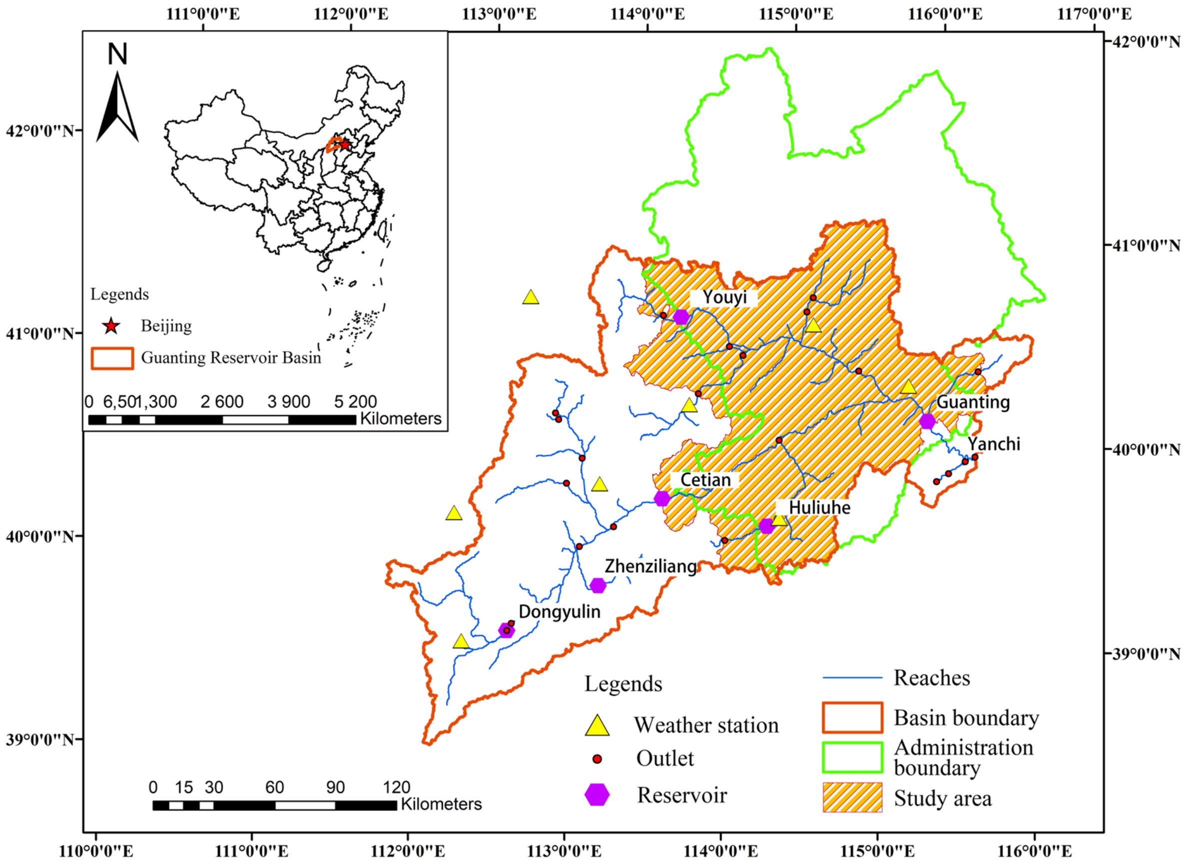

Figure 1. Overview of the study area location.

2.2. Data Sources

Input data for the SWAT model is mainly meteorological and spatial data. Spatial data includes topographic data, land use, and soil-type data. Hydrological data is also required as model validation data.

(1) Meteorological data were obtained from eight national meteorological station sites provided by the National Meteorological Information Centre (http://data.cma.cn/,

accessed on 18 April 2019), which contains average temperature, precipitation, average wind speed, relative humidity, and hours of sunshine in daily steps;

(2) The hydrological data were obtained from the *Hydrological Yearbook of the People's Republic of China*. The three rivers in the basin contain 18 hydrological stations. There are also 6 large and medium-sized reservoirs, namely, Dongyulin Reservoir, Cetian Reservoir, Zhenziliang Reservoir, Huliuhe Reservoir, Youyi Reservoir, and Guanting Reservoir. Information on the reservoirs was added to the model based on the basic indicators and outflow data of the reservoirs provided in the *Hydrological Yearbook*;

(3) Land use/cover type data were obtained from the Chinese land use status remote sensing monitoring data with 100 m resolution provided by the Resource Environment Data Cloud Platform (http://www.resdc.cn, accessed on 2 August 2019) and reclassified according to the SWAT input landcover library (Figure 2). The main reclassified land use/cover types include evergreen forest (FRSE), deciduous forest (FRSD), mixed forest (FRST), shrub (RNGB), urban built-up land (URHD), rural settlement (URLD), swamp (WETL), water body (WATR), agricultural land (AGRL), grassland (HAY), shrub grassland (RNGE), and bare land (BARR). Due to the small area of the RNGE and the similar plant physiological characteristics to RNGB, these two landcover types were collectively referred to as RNGB;

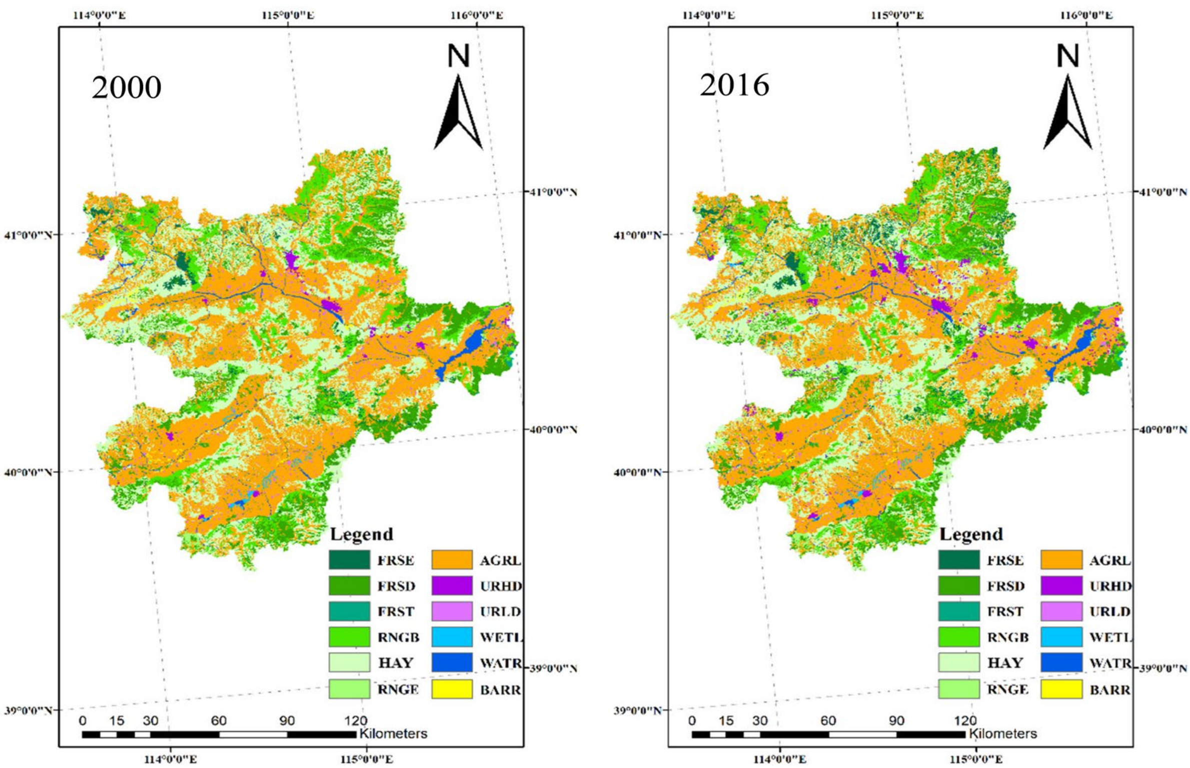

Figure 2. Spatial distribution of land use/cover types of 2000 and 2016.

