Research of Assessment Model Framework of Rainwater Resource Utilization and Driving Force in Arid and Semi-Arid Areas

Xingyuan Zhang (zxingyuan@tju.edu.cn)
Tianjin University https://orcid.org/0000-0003-3106-5395
Fawen Li
Tianjin University
Ximin Yuan
Tianjin University

Research Article

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Research of assessment model framework of rainwater resource utilization and driving force in arid and semi-arid areas

Xingyuan Zhang, Fawen Li *, Ximin Yuan

State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, 300072, Tianjin, China

* Correspondence: lifawen@tju.edu.cn

Abstract: The arid and semi-arid areas generally face the degradation of natural resources, poor vegetation conditions, and serious soil erosion. In this paper, a spatio-temporal assessment model for the rainwater resources utilization and its driving forces is studied and constructed, and a typical watershed is selected for application and verification. The model is based on SWAT (Soil & Water Assessment Tool) and GTWR (Geographically Temporal Weighted Regression) for secondary development. Two indicators are proposed to characterize the utilization of rainwater: rainwater resources utilization quantity (RRU) and rainwater resources utilization rate (RRUR). To further verify the performance of the model, the scenarios of different watershed management measures were simulated and evaluated. The results show that the model can accurately evaluate the RRU, RRUR, and driving force. The annual average value of the RRUR in the typical watershed is 0.44, and the utilization rate of the middle reaches is higher than that of the upper and lower reaches. Meanwhile, the model can evaluate the RRUR and driving force of different land management scenarios. The driving effects of meteorological, topographical, vegetation, and other factors on the regional RRUR exhibits certain spatiotemporal differences, among which the leaf area index (LAI) is the key driving factor. The framework can provide scientific guidance for improving the rainwater resources utilization rate (RRUR) and alleviating ecological problems.

Key words: Rainwater resource utilization; Assessment model; Spatio-temporal

driving force; Watershed management

1 Introduction

The degradation of natural resources is one of the main problems faced by arid and semi-arid areas (Liu et al. 2005). For a long period of time, improving the utilization ratio of rainwater has been an important method by which to alleviate the problems of soil drought and ecological degradation (Hatibu 2002), yet achieving this remains a challenge. Rainwater in the arid and semi-arid areas does not penetrate deeply into the soil profile, and most of it evaporates directly into the atmosphere after rainfall and lose (Zhang et al. 2013). Rainwater utilization (or rainwater harvesting, RWH) in watershed can reduce slope runoff, alleviates soil erosion, increases groundwater recharge (Page et al. 2016), improves ecosystem function (Aladenola and Adeboye 2010).

Rainwater harvesting and management (RWHM) technology has great potential to improve rainwater utilization efficiency and maintain rain fed agriculture in the region. For agricultural areas, rainwater utilization is more reflected in the underlying surface of the basin in addition to the form of point harvesting. Rainwater is used for agricultural production, vegetation growth and wetland improvement in these areas (Oweis 2017; Singh 2012). Many scholars are exploring the best management practices to achieve better utilization of rainwater resources.

Rainwater utilization involves many aspects, and it is necessary to fully consider a series of social and natural conditions and cooperate with multiple stakeholders (Gain et al. 2017). There is inadequate knowledge and scientific assessment on hydrological impacts and limits of up-scaling rainwater harvesting at a river basin scale (Ngigi 2003; Glendenning et al. 2012). Ngigi (2003) assessed the potential of RWH in improving food and water supplies. At the same time, there is a knowledge gap in the limitation of watershed expansion of RWH, especially in the semi-arid areas of East Africa, what is the limit of expanding rainwater utilization?

Considering the difficulty, cost and time required for physical measurements of hydrological elements, modelling often provides a cheaper, faster way to consider larger scale watershed hydrological impacts of RWH (Glendenning et al. 2012). Kadam et al. (2012) used SCS-CN method to identify potential rainwater harvesting sites in the semi-arid basaltic region of Western India with considering the hydrological, geomorphic, and geological parameter. Based on a physical, spatially distributed TRAIN-ZIN model, Shadeed and Lange (2010) calculated evapotranspiration to assess the rainwater harvesting potential and two different rainwater harvesting technologies in the arid and semi-arid Faria catchment in the West Bank of Palestine. Ghimire and Johnston (2013) used the SWAT model to simulate the baseline of urban and agricultural land use and the RWH scenarios to better understand the impact of urban domestic water and agricultural rainwater utilization on regional hydrology, and applied the method to three different watersheds in the southeastern United States. Ngigi et al. (2007) presented hydrological assessment of up-scaling rainwater harvesting (HASR) conceptual framework, which assesses the impacts of land use changes on hydrological regime in the upper Ewaso Ng'iro river basin in Kenya. Mahmoud et al. (2016) evaluated the suitability of RWH in the study area and selected five factors: soil type, land cover and land slope (topography), runoff coefficient, and remaining precipitation to determine the suitable area for RWH. This is a multi-objective, multi-standard problem. Terêncio et al. (2017) constructed a RWH suitability assessment model based on physical, socio-economic, and ecological variables to guide the implementation of rainwater utilization agricultural and forestry management measures in the catchment area.

Scholars have used various methods to study the potential and hydrological impact of rainwater utilization in the basin. In arid and semi-arid areas where land management measures are commonly implemented, it is still complicated and cumbersome how to finely evaluate the rainwater utilization of different measures and clarify the main influencing factors of regional rainwater utilization. RHW will change the water balance in the basin, and the hydrological cycle of agricultural basins will be continuously affected by natural factors such as climate change, topography, and vegetation in arid and semi-arid areas. These hydrological response includes changes in runoff, groundwater supply, evaporation, etc. (Beganskas et al. 2019; Vanloocke et al. 2010), and exhibits obvious characteristics of spatial heterogeneity and time non-stationarity (Beven 1989). For these reasons, it is also important to guide the utilization of rainwater in the watershed to explore the natural influencing factors of rainwater utilization on the spatial and temporal scales in addition to the assessment of rainwater resources.

Therefore, we aim to propose a flexible model framework for rainwater utilization and driving force assessment on a temporal and spatial scale. This paper constructs the assessment model for the rainwater resources utilization and driving forces, takes a typical watershed in arid and semi-arid areas as an example to verify the feasibility of the model, and use the model evaluate the scenarios of different watershed management measures to verify the wider applicability. The specific goals are as follows: i) Propose evaluation methods and indicators for rainwater resources utilization in arid and semi-arid areas; ii) Construct rainwater resources utilization evaluation model based on SWAT model and GTWR model; iii) Verify the applicability of the model under different watershed management scenarios, and study the impact of different management practices on changes in hydrological elements in agricultural basins. This model framework may have more practical significance in arid and semi-arid areas where management measures such as large-scale terraced construction and afforestation are more common. The research can provide scientific tools for the evaluation and utilization of rainwater resources in these areas.

