Received: 24 February 2021 | Revised: 31 July 2021 | Accepted: 25 August 2021

DOI: 10.1002/hyp.14362

RESEARCH ARTICLE

WILEY

Evaluating the long-term ecohydrological suitability of restoration efforts in a typical watershed of the Loess Plateau

Miao Sun[1] | Chengsheng Yan[1] | Nana Zhao[2] | Xining Zhao[3] | Xuerui Gao[3] | Yingxin Lian[1] | Yujie Yuan[1] | Hao Yang[1]

[1]College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shaanxi, China

[2]Institute of Wetland Research, Chinese Academy of Forestry, Beijing, China

[3]Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, China

Correspondence

Xining Zhao and Xuerui Gao, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
Email: zxn@nwsuaf.edu.cn (X. Z.) and gaoxuerui666@163.com (X. G.)

Funding information

Natural Science Basic Research Plan in Shaanxi Province of China, Grant/Award Number: 2016JQ5076; National Key Research and Development Program of China, Grant/Award Numbers: 2018YFF0215702, 2016YFC0400204; Chinese National Natural Science Foundation, Grant/Award Number: 51609243

Abstract

The vegetation growth of the Loess Plateau is often restricted by water, which seriously threatens the water sustainability of regional ecosystem. In order to clarify the relationship between supply and demand of vegetation water use after Grain for Green Project, this study selected Malian River Basin as the research area and calculated the vegetation water use and water demand using the eco-hydrological model. The results showed that the annual water demand of the basin was 570 mm, while the average annual water supply was only 294 mm, accounting only for 52.0% of the demand. From 2000 to 2018, the temporal and spatial matching degree of water supply and demand in the Malian River Basin were 0.63 and 0.65, respectively. On the whole, the water resources in Malian River Basin can basically support the growth of vegetation, but in some areas are not sustainable. Water resources in the southern region can only barely maintain the normal growth of vegetation under the current conditions, so it is not recommended to carry out new plantation in this area. The evaluation of matching degree in the northern from January to April is poor, so it is necessary to appropriately reduce the planting area of economic crops and replace it with planting herbaceous plants with small water consumption in Spring. Compared with the current conditions, under the future climate scenarios of ssp126 and ssp585, the Malian River Basin will show a trend of warming and humidification. The temporal matching degree of water supply and demand also significantly improved to 0.83 and 0.92, indicating that even if the planting structure did not change significantly, water supply would gradually meet the needs of vegetation. The study results can provide the basis for formulating more scientific and reasonable vegetation restoration policies.

KEYWORDS

eco-hydrological model, grain for green project, Malian River Basin, matching degree, vegetation restoration

1 | INTRODUCTION

The Loess Plateau, located in the middle reaches of the Yellow River, is a semi-arid and semi-humid region with a large area occupied by loess (Liang et al., 2013). The long-standing and profound farming culture and the special soil vulnerable to erosion make the problems of vegetation degradation and soil erosion increasingly prominent in the Loess Plateau (Kou et al., 2016). In order to solve the above problems, the government initiated and organized a lot of soil and water conservation measurements including afforestation, pasture reestablishment, terraces and check-dams have been implemented since the 1950s (Wang et al., 2015; Xiao et al., 2014).

Among these measures, the Grain for Green project is a large and important reforestation campaign, which was started at the end of 1990s under the support of Chinese government. This project transforms a large amount of farmland into forestland and grassland. *Robinia pseudoacacia*, *Chinese pine*, *platycladus orientalis*, *poplar*, *seabuckthorn*, *caragana microphylla* and other native or foreign dominant tree species are planted in large quantities. Under the joint influence of natural restoration and the artificial protection measures, the ecosystem and the environment on Loess Plateau were greatly improved. According to remote-sensed image, the average vegetation coverage on the Loess Plateau has been greatly increased, which is as large as 59.6% by 2013, almost double the vegetation coverage in the late 1990s (Chen et al., 2015). Studies have shown that the degree of river deposition has decreased, and the sediment reduction effect of the project is significant (Wang et al., 2018). All the above phenomena indicate that the ecological deterioration in the Loess Plateau region is gradually under control.

However, the effect of vegetation restoration in the Loess Plateau is often restricted by water (Wang et al., 2014). Whether the large-scale vegetation restoration in the Loess Plateau is sustainable has become a focus of debate in recent years. Chen et al. (2015) showed that although vegetation restoration has improved the ecological environment of the Loess Plateau, vegetation in some areas consumes too much soil water due to high local vegetation coverage and improper management. Zhao et al. (2019) also believed that the phenomenon of dry soil layer occurs frequently, which results in poor restoration effect in some areas. However, the research results of Gao et al. (2017) show that although ecological degradation exists in some areas, the total precipitation in the region can meet the water demand of vegetation. Therefore, the relationship between vegetation water supply and demand after vegetation restoration is not clear. Most of the research on the balance between vegetation water supply and demand are still at the stage of qualitative research. It is obviously not comprehensive to analyse the suitability of vegetation restoration from the perspective of soil water alone. The research conducted from the perspective of water resources is more about calculating whether the total amount of water resources in the area meets the water demand, but rarely considers the degree of water shortage in space. Whether water resources match the growth of vegetation in time and space is also the key to the healthy survival of vegetation. Therefore, it is very important to accurately analyse the relationship between vegetation water supply and demand after vegetation restoration.

In the study of influence of Grain for Green Project on regional hydrological process, traditional experimental methods are often limited by non-representative test points, which cannot accurately explain the regional scale problems (Gahegan, 2010). The research on regional water balance of vegetation is insufficient. Some studies use hydrological models such as SWAT model and VIC model (Pisinaras et al., 2010). Most of these hydrological models do not consider the detailed vegetation ecological process and the coupling interaction between ecology and hydrology. Also, most hydrological models can only simulate static vegetation, with little consideration of vegetation changes and growth. The eco-hydrological model, characterized by distributed computation, is a common method used to study regional eco-hydrological processes in recent years (Peng et al., 2013). Compared with the simple hydrological model, the eco-hydrological model can calculate the ecosystem and simulate the eco-hydrological process under the condition of vegetation restoration more accurately (Gao, Qin, et al., 2016). At the same time, the vegetation type setting of eco-hydrological model is more reasonable, which provides feasibility for future vegetation allocation research (Stephen et al., 2008).

The Regional Hydro-Ecological Simulation System (RHESSys) is a model created by Band that can simulate eco-hydrological processes in detail. It aims at the comprehensive simulation of water, carbon and nutrient cycles as well as the transport process with spatial and topographical changes on the scale of small and medium watershed (Band et al., 2000). The calculation unit of the RHESSys model is not strictly divided according to the grid, but nested at different levels according to climate characteristics, geographical characteristics and ecological variables. Therefore, it allows users to simulate different processes on different temporal and spatial scales according to actual needs, which effectively improves computational efficiency (Tague & Band, 2004). RHESSys evolved from ecological models and distributed hydrological models (Coughlan & Running, 1989), incorporating ecological and hydrological processes to simulate water transport, energy exchange and carbon and nitrogen cycle (Beven et al., 1984). Nowadays, RHESSys model is becoming more and more complete and comprehensive, which can accurately describe the change mechanism and interaction relationship of ecosystem and hydrological cycle in medium-scale region (Son et al., 2019).

The operation process of eco hydrological model has changed from traditional single hydrological process to eco hydrological coupling process, which also means that more model parameters are needed. At the same time, the consideration of vegetation growth also needs high spatial and temporal resolution, and its ecological process often needs to be carried out on a scale of 250 m or even smaller. Therefore, eco hydrological models generally have the characteristics of large amount of calculation and long running time. When eco hydrological models are applied in large-scale areas such as the Loess Plateau, it is difficult to calibrate the model parameters due to the lack of observation data and human activity data. Therefore, this study selected a typical vegetation restoration area – Malian River Basin in the Loess Plateau to study the relationship between vegetation water supply and demand. The Malian River Basin is a typical vegetation restoration area located in the middle of the Loess Plateau. The basin covers a total area of 1.9×10^4 km^2, belongs to medium scale region, which is convenient for eco-hydrological modelling. From the perspective of geomorphic features, the northern part is the loess hilly area, and the southern part is the loess remnant area, which belongs to the typical landform of the Loess Plateau. The climatic characteristics are also the same as most areas of the Loess Plateau, is continental monsoon climate. Moreover, there are no large or medium-sized water conservancy projects in the region, and the simulation results are less affected by human activities, making it easier for the eco-hydrological model to verify.

Based on this, this study selected the Malian River Basin as the research area. The eco hydrological model – RHESSys was used to calculate the regional vegetation water supply and demand. Then, the evaluation index of vegetation-water mutual suitability was proposed to further quantitatively evaluate the relationship between water balance under the current situation and future climate scenarios. The results of this study can provide the basis for formulating more scientific and reasonable vegetation restoration policies.

2 | STUDY AREA AND DATA COLLECTION

2.1 | Study area

Malian River is located in the central part of the Loess Plateau. It is a primary tributary of the Jinghe River Basin. Its geographical location is 106 ° 36 ′12 ″ ~ 108 ° 34 ′28 ″ E and 35 ° 19 ′12 ″ ~ 37 ° 24 ′ 42 ″ N, as shown in Figure 1. The basin covers area of 19 000 square kilometres, accounting for 41.9% of the Jing River Basin. The Malian River Basin is a typical temperate continental monsoon climate. In winter and spring, it is dry with little rain, while in summer and autumn it is rainy and humid. The average annual precipitation of the basin is 477 mm, and the annual distribution is extremely uneven. The precipitation in summer (May to September) accounts for 79.0% of the whole year.

