forests

MDPI

Article

The Development and Application of a GIS-Based Tool to Assess Forest Landscape Restoration Effects on Water Conservation Capacity

Enxu Yu [1], Mingfang Zhang [1,2,*], Yali Xu [1], Sheng Zhang [1], Zuozhu Meng [1] and Yiping Hou [3]

1 School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China; 201921070113@std.uestc.edu.cn (E.Y.); yalixuu@163.com (Y.X.); zhang1996zs@163.com (S.Z.); zuozhu_meng@163.com (Z.M.)

2 Yangtze Delta Region Institute (Huzhou), University of Electronic Science and Technology of China, Huzhou 313001, China

3 Department of Earth, Environmental and Geographic Sciences, University of British Columbia Okanagan, 1177 Research Road, Kelowna, BC V1V 1V7, Canada; yiping.hou@ubc.ca

* Correspondence: mingfangzhang@uestc.edu.cn; Tel.: +86-028-6183-0963

Abstract: In forest landscape restoration, one of the key objectives is to improve the water conservation capacity of the deforested land. A rapid, accurate assessment of the effects of the restoration measures on the water conservation capacity of targeted forests can help forest managers to identify the best practices for forest restoration. However, the traditional assessment tools of forest water conservation function lack a description of forest growth, and are featured by complex computation, which fails to evaluate the effects of forest restoration on the regional forest water conservation capacity in an efficient way. To address this issue, through combining the forest restoration evaluation model (equivalent recovery area, ERA), classic forest water storage capacity estimation (total water storage capacity), this study has taken advantage of ENVI/IDL, ArcGIS Engine/C#.Net to develop the Forest and Water Assessment Tool (FWAT) for assessing the changes of the regional forest landscape and the associated forest water conservation capacity in various forest restoration scenarios. This tool has been successfully applied in the Upper Zagunao watershed, a large forested watershed in the Upper Yangtze River basin. According to the assessment, the forest water conservation capacity of the study watershed consistently increased from about 1580.76 t/hm^2 in 2010 to a projected 2014.34 t/hm^2 by natural restoration, and 2124.18 t/hm^2 by artificial restoration by 2030. The artificial restoration measures yield a better effect on forest water conservation function than natural restoration. By 2030, the forest water conservation capacity of artificial restoration scenario is expected to be about 7% higher than that of natural restoration scenario. The FWAT as an efficient tool to assess the effects of forest restoration measures on regional forest water conservation capacity can provide scientific support for the design of forest restoration and management strategies worldwide.

Keywords: forest restoration; ERA; water conservation capacity; GIS; total water storage capacity

check for updates

Citation: Yu, E.; Zhang, M.; Xu, Y.; Zhang, S.; Meng, Z.; Hou, Y. The Development and Application of a GIS-Based Tool to Assess Forest Landscape Restoration Effects on Water Conservation Capacity. *Forests* **2021**, *12*, 1291. https://doi.org/10.3390/f12091291

Academic Editor: Steven McNulty

Received: 27 August 2021
Accepted: 17 September 2021
Published: 21 September 2021

1. Introduction

Forest restoration has been widely applied worldwide to recover ecosystem functions of damaged or degraded land. Given that water conservation is one of the vital ecosystem services provided by forests, improving the forest water conservation capacity is often one of the key objectives in forest landscape restoration [1–7]. A quick, accurate assessment of the effects of different forest restoration measures on water conservation capacity can be used to identify the key drivers for the recovery of targeted forests and can help forest managers to develop the best management practices for forest restoration.

Forest water conservation capacity is mainly evaluated by experimental analysis or hydrological modeling [8]. The experimental methodology involving field samplings and laboratory experiments, are mostly used in plot or stand-level studies, which have limitations in depicting the dynamic processes of water conservation capacity at larger spatial scales [9–11]. Hydrological modeling is often applied to assess the impact of forest change on water conservation capacity at both small and large spatial scales [12–14]. Nevertheless, it is difficult to generate a quick assessment of forest water conservation capacity changes as hydrological models normally require inputs of various data (e.g., vegetation, climate, topography, hydrology, and soil data) and time-consuming validation. Moreover, the hydrological models lack the ability to describe and predict the changes of forest growth, which impede us from further evaluating the spatial-temporal changes in forest water conservation capacity [15]. However, forest restoration, water resources management plans and strategy designs rely on scientific information that can be timely and visually generated at various scales from stands to watershed and regions. Therefore, it is necessary to develop a GIS-based tool that can provide a quick and visual assessment on forest restoration effects on the spatial-temporal patterns of forests and the associated changes in water conservation capacity to meet the practical demands of forest resource management.

Hybrid programming combining ENVI/IDL, ArcGIS Engine and Visual C#.NET, as a popular way to integrate the functions of a geographic information system (GIS) and remote sensing (RS) has been widely used in developing GIS-based tools for forest resource information management and decision-making support [16–18]. Xu (2012) developed a four-dimension visualization system to predict and display the spatial-temporal changes of a forest landscape and stand growth by use of ComGIS, OpenGL, and a tree growth model [19]. Similarly, McVicar (2008) developed a decision support tool for a re-vegetation program and forest resources management by Visual C#.NET and ArcGIS Engine [20]; and Kaloudis (2008) developed a goal-driven forest management planning decision support system combining a database management system (DBMS) and a geodatabase in GIS [21]. In order to evaluate forest water conservation capacity, Li (2015) developed a regional water conservation capacity estimation system to realize the calculation of long-term regional water conservation capacity using the SEBAL-SCS model, water balance method, and hybrid programming (ENVI/IDL and ArcGIS Engine/C#.NET) [22]. However, due to limited long-term experimental data of water conservation capacity dynamics as forest succession or with forest restoration measures over time, it is very challenging to predict water conservation capacity changes with forest growth over time. There is still a lack of a comprehensive and rapid evaluation tool that can simultaneously simulate and predict the spatial-temporal changes of forests with natural succession or forest restoration measures and associated changes of ecological functions such as water conservation capacity.

To address the issues above, we innovatively developed the equivalent recovery area (ERA) model for the quantification of forest changes under various forest restoration scenarios based on the concept of equivalent clear-cut area (ECA). ERA indicates the spatial-temporal cumulative changes of forests over space and time with a consideration of forest succession and the recovery of hydrological functions [23]. In this study, we developed the Forest and Water Assessment Tool (FWAT), a GIS-based tool combining the forest restoration model (ERA) and a classic forest water conservation capacity quantification method (total water storage capacity) to evaluate the forest restoration effects on spatial-temporal changes of forest landscapes and their associated forest water conservation capacity in the Upper Zagunao watershed. The FWAT mainly includes modules such as data management and processing, forest change simulation and prediction, water conservation capacity estimation and visualization. It can be an efficient tool to evaluate forest water conservation capacity from stand to regional levels, as well as to predict and display the long-term spatial-temporal changes of regional forest and water conservation capacity under different forest restoration scenarios. The main objectives of this study are: (1) to generate a forest restoration prediction model (equivalent recovery area, ERA); (2) to develop the Forest and Water Assessment Tool (FWAT) to evaluate and predict forest and water conservation capacity at a regional scale; (3) to provide an example of the application of the FWAT in the Upper Zagunao watershed. The realization of the above objectives could provide quick and accurate support for the forest and water resource managers in the decision-making of forest restoration and water supply plans, e.g., the identification of the best forest restoration measures to improve regional forest water conservation capacity.

2. Model Design

2.1. Evaluation Procedures

The key steps for assessing forest restoration effects on forest landscapes and associated water conservation function include data collection, management and processing, forest change simulation and prediction, forest water conservation capacity calculation, and spatial-temporal changes of forest water conservation capacity under different forest restoration scenarios. Spatial data (e.g., DEM, land cover and land use, vegetation distribution, precipitation, and soil map) and nonspatial data (e.g., forest restoration measures, and ERA coefficients) are required inputs for the model. Forest change simulation and prediction is based on an ERA model with forest succession processes. Forest water conservation capacities are calculated by the total water storage capacity method that includes canopy, litter and soil water conservation capacity). Changes in regional forest water conservation capacity are predicted based on the forest restoration scenarios and ERA coefficients (Figure 1).