2 Methodology

2.1 Assessment model of rainwater resources utilization

To assess the utilization of rainwater, it is necessary firstly to clarify the utilization and non-utilization components of rainwater resources. In arid and semi-arid areas, the discrete rainfall events are important components of water resources and aquifers developed in closed basins where lateral inflow is nearly absent on the long time scale (Miranda et al. 2011; Van Camp et al. 2010). At the same time, evapotranspiration (*E*), includes both productive water use, i.e. transpiration (E_t), and non-productive water use, i.e. evaporation from soil surface (E_s) and evaporation from canopy interception (E_i) (Cheng et al. 2017). This paper holds that the rainfall which may be used to improve the ecological environment in the basin space is considered utilization of rainwater, and the evaporation and runoff from the basin which are not involved in the vegetation growth process are considered non-utilization of rainwater. Therefore, we propose two indexes of rainwater utilization evaluation, namely, rainwater resources utilization quantity (RRU) and rainwater resources utilization rate (RRUR), and the calculation formula of the two indexes is as follows:

$$RRU_t = P_t - E_{s,t} - E_{i,t} - Q_t - \Delta W_t \tag{1}$$

$$RRUR = \frac{RRU_t}{P_t} \tag{2}$$

where *t* is the time step; P_t is the precipitation, mm; $E_{s,t}$ is the soil evaporation, mm; $E_{i,t}$ is the vegetation intercepted evaporation, mm; Q_t is the basin discharge, mm; ΔW_t is the precipitation loss such as water surface evaporation, and when there are water collection facilities such as reservoirs in the basin, ΔW_t includes the river water surface evaporation and reservoir evaporation, mm.

This paper constructs an assessment model of rainwater utilization and driving force based on SWAT model and GTWR model. The SWAT model is used to calculate hydrological elements such as evaporation. Then, RRUR and RRU can be calculated by combining precipitation, and GTWR model is used to analyze driving factors. The technical route of the assessment model is shown in Fig. 1. The rainfall runoff and evaporation process in the basin have a certain lag. Therefore, in order to avoid errors on a short time scale, the model is best to evaluate the rainwater utilization on a monthly or annual scale. The following studies confirm the accuracy and reliability of the model on an annual scale.

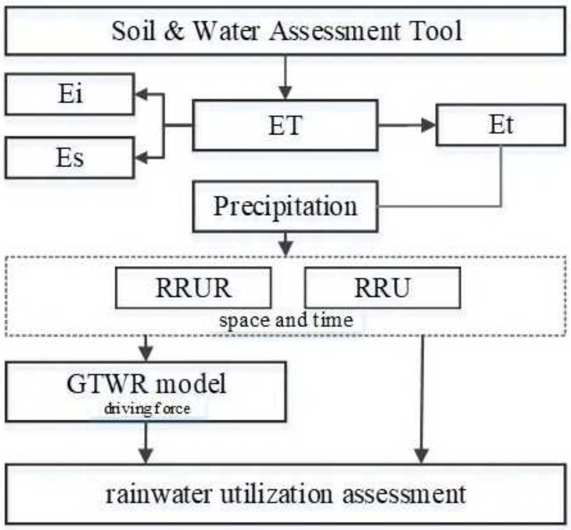

Fig.1 Technical route of rainwater utilization assessment model

2.2 Soil & Water Assessment Tool (SWAT)

As a basin modeling tool, SWAT has been used by many scholars to quantify ecosystem services (Francesconi et al. 2016). In the SWAT model, the hydrological process of the basin includes the land part of water cycle - runoff generation and slope confluence, and the water part of water cycle - river confluence. The sub-basin module controls the input of water, sediment, nutrient load, and chemical substances in the main river channel of each sub-basin. SWAT can divide several sub-basins according to the characteristics of the basin water system. The physical parameters of the sub-basin are different, to represent the spatial difference of runoff yield and concentration of the basin (Neitsch et al. 2011).

The Et, Ei and Es cannot be calculated directly by the SWAT, only E can be calculated. After obtaining E, the components need to be calculated. Among them, Ei is calculated according to canopy leaf area index (LAI) during rainfall. Partitioning of transpiration and soil evaporation can be evaluated via Beer's Law as:

$$\frac{E_t}{E_t + E_s} = 1 - \exp(-kL) \tag{3}$$

where L is the canopy leaf area index, and k is the radiation extinction coefficient. Partitioning of transpiration and soil evaporation is much more complex than Beer's law in reality (Jarvis and McNaughton 1986; Wang et al. 2014), especially at short times scales. However, this study is focused on monthly or annual time scales, at which Beer's law can provide reasonable and accurate partitioning between transpiration and soil evaporation (Kelliher et al. 1995; Wang et al. 2014).

2.3 Geographically Temporal Weighted Regression (GTWR) model

In order to consider the characteristics of rainwater utilization in time and space, and to comprehensively analyze the driving effects of weather, terrain, vegetation conditions and other factors on the RRUR, the Geographically Temporal Weighted Regression (GTWR) model is added to the assessment model. The GTWR model splits the spatial position coordinates and time coordinates into three coordinates, and considers the influence of space and time on the regression coefficient of each explanatory variable (Huang et al. 2010; Wu et al. 2019). In the time coordinate, the coordinate of spatiotemporal position i is (u_i, v_i, t_i), and the GTWR model can be expressed as follows (Fotheringham et al. 2015; Huang et al. 2010):

$$Y_i = \alpha_0(u_i, v_i, t_i) + \sum_{j=1}^{m} \alpha_j(u_i, v_i, t_i) X_{ij} + \varepsilon_i \tag{4}$$

where Y_i is the interpreted variable value of sample point i (i=1,2,…,n); n is the number of sample points; m is the number of explanatory variables; t_i is the time coordinate at sample point i; $\alpha_0(u_i, v_i, t_i)$ is the time-space intercept term of sample point i; X_{ij} is the j^{th} explanatory variable value of sample point i; and $\alpha_j(u_i, v_i, t_i)$ is the regression coefficient of the j^{th} variable at sample point i.

3 Research Area and Model Application

3.1 Research Area and Data

In this paper, the Zuli River Basin is selected as the research object. The Zuli River is a first-class tributary of the upper reaches of the Yellow River in China, and it is located in the western part of the Loess Plateau. It is a typical area for the development of agriculture and animal husbandry in arid and semi-arid areas of China (Li 2018), with a drainage area of 10,584 km^2 and an average annual runoff of 145 million m^3. The rainfall in the upper reaches is high. In the middle reaches, rainfall began to decrease and the salinity of the river water began to increase. The annual precipitation is about 300 mm, and the salinity is more than 10 g/L, making the runoff there difficult to use in the lower reaches. Jingyuan Hydrological Station is the control station at the outlet of the basin. See Fig. 2 for a topographic map of the basin.