The main vegetation types in Malian River Basin include coniferous forest, broad-leaved forest, shrub, grassland and cultivated plants. The typical vegetation species include *locust*, *poplar*, *sea-buckthorn*, *Chinese pine* and *alfalfa*. The soil types of the basin are mainly composed of *loessal soil*, *dark loessal soil* and *gray cinnamon soil*. The terrain is high in the north and low in the south. The loess hilly region is in the central and northern part, with large topographic drop and small cultivated area. The southern part is the Loess remnant wall area, the terrain drop is smaller than the central and northern part. Since the 1980s, due to the implementation of various soil and water conservation measures and the gradual implementation of Grain for Green

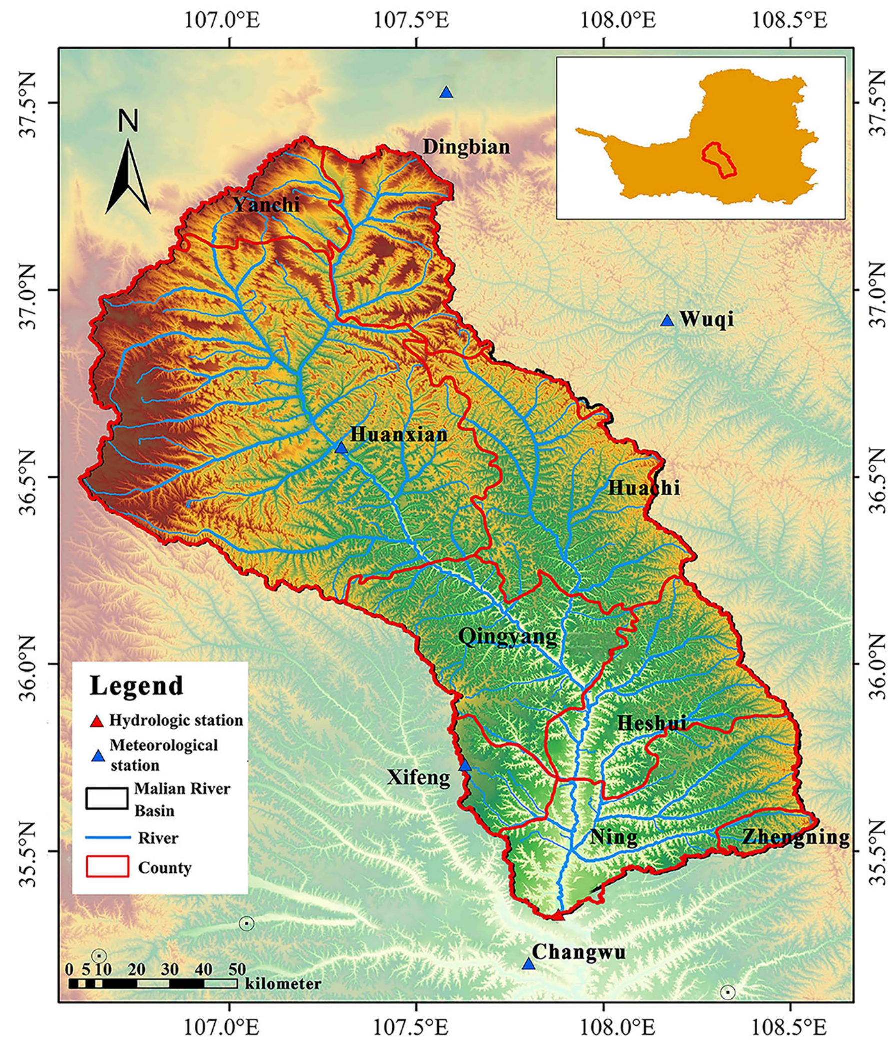


FIGURE 1 Location map of Malian River Basin

Project, the effect of vegetation restoration in the Malian River Basin is good, especially in the southern region. Most of the hydraulic engineering in the Malian River are on small scales. There are few existing reservoirs and irrigation areas, and they are located in the middle and lower reaches. The irrigation amount is low. To sum up, the study area is less affected by human activities, and the region is more suitable for medium-sized eco-hydrological research.

2.2 | Data collection

There are seven types of data collected in this paper:

1. Meteorological data: Including the observation data of precipitation, temperature, air pressure, sunshine time, wind speed and relative humidity of seven meteorological stations in and around the Malian River Basin (as shown in Figure 1). The data is download from the China Meteorological Data Network (http://data.cma.cn/). The temporal resolution is 1 day.
2. Runoff data: The observation runoff data from the Yellow River Conservancy Commission of the Ministry of Water Resources is adopted, and the temporal resolution is on a monthly scale. The data comes from Yuluoping hydrological station.
3. Soil data: The soil data comes from the Soil Science Database (http://vdb3.soil.csdb.cn/). The spatial resolution of soil type data is 1 km × 1 km.
4. Digital Elevation Model (DEM) data: DEM data is downloaded from National Aeronautics and Space Administration (http://https://www.nasa.gov/), with a spatial resolution of 30 m × 30 m.
5. Land use and vegetation type data. Raster data with a spatial resolution of 1 km × 1 km is from the Resources and Environmental Sciences and data centre (http://www.resdc.cn/), including land use changes observed from 1980 to 2015.
6. LAI and NDVI data: These data were download from Geospatial Data Cloud (http://gscloud.cn). The temporal resolution is 8 days, and the spatial resolution is 250 m × 250 m.
7. Future climate data: Future climate data from 2021 to 2040 used for eco-hydrological simulation are extracted from CMIP6 model outputs (https://www.worldclim.org/data/cmip6/cmip6_clim2.5m.html), which include monthly average minimum temperature, average maximum temperature and total precipitation. All data are multi-year monthly scales with spatial resolutions of 0.25° × 0.25°. The dataset considers shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs). In this study, two extreme scenarios (SSP126 and 585) were selected for future eco-hydrological process simulation. SSP126 is the updated scenario of RCP2.6 that uses a sustainable world that takes a green pathway, with (SSP1)-RCP2.6 forcing at a low level of greenhouse gas emissions; and SSP585 is the updated scenario of RCP8.5 that uses a world with rapid fossil fuel evolution, with (SSP5)- RCP8.5 (O'Neill et al., 2017) forcing at a high level of greenhouse gas emissions (Gillett et al., 2016).

3 | METHODS

In this study, an eco-hydrological model-RHESSys was used to simulate the vegetation water utilization in the Marin River Basin, and the water balance between water supply and demand was analysed to evaluate the rationality of current vegetation distribution.

3.1 | RHESSys model

3.1.1 | Model description

RHESSys is a GRASS GIS-based, hydro-ecological modelling framework. Its internal structure uses a hierarchical representation to define the landscape and combines several different process models TOPMODEL (Beven & Kirby, 1979), BIOME-BGC (Running & Hunt, 1993) and MTN-CLIM (Running et al., 1987), along with two distributed hydrologic models TOPMODEL (Beven & Kirby, 1979) and DHSVM (Wigmosta et al., 1994) making it possible to study fluxes at different scales. RHESSys has complete physical mechanism in ecological process, hydrological cycle and their interaction, which means that it can accurately and effectively reflect the vegetation water transport process in the watershed under the vegetation restoration (Band et al., 2000). Detailed theory of RHESSys is provided in Tague and Band (2004), Tague et al. (2013), Garcia et al. (2016). The code of RHESSys model is open-source and available online at https://github.com/RHESSys/RHESSys; (version 6.0 was used for this paper).

This paper briefly summarizes several key processes related to vegetation water use in the model. RHESSys can explicitly simulates regional runoff processes, soil moisture changes, vegetation transpiration, and soil evaporation. Phillip's infiltration equation (Philip, 1957) was used in the model to estimate infiltration at each time step, and the potential capillary rise in the unsaturated zone was calculated according to the method used by Eagleson (1978). Soil evaporation is calculated using Penman–Montieth equation (Monteith, 1965). Stomatal conductance utilizes the Jarvis multiplicative model (Jarvis, 1976) assuming that various environmental limitations (e.g., radiation, CO_2, leaf water potential, and vapour pressure deficit) are determined with the maximum stomatal conductance, which expands the range of hydraulic conductivity by using LAI information. Photosynthesis and evapotranspiration share values of hydraulic conductivity. The Jarvis-type sub-model coupled with Penman–Monteith equation (Monteith, 1965) are used to calculate the vegetation transpiration. The Farquhar sub-model (Farquhar, 1982) and the CENTURY sub-model (Parton et al., 1996) were used to simulate photosynthesis and respiration to maintain the dynamic growth of vegetation.

3.1.2 | Running process of RHESSys model

The running process of RHESSys model can be roughly divided into three parts, as shown in Figure 2.

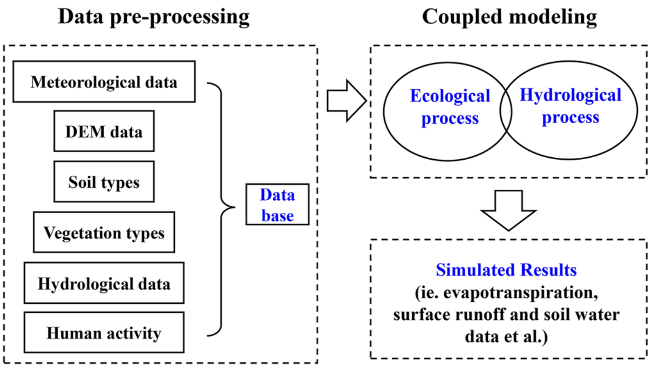


FIGURE 2 Running process of RHESSys model

The first step is to build the database. The data of topography, meteorology, soil, vegetation, hydrology are processed by using GRASS software (https://grass.osgeo.org/download/) to generate database (Neteler & Mitasova, 2008).