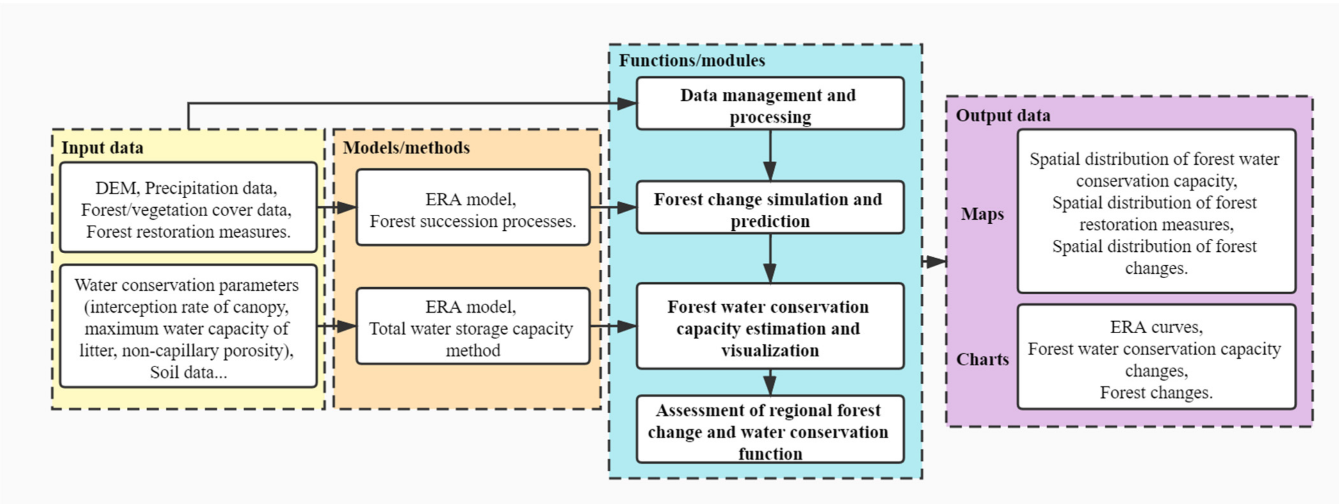


Figure 1. The framework of evaluation processes.

2.2. Model Structures

The Forest and Water Assessment Tool (FWAT) mainly includes data management and processing, forest change simulation and prediction, forest water conservation capacity estimation and visualization.

2.2.1. Data Management and Processing

The spatial and nonspatial data are managed and processed by the data management and processing modules prior to application in the model. The data management module mainly includes documents, spatial data and database management. The data processing module mainly consists of vector data and raster data processing, field processing, format conversion and pretreatment. The pretreatment can be used to extract daily maximum precipitation and generate forest age grouping.

2.2.2. Forest Change Simulation and Prediction

This module consists of forestation screening and planning, forest change simulation (including specified change by attributes and random change), and forest change prediction (Figure 2). In forestation screening and planning, we can extract land by specified attributes (e.g., elevation, slope, and forest types) to generate a forest restoration measures layout based on restoration plans. Future spatial-temporal changes of forest landscape under a planned forest restoration measures scenario can be predicted by ERA model in forest change prediction. The input data for forest change prediction include spatial data (e.g., land cover) and nonspatial data (e.g., growth curves of dominant tree species, hydrological parameters for forest restoration measures, and ERA recovery coefficients).

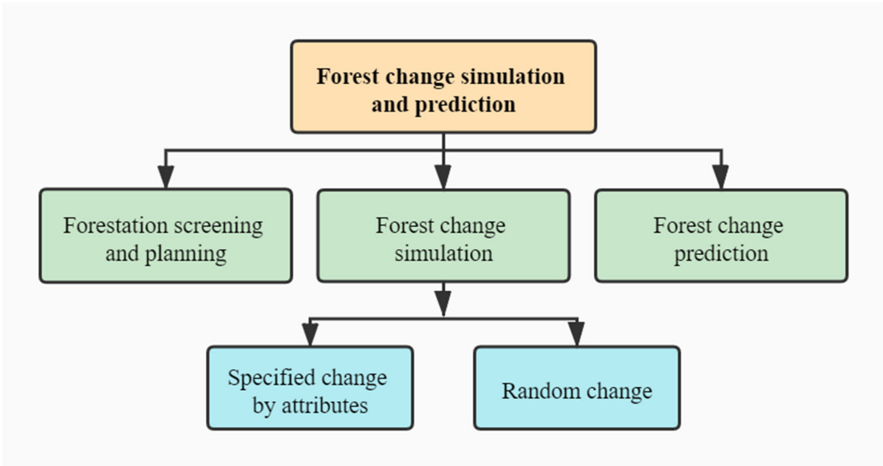


Figure 2. Forest change simulation and prediction.

The core of the forest change prediction module is ERA (equivalent recovery area) model which is a modification of ECA (equivalent clear-cut area) model for describing the hydrological function recovery with forest change after different types of forest disturbances (for example, wildfire, insect pest, and harvesting) by ECA coefficient and estimating regional-scale cumulative forest changes over space and time after forest disturbances [23–25]. Unlike the ECA, which represents cumulative disturbed forest area with a consideration of hydrological recovery, the ERA is an express of cumulative forest recovery area after forest restoration. In the ERA model, the ERA coefficient of 0% indicates no recovery in the hydrological function of restored forest lands, while the ERA coefficient of 100% suggests a full hydrological recovery which is equal to the ultimate goal of hydrological function restoration, e.g., the hydrological function of the top forest community such as the natural coniferous forest in the Upper Zagunao watershed [26]. The ERA coefficients for forests experiencing different restoration measures can be determined by establishing the relationship between forest vegetation growth (age or tree height) and hydrological recovery rate over forest succession from the references [24]. The ERA can then be quantified based on ERA coefficients and forest areas under different restoration measures. The detailed calculation of the ERA is described as follows:

$$CERA_{ij} = R_{ij} \cdot S_i \tag{1}$$

$$ERA_{ij} = CERA_{ij} - CERA_{i(j-1)} \tag{2}$$

where $CERA_{ij}$ is cumulative equivalent recovery area of the ith type of forest at the jth year (m^2); R_{ij} is ERA coefficient of the ith type of forest at the jth year (%); S_i is area of the ith type of forest (m^2); ERA_{ij} is equivalent recovery area of the ith type of forest at the jth year (m^2).

2.2.3. Forest Water Conservation Capacity Estimation and Visualization

The forest water conservation capacity estimation and visualization module can be used to calculate and predict forest water conservation capacity based on spatial data (e.g., land cover, maximum daily precipitation, and soil depth) and nonspatial data (e.g., hydrological parameters for water conservation capacity calculation, and ERA coefficients) (Figure 3).

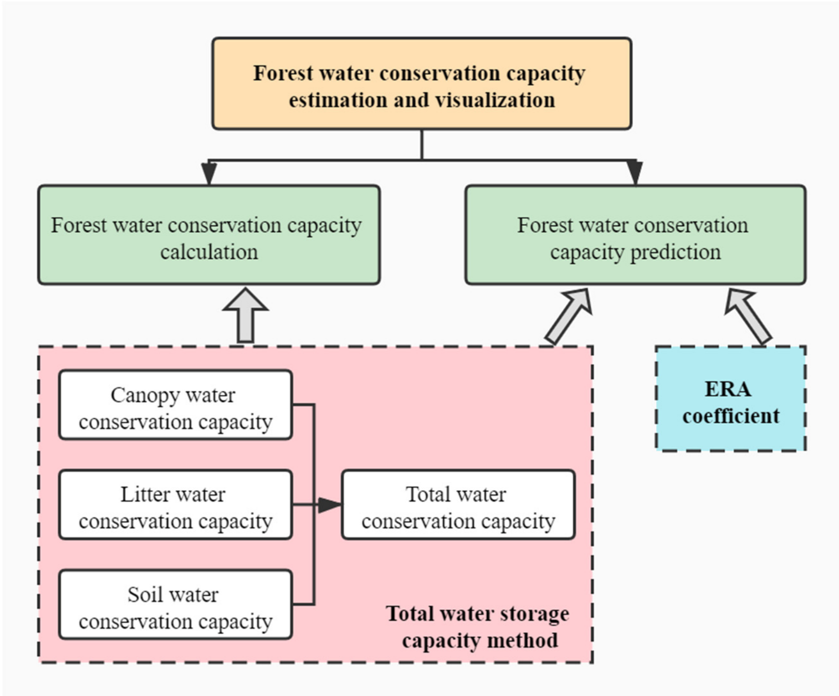


Figure 3. Assessment of water conservation function.

The forest water conservation capacity is calculated by the total water storage method, where the water conservation capacity (*WR*, m^3) of a given forest is the sum of the water conservation capacities of three layers—canopy (*C*, m^3), litter (*L*, m^3) and soil (*S*, m^3) [27] (Equation (3)). Canopy water conservation capacity is calculated by interception rate of canopy (α, %) and annual maximum daily precipitation (*R*, m). Litter water conservation capacity is estimated by maximum water capacity of litter (β, m^3/hm^2) while soil water conservation capacity is computed by noncapillary porosity (γ, %) and soil depth (*D*, m). The detailed calculation is described as follows:

$$WR = C + L + S \tag{3}$$

$$C = \sum_{i=1}^{n} \alpha_i \times R \times A_i \tag{4}$$

$$L = \sum_{i}^{n} \beta_i \times A_i \tag{5}$$

$$S = \sum_{i}^{n} \gamma_i \times D \times A_i \tag{6}$$

where A_i is the area of the *i*th forest type (hm^2).

Forest water conservation capacity under different forest restoration scenarios can be predicted by ERAs for different restoration measures or forest types with a reference of the water conservation capacity of the top forest community (e.g., natural coniferous forest) at the baseline year. The detailed calculation of the future forest water conservation capacities under different forest restoration scenarios is shown as follows:

$$S_{ij} = ERA_{ij} \times S_0 \tag{7}$$

$$L_{ij} = ERA_{ij} \times L_0 \tag{8}$$

$$C_{ij} = ERA_{ij} \times C_0 \quad (9)$$

$$WR_{ij} = ERA_{ij} \times WR_0 \quad (10)$$

where S_{ij}, L_{ij}, C_{ij},and W_{ij} are soil, litter, canopy and total water conservation capacity of the *j*th forest type in the *i*th year under different forest restoration measures, respectively (t/hm^2); ERA_{ij} is the equivalent recovery area of the *j*th forest type in the *i*th year under different forest restoration measures; S_0, L_0, C_0, and WR_0 are soil, litter, canopy and total water conservation capacity of the reference forests at the baseline year, respectively (t/hm^2).