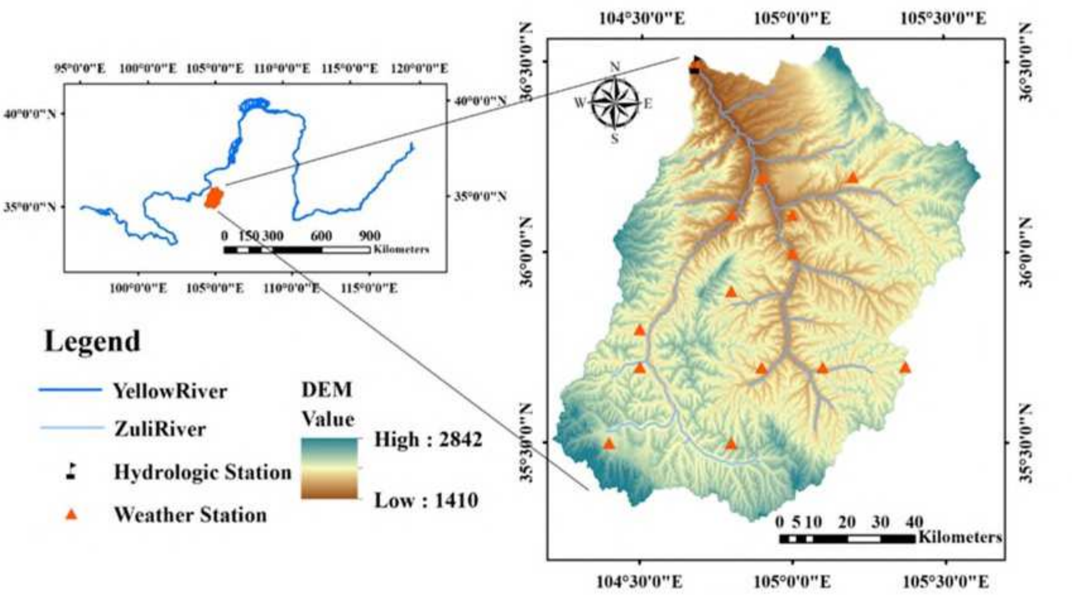

Fig. 2 Overview of the Zuli River Basin

In the Zuli River Basin, the loess deposits are thick, and the main soil types are calcium soil. The main natural vegetation is temperate semi-arid grasslands and arid grasslands, and forests are scarce. The overall vegetation condition in the upper reaches is superior to that in the middle and lower reaches, and it is the worst near the estuary area.

The hydrological and meteorological data that support the findings of this study are from the Yellow River Committee. Evaporation data of 1981-1990 is available from CSIRO at the following url: https://www.csiro.au/en/Research/LWF. Geographic data comes from Geospatial Data Cloud (http://www.gscloud.cn/home) and Resource and Environment Science and Data Center (https://www.resdc.cn/Default.aspx).

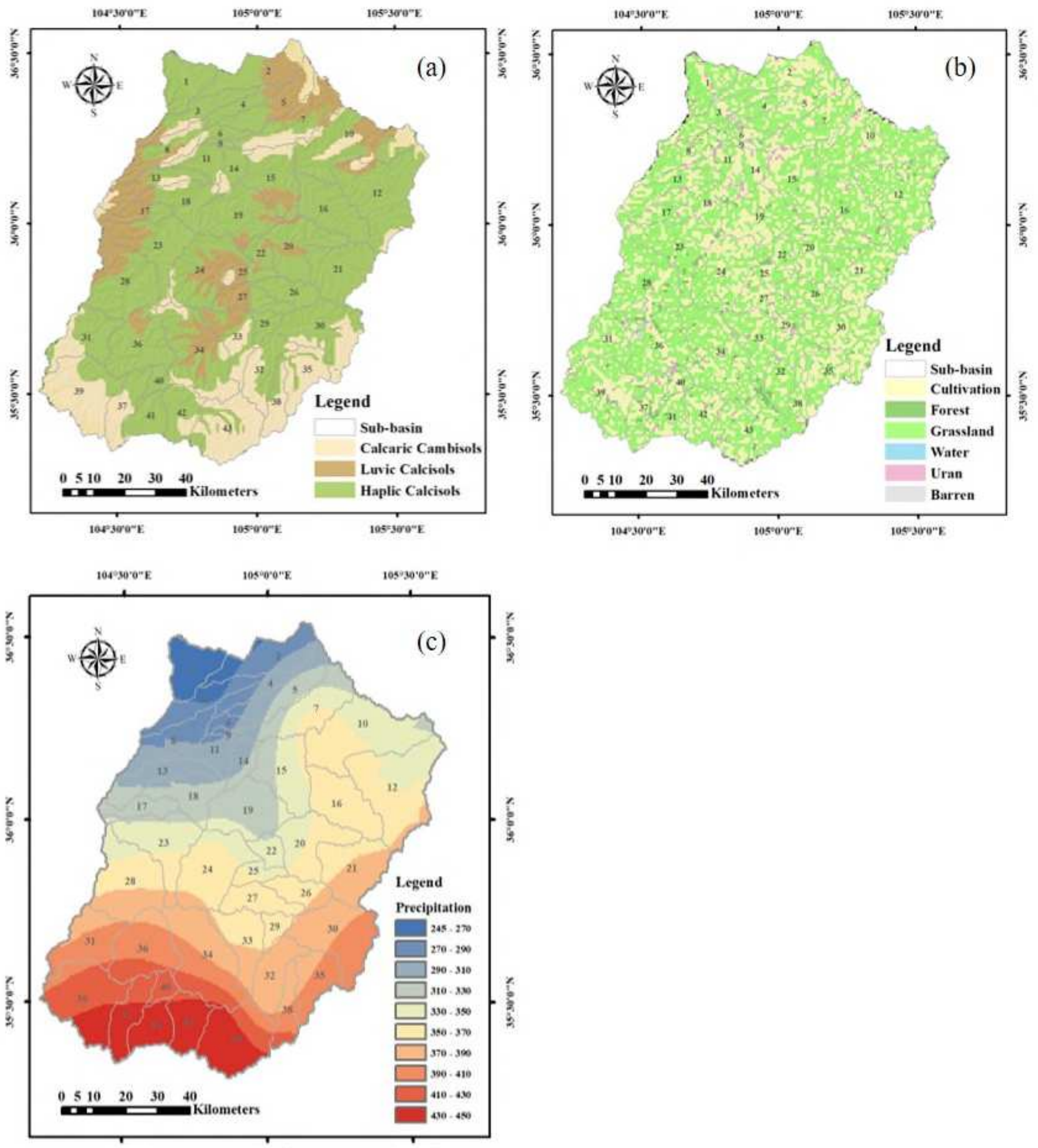

Fig. 3 Distribution of soil types(a), land use(b), precipitation(c) and sub-basin division in the research area

3.2 Construction of the Assessment Model

In this paper, the period of 1972-1990 (1972-1980: calibration period; 1981-1990: verification period) is selected as the research period, and the land cover data of 1980 are used as the benchmark. We constructed a complete assessment model of rainwater utilization in Zuli River Basin, and analyzed the characteristics and applicability of the model framework. First, based on the characteristics of topographic confluence, the research area is divided into 43 sub-basins (Fig. 3), and 1,297 hydraulic response units (HRUs) are subdivided according to soil type, land use, and topographic slope. There are 14 single rainfall stations in the basin, and rainfall daily data comes from these stations (see Fig. 2 for the distribution of rainfall stations). Other weather data come from four comprehensive weather stations adjacent the basin.