(4) Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM); a 90 m resolution DEM dataset provided by the China Geospatial Data Cloud (http://www.gscloud.cn, accessed on 8 December 2018), which was used to generate the river network and subbasin boundaries within the basin (Figure 3 left);

(5) The soil data were obtained from the Homogenous World Soil Database (HWSD), published by the International Food and Agriculture Organization (FAO), which provides a global map of soil types at 1 km resolution, as well as a database of different soil texture compositions (Figure 3 right). The full names of the soil types corresponding to the abbreviations are shown in Table S1;

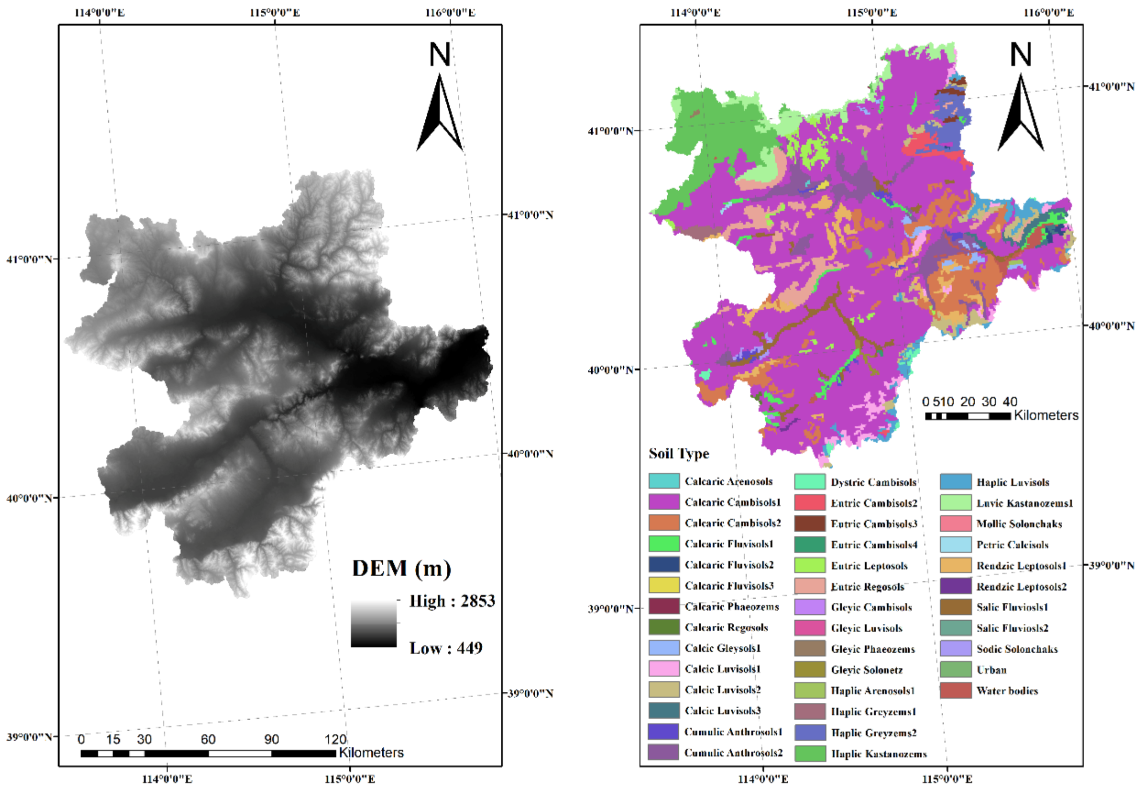

Figure 3. Distribution of DEM and soil types.

(6) The farm-management data were obtained from field measurements provided by the Zhangjiakou Academy of Agricultural Sciences, including farm irrigation and fertilizer information from 2008 onwards, with a few missing data replaced by the average of each indicator. The main data used in this study are irrigation information.

2.3. Model Calibration and Validation

In this study, the SWAT model was calibrated and validated in monthly steps by setting the warm-up period to 2008–2009, the calibration period to 2010–2013, and the validation period to 2014–2016. To assess the error between the simulated and observed values introduced by the input data or the initial database of the model, the Nash efficiency factor (NSE) [32], the goodness of fit (R2), and the percentage bias error (PBIAS) were introduced to evaluate the effectiveness of the model fit. The two indicators were calculated as follows.

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(OBS_i - \overline{OBS_i}\right)\left(SIM_i - \overline{SIM_i}\right)\right]^2}{\sum_{i=1}^{n}\left(OBS_i - \overline{OBS_i}\right)^2\left(SIM_i - \overline{SIM_i}\right)^2} \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(OBS_i - SIM_i\right)^2}{\sum_{i=1}^{n}\left(OBS_i - \overline{OBS_i}\right)^2} \tag{2}$$

$$PBIAS = 100 \times \frac{\sum_{i=1}^{n} OBS_i - SIM_i}{\sum_{i=1}^{n} OBS_i} \tag{3}$$

where OBS_i and SIM_i are the observed and simulated values per unit time step, and $\overline{OBS_i}$ and $\overline{SIM_i}$ are the mean values of the observed and simulated values. R^2 describes the degree of deviation of the model's simulation results from the measured results, with values between 0 and 1. A larger value means a better simulation effect; a value of 0.5 is considered adequate [33]. For simulations with monthly steps, the fit is very good when $0.75 < NSE \leq 1$, good when $0.65 < NSE \leq 0.75$, acceptable when $0.50 < NSE \leq 0.65$, and unacceptable when $0.50 \leq NSE$ [34], and $PBIAS \leq \pm 25\%$ is required [35].

2.4. Quantification of Water Conservation

Soil water content accounts for more than 90% of the overall water conservation of the forest ecosystem. In this study, the depth of water conservation is expressed as the difference between the soil water content in each Hydrological Response Unit (HRU) at the end and beginning of the simulation. Based on the water-balance equation, SWAT calculates soil water content as:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \quad (4)$$

$$WCD = SW_{init} - SW_{end} \quad (5)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is time (days), R_{day} is precipitation on day i (mm H_2O), Q_{surf} is surface runoff on day i (mm H_2O), E_a is evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), Q_{gw} is baseflow on day i (mm H_2O), WCD is the water-conservation depth (mm H_2O), and SW_{init} and SW_{end} are the soil water content at the beginning and end of the simulation, respectively. If WCD is greater than zero, water is conserved, otherwise is lost.

2.5. Scenario Setting and Impact Factor Analysis

The model was run with 2000 meteorological data to isolate the impact of changes in meteorological conditions on water conservation. After model calibration, the landcover data in the study area was changed to 2016 to eliminate the impact of landcover change outside the study area on water conservation. By comparing water conservation under different landcover types and fixed meteorological conditions, the influencing factors of water-conservation change in the region were studied.