After the construction of the database, the model reads the database to simulate. The simulation process can be divided into horizontal and vertical. Vertical simulation includes hydrological process, ecological process and energy process. Horizontal simulation includes surface runoff, unsaturated laminar flow, nutrient transport and groundwater movement.

Finally, the model outputs the results. The simulation results such as soil evaporation, vegetation transpiration, runoff, soil water content in root zone, vegetation carbon sequestration and soil carbon sequestration can be output by RHESSys model. In this study, evapotranspiration, surface runoff and soil water data were extracted for subsequent calculation of vegetation water supply and demand.

3.2 | Calculation method of vegetation water supply and demand

The Malian River Basin in the study area belongs to the typical landform of the Loess Plateau, with deep soil layers and groundwater depth. The potential of rainwater resources utilization in the study area is the vegetation water supply. At present, potential rainwater resources utilization include surface runoff and soil water in two parts (Zhang et al., 2013). It can be calculated as follows:

$$W = \sum_{i=1}^{m} \sum_{j=1}^{n} (R_{ij} + \Delta S_{ij}) \quad (1)$$

$$\Delta S = \begin{cases} S_e - S_s & \Delta S > 0 \\ 0 & \Delta S < 0 \end{cases} \quad (2)$$

Among them, W is the available water amount of regional vegetation, *mm*; R is the surface runoff, *mm*; i is the number of time period; j is the number of sub-basins; ΔS is the net increase of soil available water in the root system layer, *mm*; S_e is the soil water storage of root layer at the end of time period, *mm*; S_s is the soil water storage of root layer at the initial time period, *mm*.

Vegetation growth is closely related to soil moisture. Only after precipitation and groundwater are transformed into soil water in the root layer can be able to absorb and utilized (Resendes et al., 2008). Soil available water is the main component of the potential rainwater in the Loess Plateau (Kimura et al., 2005). Therefore, the calculation depth of soil water should be determined. The soil in the model is divided into root layer, unsaturated layer and saturated layer. The soil water in root layer can be directly used by vegetation, so the water in this layer is used as part of the available water for vegetation. The root layer of the RHESSys model used in this paper is dynamic, which is related to the vegetation types. The main vegetation types in Malian River Basin include coniferous forest, broad-leaved forest, shrub, grassland and cultivated plants. Therefore, five planting types (deciduous forest, shrub, grassland, evergreen, and farmland) are considered in the RHESSys model. The vegetation parameters involved in the model are shown in Table 1.

3.3 | Evaluation index of vegetation-water mutual suitability

After calculating the amount of water needed for vegetation and the amount of water available for vegetation, it is necessary to evaluate whether the two are suitable. In general, the total amount of vegetation water supply must meet the water demand, but the total amount of water cannot completely represent the water supply during the vegetation growth period. Whether the spatial distribution of vegetation water supply and demand in the whole basin is matched should also be judged. Therefore, this study uses the temporal and spatial matching degree method to evaluate the vegetation-water mutual suitability. The method is proposed refer to the method of soil water evaluation by Gao, Wang, et al. (2016). The specific methods are as follows:

The matching degree of vegetation water supply and demand is calculated as follows

$$M_{ij} = \begin{cases} e^{\frac{VAW_{ij} - VWR_{ij}}{VWR_{ij}}} & VAW_i - VWR_i < 0 \\ 1 & VAW_i - VWR_i > 0 \end{cases} \quad (3)$$

$$M_t = \frac{\sum_{i=1}^{12} \sum_{j=1}^{n} M_{ij} \cdot A_j}{12A} \quad (4)$$

$$M_s = \frac{\sum_{j=1}^{n} M_j}{A_j} \quad (5)$$

Among them, M_{ij} is the matching degree of jth sub-basin in ith month, and the calculated value is between 0 and 1. The closer the value is to 1, the better the sustainability of vegetation. M_t is the annual temporal matching degree; M_s is the spatial matching degree; VAW_{ij} is the vegetation water supply of jth sub-basin in ith month, *mm*; VWR_{ij} is the vegetation water demand of jth sub-basin in ith month, *mm*. A_j is the area of jth sub-basin, km^2; A is the total area of the study area.

TABLE 1 Parameter settings related to hydrological process of RHESSys model (White et al., 2000)

Parameters	Units	Deciduous forest	Evergreen	Shrub	Grassland	Farmland
gsurf_intercept	1 LAI^{-1} day^{-1}	0.4	0.052	0.35	0.225	0.03
epc.ext_coef	Dimensionless	0.54	0.51	0.55	0.48	0.5
epc.max_root_depth	m	10	10	5	1	2
epc.psi_open	Mpa	−0.34	−0.65	−0.81	−0.73	−0.5
epc.psi_close	Mpa	−2.2	−2.5	−4.2	−2.7	−2.3
epc.vpd_open	Pa	1.1	0.61	0.97	1	0.97
epc.vpd_close	Pa	3.6	3.1	4.1	5	4.5

Note: The gsurf_intercept is the water interception coefficient. The epc.ext_coef is the canopy light extinction coefficient. The epc.max_root_depth represents the maximum effective root depth range. The epc.psi_open and epc.psi_close represent the leaf water potential for full stomatal conductance and complete stomatal closure. The epc.vpd_open and epc.vpd_close are vapour pressure deficit for full stomatal conductance and complete stomatal closure, respectively.

TABLE 2 Value range division of matching degree between water supply and demand

Value range of matching degree	Evaluation results
0.8–1	Water resources are sufficient to support the vegetation growth
0.6–0.8	Water resources can support the vegetation growth
0.4–0.6	Water resources can barely support the vegetation growth
0–0.4	Water resources cannot support the vegetation growth

According to the matching degree calculated by the above formula, it is divided into four categories according to quality. The details are shown in Table 2.

(1) When the matching value is between 0.8 and 1, the vegetation water shortage ratio is less than 0.2, indicating that the regional water resources are sufficient to support the growth of vegetation, and the vegetation water use has good sustainability. (2) When the matching degree is between 0.6 and 0.8, the water deficit ratio of vegetation is range from 0.2 to 0.5. Regional water resources can maintain the growth of vegetation, but it is not recommended to continue vegetation restoration. (3) When the matching degree is between 0.4 and 0.6, the unsatisfied proportion of vegetation water demand is from 0.5 to 0.8. It means that the regional water resources can barely support the vegetation growth under the current conditions. Considering that perennial vegetation also has certain drought resistance, the water sustainability can be increased by adjusting the density. But in this case, economic crops are not suitable for further cultivation, so vegetation types should be considered to change. (4) When the matching degree is between 0 and 0.4, the vegetation water supply is less than one-tenth of the water demand. In this case, the vegetation will gradually degenerate until death. Therefore, when the matching degree value is less than 0.4, we believe that water resources cannot support the current vegetation growth, and vegetation types that consume less water must be replaced.

3.4 | Model calibration and verification

In this study, Nash Sutcliffe Efficiency coefficient (*NSE*) and determination coefficient (R^2) are used to evaluate the accuracy of simulation results.

The calculation equation of *NSE* is as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_{i,obs} - Q_{i,sim})^2}{\sum_{i=1}^{n} (Q_{i,sim} - \overline{Q_{i,obs}})^2} \tag{6}$$

Among them, $Q_{i,obs}$ is the observed value, $Q_{i,sim}$ is the simulated value, $\overline{Q_{i,obs}}$ is the average observed value. The value of NSE is between 0 and 1, and the closer to 1, the better the fitting degree between the observed value and the simulated value.

The calculation formula of R^2 is:

$$R^2 = \left[\frac{\sum_{i=1}^{n} (Q_{i,obs} - \overline{Q_{i,obs}})(Q_{i,sim} - \overline{Q_{i,sim}})}{\sqrt{\sum_{i=1}^{n} (Q_{i,obs} - \overline{Q_{i,obs}})^2 \sum_{i=1}^{n} (Q_{i,sim} - \overline{Q_{i,sim}})^2}} \right]^2 \tag{7}$$

Among them, $Q_{i,obs}$ is the observed value, $Q_{i,sim}$ is the simulated value, $\overline{Q_{i,obs}}$ is the average value of the observed value, $\overline{Q_{i,sim}}$ is the average simulated value. The closer the coefficient of determination is to 1, the better the fitting degree is.

There are four sensitive parameters to be calibrated for the RHESSys model (Peng et al., 2013). The description and value range are shown in Table 3. The RHESSys model uses Monte Carlo sampling method to randomly generate 500 combinations in a given interval, and each set of parameters are brought into the model for calculation.