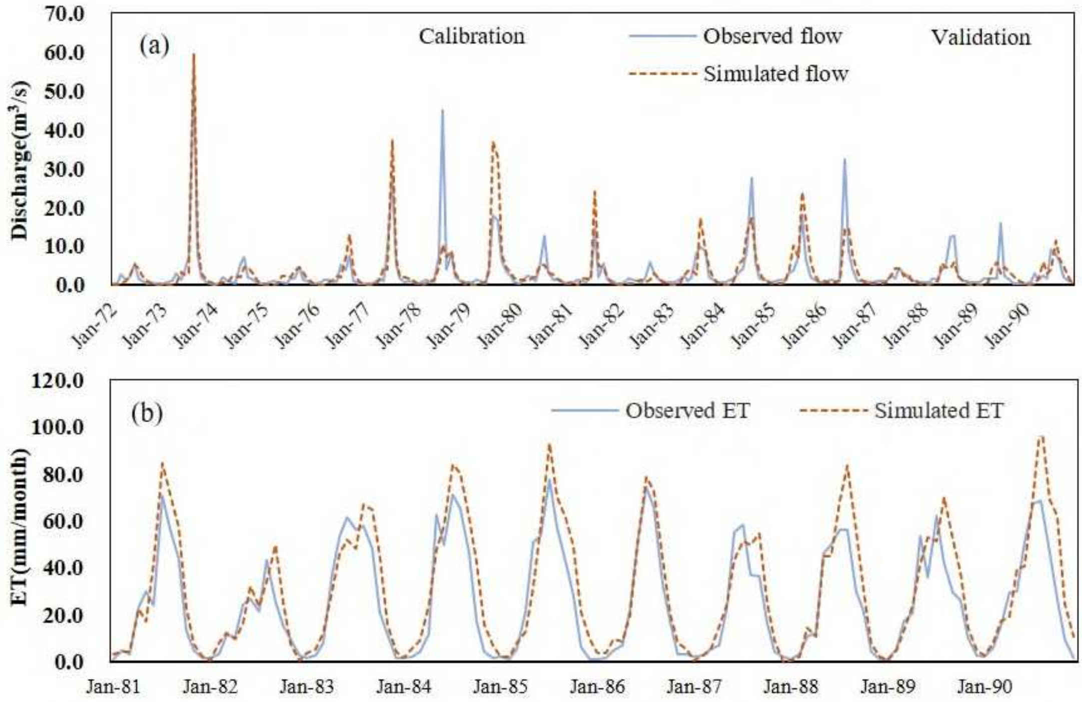

Fig. 4 Calibration and validation of runoff results(a) and validation of evaporation(b)

The runoff results of the assessment model are calibrated and verified by the monthly measured runoff series of Jingyuan Hydrological Station for the periods of 1972-1990 (Fig. 4), and the evaporation is verified by the PML estimates 1981-1990 data (Zhang et al. 2016) (Fig. 4). NSE, PBIAS and R^2 are selected as the evaluation indexes (Table 1), and the calibrated parameters of the model are shown in Table 2.

Table 1 Model calibration and validation evaluation index value

	Discharge Calibration (1972-1980)	Discharge Validation (1981-1990)	ET Validation (1981-1990)
NSE	0.64	0.56	0.75
PBIAS	-6.62%	-2.78%	20.27%
R^2	0.69	0.56	0.85

Notes: Due to some data limitations, the model is difficult to achieve better flow calibration and verification results. However, the model can well reflect the trend of the hydrological cycle and does not affect the further study of the model.

Table 2 Model calibrated parameters

ID	Parameter	Range	Value
1	v__ALPHA_BF.gw	0-1	0.148333
2	v__ALPHA_BNK.rte	0-1	0.304333
3	v__CH_K2.rte	0.01-500	3.509930
4	v__CH_N2.rte	0.01-0.3	0.077183
5	r__CN2.mgt	-0.5-0.5	-0.224333
6	v__ESCO.hru	0-1	0.805667
7	v__GW_DELAY.gw	0-500	165.833344
8	v__GW_REVAP.gw	0.02-0.2	0.078380
9	v__OV_N.hru	0.01-30	8.077310
10	r__SOL_AWC().sol	-0.9-0.9	0.159000
11	r__SOL_BD().sol	-0.9-0.9	-0.743400
12	r__SOL_K().sol	-0.9-0.9	0.103800
13	v__SURLAG.bsn	0.05-24	8.983350
14	v__CANMX.hru	3-15	10.388000

Then, the dependent variable and explanatory variables are selected to construct GTWR model. The RRU is directly related to rainfall, so it is difficult to reflect the deep driving force of rainwater resources utilization by analyzing its influencing factors. The RRUR is the utilization rate (the ratio of RRU to rainfall), which can better reflect the impact of temporal and spatial factors on the utilization of rainwater as a dependent variable. The selected explanatory variables are: temperature (Tmp), precipitation (Precip), area (Area), slope (Slope), elevation (EIev), soil infiltration coefficient (Sol), potential evaporation (PET), and leaf area index (LAI), and the explanatory variables were normalized. The selection of explanatory variables is very flexible and can be determined based on analysis of the actual conditions of the river basin, which is also important for studying the temporal and spatial effects of rainwater utilization. The 43 sub-basins were selected as spatial samples, and the time scale was 18 years from 1972 to 1990, so there are 817 spatiotemporal samples. The RRUR is the dependent variable, and the year and spatial position are taken as the time and spatial coordinates to form the three-dimensional coordinates of the sample points. In this way, the model is completed (Equation 5), which can analyze the driving effects of different factors on RRUR and explore its temporal and spatial variation law.

$$R_{STi}=\alpha_{0i}+\alpha_{TMi}TM_i+\alpha_{PRi}PR_i+\alpha_{ARi}AR_i+\alpha_{SLi}SL_i+\alpha_{EIi}EI_i+ \\ \alpha_{SOi}SO_i+\alpha_{PEi}PE_i+\alpha_{LAi}LA_i+\varepsilon_i \qquad (5)$$

where R_{STi} is the RRUR of the i^{th} sample, and all regression coefficient α changes with time and space. The weight function is the Gaussian function. The space-time distance ratio of the model is determined by automatic optimization, while the optimal bandwidth is determined by the AICc criterion.

4 Results and Discussion

4.1 Temporal and spatial situation of rainwater utilization

Through the calculation of the assessment model, the RRU and RRUR can be obtained, and the rainwater utilization changes in the basin can be analyzed. The spatial distribution of RRU and RRUR can also be obtained to further clarify the spatial difference of rainwater utilization.

The results show that the average value of the RRU is 164 mm in study period, and the increase of precipitation will lead to the increase of RRU. The RRU in the years with higher precipitation may exceed 200 mm. For the RRUR, the annual average value is 0.44. The higher the precipitation is, the larger the RRUR will be. The highest RRUR was 0.53 and the lowest was 0.32, and it is within the range of 0.4-0.5 in most years. In the overall trend, the RRUR of the Zuli River Basin shows a decreasing trend during the study period. Greater amounts of rainwater resources are lost, thereby leading to the aggravation of the basin drought, the deterioration of the ecological environment, and the further reduction of the water storage and water conservation capacity of the basin.