3. Model Development

We developed the FWAT based on the ENVI/DIL and ArcGIS Engine/C#.NET. ENVI/IDL is able to process remote sensing data, but with the lack of a visualization tool. ArcGIS Engine is featured by powerful GIS functions and a visualization tool by C#, which can support flexible software development in COM environments. In this study, we took full advantage of ENVI/DIL and ArcGIS Engine/C#.NET to develop an integrated GIS tool with RS functions. The FWAT was developed with three layers (data, business logic and display layer) (Figure 4) and designed with five modules (data management, data processing, forest change, forest water conservation, and visualization) (Figure A1). The data layer mainly stores and manages data on soil, climate, DEM, forest and so on. The business logic layer covers data access, data processing, model calculation and simulation functions. In the data access, we can read, write and manage the vector, raster or Excel data and database, while in the data processing function, we can perform functions such as pretreatment, radiative calibration, resampling, format conversion, clipping, mosaic, extraction, merge, field processing and batch processing. The model calculation and simulation functions include forest change simulation (changes by categories and random change) to create various forest restoration scenarios, forest change prediction to predict forest changes by ERA model, and forest water conservation capacity estimation (by total water storage capacity method) to compute water conservation capacity at both stand and regional levels. Forest change prediction can provide the estimations of water conservation capacity under different forest restoration scenarios. The display layer was developed based on Visual Studio 2010, .NET 4.0, C# and ArcEngine 10.2, as well as DotNetBar, a UI design tool to implement the designs of software user menu, WinForm, work directory and toolbox, basic GIS mapping, thematic mapping, layer rendering, statistical analysis, plotting and spatial-temporal pattern analysis.

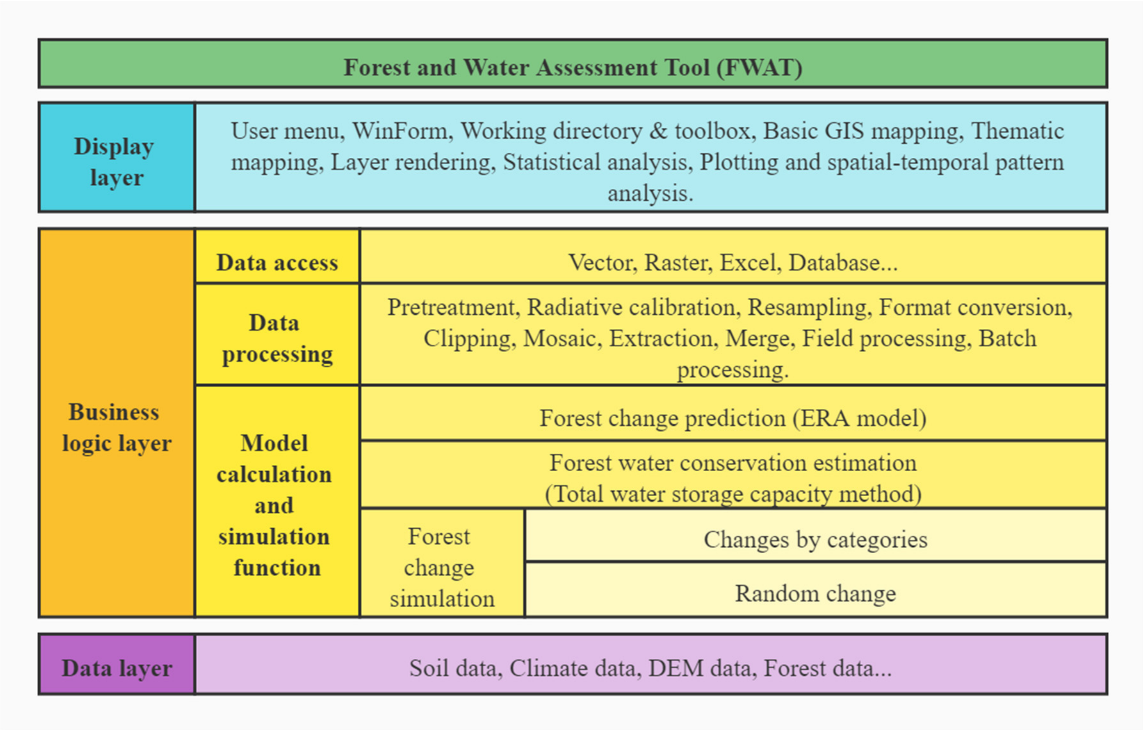


Figure 4. FWAT structure.

4. Model Application

The FWAT was applied in the Upper Zagunao watershed as an example in this study to demonstrate its performance in assessing forest restoration effects on watershed forest water conservation capacity.

4.1. Study Area

The Upper Zagunao River with a drainage area of 2242 km^2, is a tributary of the Minjiang River in the northwest of Sichuan Provence, China. Located in the transitional zone between the Qinghai−Tibet plateau and the Sichuan basin, this watershed belongs to the typical alpine canyon landform with the elevation ranging from 1789 to 5632 m above sea level. The study watershed is situated in an alpine climate zone with cold winters and cool summers. The annual mean temperature is 11.20 °C with the minimum temperature of −3.30 °C in January and the maximum temperature of 26.90 °C in July. The annual precipitation varies between 627.50 mm and 1478.00 mm with a long-term average annual precipitation of 1067.60 mm. Soils such as leptosols, cambisols and luvisols are predominant in the Upper Zagunao watershed. The major forest types in the watershed include alpine meadow and subalpine coniferous, covering about 47% and 32% of the total watershed area, respectively. The area with an elevation between 2000 and 4000 m is covered with dark coniferous forest, while the higher elevation area (>4000 m) is occupied by shrubs and alpine meadows. Coniferous forests with *Abies faxoniana* and *Picea asperata* as the dominant tree species in the study area were seriously harvested from the 1950s to the 1970s, especially with about 1% of the watershed area harvested annually during the period from 1955 to 1962. Then forest harvesting greatly declined from the late 1970s and eventually stopped completely in 1998. Since then, the forest land in Upper Zagunao watershed has been gradually restored under the Natural Forest Protection Project in China.

4.2. Data

The data used in this study cover topography, land cover, climate, soil, forest, forest restoration measures and hydrological parameters. Detailed information of data is shown in Tables 1–3.

Table 1. Data introduction.

Data	Products	Spatial Resolution	Temporal Resolution	Format	Sources
Forest map	-	-	yearly	Vector	Western Sichuan Forestry Bureau
Land cover	China Cover 2010	30 m	yearly	Raster	http://www.geodata.cn/, accessed on 27 August 2021
Precipitation	Daily precipitation	500 m	daily	Raster	http://data.cma.cn/(ANUSPLIN interpolation, accessed on 27 August 2021)
Soil data	HSWD	1:1,000,000	yearly	Raster	http://westdc.westgis.ac.cn/, accessed on 27 August 2021)
Topography	ASTER DEM	30 m	yearly	Raster	http://www.gscloud.cn/, accessed on 27 August 2021

Table 2. The restoration measures for major forest types [28,29].

Forest Types	Restoration Measures	Dominant Species
Natural coniferous forest (NCF)	Natural recovery	*Abies fabri*
Planted coniferous forest (PCF)	Thinning out, tending, density adjustment	*Picea asperata, cupressus chengiana*
Natural mixed forest (NMF)	Thinning out, pruning	*Abies fabri, betula platyphylla*
Planted mixed forest (PMF)	Tending (shrub cutting and weeding)	*Picea asperata, betula platyphylla*
Natural evergreen broad-leaved forest (NEBF)	Natural recovery	*Quercus semicarpifolia*
Natural deciduous broad-leaved forest (NDBF)	Clearing, shrub cutting and weeding	*Betula platyphylla*
Alpine shrub (AS)	Clearing, replanting	*Salix cupularis*
Dry valley shrub (DVS)	Clearing	–
Shrub	Natural recovery	–
Landslide area (LA)	Seeding	–

Table 3. Hydrological characteristics of NCF in the Upper Zagunao watershed [30,31].