The effect of different reforestation methods on the depth of water conservation was assessed by analyzing the changes in WCD for HRUs with landcover types of agricultural land in 2000 and evergreen forest, deciduous forest, shrubs (including shrub grassland), and grassland in 2016, with the four reforestation modes denoted by AfE, AfD, AfR, and AfH, respectively. As landscape and soil characteristics do not change in a short period of time without extreme natural phenomena, the effect of slope and soil type on WCD can be studied by comparing the differences in WCD under different slopes and soil types within the same reforestation method in order to ensure sample quantity.

A redundancy analysis (RDA) was conducted using different reforestation patterns, slopes, soil types, and the corresponding changes in WCD as input data. A Type I scale for nominal variables was selected for analysis of the interaction between reforestation pattern, soil type, and WCD change, and a Type II scale for non-nominal variables was selected for analysis of the slope and water-retention relationship. Monte Carlo permutation tests based on 499 random permutations were conducted to test the significance of eigenvalues for all canonical axes and the significance of marginal and conditional effects. The contribution of different soil types to changes in WCD across multiple reforestation patterns and slope differences was tested by a mixed linear model.

3. Results

3.1. Model Validation

The parameters related to hydrological processes were selected from the SWAT input/output documentation, and global and one-at-a-time sensitivity analyses were conducted using SWAT–CUP to determine sensitive parameters. Then, the SUFI-2 algorithm was employed to automatically calibrate the optimized value of those parameters, and the results were presented in Table S2.

The model performed well in the simulation of monthly runoff (Figure 4). The Nash–Sutcliffe coefficient (NSE) was greater than 0.5, the determination coefficient (R2) was greater than 0.7, and the percentage deviation (PBIAS) was less than 25%. The SWAT model was suitable for the simulation in the Guanting reservoir basin.

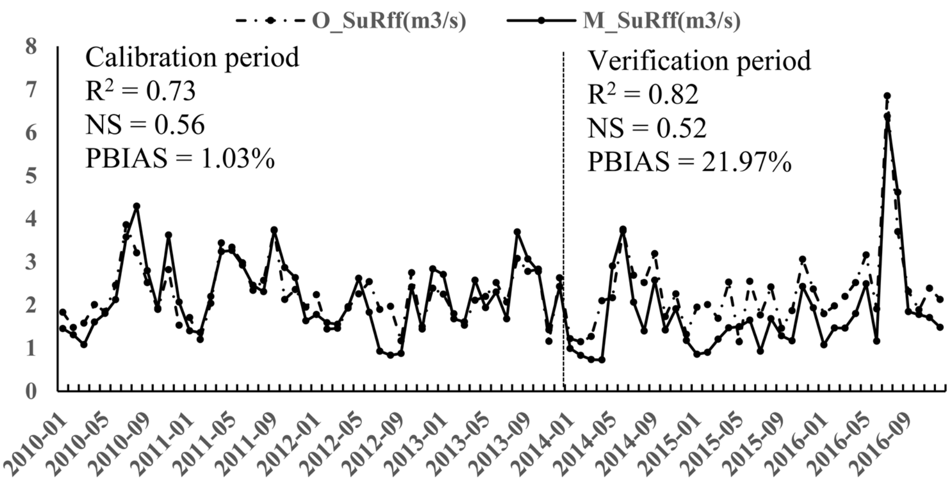

Figure 4. SWAT simulation result verification.

3.2. Change Characteristics of Forest and WCD

The study area experienced a change in land use area of 264,085 hectares from 2000 to 2016, which accounted for 12.32% of the total region. Of this change, 55,156 hectares of AGRL were returned to forests, accounting for 20.89% of the total change area. Significant changes in the spatial distribution of forest and grass, and the spatial distribution of different reforestation patterns, are shown in Figure 5.

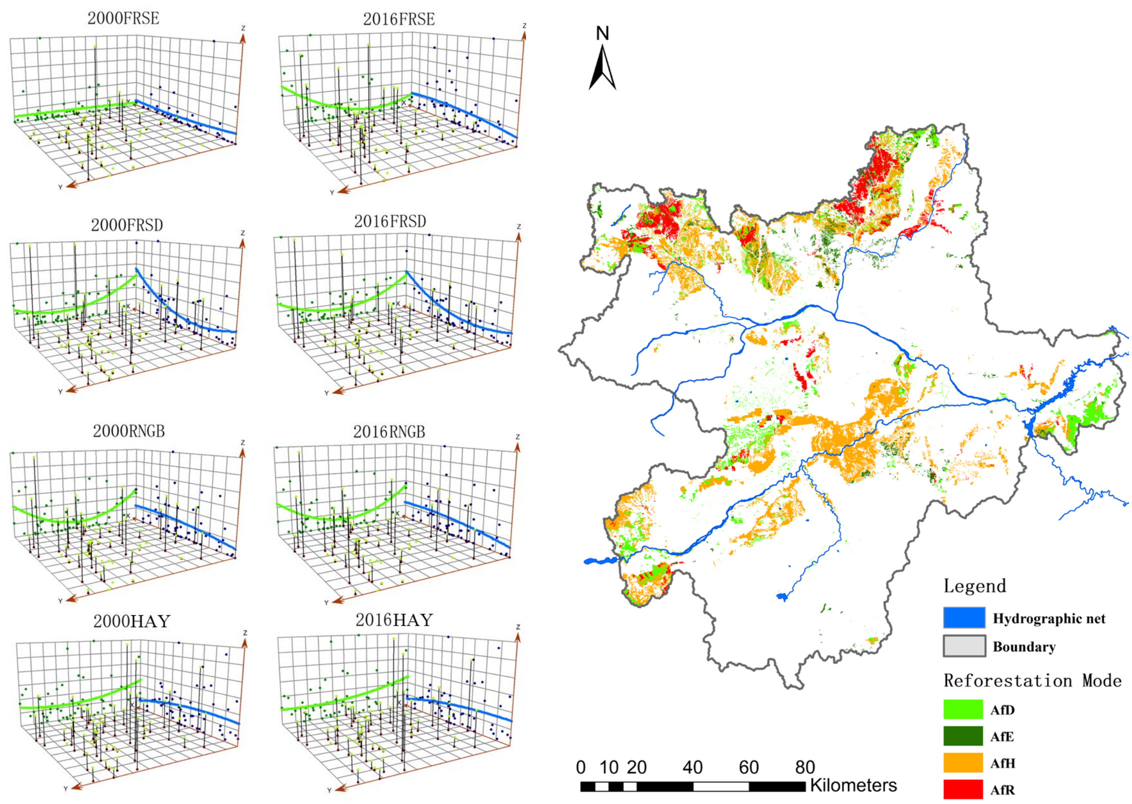

Figure 5. Spatial distribution forest area and reforestation patterns (north in Y direction, east in X direction). The green and blue curves characterize the distribution of forest or grassland area in the north-south and east-west directions.

The area of FRSE grew significantly in the northern and eastern study area, showing the distribution characteristics of high in the north and low in the south and high in the east and low in the west; 11,970 ha of AfE were implemented, with more transformation occurring in the areas with steeper slopes in the north. The spatial distribution pattern of FRSD does not change significantly, and 32,058 AfD occurred in the study area, most of which is concentrated in the northern mountainous areas, making the area of FRSD grow in the north. AfR and AfH were implemented over the whole area of 819 ha and 10,309 ha, respectively. AfR occurred mainly in the northern part of the study area, while AfH occurred mainly in the central and northern areas. The north–south and east–west differences in the distribution of HAY were further increased. The spatial distribution pattern of RNGB and HAY did not vary as significantly as FRSD and FRSE.