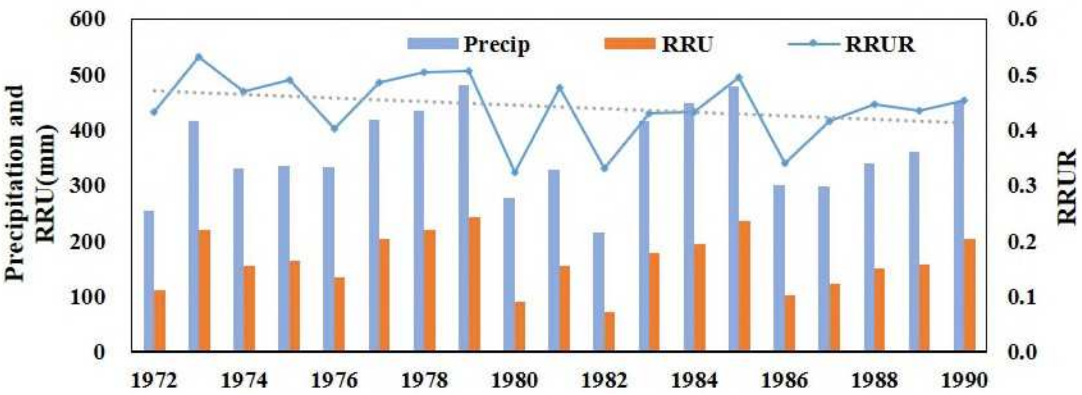

Fig. 5 Current rainwater utilization situation in the Zuli River Basin

At the same time, the average RRU in the southwest and middle reaches of the basin is relatively high, the spatial distribution of RRUR from assessment model show that the annual average RRUR in the western area of the upper and middle reaches of the basin are relatively high, while those in the eastern areas of the middle and upper reaches are relatively low (Fig. 6). In a concentrated area in the upper reaches of the basin, more than 70% of rainwater resources have been lost. The spatial difference of the RRUR is related to the spatial distribution of land use types. The RRUR is relatively high in the areas with greater amounts of cultivated land and less grassland. The reason for this phenomenon is that the Zuli River Basin is mainly cultivated land and grassland, among which the grassland vegetation condition is poor. For the research basin, the upstream rainfall is relatively large, and the RRUR is small, which theoretically has greater rainwater utilization potential.

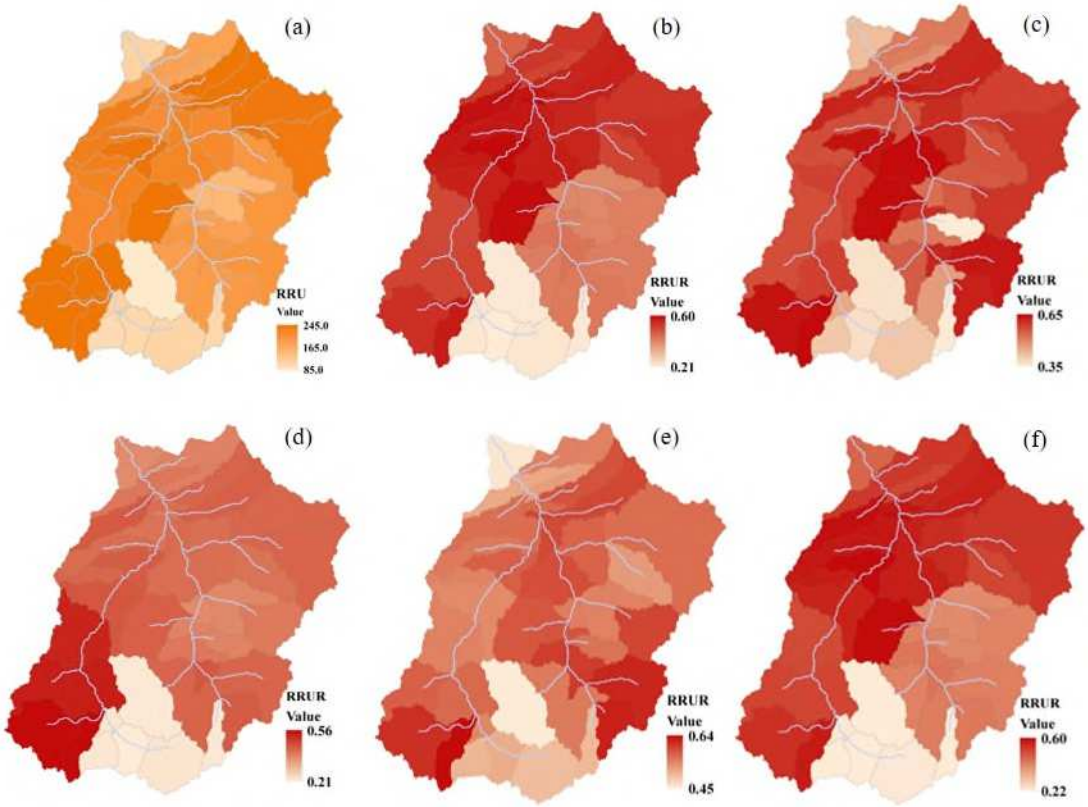

Fig. 6 Spatial distribution of RRU under current conditions (a), and RRUR under current conditions(b), forest rehabilitation (c), grassland rehabilitation (d), cropping rotations (e), parallel terrace (f).

4.2 Temporal and spatial situation of driving force

Global Moran's I is a coefficient that characterizes spatial autocorrelation. The Global Moran's I of the RRUR is 0.44 and the z-score is 3.98, which indicates that the distribution of the RRUR has a high positive spatial correlation, thus the assessment model based on GTWR is applicable for regression analysis. Fig. 7 shows the regression distribution of the sample. The regression result R^2 is 0.97, AICc is -3,417.29, and RSS is 0.46. The R^2 is the determining coefficient between the actual value and simulated value of the sample point. AICc is an important criterion for the goodness of model fitting. The smaller the value is, the higher the model accuracy will be. The RSS is the sum of the squares of the residuals. The results show that the driving force evaluation ability of the model is strong, and the model calculation results are reliable and can reflect the influence of each explanatory variable on the dependent variable.