4 | RESULTS

4.1 | Calibration and validation of RHESSys model

This study collected observed monthly runoff data at Yuluoping hydrological station to calibrate and validate RHESSys model. The

TABLE 3 Calibration parameters and value ranges of RHESSys model

Parameter name	Parameter description	Minimum	Maximum
m	Attenuation coefficient of hydraulic conductivity with depth	0.01	20
K	Coefficient of saturated hydraulic conductivity	0	600
gw1	Percentage of infiltration volume into deep groundwater	0.001	0.3
gw2	Deep groundwater outflow ratio	0.01	0.9

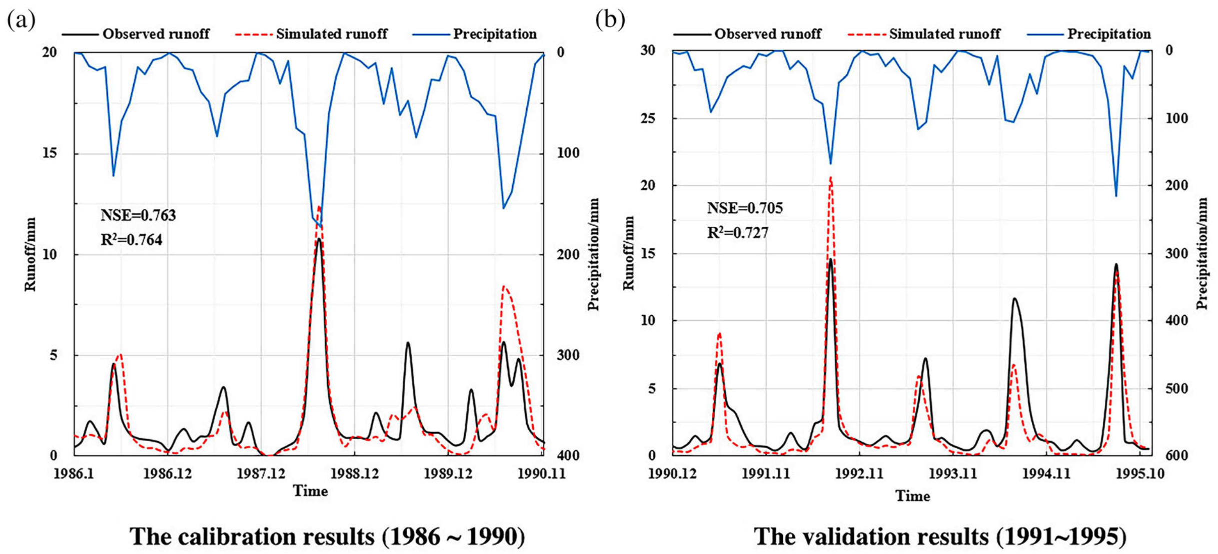


FIGURE 3 Calibration and validation results of Malian River Basin

period from 1986 to 1990 was selected as the calibration period and 1991–1995 as the validation period. The specific results are shown in Figure 3.

On the monthly scale, the NSE in the calibration and validation period is 0.763 and 0.764 respectively, while R^2 is 0.764 and 0.727. When NSE and R^2 values are greater than 0.6, the simulation results are highly reliable. The results showed that the model simulated well in the mid-flow area, but the simulation value of the flood peak is slightly higher. Generally speaking, the simulation results have good reliability and can be used for hydrologic analysis.

4.2 | Temporal and spatial analysis of vegetation water demand

The annual distribution of the average vegetation water demand is shown in Figure 4.

Under current vegetation conditions, the annual average vegetation water demand in the basin is 570 mm. Among them, the water demand in summer is the largest, reaching 312 mm, accounting for 55.5% of the whole year. The vegetation water demand in winter is the smallest, only accounting for 5.2%.

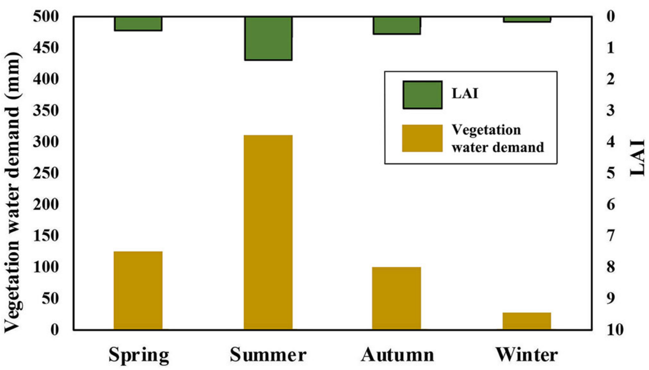


FIGURE 4 Vegetation water demand and LAI in four seasons of Malian River Basin

By comparing the water demand and the average value of LAI, it can be found that the large water demand in summer is mainly due to the lush vegetation and strong transpiration. In contrast, LAI in spring is smaller than that in autumn, but its water demand is larger. This is because the vegetation is germinating in the spring and the root system needs more water to grow than in the autumn. In winter, when most branches and leaves have withered, vegetation needs less water.

The spatial distribution of vegetation water demand is shown in Figure 5.

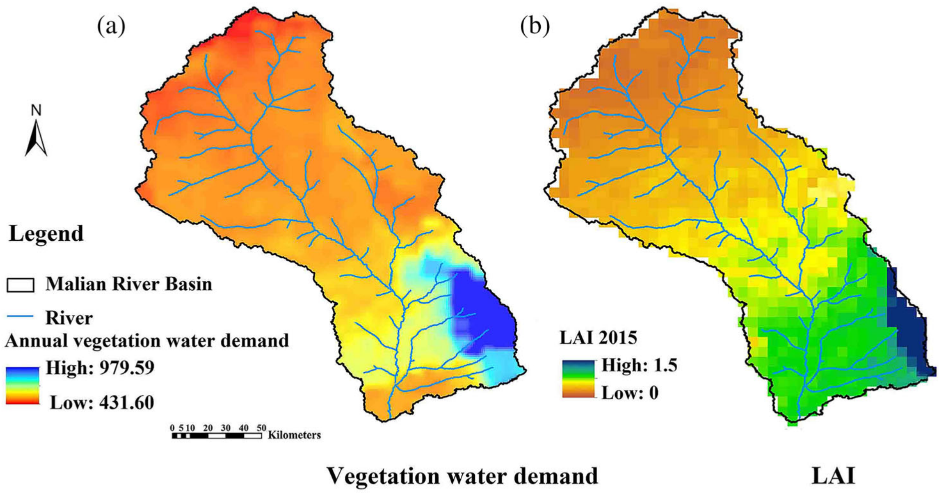


FIGURE 5 Distribution of vegetation water demand and LAI in Malian River Basin

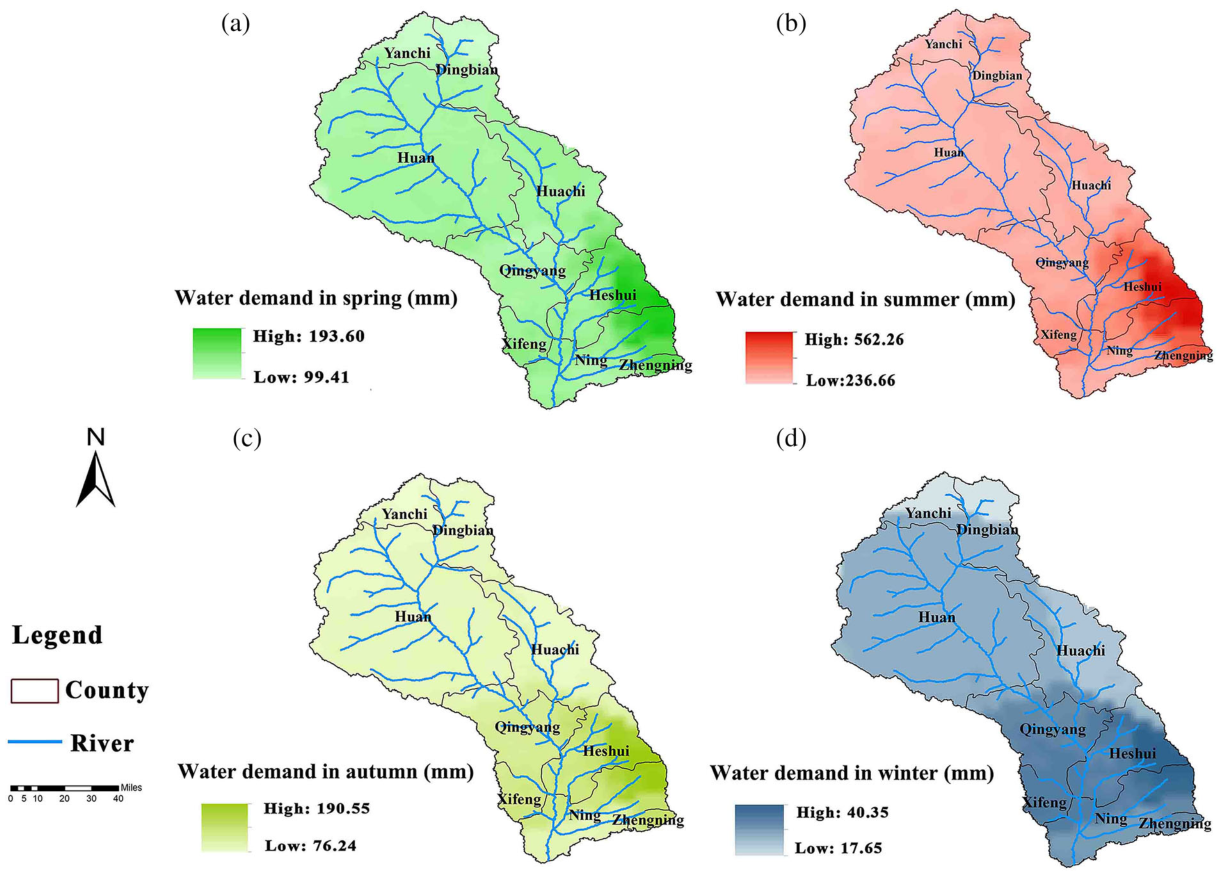


FIGURE 6 Distribution of vegetation water demand in four seasons of Malian River Basin

The vegetation water demand is decreasing from southeast to northwest. The annual vegetation water demand in Zhengning and Heshui in the southeast is relatively large, with the highest value of 980 mm. The vegetation water demand of Qingyang and Ningxian in the middle of the basin is close to the average value of the basin, ranging from 500 to 600 mm. The minimum vegetation water demand is 432 mm in the north of the basin.