The effect of reforestation on the allocation pattern of precipitation is shown in Figure 6. Precipitation allocation patterns were significantly altered ($p < 0.01$) in the areas where the reforestation project occurred, with evapotranspiration decreasing by 4.49%, and soil water content and water yield increasing by 70.37% and 77.09%, respectively. The proportion of surface runoff, lateral flow, and baseflow contributing to water yield also underwent variation. In 2016, surface runoff significantly decreased, by 81.67%, in comparison to 2000, while lateral flow and baseflow exhibited an increase by 1.16 and 4 times, respectively. There was a significant increase in the proportion of slow runoff, leading to a greater tendency for precipitation to be retained in the soil. Changes in the allocation of precipitation and the internal component of water yield suggested that, under constant meteorological conditions, replacing heavily irrigated and evapotranspiring AGRL with forests or grasslands could lead to a reduction in the rate of precipitation loss.

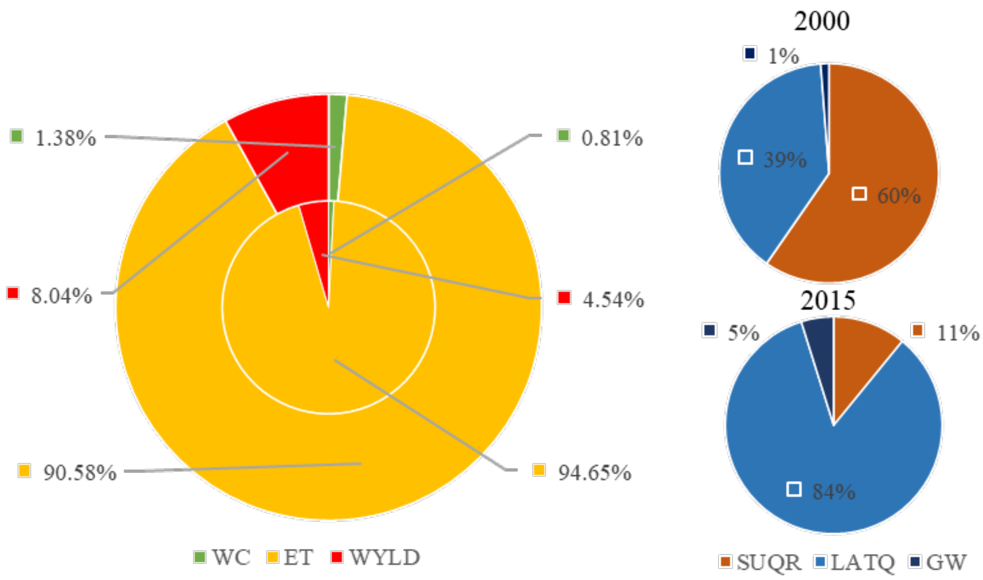

Figure 6. Changing of rainfall distribution patterns in areas of reforestation. The outer and inner circles are the proportions of precipitation distribution in 2016 and 2000, respectively. WC, ET, and WYLD represent the contribution of precipitation to soil stored water, evapotranspiration, and water yield, respectively. SURQ, LATQ, and GW are the percentages of surface runoff, lateral flow, and baseflow in WYLD, respectively.

The regional water-conservation depth significantly increased by 17.78%, from 5901.68 mm in 2000 to 6950.77 mm in 2016. In terms of spatial distribution, the absolute and relative changes in water-conservation depth were generally consistent (Figure 7), showing a higher increase in the northern part of the study area where afforestation is concentrated and an average increase in other areas. It is also noted that some of the afforestation areas showed a reduction in water-conservation depth and that the afforestation patterns in these areas are mainly AfD and AfH.

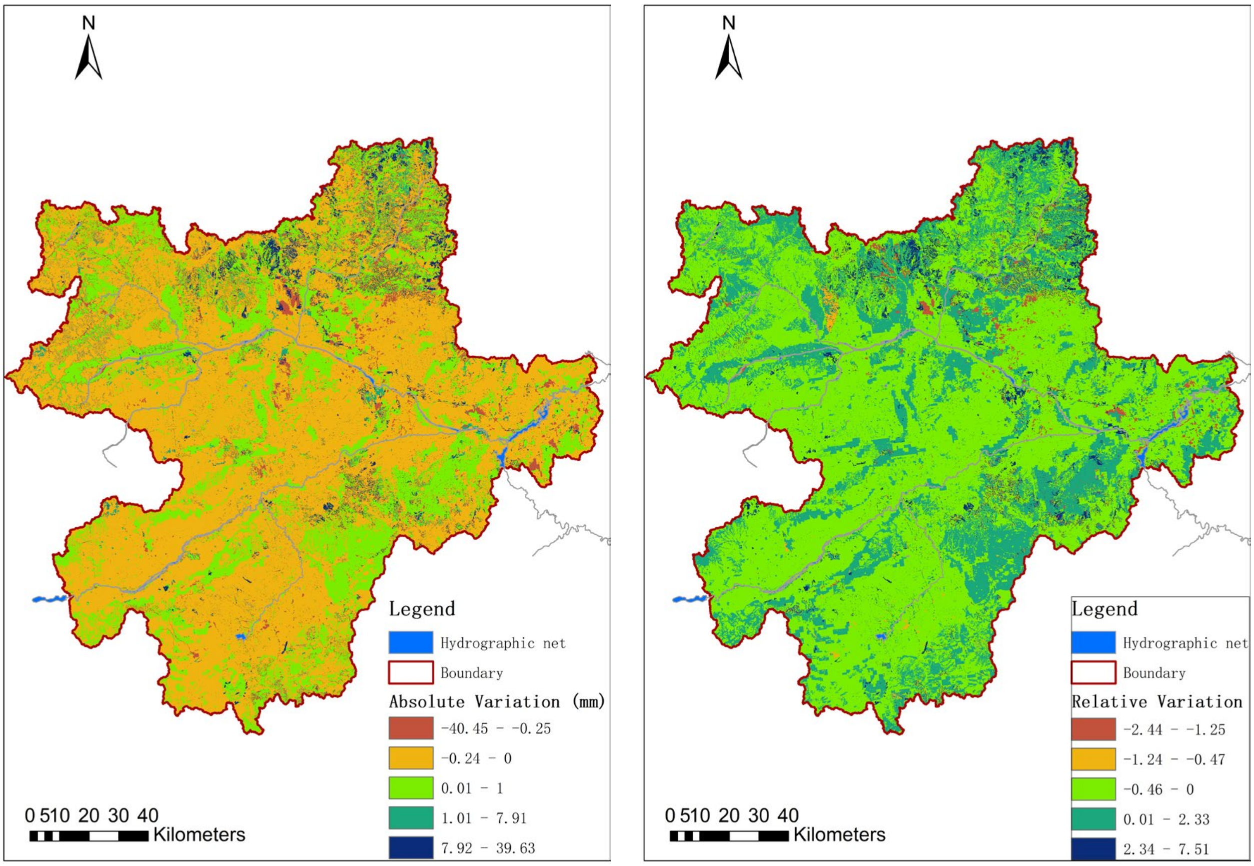

Figure 7. Spatial variation of water-conservation depth.