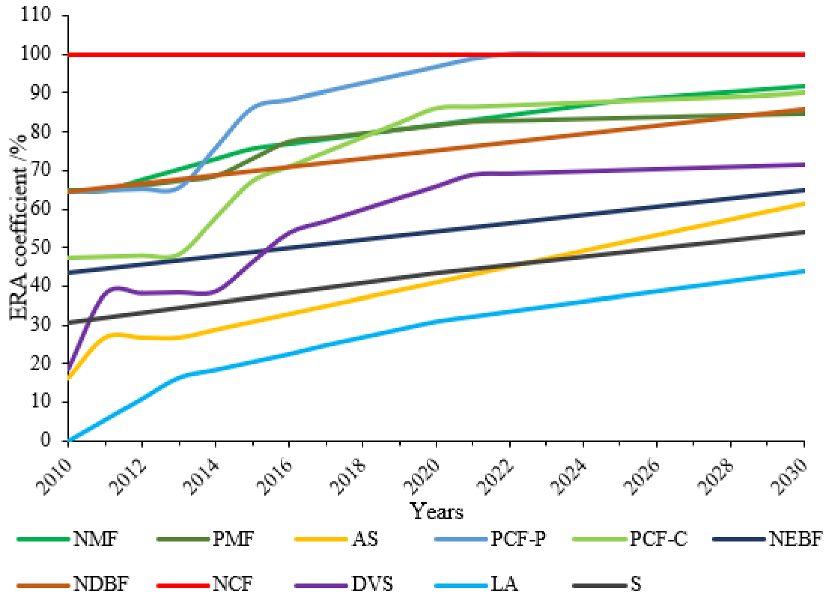
Forest Type	Canopy Water Conservation Capacity (t/hm^2)	Litter Water Conservation Capacity (t/hm^2)	Soil Water Conservation Capacity (t/hm^2)	Total Water Conservation Capacity (t/hm^2)
NCF	32.22	225.00	2315.00	2572.22

4.3. Results

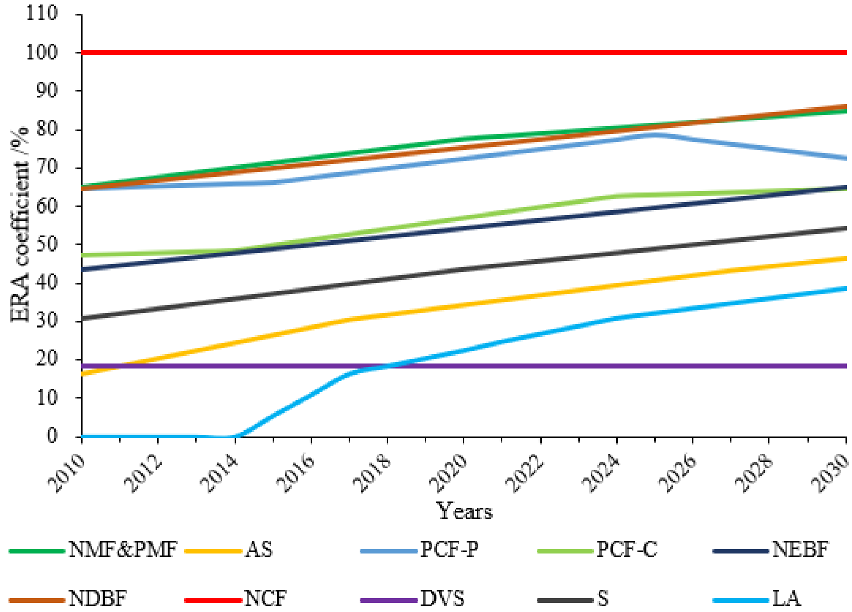
4.3.1. Forest Changes under Forest Restoration Scenarios

In this study, forest changes caused by forest restoration measures were simulated and predicted by use of the forest change simulation and prediction module of FWAT. Firstly, the layout of forest restoration measures in the Upper Zagunao watershed was implemented according to the data of DEM, precipitation, land cover, and tree species and parameters of forest restoration measures (Table 2 and Figure A2). Here, two forest restoration scenarios—natural recovery and artificial recovery were created. All forest types were recovered naturally without artificial restoration measures under the natural recovery scenario while under artificial recovery scenario, all forest types except natural coniferous and natural evergreen broad-leaved forests were restored with artificial measures.

Then, we determined the equivalent recovery area coefficients (ERA coefficient) for each forest type with a specified restoration measure based on the experiment data in the study watershed (Figure 5) [24,32–38] and then the watershed-scale ERA coefficients of the two forest restoration scenarios were calculated by the ERA model in the forest change simulation and prediction module of the FWAT (Figure 6). As shown in Figure 5, the ERA coefficient increased in the Upper Zagunao watershed with the implementation of natural and artificial restoration measures from 2010 to 2030. The ERA coefficients of the Upper Zagunao watershed under natural and artificial restoration scenarios were similar during the first three years, and then the watershed-scale ERA coefficient under the artificial restoration scenario was gradually higher than that under the natural restoration scenario. By 2030, the ERA coefficients under the natural and artificial restoration scenarios would increase to 78.32% and 82.59%, respectively.



(**a**)



(**b**)

Figure 5. ERA coefficients of different land cover types under (**a**) natural and (**b**) artificial restoration measures from 2010 to 2030. NMF: natural mixed forest; PMF: planted mixed forest; AS: Alpine shrub; PCF-P: planted coniferous forest—*Picea asperata*; PCF-C: planted coniferous forest—*Cupressus chengiana*; NEBF: natural evergreen broad-leaved forest; NDBF: natural deciduous broad-leaved forest; NCF: natural coniferous forest; DVS: dry valley shrub; LA: landslide area; S: shrub.

Based on the layouts of the forest restoration measures and the forest cover map of the Upper Zagunao watershed in 2010, coupled with ERA coefficients for each forest type under specified restoration measures, the future forest landscape changes were simulated and predicted by the ERA model in the forest change simulation and prediction module of FWAT. As shown in Figure 7 and Table 4, the upper Zagunao watershed was mainly covered by natural mixed forest (20.25%), planted coniferous forest (5.77%), natural coniferous forests (4.95%), planted mixed forest (4.57%), natural evergreen broad-leaved forest

(3.77%), and natural deciduous broad-leaved forests (1.67%), where young natural mixed forest occupied 8.08% in 2010. In 2030, all young natural mixed forests will become near-mature natural mixed forests while all mature planted mixed forests will be over-mature planted mixed forests in both natural and artificial restoration scenarios. In addition, under the artificial restoration scenario, the landslide and earthquake damaged slopes will be converted to planted deciduous broad-leaved forests while the degraded dry valley and alpine shrubs will be planted coniferous forests.

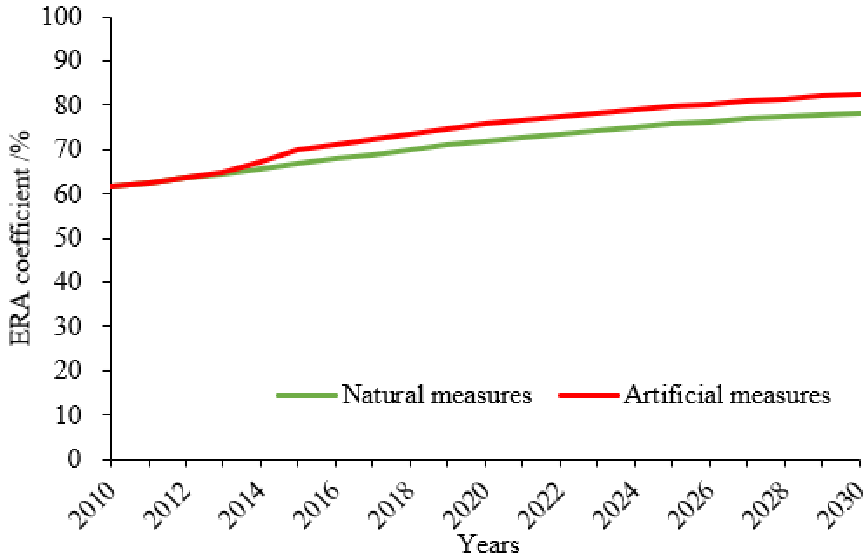


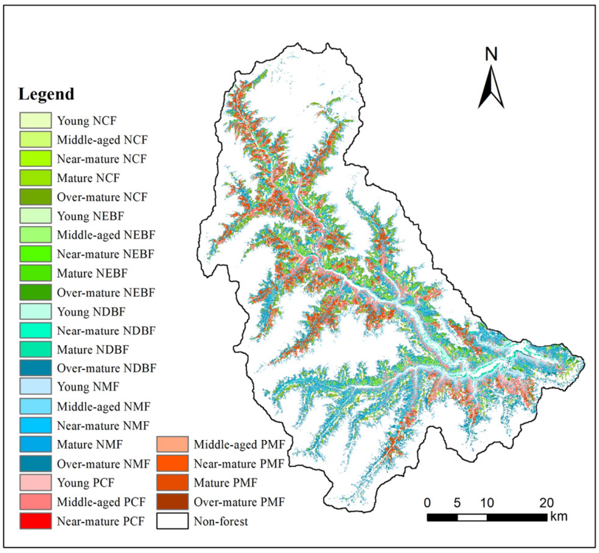
Figure 6. ERA coefficients of natural and artificial restoration measures in the Upper Zagunao watershed from 2010 to 2030.

Table 4. Forest changes under natural and artificial restoration scenarios.