It can be seen from Figure 4 that the LAI value in the study area is also higher in the southeast and lower in the northwest. The distribution trend of vegetation water demand and LAI value in Malian River Basin is consistent, which indicates that the richer the vegetation, the greater the vegetation water demand. It should be noted that the vegetation excessive water demand in the south of the basin may be a potential threat to the water sustainability.

In order to understand the spatial variation of vegetation water demand in the study area more accurately, it is necessary to draw the water demand map of four seasons. The results are shown in Figure 6.

The results show that the vegetation water demand in the four seasons decreasing from southeast to northwest. The distribution of vegetation water demand in spring and summer has a great correlation with LAI value, and the distribution pattern is similar to the annual scale. However, vegetation water demand is closely related to the distribution of meteorological stations in autumn and winter, which indicates that water demand mainly comes from soil evaporation after vegetation leaves fall. The reason for the above phenomenon is that most of the vegetation in Malian River Basin is deciduous vegetation. Generally speaking, the increase of LAI value will lead to the increase of vegetation water demand (Chen et al., 2015). Therefore, vegetation restoration on the Malian River Basin should be limited, the plant density should be reduced in the area with excessive water demand. Otherwise, it will cause soil dry layer phenomenon and other ecological problems.

4.3 | Temporal and spatial analysis of vegetation water supply

The curve of average monthly vegetation water supply in Malian River Basin is shown in Figure 7.

After the Grain for Green Project, the annual average vegetation water supply in Malian River Basin is 294 mm. As can be seen from the above figure, vegetation water supply shows no significant increase trend after 2000, with the rate of 1.24 mm·year^{-1}. The annual distribution of vegetation water supply is extremely uneven. The available water of vegetation is the largest in summer, which reaches 161 mm, accounting for 54.6% of the whole year. The available water in winter is relatively low, less than one tenth of that in summer. Due to the uneven distribution of precipitation during the year, resulting in large variations in the annual distribution of vegetation water supply. This is another potential threat to the balance of vegetation water supply and demand.

In terms of spatial distribution, the vegetation water supply in the southern basin is relatively low, while that in the north is relatively large. As shown in Figure 8, the vegetation water supply in the study area increases from south to North. According to MK trend test, the vegetation water supply in 14 sub basins showed no obvious increase trend, and the increase rates were between 0.98 and 1.79 mm·y^{-1}. After 2000, the available water of vegetation in each sub basin increased, which also provided favourable conditions for vegetation restoration.

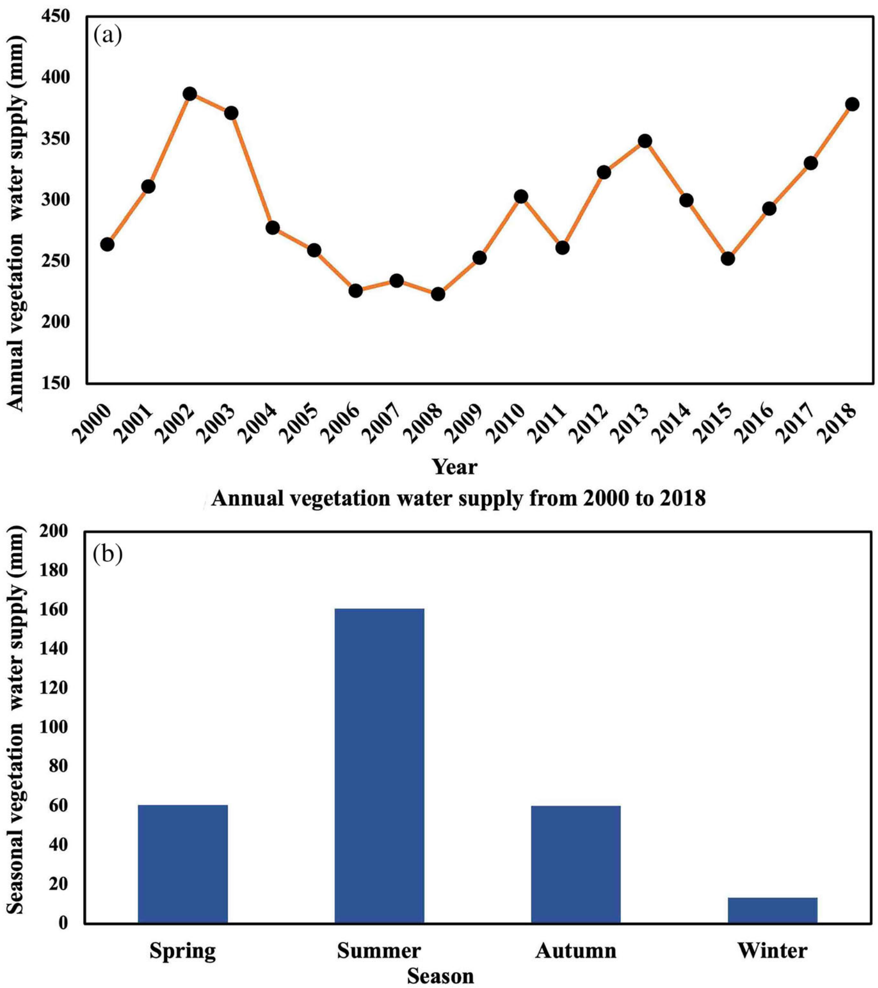


FIGURE 7 Variation trend of vegetation water supply in Malian River Basin

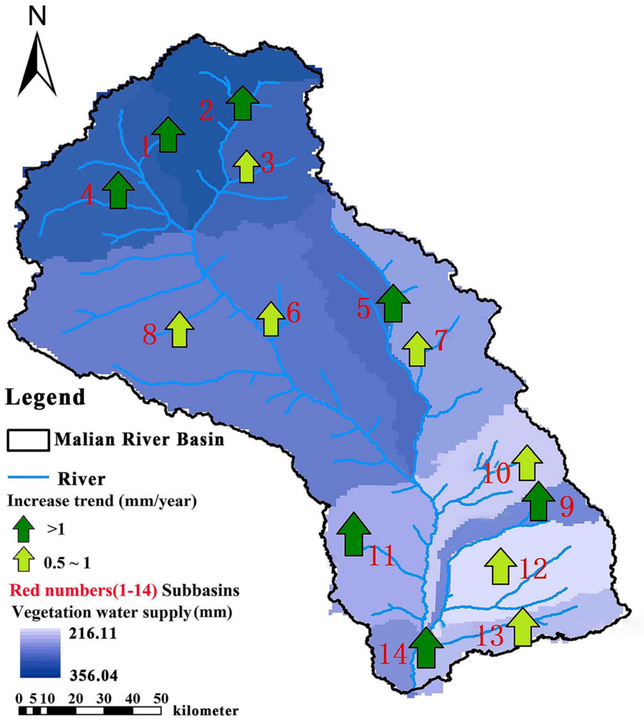


FIGURE 8 Spatial distribution of water supply in Malian River Basin

4.4 | Temporal and spatial matching degree of vegetation water supply and demand

This study calculated the temporal and spatial matching degree of vegetation water supply and demand, and the moisture suitability degree of the study area was evaluated.

4.4.1 | Temporal matching degree of vegetation water

In this study, the temporal vegetation-water mutual suitability on monthly scale was evaluated. The specific results are shown in Figure 9.

It can be concluded from the above figure that 15.8% of the 228 months (from January 2000 to December 2018) were rated as 'excellent', 28.1% as 'good', 54.4% as 'average', and 1.7% as 'poor'. Among them, the months of 'excellent' matching degree evaluation are mainly from August to November, the months of 'good' are mainly from July to October, and the months of 'poor' are mainly from January to April. From the above analysis, it can be concluded that the monthly scale of vegetation water supply and demand match well, and the probability of vegetation drought is low from July to November. But the Malan River Basin is often affected by spring drought.

On the whole, the regional water resources can support vegetation growth under the current conditions. But 54% of the vegetation will grow under greater water stress, so it is necessary to adjust the density to maintain water sustainability. The vegetation restoration in15.8% parts of the Malian River Basin can be continued, but deciduous vegetation should be selected as far as possible in the construction of forest, and the vegetation with less water consumption from January to April should be selected.

4.4.2 | Spatial matching degree of vegetation water

Based on the above data of vegetation water supply and demand, this study calculated the spatial matching degree of the Malian River Basin in 14 sub-basins, respectively. The spatial matching degree of 14 sub-basins is shown in Figure 10.

According to above results, the average spatial matching degree of the study area from 2000 to 2018 is 0.65. Generally speaking, the regional water resources can maintain vegetation growth under current conditions. The spatial matching degree of each sub-basin decreased from north to south. The matching degree of the middle and northern part of the basin was better, which was more than 0.60. The matching degree of the southern sub-basin is generally 0.50–0.57. According to the distribution of LAI and water demand of vegetation, it can be found that the southern part of the basin is mostly planted cultivated vegetation, which consume a large amount of water, so the matching degree is general. Long term planting of cultivated vegetation in this area will form dry soil layers. Supplementary irrigation measures should be taken or vegetation types with low water consumption should be replaced, such as *Chinese pine*, *se-buckthorn*, *caragana microphylla*, and so on.