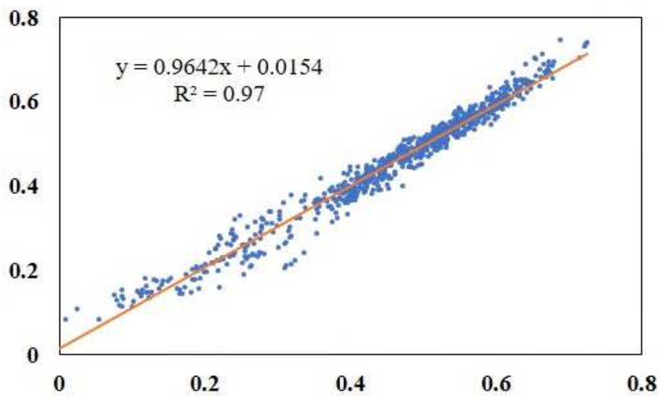

Fig. 7 Regression distribution of the sample points

It can be seen from Fig. 8 that the regression coefficient values of explanatory variables such as EIev, Tmp, PET, and LAI are widely distributed, which shows that the driving effect of these factors on rainwater utilization exhibits significant spatial heterogeneity and time non-stationarity. The LAI is the most important factor affecting the utilization of rainwater. The mean value of regression coefficient is 0.49, and the value of regression coefficient of some sample points exceeds 0.8. This shows that the driving effect of vegetation conditions on the rainwater utilization in the research basin is clear, exhibiting a positive correlation. The increase of the LAI will significantly affect the water cycle process, while the evaporation will increase with the increase of the LAI (Zhang et al. 2016,2015; Scott et al. 2013). With the increase of LAI, the transpiration of vegetation will be enhanced, the evaporation of soil will be reduced, and finally RRUR will be increased. The vegetation canopy can also effectively intercept rainfall, reduce surface runoff, affect the circulation of atmospheric water, and significantly alter the precipitation characteristics (Spracklen et al. 2012), further increasing rainwater utilization.

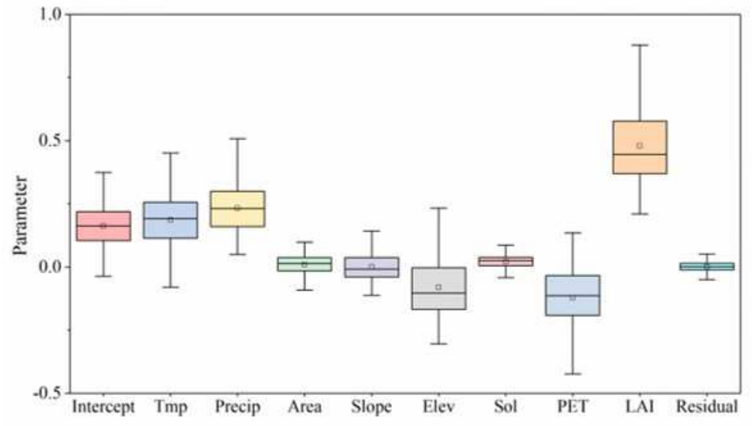

Fig. 8 Value distribution of the regression coefficient of the explanatory variables

PET can characterize regional evaporation capacity. The average regression coefficient in the research basin is -0.14, and the values are mainly distributed downward. This shows that PET has a weak negative correlation with the utilization of rainwater, and the areas with strong evaporation capacity may have a low RRUR. The mean value of the regression coefficient of the Area, Slope, and Sol are very close to 0, and the distribution is relatively concentrated. This reveals that the three explanatory variables have no obvious driving effect on the rainwater utilization in the spatial scale. The RRUR is basically not affected by elevation, and the average regression coefficient of Elevation is -0.09. The regression coefficient distribution of Precip and Tmp in this area is relatively consistent, and the mean values of the regression coefficient are 0.24 and 0.19 respectively. As an important aspect of the hydrological cycle of a basin, meteorological factors have a positive driving effect on the utilization of rainwater. To a certain extent, the increase of precipitation and temperature will increase the RRUR.

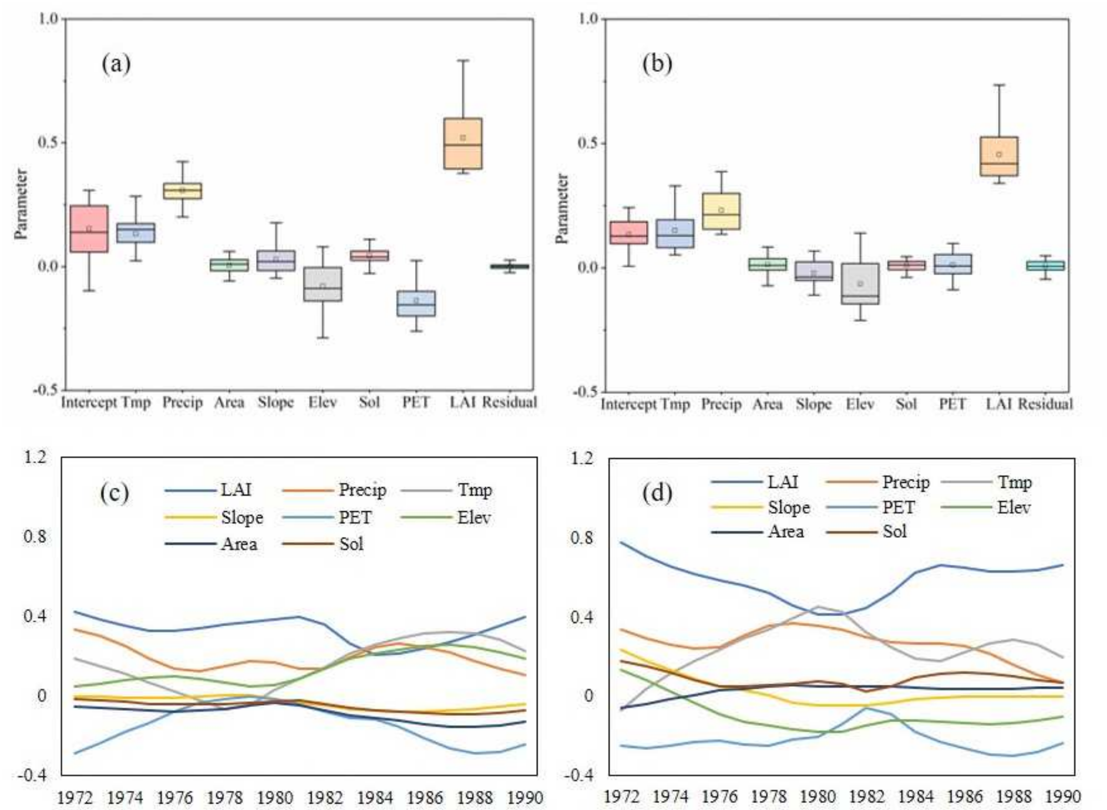

Fig. 9 Distribution of regression coefficient of each explanatory variable in wet years(a) and dry years(b), and change of the regression coefficient values of each explanatory variable in sub-basin 1 (c) and sub-basin 39 (d)

The results of the assessment model show the driving effect of various variables on RRUR, and can be reasonably explained and analyzed. At the same time, the model can further compare the inter-annual and spatial differences of driving factors to support more detailed analysis and research. Fig. 9 shows the respective regression coefficient distribution of the explanatory variables in the wet (1979) and dry (1982) years. The mean values of the regression coefficient of the Prep and LAI in the wet years are greater than those in the dry years, which has a greater driving effect on the RRUR, and the Prep coefficient values are distributed intensively. The mean regression coefficient of the PET in wet years is smaller than that in dry years, and has a more substantial negative driving effect. The RRUR in dry years is less affected by factors other than meteorological and vegetation. Fig. 9 shows the comparison results of driving forces between lower sub-basin (1) and upper sub-basin (39) of Zuli River Basin. Sub-basin 39 has more annual rainfall and better vegetation conditions than sub-basin 1. The results show that RRUR in the upper reaches is affected by a greater number of factors, while there are fewer major factors influencing the driving effect in the lower reaches. In the upper reaches, the influence of LAI, Prep, and Tmp on RRUR is greater, while in the lower reaches it is mainly affected by the LAI. Therefore, LAI is the most critical driving force for rainwater utilization in arid and semi-arid regions. In the planning and implementation of rainwater utilization measures in the basin, changes in LAI should be properly considered.