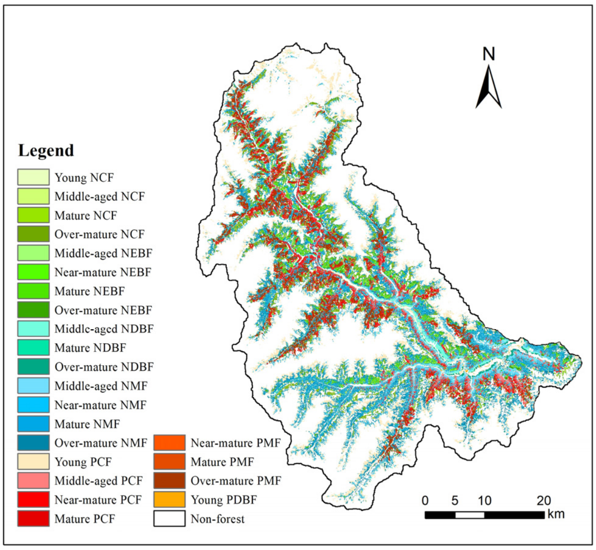
Forest Type	Age Group	Proportion (in 2010)	Proportion (Natural Recovery in 2030)	Proportion (Artificial Recovery in 2030)
Natural evergreen broad-leaved forest (NEBF)	Young	1.10%	0	0
	Middle-aged	0.17%	0	0
	Near-mature	0.37%	1.10%	1.10%
	Mature	0.43%	0.54%	0.54%
	Over-mature	1.70%	2.13%	2.13%
Natural coniferous forest (NCF)	Young	1.07%	1.07%	1.07%
	Middle-aged	0.51%	0	0
	Near-mature	0.24%	0.51%	0.51%
	Mature	0.04%	0.24%	0.24%
	Over-mature	3.09%	3.13%	3.13%
Natural deciduous broad-leaved forest (NDBF)	Young	0.86%	0	0
	Near-mature	0.05%	0.86%	0.86%
	Mature	0.74%	0.05%	0.05%
	Over-mature	0.01%	0.75%	0.75%
Natural mixed forest (NMF)	Young	**8.08%**	0	0
	Middle-aged	0.31%	0	0
	Near-mature	1.85%	**8.08%**	**8.08%**
	Mature	1.99%	2.16%	2.16%
	Over-mature	8.02%	10.02%	10.02%
Planted coniferous forest (PCF)	Young	**1.84%**	0	0
	Middle-aged	3.88%	**1.84%**	10.87%
	Near-mature	0.04%	0.09%	0.09%
	Mature	0	3.84%	3.84%

Table 4. *Cont.*

Forest Type	Age Group	Proportion (in 2010)	Proportion (Natural Recovery in 2030)	Proportion (Artificial Recovery in 2030)
Planted mixed forest (PMF)	Middle-aged	0.28%	0	0
	Near-mature	0.28%	0	0
	Mature	3.95%	0.56%	0.56%
	Over-mature	0.06%	4.01%	4.01%
Shrub and broad-leaved forest (SBF)	–	0	0.06%	0
Planted deciduous broad-leaved forest (PDBF)	Young	0	0	0.06%
Non-forest	–	59.04%	58.98%	49.95%

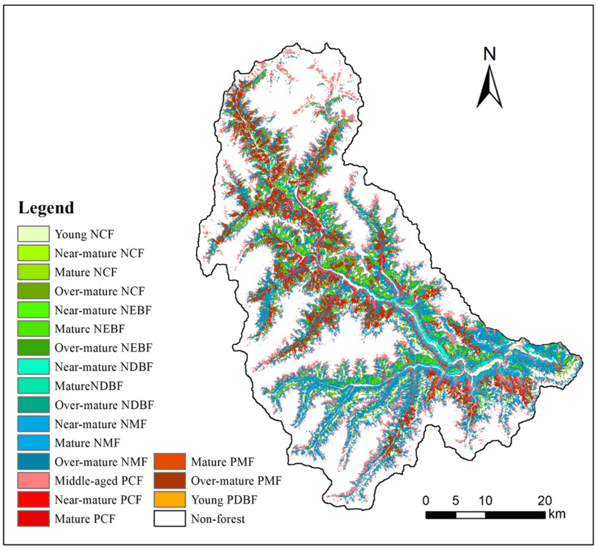


(**a**) (2010)



(**b**) (2020)

Figure 7. *Cont.*



(**c**) (2030)

Figure 7. Forest change prediction under artificial restoration scenarios in 2010, 2020 and 2030.

4.3.2. Effects of Forest Restoration Measures on Water Conservation Capacity

The water conservation capacity (Table 3) of the natural coniferous forest in the Upper Zagunao watershed regarded as the restoration objective with an ERA coefficient of 100%. In 2010, the canopy, litter, soil and the total water conservation capacities in the Upper Zagunao watershed were 19.80, 138.29, 1423.13 and 1580.76 t/hm^2, respectively, according to the calculation using the functions of the forest water conservation module in the FWAT. Based on the water conservation capacities of the different layers of natural coniferous forest (Table 3) and ERA coefficients for different forest types with specified restoration measures (Figures 5 and 6), the watershed-scale forest water conservation capacity from 2011 to 2030 was predicted using the function of the forest water conservation prediction module in FWAT. The results (Figures 8 and 9, and Table 5) showed that the canopy, litter, soil and total water conservation capacities were increased by 5.43, 37.93, 389.78, and 433.58 t/hm^2, respectively, by 2030, compared to those of 2010 under a natural restoration scenario, while they were increased by 6.81, 47.53, 488.77, and 543.42 t/hm^2 under the artificial restoration scenario, respectively. Overall, the total watershed forest water conservation capacity was increased by 27.43% and 34.38% under the natural and artificial restoration scenarios from 2010 to 2030, respectively, indicating water conservation capacity in artificial restoration scenario is higher (about 7%) than that in the natural recovery scenario.

Table 5. Forest water conservation capacity under different forest restoration scenarios (t/hm^2).

Restoration Scenario	Years	Canopy Water Conservation Capacity	Litter Water Conservation Capacity	Soil Water Conservation Capacity	Total Water Conservation Capacity
Natural	2010	19.80	138.29	1423.13	1580.76
	2015	21.48	149.97	1542.87	1714.27
	2020	23.18	161.86	1665.34	1850.26
	2025	24.43	170.57	1755.09	1949.84
	2030	25.23	176.22	1812.91	2014.34
Artificial	2010	19.80	138.29	1423.13	1580.76
	2015	22.46	156.88	1614.02	1793.30
	2020	24.38	170.27	1751.77	1946.44
	2025	25.65	179.14	1843.18	2047.89
	2030	26.61	185.83	1911.91	2124.18

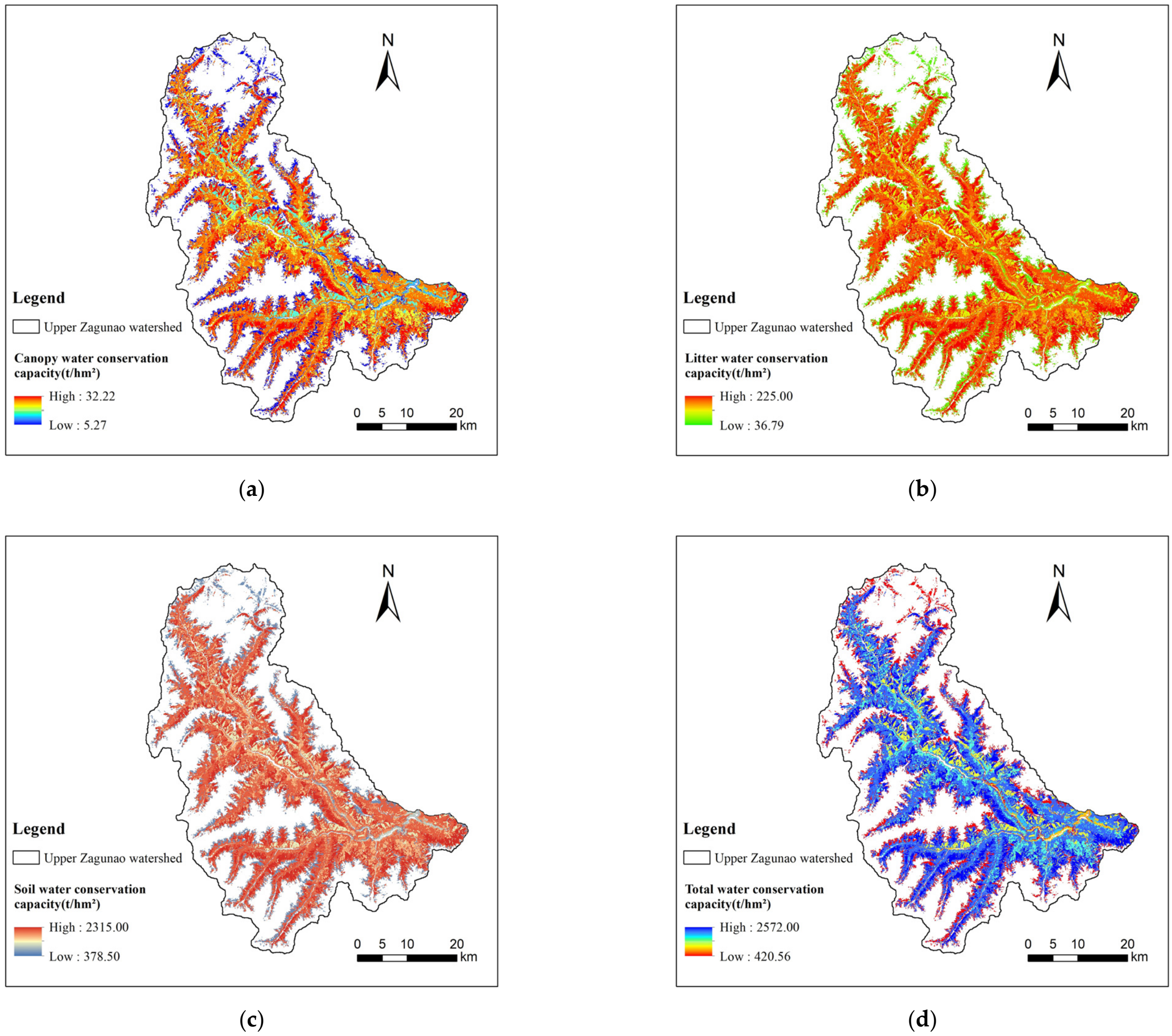


Figure 8. Spatial distribution of (**a**) canopy, (**b**) litter, (**c**) soil and (**d**) total water conservation capacity in 2010.