From Figure 11, it can be found that each sub-basin matches well in spring, showing a decreasing trend from south to north. In summer, the matching degree of each sub-basin is greater than 0.6, and the overall matching degree is good. The matching degree of the sub-basins 1–8, 11 and 14 is excellent, and the remaining sub-basins are good. In autumn, the matching degree of almost all sub-basins reaches 1 and the evaluation of matching degree is excellent. This is due to the climatic characteristics of the Malian River Basin. 70% of the precipitation is concentrated in summer and autumn. In winter, the matching degree evaluation of 5–14 sub basins in the middle and south is general, while that of 1–4 sub basins in the north is poor, showing a decreasing trend from south to north. In the northern region, the planting structure should be adjusted and the planting area of economic crops should be reduced. Due to the poor evaluation of matching degree, it is suggested to plant annual herbs to gradually improve the soil environment and the regional vegetation planting capacity.

In summary, the spatial matching degree of vegetation in summer and autumn is very high, followed by spring, and the spatial matching degree in winter is the worst. This is consistent with the temporal matching degree. In the process of ecological restoration in Malian River Basin, more attention should be paid to the matching of water supply and demand in winter.

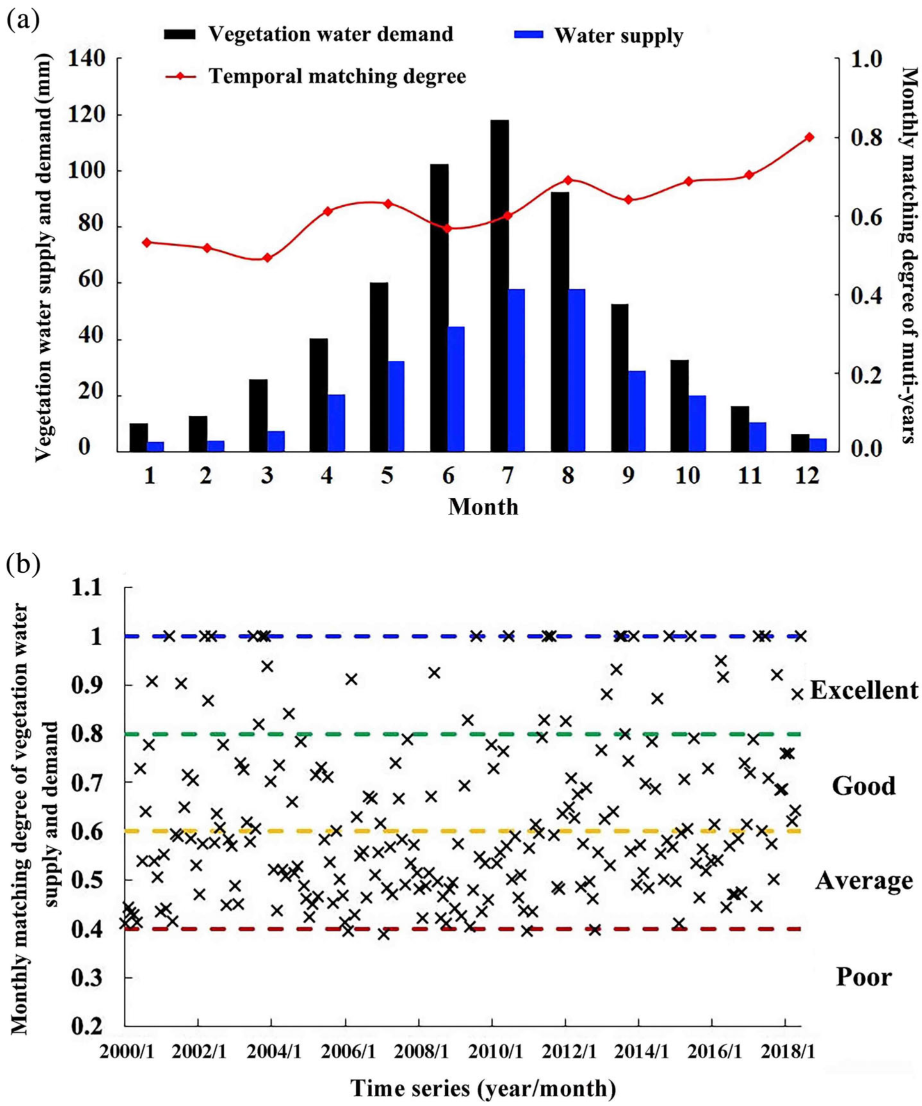


FIGURE 9 (a) Monthly matching degree of vegetation water supply and demand. (b) Evaluation of vegetation-water mutual suitability. The individual x represents the matching degree of vegetation water supply and demand in each month from 2000 to 2018

5 | DISCUSSION

5.1 | Analysis of spatial vegetation-water mutual suitability in future climate scenarios

Before the Grain for Green Project (1961–2000), the runoff of the Malian River Basin showed a decreasing trend due to the reduction of rainfall, and the regional warming and drying became more and more serious. With the increase of vegetation coverage, whether the rainwater in the next few decades is enough to support the growth of vegetation has become another problem.

This study selects ssp126 and ssp585 greenhouse gas emission scenarios as two extreme future climate scenarios. Meteorological dataset from 2020 to 2040 and land use data in 2010 were used to drive the RHESSys model then simulate and calculate the vegetation-water mutual suitability under the two scenarios. The results are shown in Figure 12.

The results showed that the average vegetation-water mutual matching degree was 0.83 in the scenario of ssp126 and 0.92 in the scenario of ssp585 in the Malian River Basin. And the vegetation water supply in the two scenarios could basically satisfy the vegetation growth, while the satisfying degree was higher in the scenario of ssp585.

From the perspective of spatial distribution, the overall vegetation-water mutual suitability in the basin was greatly improved. Only a small part of the southeast and northwest has room for improvement. The southeastern region should reduce vegetation that needs more water, such as forest land and shrubs, while the central region should consider planting vegetation that needs less water, such as grassland, or increasing vegetation coverage to supplement its water consumption. In conclusion, under the future climate scenario, the vegetation-water mutual suitability in the Malian River Basin will be significantly improved due to the increase of precipitation. According to the results, even if the planting structure does not change significantly, the drought situation in the region will be alleviated to some extent.

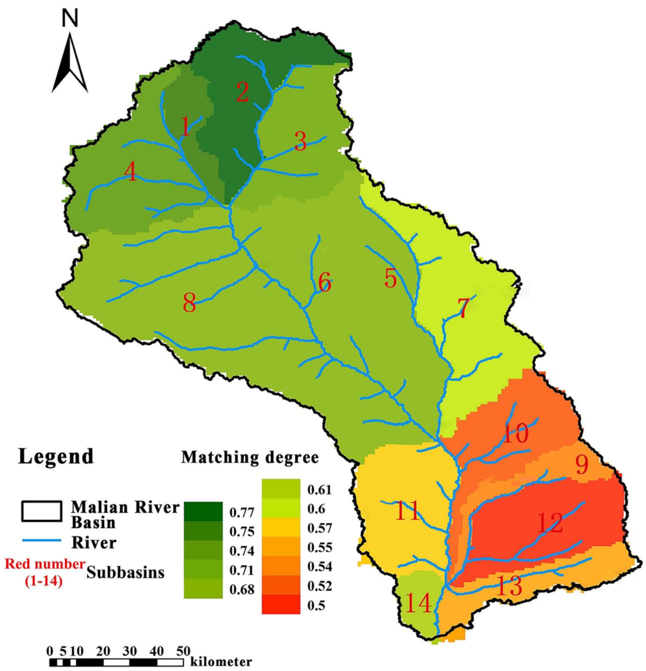


FIGURE 10 Spatial matching degree of Malian River Basin in 14 sub-basins

5.2 | Suggestions on vegetation restoration in Malian River region

Climate and vegetation influence the vegetation-water mutual suitability of Malian River Basin jointly. The southern part of the Malian River Basin is mostly temperate deciduous broad-leaved forest, deciduous orchard and grain crops, with large area, good growth and large water demand of vegetation, so the matching degree is general. The vegetation-water mutual suitability of the whole basin in winter is poor, which is caused by uneven distribution of precipitation and less available water in winter. In the next step of ecological restoration, more attention should be paid to the scientific and reasonable construction of vegetation. The evaluation method of vegetation-water mutual suitability used in this study can provide method support for vegetation restoration.