3.3. Characteristics of Factors Affecting WCD Change

The implementation of reforestation and grass restoration increased the depth of water content in the study area by 62.16%, amounting to 3.6 times the total water-conservation increase, suggesting that there were LUCC patterns in the region that negatively impacted the WCD. Figure 8 shows the results of the Welch's one-way ANOVA. The contribution of landcover to the WCD significantly varied ($p < 0.05$), with FRSE making the highest contribution of 16.58 mm, followed by HAY (0.86 mm) and RNGB (0.51 mm). Meanwhile, FRSD and AGRL showed a reduction in the WCD by −1.46 mm and −1.6 mm, respectively. The root systems of shrubs and grasslands are not as rich as arbor forests, leading to lesser soil pore space and weaker water-retention capacity than arbor forests [7]. However, FRSD has a large evapotranspiration and usually has a negative impact on water conservation [36].

The difference in WCD variation was significant ($p < 0.05$) under different reforestation patterns. AfE increases WCD the most (13.8 mm), followed by AfR (1.5 mm), while AfD and AfH carried out in the study area reduce WCD by 1.68 mm and 3.58 mm, respectively. The effect characteristics of AfH on WCD change showed opposite characteristics to the contribution of HAY to WCD, where the overall contribution of HAY to WCD was positive but switching from AGRL to HAY resulted in a reduction of WCD. Meteorological conditions had been kept constant in the experiment, suggesting that the underlying surface characteristics of different reforestation areas had effects on WCD enhancement.

The results of the Redundancy Analysis (RDA) are presented in Table 1, which includes only factors that had a statistically significant impact on WCD. The selected explanatory variables, namely reforestation pattern, slope, and soil type, account for 62% of the variation in WCD enhancement. The top three factors with the greatest influence on enhancement were AfE, AfH, and slope. Specifically, AfE demonstrated a considerably higher explanatory power than the other factors. AfE had a positive effect on WCD; AfH had the opposite characteristics of AfE on WCD, and the increase in slope also had a negative effect on WCD. The remaining significant factors came from reforestation patterns and soil type, respectively.

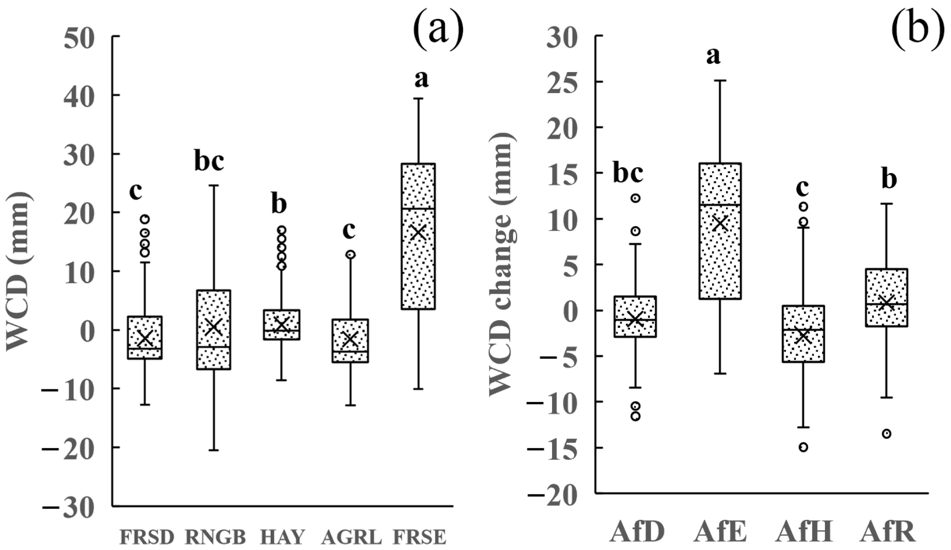

Figure 8. Contribution of different landcovers to water conservation (**a**) and contribution of different reforestation patterns to WCD change (**b**). The lower letters above each bar is the labeling of the significance of the difference.

Table 1. The RDA of environmental factors and changes in WCD.

Axis	1	2	3	4
Eigenvalues	0.62	0.38		
Explained variation (cumulative)	62	100		
Global significance	p = 0.001			
	explanatory variable	Explains %	pseudo-F	p
Conditional Effects:	AfE	36.8	89	0.002
	AfH	(10)	30.5	0.002
	Slope	(6.9)	20.3	0.002
	Eutric Leptosols	(5.7)	16.5	0.002
	AfD	(5.2)	15.1	0.002
	Salic Fluviosls	(4.9)	14.1	0.002
	Calcic Luvisols	2.5	6.9	0.01
	Rendzic Leptosols	2	5.5	0.024

Note: Only explanatory variables that have significant a effect on the response variable are listed here. Parentheses indicate that the factor has a negative effect on WCD variation.

The environmental elements were further uncoupled to analyze how slope and soil type affect the change in WCD under various reforestation patterns, and the results are shown in Table 2. According to the results of the RDA analysis, the explanatory capacity of soil type and slope for WCD changes under AfD, AfE, AfR, and AfH were 42.9%, 56.7%, 60.8%, and 59.4%, respectively. In the reforestation model with arbor forest replacing agricultural land, soil type has a greater influence on WCD than slope, but its explanatory capacity is not much greater than that of slope. In the reforestation model where shrubs and grasslands replace agricultural land, slope plays a major role in influencing WCD changes and has a much greater explanatory capacity than soil type. A sloping underlying surface is more likely to cause soil water loss. The root system of arbors is known for increasing the pore space of the soil, which results in a greater ability to retain water at a particular slope. Therefore, the effect of returning agricultural land to arbors on WCD changes is more robust under changes in slope, and soil type has a stronger effect on WCD when replacing AGRL with arbors. Soil thickness is one of the factors determining the water-holding capacity of the soil. Single-layer soils have a weak water-retention capacity, and precipitation is more likely to form quickly runoff [37]. Thus, thin soil could negatively affect WCD under different reforestation patterns.

Table 2. Summarized effects of soil type and slope under the same reforestation pattern.

Model	Explanatory Variable	Explains %	Pseudo-F	*p*
AfD		42.9		
	Eutric Leptosols	(10)	10.6	0.004
	Calcaric Fluvisols	9	9.5	0.018
	SLOPE	(8.4)	8.8	0.01
	Salic Fluviosls	5.6	5.7	0.018
AfE		56.7		
	Eutric Leptosols	(18.4)	14.7	0.002
	SLOPE	(9.6)	6.9	0.012
	Salic Fluviosls	5.9	4.1	0.048
	Cumulic Anthrosols	5.9	4.1	0.044
AfH		60.8		
	SLOPE	(39)	45.5	0.002
	Calcic Luvisols	8.9	6.9	0.018
	Rendzic Leptosols	(6.8)	5.2	0.03
	Eutric Leptosols	(4.9)	3.6	0.08
AfR		51.4		
	SLOPE	(33)	17.2	0.002
	Rendzic Leptosols	(13.9)	5.7	0.022
	Calcaric Cambisols	10.5	4.1	0.07

Note: Only explanatory variables that have a significant effect on the response variable are listed here.