Since the human behavior in this period did not have much sustained impact on land use in research basin, human behavior is not included in the analysis of driving forces. And the regression results also show that the choice of explanatory variables is reasonable. In many areas, human intervention is the main culprit leading to climate change and land degradation. It is necessary to consider the impact of human intervention on rainwater utilization, and it can also be reflected indirectly through natural factors.

4.3 Application of rainwater utilization scenario

Under global climate change and ecological protection, many regions are implementing large-scale watershed management measures. The Loess Plateau where the research basin is located is a typical arid and semi-arid region, and the most typical area of loess distribution (Wei et al. 2017). In order to restrain the soil degradation, China has taken continuous measures to strengthen the utilization of rainwater and the restoration of the water environment in this area (Li and Qian 2018). Therefore, the assessment model should be flexible, and scientific assessment can be carried out for different management measures of the basin, to play a more positive role in practical.

In order to verify the wide applicability of the evaluation model, a variety of land management measures were designed and evaluated in the research basin, including four scenarios of forest rehabilitation (Dan 2016), grassland rehabilitation (LIAN and HUANG 2019), cropping rotations (Lautenbach et al. 2013) and parallel terraces (Park et al. 2014), and the temporal and spatial changes of RRU and RRUR were analyzed. Fig. 10 shows the schematic diagram for the implementation of the forest rehabilitation, grassland rehabilitation and parallel terrace scenarios. And the specific implementation scheme is shown in Table 3.

Table 3 Specific evaluation scenarios

	Implementation scope	Change	Area (km^2)	Proportion
Forest rehabilitation	cultivated land of sub-basins with forest land growth under the natural conditions	mixed forest (Maximum LAI value is 4)	3,653	35%
Grassland rehabilitation	cultivated land in the middle and lower reaches	shrub bluestem (Maximum LAI value of 2)	2,550	24%
Parallel terraces	3°~25° gentle slope farmland	slope-to-terrace	3,593	34%
Cropping rotations	all the cultivated lands	corn-winter wheat-soybean-fallow	4,160	39%

Note: Since the scenarios research mainly focuses on the performance of the assessment model, rather than the design of scenarios, this scheme is just a hypothesis based on actual conditions.

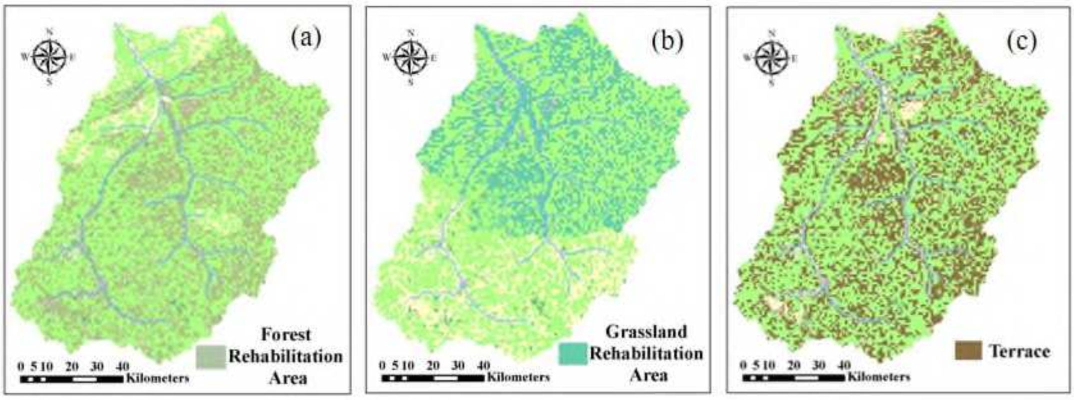

Fig. 10 Implementation area of rainwater utilization scenarios in the research basin, forest rehabilitation (a), grassland rehabilitation (b), and parallel terrace (c).

4.3.1 Forest rehabilitation

Forest rehabilitation seeks to end the cultivation of sloping farmland that is prone to soil erosion in a step-by-step and systematic manner, and to plant trees according to local conditions and restore forest vegetation in accordance with the principle of suitable land for suitable trees (Hai et al. 2015; Chen et al. 2015). To ensure the growth environment of forest land, the cultivated land of sub-basins with forest land under the current conditions is selected for forest rehabilitation (Fig. 10).

From the results of the assessment model, the RRUR has been significantly improved after the implementation of forest rehabilitation scenario in the research basin, the annual average value of the RRUR is 0.54, which is 0.1 higher than the original situation (Fig. 11). The annual increase of RRU is 36.42mm, and the water volume is 3.85×10^{8} m^3. In the years with more precipitation, the increase in RRUR is greater. The increase in 1979 was 0.11 in comparison to the original situation. In 1983, with the less rainfall and RRUR, the increase was 0.07. After afforestation, the annual average value of soil evaporation in the basin was reduced by 38.64 mm, which effectively reduced the loss of rainwater resources; however, the vegetation intercepted evaporation increased slightly. The soil water content and groundwater recharge both changed. The runoff at the outlet of the basin decreased by 10%. In terms of spatial distribution, the utilization rate of the area where the scenario has been implemented has been obviously improved, and the change in the upper reaches of the basin is relatively significant. And the area with high rainfall is more suitable for afforestation. The average RRUR in the sub-basin 43 has increased from 0.22 to 0.44.

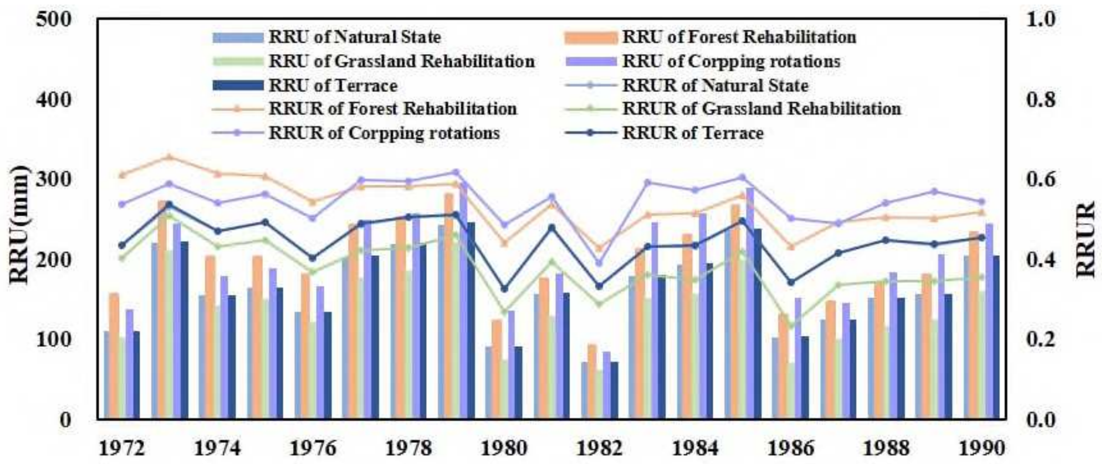

Fig. 11 RRU and RRUR of the Zuli River basin after implementation of each scenario

4.3.2 Grassland rehabilitation

Grassland rehabilitation aims to end the farming of cultivated land, plant grass to prevent and control water and soil loss, restore vegetation. According to the climate and grass growth characteristics in arid and semi-arid areas, the utilization scheme of rainwater resources dominated by grassland rehabilitation is generally implemented in areas with annual precipitation of less than 400 mm (Jinren 2004). Therefore, the grassland rehabilitation scheme chooses to convert the cultivated land in the middle and lower reaches of the Zuli River Basin (Fig. 10).