According to the above evaluation of vegetation-water mutual suitability and the current vegetation in Malian River Basin, the following suggestions are proposed for vegetation restoration in the basin:

1. Vegetation restoration in Malian River Basin should choose drought-tolerant vegetation with small water demand from January to April. According to the analysis of vegetation water supply, it is found that the vegetation water supply in the study area is relatively less from January to April, and some economic forests and winter growing crops may need to supplement deficient water by irrigation. Therefore, in the next stage of vegetation restoration, the vegetation type with drought-tolerant and small water demand should be selected from January to April, and herbal plants such as *pinus tabulaeformis*, *hippophae rhamnoides*, *caragana rubra* or *artemisia chinensis*, *dogtail grass* and *alfalfa* should be preferentially selected to improve the survival rate of vegetation and enhance the effect of vegetation restoration.
2. Strengthen vegetation restoration in the central area of the basin. At present, most of the vegetation types in Huan and Huchi are grass, meadows and steppe, whose vegetation-water mutual suitability is good. Local water resources can support the vegetation growth under the current conditions. Therefore, we can increase the intensity of vegetation restoration in this region, and properly plant plantations such as pinus tabulaeformis and *hippophae rhamnoides*, as well as mixed forests, so as to achieve better soil and water conservation and ecological restoration effects.
3. Maintain the vegetation status in the south of the basin. The vegetation types of Heshui, Ning and Zhengning counties in the south of Malian River Basin are mostly deciduous broad-leaved forest, deciduous orchard and cultivated crops, and their water matching degree is general. The regional water resources can barely support the vegetation growth under the current conditions. It is not recommended to plant new plantations to maintain the current vegetation status.
4. Adjust the planting structure in the northern basin. Most vegetation types in Dingbian County of the northern Malian River Basin are temperate coniferous forests, orchards and economic crops. Although the matching degree of annual scale is good, the matching degree between January and April is poor. Therefore, it is necessary to appropriately reduce the planting area of economic crops in the northern basin, and instead plant annual herbs (such as *Artemisia frigida*, Dogweed, alfalfa) with less water consumption from January to April.

5.3 | The contributions and shortcomings of this study

Vegetation restoration can not only promote the development of the regional ecosystem, but also effectively alleviate soil erosion, improve soil properties and increase soil storage capacity (Chen et al., 2015; Wang et al., 2016). However, in the study of soil water in small-scale areas, it is found that the vegetation density and unreasonable selection of vegetation types in some areas will cause excessive soil moisture consumption (Chen et al., 2008). The future vegetation restoration faces lots of difficulties and challenges. Regional water resources research and local soil water scale should be combined to carry out more scientific and in-depth research.

This study proposed the matching degree index of vegetation water supply and demand, which can provide methodical support for the study of water supply and demand in other regions. On the basis of this evaluation index, the sustainability of vegetation in Malian River Basin under the existing conditions is further analysed to guide the vegetation restoration in Malian River Basin. There are also some limitations in this study. For example, this study only evaluates the

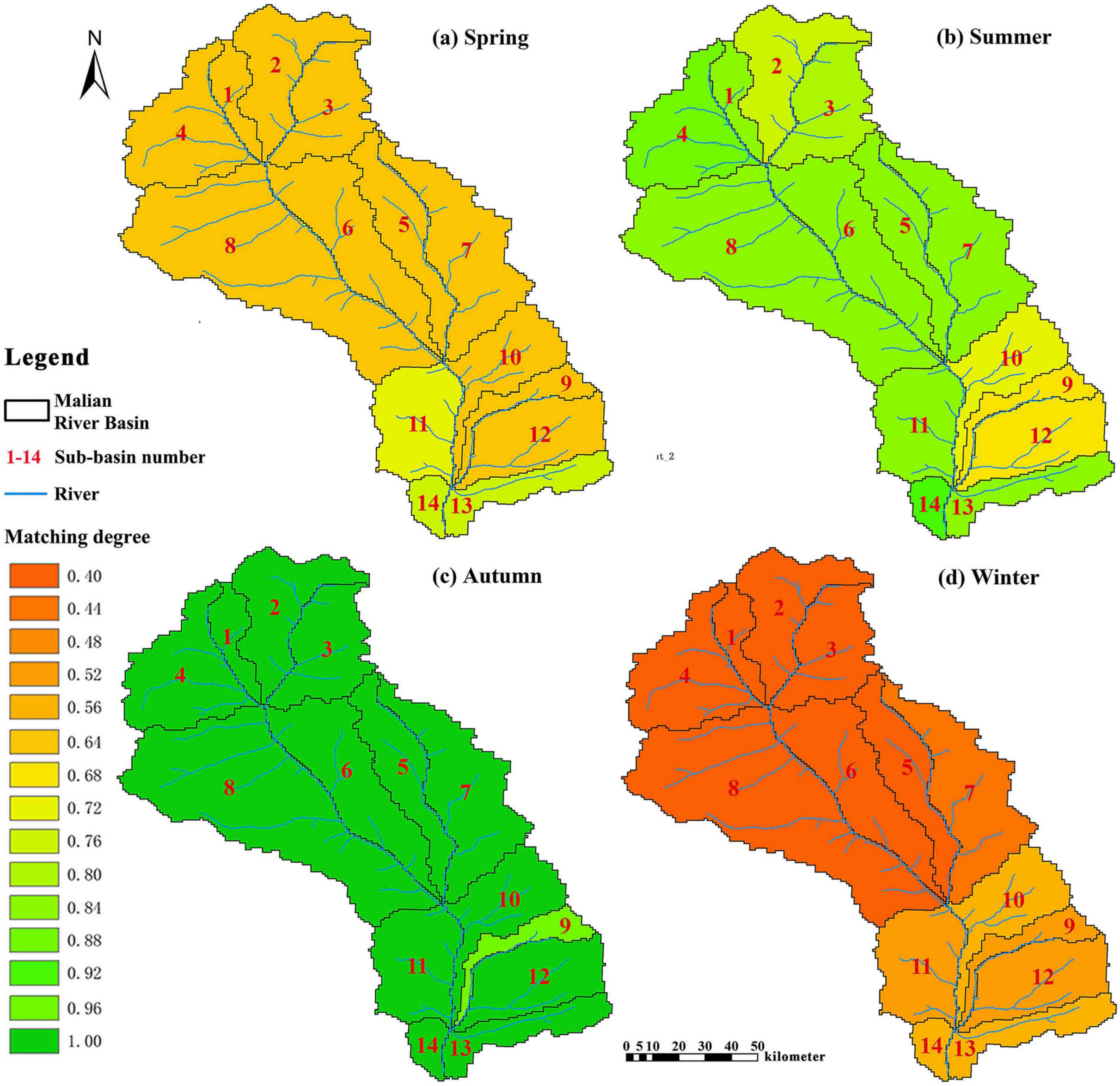
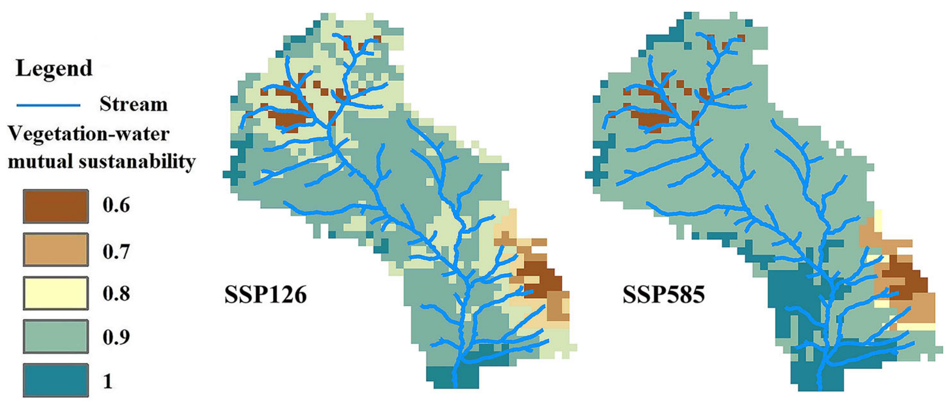


FIGURE 11 Spatial matching degree in four seasons of Malian River Basin

FIGURE 12 Spatial distribution of vegetation-water mutual suitability in Malian River Basin under ssp126 and ssp585 scenarios



current vegetation and does not conduct vegetation optimization research. In the following study, the vegetation types with high ecological benefits should be selected according to the sustainability evaluation results of vegetation restoration, and the planting density of each vegetation type should be determined quantitatively to realize the optimal allocation of regional suitable water vegetation.

6 | CONCLUSIONS

Since the implementation of the Grain for Green Project, whether the regional water supply can meet the needs of vegetation has been widely discussed. In this study, the Marian River Basin was taken as an example, and the ecological hydrological model RHESSys was used to calculate the vegetation water supply and demand, and the spatial–temporal matching degree was analysed. According to the evaluation of vegetation-water mutual suitability, some suggestions for vegetation restoration were put forward. The main conclusions are as follows:

1. The RHESSys model has a good applicability in the Marin River basin. The NSE in the calibration and validation period is 0.763 and 0.764 respectively, while R^2 is 0.764 and 0.727.
2. The annual average water demand of Malian River Basin is 570 mm. The vegetation water demand was significantly different from north to south due to differences in climate and vegetation distribution. Among them, the southern vegetation requires a large amount of water, up to 980 mm. The water demand of the central vegetation is close to the average value of the basin, between 450 and 600 mm. The vegetation in the northern part needs less water, and the minimum value is 432 mm.
3. The vegetation water supply in the study area showed an upward trend, but the distribution was very uneven throughout the year. From 2000 to 2018, the average annual vegetation water supply in the Mali River Basin was 294 mm, with no significant increase trend. The uneven distribution of precipitation during the year led to a big seasonal fluctuation of the vegetation water supply, which was 54.6% in summer and only 4.5% in winter.
4. The overall evaluation of vegetation water supply and demand in Malian River Basin is good. From 2000 to 2018, the temporal and spatial vegetation-water mutual suitability of Malian River Basin are both greater than 0.6, which indicates the regional water resources can support the vegetation growth under the current conditions. Under different future climate scenarios, the vegetation-water mutual suitability will be significantly improved to above 0.8 due to the increase of precipitation.
5. Although the water resources in Malian River Basin can support the normal growth of vegetation, there are still problems in some areas. For example, the water demand of vegetation in the south of the basin is too large. Under the current conditions, it is difficult for local water resources to support the growth of vegetation. In the northern region, the vegetation-water matching degree is poor from January to April. Therefore, it is not recommended to continue vegetation restoration in the south, and the planting density of trees should be appropriately reduced. In the northern region, it is necessary to reduce the planting area of commercial crops and plant annual herbs instead, so as to gradually improve the soil environment and regional planting capacity.