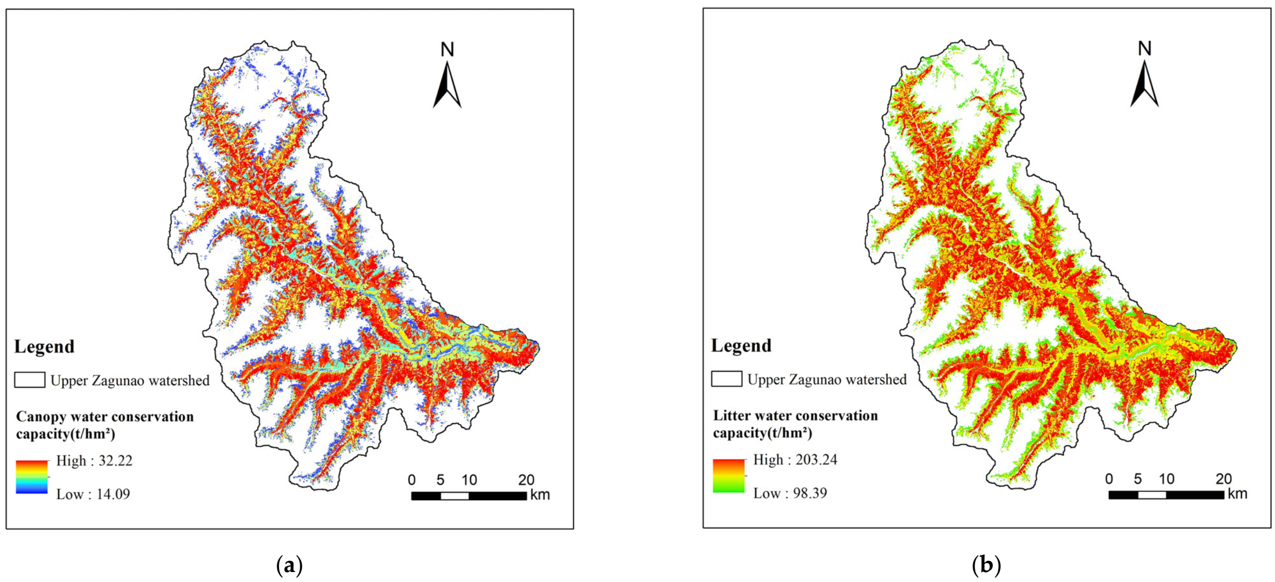
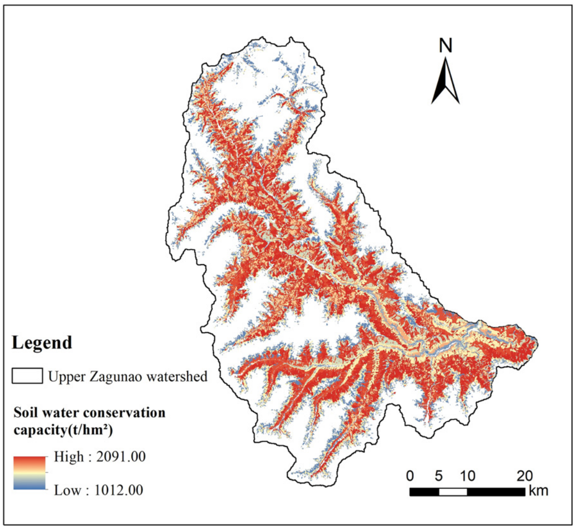
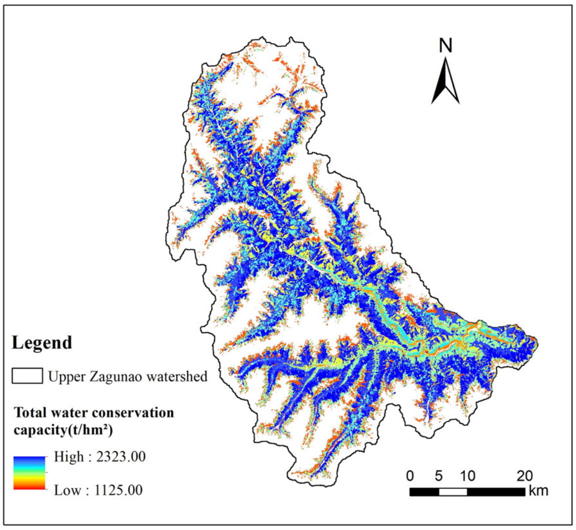


Figure 9. *Cont.*



(**c**)



(**d**)

Figure 9. Spatial distribution of (**a**) canopy, (**b**) litter, (**c**) soil and (**d**) total water conservation capacity under artificial restoration scenarios in 2030.

5. Limitations

The spatial data of land cover, precipitation, and topography in this study were obtained from official sources with high data quality. The parameters for the calculation of ERA coefficients and water conservation capacity are from peer-reviewed publications and our field observations or experiments. The method for the calculation of water conservation capacity is the total water storage capacity, which is a widely used classic method. Therefore, we believe the data and modelling results are reliable in this study. However, given that the extrapolation of hydrological parameters from field measurements in sample sites to watershed levels may be insufficient for representing spatial heterogeneity of forest hydrological functions, the associated uncertainties may arise in this study. More extensive and easy access of field observations are needed in future studies. In addition, we assume the hydrological functions of soil, litter and canopy layers for each forest type with a specific restoration measure have the same recovery rates (ERA coefficients) over time. It would be ideal if we could distinguish the different hydrological recovery rates of soil, litter and canopy layers. However, according to our literature collection, limited data can be applied to generate a long-term time series of hydrological recovery rates for each layer for every forest type with a specific restoration layer. Thus, the simplification was made with the best available data. Given the close relationships between the hydrological functions of soil, litter and canopy, we believe this simplification is acceptable. In future, it would be necessary to carry out more long-term experimental observations of forest hydrological functions at different layers of various forest types or under various restoration measures to further improve the prediction accuracy of the model.

6. Conclusions

In this study, a forest restoration evaluation model (ERA) was innovatively developed for the quantification of forest changes under various forest restoration scenarios. We then designed and implemented the Forest and Water Assessment Tool (FWAT) which combines the ERA model, classic forest water storage capacity estimation (total water storage capacity) to quantitatively evaluate and predict the impact of forest restoration measures on the regional/watershed forest water conservation capacity by using the GIS secondary development platforms (ENVI/IDL, ArcGIS Engine, C# and .NET). According to the application of the FWAT in the Upper Zagunao watershed, in 2030, all young natural mixed forests will become near-mature natural mixed forests in both natural and artificial restoration scenarios. The forest water conservation capacity of the study watershed was 1580.76 t/hm^2 in 2010. Under both natural and artificial restoration scenarios, the canopy, litter, and soil layers and total water conservation capacities increased consistently from 2010 to 2030. The watershed total water conservation capacity in natural and artificial restoration scenarios was increased by 2014.34 t/hm^2 (27.43%) and 2124.18 t/hm^2 (34.38%) by 2030, respectively. By 2030, the watershed-scale water conservation capacity under the artificial restoration scenario was on average 7% higher than that in the natural restoration scenario. The successful application of the FWAT in the Upper Zagunao watershed demonstrates that the FWAT can be an efficient tool to evaluate forest water conservation capacity from stand to regional levels, as well as to predict and display the long-term spatial-temporal changes of regional forest and water conservation capacity under different forest restoration scenarios.

Author Contributions: Data collection, Y.X. and Y.H.; data analysis, E.Y.; manuscript drafting, E.Y. and M.Z.; software development, Z.M. and S.Z.; research design, M.Z.; manuscript revision, M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by China National Science Foundation, grant number 31770759 and National Program on Key Research and Development Project of China, grant number 2017YFC0505006.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article and available on request from the corresponding author.

Acknowledgments: We thank all the scientists, engineers, and students who participated in forest-water resources field campaigns. We thank all the teammates for their assistance in the field work.