The relationship between WCD variation and slope is shown in Figure 9. The change of WCD under different reforestation patterns indicates a decreasing trend with increasing slope, because the potential energy of water due to gravity in the soil increases with slope, making it easier for water to escape and generate surface runoff [38]. The water-conservation variation decreases fastest with slope under AfH, with a decrease of 0.37 mm per 1° increase in slope, and 0.12 mm/°, 0.18 mm/°, and 0.21 mm/° for the AfD, AfE, and AfR, respectively. Most of the AfH in the current study area occurs in areas with steep slopes, and the occurrence of AfH at more than 16.19° leads to a decrease in WCD. Such a reforestation pattern has a negative impact on WCD. This is why the contribution of HAY to WCD is positive, but AfH tends to decrease WCD. The contribution of AfD to WCD variation varies little with slope and WCD decreases in most areas where AfD occurs. On smaller slopes, AfD contributes no more to WCD increase than AfH. It should be noted that the limited ability of slope to explain changes in WCD under different reforestation patterns may be influenced by mixing effects [39].

Taking soil type as the main factor, reforestation pattern as the categorical variable, and setting slope and reforestation pattern as fixed effects affecting WCD change, the ability of soil type to influence WCD change was tested by a mixed linear model, and the results were shown in Table 3. Soil type had some influence ($p < 0.05$) in the effect analysis of the reforestation pattern and slope on WCD. Under different soil types, slope and reforestation patterns other than AfR had a significant effect on WCD change. AfD and AfH in the current study area resulted in a decrease in WCD, while AfR did not have a significant effect on WCD. AfH reduced WCD more than AfD. The above characteristics are consistent with the conclusion obtained when soil type was not decoupled. For each 1° increase in slope, WCD decreased by 0.2 mm. Such an effect characteristic is similar to the conclusion obtained when soil type was not decoupled (0.22 mm/°). Covariance estimation is the result of the random effects test, which shows that the variation of WCD is aggregated on different soil types; namely, afforestation on different soils has an effect on the variation of

WCD. The characteristic analysis of the influence of soil type on WCD will be analyzed by establishing a relationship between soil physical properties and WCD variation.

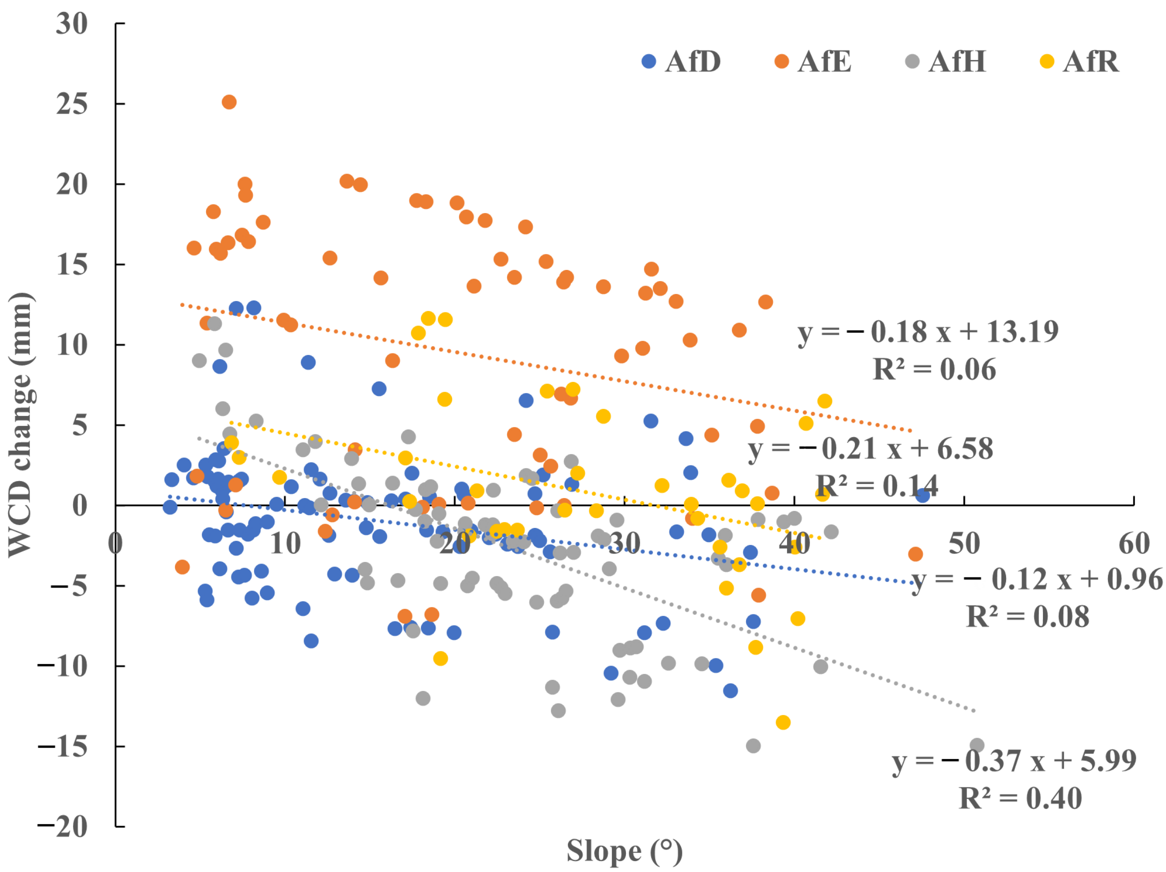

Figure 9. Relationship between WCD change and slope under different reforestation patterns.

Table 3. Mixed linear model analysis results.

	Parameter	Parameter Estimation	Sig.
Fixed effects estimation	AfD	−4.46	$p < 0.01$
	AfE	6.56	$p < 0.01$
	AfH	−4.54	$p < 0.01$
	AfR	~	$p < 0.01$
	Slope	−0.2	$p < 0.01$
Covariance estimation	Soil type	-	$p < 0.05$

Note: "~" and "-" represent redundant parameter and parameter to be further decomposed, respectively.

The regulation of water and soil is mainly dependent on the physical properties of the soil. Soil bulk density (BD), effective water content (EWC), and saturated hydraulic conductivity (Ks) are the three main properties that influence soil water-retention capacity [40,41]. The correlations between the physical properties of the different soil types and the changes in WCD are shown in Table 4. There was a significant correlation ($p < 0.05$) between the first soil layer and WCD variation under different reforestation patterns, while the second layer of soil had no significant effect on the variation in WCD. The relationship between soil bulk density and WCD was inversely correlated, saturated hydraulic conductivity was positively correlated with WCD, while the relationship between effective soil water content and WCD was relatively complex and mostly positive, but negative under deciduous forest.

Table 4. Correlations between different soil properties and variations in WCD.

	AfE	AfD	AfR	AfH
BD I	−0.278 (0.038)	−0.093 (0.028)	−0.049 (0.023)	−0.252 (0.041)
EWC I	0.162 (0.033)	−0.044 (0.051)	0.665 (0)	0.486 (0)
Ks I	0.129 (0.042)	0.022 (0.043)	0.805 (0)	0.286 (0.027)
Bulk Density II	−0.026 (0.851)	−0.016 (0.083)	−0.428 (0.055)	0.264 (0.052)
EWC II	0.02 (0.882)	−0.023 (0.036)	−0.025 (0.877)	−0.183 (0.162)
Ks II	0.079 (0.563)	0.034 (0.059)	0.747 (0.62)	0.209 (0.11)

Note: I and II represent the first layer (0–30 cm) and the second layer (30–100 cm) of soil, respectively. Significant *p* values for correlations are in parentheses.