ACKNOWLEDGEMENTS

The authors thank the Chinese National Natural Science Foundation (No. 51609243) and the National Key Research and Development Program of China (2016YFC0400204 and 2018YFF0215702) due to their help. The research also gained help from Natural Science Basic Research Plan in Shaanxi Province of China as well (No. 2016JQ5076).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Xuerui Gao https://orcid.org/0000-0002-9985-9995

REFERENCES

Band, L., Tague, C., Brun, S., Tenenbaum, D., & Fernandes, R. (2000). Modelling watersheds as spatial object hierarchies: Structure and dynamics. *Transactions in GIS*, *4*(3), 181–196.

Beven, K., Kirkby, M., Schofield, N., & Tagg, A. (1984). Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. *Journal of Hydrology*, *69*(1-4), 143.

Beven, K. J., & Kirby, M. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences*, *24*, 43–69.

Chen, H., Shao, M., & Li, Y. (2008). Soil desiccation in the Loess Plateau of China. *Geoderma*, *143*(1), 91–100.

Chen, Y., Wang, K., Lin, Y., Shi, W., Song, Y., & He, X. (2015). Balancing green and grain trade. *Nature Geoscience*, *8*(10), 739–741.

Coughlan, J., & Running, S. (1989). An expert system to aggregate biophysical attributes of a forested landscape within a geographic information system. *AI Applications in Natural Resource Management.*, *4*(3), 35–43.

Eagleson, P. S. (1978). Climate, soil, and vegetation: 3. A simplified model of soil moisture movement in the liquid phase. *Water Resources Research.*, *14*(5), 722–730.

Farquhar, G. D. (1982). Modelling of photosynthetic response to environmental conditions. *Encyclopedia of Plant Physiology*, *12/B*, 549–587.

Gahegan, M. (2010). On the application of inductive machine learning tools to geographical analysis. *Geographical Analysis.*, *32*(2), 113–139.

Gao, B., Qin, Y., Wang, Y., Yang, D., & Zheng, Y. (2016). Modeling ecohydrological processes and spatial patterns in the upper Heihe Basin in China. *Forests*, *7*(1), 10.

Gao, X., Sun, M., Zhao, Q., Wu, P., Zhao, X., Pan, W., & Wang, Y. (2017). Actual ET modelling based on the Budyko framework and the sustainability of vegetation water use in the Loess Plateau. *Science of the Total Environment.*, *579*, 1550–1559.

Gao, X., Wang, J., Wu, P., Yong, Z., Zhao, X., & Fan, H. (2016). Evaluation of soil water availability (SWA) based on hydrological modelling in arid and semi-arid areas: A case study in Handan city, China. *Water*, *8*, 360.

Garcia, E. S., Tague, C. L., & Choate, J. S. (2016). Uncertainty in carbon allocation strategy and ecophysiological parameterization influences on carbon and streamflow estimates for two western US forested watersheds. *Ecological Modelling*, *342*, 19–33.

Gillett, N., Shiogama, H., Funke, B., Hegerl, G., & Tebaldi, C. (2016). The detection and attribution model Intercomparison Project (DAMIP v1. 0) contribution to CMIP6. *Geoscientific Model Development*, *9*, 3685–3697.

Jarvis, P. G. (1976). The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London*, *273*, 593–610.

Kimura, R., Liu, Y., Takayama, N., Zhang, X., Kamichika, M., & Matsuoka, N. (2005). Heat and water balances of the bare soil surface and the potential distribution of vegetation in the Loess Plateau, China. *Journal of Arid Environments.*, *63*(2), 439–457.

Kou, M., Jiao, J., Yin, Q., Wang, N., Wang, Z., Yu, W., Wei, Y., Yan, F., & Cao, B. (2016). Successional trajectory over 10 years of vegetation restoration of abandoned slope croplands in the hill-gully region of the Loess Plateau. *Land Degradation & Development.*, *27*, 919–932.

Liang, K., Liu, C., Liu, X., & Song, X. (2013). Impacts of climate variability and human activity on streamflow decrease in a sediment concentrated region in the Middle Yellow River. *Stochastic Environmental Research and Risk Assessment.*, *27*(7), 1741–1749.

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, *19*, 205–234.

Neteler, M., & Mitasova, H. (2008). *Open source GIS: A GRASS GIS approach*. Springer US.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., & Rothman, D. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change.*, *42*, 169–180.

Parton, W. J., Mosier, A. R., Ojima, D. S., Valentine, D. W., & Kulmala, A. E. (1996). Generalized model for N2 and N2O production from nitrification and denitrification. *Global Biogeochemical Cycles*, *10*, 401–412.

Peng, H., Jia, Y., Qiu, Y., Niu, C., & Ding, X. (2013). Assessing climate change impacts on the ecohydrology of the Jinghe River Basin in the Loess Plateau, China. *Hydrological Sciences Journal.*, *58*(3), 651–670.

Philip, J. R. (1957). The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Science*, *84*, 257–264.

Pisinaras, V., Petalas, C., Gikas, G., Gemitzi, A., & Tsihrintzis, V. (2010). Hydrological and water quality modeling in a medium-sized basin using the. *Soil and Water Assessment Tool (SWAT).*, *250*(1), 274–286.

Resendes, M., Bryla, D., & Eissenstat, D. (2008). Early events in the life of apple roots: Variation in root growth rate is linked to mycorrhizal and nonmycorrhizal fungal colonization. *Plant & Soil.*, *313*(s1-2), 175–186.

Running, S., & Hunt, E. (1993). 8-Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In J. Ehleringer & C. Field, (Eds.) *Scaling Physiological Processes*, (pp. 141–158). San Diego: Academic Press.

Running, S. W., Ramakrishna, R. N., & Hungerford, R. D. (1987). Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. *Canadian Journal of Forest Research*, *17*, 472–483.

Son, K., Lin, L., Band, L., & Owens, E. (2019). Modelling the interaction of climate, forest ecosystem, and hydrology to estimate catchment dissolved organic carbon export. *Hydrological Processes*, *33*(10), 1448–1464.

Stephen, T., John, D., Jansen, G., Nanson, T., & Coulthard, T. (2008). Riparian vegetation and the late holocene development of an anabranching river: Magela creek, northern Australia. *Geological Society of America Bulletin.*, *120*(7–8), 1021–1035.

Tague, C., & Band, L. (2004). RHESSys: Regional hydro-ecologic simulation system – An object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions.*, *8*(19), 1–42.

Tague, C. L., Mcdowell, N. G., Allen, C., & Ben, B. L. (2013). An integrated model of environmental effects on growth, carbohydrate balance, and mortality of *Pinus ponderosa* forests in the southern Rocky Mountains. *PLoS One*, *8*, e80286.

Wang, B., Zhang, G., Shi, Y., & Zhang, X. (2014). Soil detachment by overland flow under different vegetation restoration models in the Loess Plateau of China. *Catena*, *116*, 51–59.

Wang, S., Fu, B., & Piao, S. (2015). Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nature Geoscience*, *9*, 38–41.

Wang, S., Fu, B., Piao, S., Lu, Y., Ciais, P., Feng, X., & Wang, Y. (2016). Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nature Geoence*, *9*(1), 38–41.

Wang, Y., Shao, M., Zhu, Y., Sun, H., & Fang, L. (2018). A new index to quantify dried soil layers in water-limited ecosystems: A case study on the Chinese Loess Plateau. *Geoderma*, *322*, 1–11.

White, M. A., Thornton, P. E., Running, S. W., & Nemani, R. R. (2000). Parameterization and sensitivity analysis of the BIOME–BGC terrestrial ecosystem model: Net primary production controls. *Earth Interactions*, *4*, 1–85.

Wigmosta, M. S., Vail, L. W., & Lettenmaier, D. P. (1994). A distributed hydrology-vegetation model for complex terrain. *Water Resources Research*, *30*, 1665–1679.

Xiao, L., Xue, S., Liu, G., & Zhang, C. (2014). Soil moisture variability under different land uses in the Zhifanggou catchment of the Loess Plateau, China. *Arid Land Research & Management.*, *28*(3), 274–290.

Zhang, B., Wu, P., Zhao, X., & Wang, Y. (2013). Rainwater harvesting potential and its spatial-temporal variation in Loess Plateau of China. *Paiguan Jixie Gongcheng Xuebao/Journal of Drainage and Irrigation Machinery Engineering.*, *31*(7), 636–644.

Zhao, C., Jia, X., Gongadze, K., Shao, M., Wu, L., & Zhu, Y. (2019). Permanent dry soil layer a critical control on soil desiccation on China's Loess Plateau. *Scientific Reports*, *9*(1), 3296.

How to cite this article: Sun, M., Yan, C., Zhao, N., Zhao, X., Gao, X., Lian, Y., Yuan, Y., & Yang, H. (2021). Evaluating the long-term ecohydrological suitability of restoration efforts in a typical watershed of the Loess Plateau. *Hydrological Processes*, *35*(9), e14362. https://doi.org/10.1002/hyp.14362