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

Appendix A

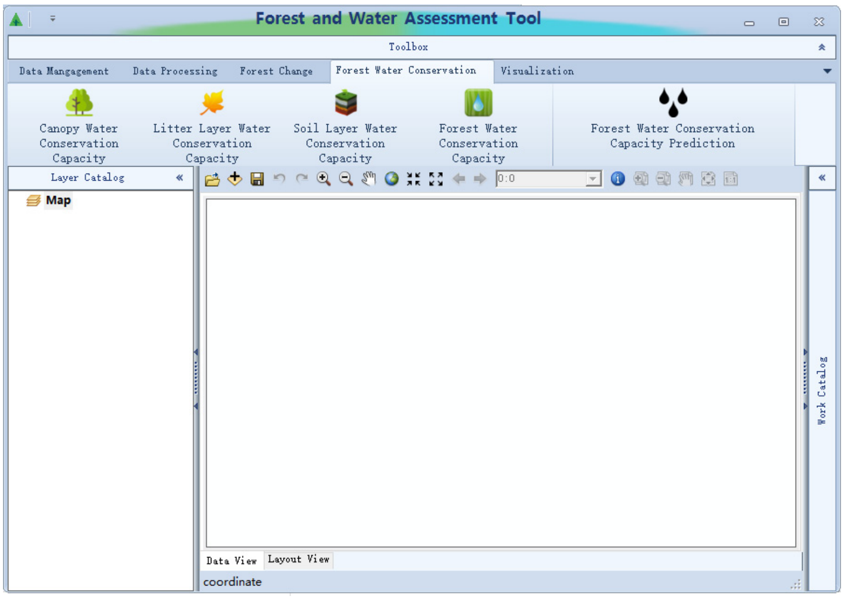
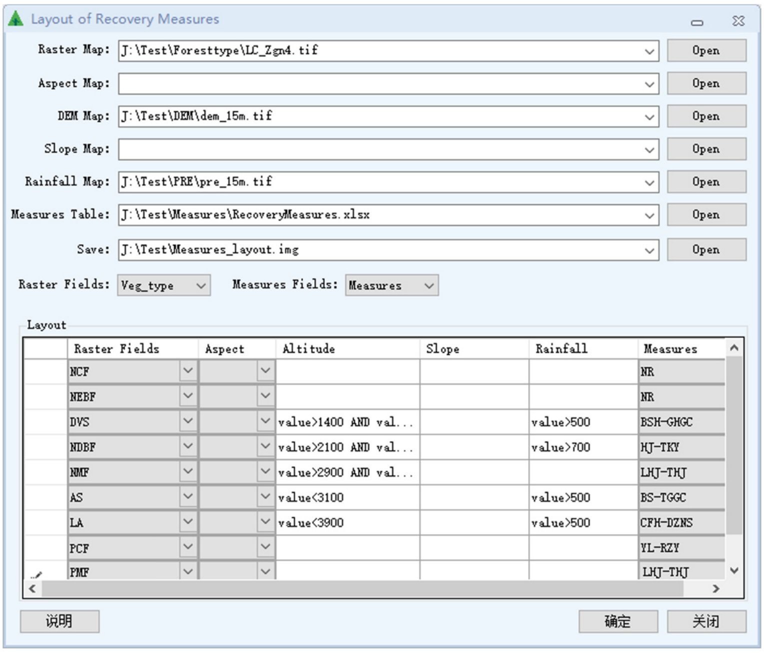
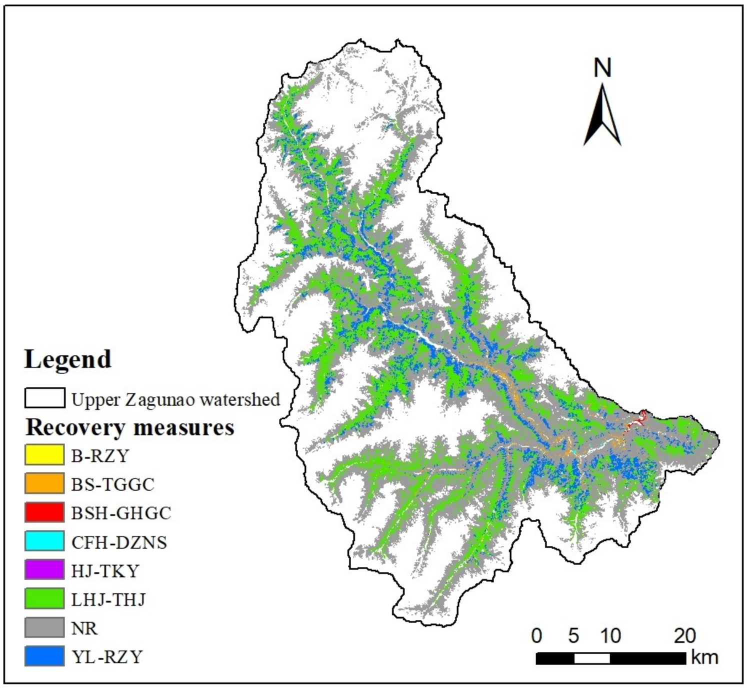


Figure A1. FWAT main interface.

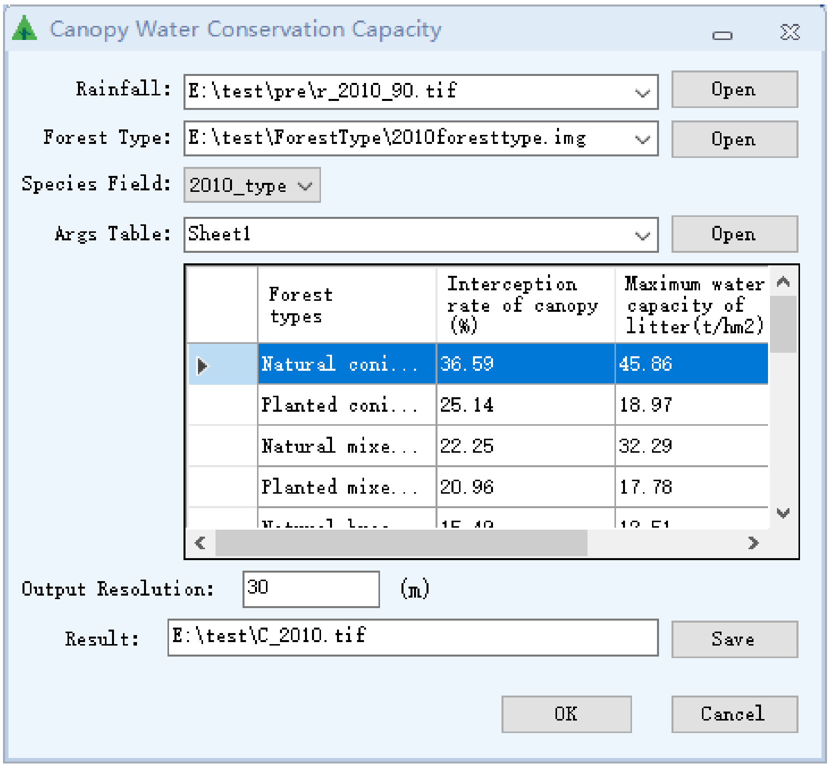


(a)

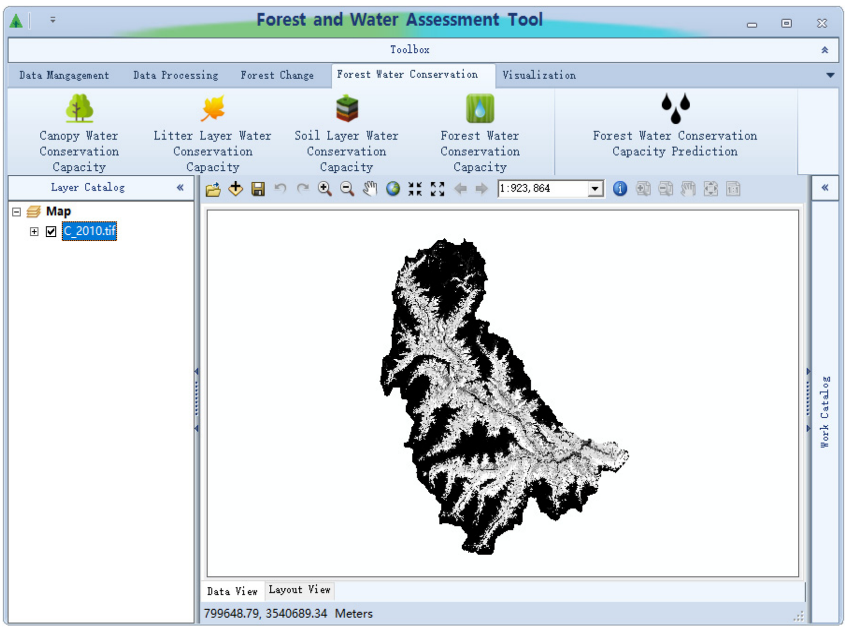


(b)

Figure A2. The layout of forest restoration measures in the Upper Zagunao watershed. (**a**) Parameters input; and (**b**) the results from FWAT. B-RZY, restoration measure for *Cupressus chengiana*; BS-TGGC, restoration measures for severely degraded shrub lands in alpine canyon; BSH-GHGC, restoration measures for shrub lands in humid and fertile areas in dry valleys; CFH-DZNS, restoration measures for landslide and earthquake damaged slopes; HJ-TKY, restoration measures for *Arrow Bamboo* and *Betula platyphylla* secondary forest; LHJ-THJ, restoration measures for *Fargesia, betula* and *Abies faxoniana* natural mixed forest; NR, natural recovery; YL-RZY, technology of restoration measures for *Picea* plantation.