4. Discussion

4.1. Effect Characteristics of Reforestation Patterns on WCD

Soil and water conservation projects increase soil water content by altering hydrological paths, reducing hydrological connectivity, reducing runoff velocity, and increasing water-infiltration time. These alterations lead to the achievement of water conservation and runoff regulation functions [42]. Reforestation pattern, slope, and soil type characteristics had significant effects on the water-conservation enhancement [27,43,44], and the reforestation pattern had the most significant effect on WCD variation.

Since the saturated hydraulic conductivity of the soil increases with vegetation succession, the water-retention capacity of the soil increases, so that the water-conservation function of arbors is generally stronger [38]. In terms of the contribution of different landcover to WCD, the WCD of the FRSE is much greater than that of other landcover. HAY has a slightly weaker water-conservation capacity than RNGB, while FRSD and AGRL tend to lead to lower WCD because of their great evaporation, and these findings are consistent with the results of established studies [45,46]. However, from the perspective of different reforestation patterns, reforestation patterns other than AfE significantly reduced WCD, and AfH had the strongest negative effect on WCD, which is contrary to the conclusions obtained by previous researchers [47,48]. It is important to note that most of the current studies are statistical analyses based on multiple static scenarios and do not take into account the effects of spatial heterogeneity of slope and soil type where LUCC occurs. From the results of this study, it can be seen that WCD does not definitely increase when switching from a landcover with a small static WCD to a landcover with a large static WCD.

4.2. Effect Characteristics of Underlying Surface Properties on WCD

WCD is influenced by various factors, including slope, which affects WCD variation during LUCC. This study discovered that WCD reduces with an increase in slope, contradicting some previous research findings. Currently, most studies on the relationship between WCD and slope have been conducted on larger spatial scales. These studies found that WCD increases with steeper slopes [28,49], which is due to the fact that forests grow on steeper slopes, and forests generally have larger WCD. However, some studies at the plot scale found that WCD decreased with increasing slope [50,51], which is consistent with the results in this study.

It argues that studying WCD influencing factors based on one or more fixed scenarios alone is insufficient to guide land-use planning, as the specific characteristics of WCD change under the synergistic effect of multiple influencing factors in the LUCC process must be considered. In few studies, the effect of slope on water conservation was investigated, and it was found that the characteristics of the WCD change with slope under different LUCC patterns were different, and the rate of change of forest WCD with slope was slower than that of RNGB and HAY [38], which was consistent with the results of this study. Based on the previous study, we further characterized the change of water-conservation enhancement with increasing slope when different forest types were selected for afforestation and found that the threshold slopes of AfD, AfH, and AfR for the change of direction of the WCD effect were 8°, 16.19°, and 31.33 (mean 18.51°), which is consistent with the slope range identified in the previous study that can increase water conservation [51]. The WCD enhancement of AfH on small slopes is better than that of AfD, but its WCD decreases faster with slope increasing than AfD. AfD can counteract the effect of slope on WCD variation through root and canopy retention of precipitation [28].

Under the same reforestation pattern, soil properties have an impact on water-conservation enhancement. The soil properties of 0–30 cm under the four reforestation patterns are more closely related to WCD enhancement [52–54]. The 0–30 cm layer is crucial, as it is where plant roots are distributed the most. The root system makes the soil loose and porous, promoting water-retention capacity, which could explain the close relationship with WCD enhancement. Soil bulk density represents the compactness of the soil, and the higher the value, the more compact the soil is; soils that do not have a loose structure have difficulty storing precipitation, resulting in a negative correlation between water conservation and soil bulk density [55]. Soil saturation hydraulic conductivity responds to the infiltration of water in the soil and is positively correlated with the WCD [56,57]. Effective soil water content refers to the amount of water in the soil that can be absorbed and used by plants, and its relationship with WCD is more complex. It was found that there is not a strict positive correlation between WCD and effective soil water content [58]. In this study, the effective soil water content of AfE, AfR, and AfH was positively correlated with WCD enhancement, while the opposite characteristic was shown under AfD. Due to the high evapotranspiration of FRSD [59], more effective soil water content will result in more soil moisture flowing to evapotranspiration rather than remaining in the soil. Although AfD reduces evapotranspiration from overirrigated agricultural fields, the increased evapotranspiration of canopy water causes its not satisfactory WCD enhancement.

4.3. Landcover Optimization Strategy

Returning farmland to forests and grasses on slopes larger than 15° can alleviate water scarcity [60]. Based on this conclusion, some current studies have proposed a general landcover adjustment scheme that is beneficial to ecosystem services [61], taking into account the slope characteristics of the landcover distribution. However, the applicability of different reforestation patterns to enhance water conservation, and the comprehensive impact of slope on the enhancement effect, have not received sufficient attention. In addition, insufficient consideration of the interactions between different ecosystem services may limit the development of other water-related ecosystem services [62,63]. As a result, relevant landcover optimization policies may not be able to meet the needs of simultaneous development of water conservation and other ecosystem services.

Based on the contribution characteristics of different reforestation patterns to WCD exhibited under different slopes, an optimal landcover configuration strategy that promotes WCD enhancement and synergistic development of the other two WRES can be proposed. Since the implementation of the reforestation project, water conservation in the study area has been improved. However, the distribution of landcover in the region is yet to be optimized. Significant differences ($p < 0.01$) were found in the slope under different afforestation patterns in the study area. The slope was greatest where AfH occurred (22.27°), followed by AfR (18.93°), and AfE (17.87°), and the slope where AfD occurred was smallest (14.47°). Namely, AfH was carried out on large slopes and AfD on small slopes. Such a reforestation pattern would greatly limit the effect of WCD enhancement, and even lead to WCD decline. In the future, during the implementation of GFGP, we should consider the slope adaptability of the reforestation patterns in enhancing water conservation. The approach for AfH should be conducted on small-slope conditions, whereas AfE should be applied for great-slope conditions and avoid planting vegetation types with high evapotranspiration capacity on soils with high effective soil water content to prevent weakening water conservation.

The current national policy has certain area requirements for AGRL, so subsequent landcover adjustments should be made in areas where GFGP occurred to preserve maximum AGRL. Taking into account the reforestation patterns and slopes that have the greatest impact on water conservation, Table 5 compares eight landcover optimization adjustment methods developed for the current GFGP region, revealing the characteristics of regional water conservation and its closely related water yield and evapotranspiration changing characteristics.

Table 5. WCD, ET, and WYLD variation under different alternative scenarios.

Number	Alternative Scenarios for Areas Where GFGP Occurs	ΔWCD	ΔET	ΔWYLD
1	Replace all with FRSE	17.24%	12.80%	−7.55%
2	Replace all with FRSD	−9.27%	20.34%	−15.90%
3	Replace all with HAY	8.71%	−2.98%	4.37%
4	Replace all with RNGB	−1.48%	6.20%	3.86%
5	Replace HAY with FRSE at slopes greater than 16.19° and the rest remains the same	10.77%	7.68%	−3.13%
6	Replace FRSD with FRSE at slopes less than 16.19° and the rest remains the same	12%	−0.41%	1.87%
7	Replace FRSD with HAY at slopes less than 16.19° and the rest remains the same	6.24%	−1.15%	2.59%
8	Replace HAY with FRSE at slopes greater than 16.19°, replace FRSD with HAY at slopes less than 16.19°	12.91%	0.84%	1.17%

Note: ET and WYLD denote evapotranspiration and water yield, respectively.

As shown in Table 5, when FRSE is taken as the only substitution for optimization, both WCD and ET increase, WYLD decreases, and WCD increases the most, with an increment of 17.24%. When FRSD is taken as the only substitution, evapotranspiration will increase by 20.34%. Precipitation will be more likely to return to the atmosphere to rejoin the water cycle, which directly leads to the reduction of rapid runoff, while the water dissipated in the plant body will need to be replenished by soil water, which will reduce WCD. Both HAY and RNGB increase WYLD when taken as substitutions. HAY enhances WCD and reduces ET, and RNGB acts on both with characteristics opposite to HAY. In general, when a single plant type is used as a substitution, there is a large increase in one water-related ecosystem service but also a large decrease in the other one. HAY and RNGB contribute less to the difference between different water-related ecosystem services than FRSD and FRSE.

Considering the influence of GFGP's underlying characteristics on WCD, four scenarios of optimal landcover configuration were developed. Since AfH greater than 16.19° tends to reduce WCD, replacing HAY with FRSE will enhance WCD, and the change characteristics of ET and WYLD are consistent with alternative scenario 1, but the difference between WCD and WYLD becomes smaller after optimization. Comparing scenarios 6 and 7, in the GFGP area with a slope less than 16.19°, replacing FRSD, which contributes less to WCD enhancement, with either FRSE or HAY can lead to WCD and WYLD enhancement, but the difference between WCD and WYLD becomes smaller after optimization when HAY is taken as a substitution. It has been suggested that the magnitude of differences in the contribution of different influence factors to changes in two ecosystem services is a determinant of the magnitude of their contribution to the intensity of ecosystem service tradeoffs [39]. Comparing optimization scenarios 1–4 and 5–7, it can be found that the optimization strategy of landcover configuration, considering the influence of underlying characteristics, will enhance the WCD while reducing the differences between different WRES, i.e., balancing the tradeoffs between them.

The final optimization plan is proposed, taking into account the sustainability of the ecosystem services while enhancing regional water conservation as much as possible. Replace HAY with FRSE at slopes greater than 16.19° and replace FRSD with HAY at slopes less than 16.19°. Such an optimization method could increase WCD, ET, and WYLD by 12.91%, 0.84%, and 1.17%, respectively; thus the three WRESs will develop synergistically.

4.4. Limitations and Future Research

Most studies do not consider the effects of vegetation type and topography on ecosystem services when assessing ecosystem services, and the lack of such information makes it difficult to develop detailed landcover adjustment programs and carry out effective afforestation treatments [64,65].

By comparing WCD variations under different LUCCs, this study clarifies the effect characteristics of different afforestation patterns on WCD change. Through such dynamic analysis, we found differences between the patterns of ecosystem-service variation affected by LUCC and the characteristics of different landcovers' contribution to the corresponding ecosystem services. For example, although HAY contributes positively to WCD, AfH does not necessarily enhance WCD, and the effect on WCD enhancement also depends partly on the characteristics of the underlying in the area where afforestation occurs. Our study can provide information about the differences in the contribution of various afforestation patterns to WCD variation on a different underlying, which can be used as a reference for policymakers to develop vegetation restoration policies. However, it should be noted that plantation growth characteristics and various biophysical and chemical parameters are different from those of natural plants. Directly using natural forest parameters from the SWAT model expert library as the parameters of the substitute plants for afforestation will limit simulation accuracy and further limit the practicality of the afforestation plan formed based on simulation. Establishing a more refined expert parameter library of plant types can provide more accurate quantitative simulations of various ecosystem services after anthropogenic interventions, which can be beneficial for developing more specific afforestation schemes.

Elevation is another geographical factor that affects ecosystem services [61]. At higher altitudes, with stronger UV rays, higher wind speeds, and lower temperatures, plants tend to reduce their canopy area and their stems tend to be shorter, thus enhancing their resistance to collapse and insulation, avoiding as much as possible the destruction of chlorophyll and preventing the inhibition of photosynthetic efficiency. [66]. Therefore, the proportion of grassland area is usually higher than that of forest in high-altitude areas [44]. The study area of this study is mostly plains and hills, and the recommendations given under current conclusions may not be applicable to high-altitude areas, and relevant studies considering altitude are yet to be added. In addition, in order to study the impacts of GFGP on the changes in water conservation, the impacts of the linkage of upstream and downstream hydrological processes on water conservation were inhibited in this study. The intensity and distance of the influence of upstream landcover changes on water conservation are also important in the development of long-term landcover allocation strategies and ecological compensation policies [39], but there have been fewer related studies so far. In the future, the advantages of ecosystem process modeling can be exploited to explore the influence of the dynamic linkage of upstream and downstream hydrological processes on the development of regional ecosystem services over a long period of time.

Ecosystem services are dependent on scale and differ in spatial distribution. They are pivotal in achieving sustainable development. Policymakers often formulate landcover adjustment policies with different objectives based on the spatial and temporal characteristics of ecosystem services, and research on the scale characteristics of ecosystem services is receiving increasing attention [67,68]. It has been suggested that the effects of LUCC on ecosystem services show different characteristics at different spatial scales [69]. At larger spatial scales, the influence of meteorological elements on ecosystem services is stronger than that of LUCC. The effects of some ecosystem services are not reflected in the short term [70], and changes in ecosystem services over different time scales can affect the fairness of intergenerational access to ecosystem services. The scale used in this study is HRU, the smallest unit of the SWAT model, and the scale effect of ecosystem services is difficult to reflect at a single scale with a single time interval. Ecosystem-service studies at larger spatial scales and multiple temporal scales still need to be added.

5. Conclusions

In this study, we clarified the impact characteristics of LUCC and its underlying slope and soil type on WCD and found the difference between the contribution of land use/cover to water conservation and the impact characteristics of LUCC containing this land use/cover on water-conservation changes, which made up for the shortcomings of the research on the response pattern of water conservation to LUCC changes. The study found that under the condition of constant meteorological conditions, reforestation changed the distribution pattern of precipitation, thus increasing the water conservation depth and enhancing the water-conservation capacity. The afforestation mode is the most important factor affecting the enhancement of water conservation. Landcover that contributes more to water conservation does not necessarily contribute positively to WCD increase in the LUCC that contains that landcover. Grassland contributes the most to water conservation, but the reforestation pattern that contributes to WCD increase is AfE. The effect of LUCC on changes in water conservation can be influenced by the underlying surface heterogeneity. The topography and soil characteristics of the underlying at the GFGP plots make different reforestation patterns develop their own water-conservation enhancement characteristics. In terms of slope characteristics, the effect of water-conservation enhancement of all reforestation patterns decreases with the increase of slope, and the WCD decreases by 0.2 mm for each 1° increase in slope. Water conservation is most affected by slope in HAY, and the application of AfH on large slopes will reduce WCD. From the perspective of soil characteristics, planting vegetation types with higher evapotranspiration capacity on the underlying with a higher effective soil water content and a thinner soil layer will have a negative impact on the water-conservation enhancement. Our results suggest that converting grassland to evergreens at slopes greater than 16.19° and converting deciduous to grassland at slopes less than 16.19° would result in the simultaneous enhancement of water conservation, evapotranspiration, and water yield. This study provides an important reference for the management and sustainable development of landcover optimization in a water-scarce area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14102020/s1, Table S1: Soil type abbreviations vs. full names; Table S2: Calibrated parameters for the SWAT model.

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