(a)



(b)

Figure A3. An example of canopy water conservation capacity calculation by use of the FWAT. (**a**) Parameters input; and (**b**) the result displayed in FWAT.

References

1. Valtera, M.; Schaetzl, R. Pit-mound microrelief in forest soils: Review of implications for water retention and hydrologic modelling. *For. Ecol. Manag.* **2017**, *393*, 41–51. [CrossRef]
2. Oishi, Y. Evaluation of the Water-Storage Capacity of Bryophytes along an Altitudinal Gradient from Temperate Forests to the Alpine Zone. *Forests* **2018**, *9*, 433. [CrossRef]
3. Lee, Y.-S.; Lee, S.; Jung, H.-S. Mapping Forest Vertical Structure in Gong-ju, Korea Using Sentinel-2 Satellite Images and Artificial Neural Networks. *Appl. Sci.* **2020**, *10*, 1666. [CrossRef]
4. Seidl, R.; Spies, T.; Peterson, D.; Stephens, S.; Hicke, J. Searching for resilience: Addressing the impacts of changing disturbance regimes on forest ecosystem services. *J. Appl. Ecol.* **2016**, *53*, 120–129. [CrossRef]
5. Hoelting, L.; Beckmann, M.; Volk, M.; Cord, A. Multifunctionality assessments—More than assessing multiple ecosystem functions and services? A quantitative literature review—ScienceDirect. *Ecol. Indic.* **2019**, *103*, 226–235. [CrossRef]
6. Ferraz, S.; Lima, W.; Rodrigues, C. Managing forest plantation landscapes for water conservation. *For. Ecol. Manag.* **2013**, *301*, 58–66. [CrossRef]
7. Mansourian, S.; Stanturf, J.; Derkyi, M.; Engel, V. Forest Landscape Restoration: Increasing the positive impacts of forest restoration or simply the area under tree cover? *Restor. Ecol.* **2017**, *25*, 178–183. [CrossRef]
8. Chen, X.; He, Y.; Zhang, D.; Zeng, W. Review on the Eco-Efficiency Evaluation of Forest Ecosystem Restoration and Reconstruction in China. *Iss. For. Econ.* **2008**, *28*, 192–196.
9. Yao, X. Quantitative analysis on water retaining benefit of forest for erosion control in Jinzhai county of Anhui province. *Soil Water Conserv. China* **1996**, *4*, 23–25, 59–60.
10. Gong, Y.; Chen, L.; Zhang, J.; Luo, C. Effects of vegetation restoration on channel runoff in the low-mountain and rainstorm area of the upper Jialing River. *J. Soil Water Conserv.* **2009**, *23*, 1–5.
11. Celentano, D.; Rouss, G.; Engel, V.; Zelarayan, M.; Oliveira, E.; Araujo, A.; Moura, E. Degradation of riparian forest affects soil properties and ecosystem services provision in eastern Amazon of Brazil. *Land Degrad. Dev.* **2017**, *28*, 482–493.
12. Sang, W.; Ma, K.; Chen, L.; Zheng, Y. A brief review on forest dynamics models. *Chin. Bull. Bot.* **1999**, *16*, 193–200.
13. Yu, X.; Zhou, B.; Lv, X.; Yang, Z. Evaluation of water conservation function in mountain forest areas of Beijing based on invest model. *Sci. Silv. Sin.* **2012**, *48*, 1–5.
14. Sitch, S.; Prentice, I.; Arneth, A.; Bondeau, A.; Cramer, W.; Kaplan, J.; Levis, S.; Lucht, W.; Sykes, M.; Thonicke, K.; et al. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Chang. Biol.* **2010**, *9*, 161–185. [CrossRef]
15. Dai, E.; Wu, Z.; Wang, X.; Fu, H.; Xi, W.; Pan, T. Progress and prospect of research on forest landscape model. *J. Geogr. Sci.* **2014**, *25*, 113–128. [CrossRef]
16. Wang, Y.; Zhuang, D.; Xu, X.; Jiang, D. Design of macro-ecological environment remote sensing monitoring system and the key technologies. *Geo-Inf. Sci.* **2011**, *13*, 672–678.
17. Baskent, E.; Terzioglu, S.; Baskaya, S. Developing and Implementing Multiple-Use Forest Management Planning in Turkey. *Environ. Manag.* **2008**, *42*, 37–48. [CrossRef]
18. Erik, N. A spatial decision support system for long-term forest management planning by means of linear programming and a geographical information system. *Scand. J. For. Res.* **1997**, *12*, 77–88.
19. Liu, Y.; Feng, Z. Research and implementation of forest landscape four-dimensional visual system based on ComGIS. *J. Beijing For. Univ.* **2005**, *4*, 36–39.
20. McVicar, T.; Li, L.; Van Niel, T.; Zhang, L.; Li, R.; Yang, Q.; Zhang, X.; Mu, X.; Wen, Z.; Liu, W.; et al. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *For. Ecol. Manag.* **2008**, *251*, 65–81.
21. Spiridon, K.; Constantina, I.; Nikos, A.; Alexander, B.; Michael, K. Design of forest management planning DSS for wildfire risk reduction. *Ecol. Inf.* **2008**, *3*, 122–133.
22. Li, S. *Research and Development of the Water Conservation Estimation System Based on RS and GIS in the Southern Slope of Qilian Mountains*; Qinghai Normal University: Xining, China, 2015.
23. Wei, X.; Zhang, M. Research Methods for Assessing the Impacts of Forest Disturbance on Hydrology at Large-scale Watersheds. In *Landscape Ecology in Forest Management and Conservation: Challenges and Solutions for Global Change*; Li, C., Lafortezza, R., Chen, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 119–147.
24. Zhang, M.; Wei, X.; Sun, P.; Liu, S. The effect of forest harvesting and climatic variability on runoff in a large watershed: The case study in the Upper Minjiang River of Yangtze River basin. *J. Hydrol.* **2012**, *464*, 1–11. [CrossRef]
25. Lin, Y.; Wei, X. The impact of large-scale forest harvesting on hydrology in the Willow watershed of Central British Columbia. *J. Hydrol.* **2008**, *359*, 141–149. [CrossRef]
26. Meng, Z. *Evaluation and System Realization for Regional Forest Change and Water Conservation Function*; University of Electronic Science and Technology of China: Chengdu, China, 2019.
27. Li, J.; Shao, Q.; Liu, J. Forest conservation estimation based on the integrated storage capacity method—A case study of Xingguo county in Jiangxi. *J. Northw. For. Univ.* **2012**, *27*, 83–87.
28. Feng, Q.; Liu, X.; Lu, C.; Wu, X.; Pan, H.; Ma, B.; Liu, S. Effects of different forest management regimes on woodland hydrological effects of natural secondary forests in a sub-alpine region of western Sichuan, China. *Acta Ecol. Sin.* **2016**, *36*, 5432–5439.

29. Liu, Y. *Research on the Changes of Aboveground Biomass and NPP in Recovery Process for Main Forest Types in Subalpine Region of Western Sichuan*; Chinese Academy of Forestry: Beijing, China, 2010.
30. He, L.; Qiang, W.; Zhang, Y.; Liu, Y.; Liu, B.; Pang, X. Effect of secondary succession on soil water holding capacity of subalpine coniferous forest in western Sichuan, China. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 639–647.
31. Zhang, Y.; Liu, S.; Luo, C.; Zhang, G.; Ma, J. Water holding capacity of ground covers and soils in different land uses and land covers in subalpine region of Western Sichuan, China. *Acta Ecol. Sin.* **2009**, *29*, 627–635.
32. Xu, Z.; Yang, X.; Chen, J.; Feng, Q.; Li, D.; Li, X.; Cai, L.; Liu, X.; Zhang, L. Effect of thinning on the water conservation capacity of Picea asperata of different ages. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 657–666.
33. Pang, X.; Bao, W.; Zhang, Y.; Leng, L.; Yuan, Z. Geographical comparison of soil physical properties under Cupressus chengiana forests. *Chin. J. Appl. Environ. Biol.* **2004**, *10*, 596–601.
34. He, S.; Gong, Y.; Zheng, Z. Water conservation capacity of litters in different vegetation restoration patterns in the upper reaches of Minjiang River. *Resour. Environ. Yangtze Basin.* **2020**, *29*, 1986–1994.
35. He, L.; Pang, X. Soil water holding capacity of four typical shrub islands and its influencing factors in subalpine western Sichuan. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 632–638.
36. Liu, Y.; Wen, Y.; Zhang, Y.; Tan, B.; You, C.; Zhang, L.; Yang, W.; Xu, Z.; Li, H. Soil water-holding dynamic characteristics of six colored-leaf forest communities in the subalpine forest of western Sichuan. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 648–656.
37. Zhu, W.; Sheng, Z.; Shu, S.; Wang, W.; Li, X. Comprehensive evaluation of ecological function restoration of the natural secondary forests in a sub-alpine region of western Sichuan. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 694–704.
38. Deng, L. *Study on the Scale Transformation of Water Conservation Function of Forest Ecosystem in the Upper Reaches of Minjiang River*; University of Electronic Science and Technology of China: Chengdu, China, 2020.