After the implementation of the scenario, the annual average value of the RRUR in the research basin is 0.38, which is 15% lower than the original situation, and the reduction of RRU is 54.63 mm. In the areas where the grassland rehabilitation measures have been taken, neither the RRU nor the RRUR reach a high level (Fig. 11). The selected species of returning grass in the scheme is bluestem, the leaf surface and canopy conditions are poor during the growth period, and the implementation area is relatively dry, none of which effectively increase the vegetation transpiration or soil water content. The original cultivated land crop is grain, and the vegetation condition is better than grassland overall. Therefore, this led to the model evaluation results of the scheme, which also verifies the results of the driving force analysis.

4.3.3 Crop rotations

Crop rotation refers to the planting pattern of sequential rotation of different crops, or multiple cropping combinations between seasons and years in the same field. The plan is selected to be implemented in all of the cultivated lands of the Zuli River Basin, which changes from original grain of one season a year to "corn-winter wheat-soybean-fallow" of three seasons in two years.

The annual average value of the RRUR under the cropping rotations scenario is 0.54, which is 0.10 higher than the original situation (Fig. 11). In 1979, which had a rather high precipitation, the RRUR reached 0.62, with an increase of 0.18 compared with the original situation, and in 1982, which had less rainfall, the increase was 0.06. The overall leaf area index is shown to have increased by 30% on average, the annual average vegetation transpiration has increased by 26%, and the soil evaporation has decreased by 31%. Particularly during the growth period of winter wheat, rainwater resources have been effectively utilized. The runoff, soil water content and groundwater recharge of the basin are shown to have decreased. In terms of spatial distribution, RRUR has increased even more in the sub-basins with more cultivated land and greater rainfall.

4.3.4 Parallel terrace

Parallel terraces are terraced fields that change gentle slopes into horizontal ones for the purpose of soil and water conservation and planting of crops or trees. In China's arid and semi-arid areas, parallel terraces are widely used to control soil erosion, increase soil water storage, and regulate rainwater resources. In this study, the 3°~25° gentle slope farmland in the Zuli River Basin is selected to implement the slope-to-terrace measure.

After the implementation of scenario, the model results show that the annual growth rate of RRUR is very small (Fig. 11). The annual average value of the RRUR is the same as the original situation. In the years with high rainfall (1976, 1979, 1985), the RRUR is shown to have increased by 0.01 compared with the original situation. There is almost no change in RRUR in years with low rainfall. Analyzing the reasons, terrace is the transformation of microtopography of sloping farmland, which mainly lags the process of yield and confluence of sloping land, reduces runoff in the basin (Arnáez et al. 2015; Yang et al. 2009), but has little impact on vegetation water cycle. In addition, the changes in the hydrological cycle process are not so obvious on the annual scale. On the scale of space, the increase in the RRUR in the upper reaches of the basin with higher rainfall is greater than that in the middle and lower reaches with lower rainfall.

4.4 Discussion

Through the application of various scenarios, the assessment model shows wide applicability and guiding value of regional rainwater utilization. We use this model to evaluate the utilization of rainwater resources area and analyze the driving factors of the study on the spatial and temporal scales. In the process of evaluation of various scenarios, the above analysis conclusion is confirmed and the evaluation results are also consistent with some of our previous understandings of hydrology. Due to the large evaporation and low runoff coefficient in the research areas, rainwater is mainly lost through the evaporation of soil and vegetation. The RRU and RRUR are more related to vegetation. Land cover is an important factor that affects the hydrology of the basin (Caja et al. 2018). The main driving factor is LAI, and the variation of RRUR was consistent with that of LAI. In other arid climate areas, studies have also shown that strategies to improve ecosystem services should rely on adequate management of vegetation to reduce surface flow, and this reduction contributes to higher soil moisture contents, less intense erosive processes, and higher stocked soil carbon (Andrade et al. 2020). The model can also quantitatively evaluate the temporal and spatial changes of rainwater resources and hydrological elements in a watershed, which is of great significance for guiding agricultural river basins to take rainwater utilization and land management measures (Glendenning et al. 2012).

Compared with model applicability, model evaluation accuracy is also very important. The hydrological simulation of the assessment model is based on the SWAT, and its calculation effect has been widely verified. The selection of time scale may affect the evaluation results because the rainfall runoff and evaporation process in the basin have a certain lag. There may be errors in the evaluation on a short time scale. However, on the longer scale (monthly or annual scale), the error will be significantly reduced, and the model can accurately evaluate the utilization of rainwater resources.

While verifying the performance of the model, the utilization status of rainwater resources after the management measures in the study area was evaluated in detail. However, it should be noted that multiple drivers often interact in complex and non-additive ways (Wen et al. 2018). For example, on a wider spatial and ecological scale, although the increase of forest land coverage positively related to rainwater use and soil water storage, it may have a negative impact on other ecological services, especially food production (Iacob et al. 2014). And it may affect the interaction between riparian forest land, terrestrial and aquatic ecosystems, leading to nutrient migration, microclimates, and ecological changes in floodplains (Swanson et al. 1991). In addition, rainfall variability, runoff quality and quantity, local skills and investment capacity, labour availability and institutional support also influence sustainability of rainwater harvesting and utilization (Pachpute et al. 2009). Although, the possible wide-ranging impact is not considered in the performance verification process of this assessment model, it can consider these by refining the simulation settings to calculate more elements. Therefore, the model provides as detailed evaluation performance as possible for rainwater utilization and hydrological elements, and other functions such as ecosystem services assessment can be added in the later stage, considering the provisioning, regulating, cultural and other aspects to support the watershed management.

5 Conclusions

Improving the utilization rate of rainwater resources is one of the keys to alleviate the ecological and environmental problems in arid and semi-arid areas. The rainwater utilization or management in the watershed should be based on adequate evaluation studies. We put forward the concept of RRU and RRUR，and construct a spatio-temporal assessment model for the rainwater resources utilization and driving forces. Taking the Zuli River Basin of the Loess Plateau as the research area, and extensive performance verification was carried out to analyze the applicability and accuracy of the model.

The main conclusions and findings of this study can be summarized as follows:

(1) Overall, the performance of the assessment model is very good, which can accurately evaluate the utilization of rainwater resources and driving factors in the watershed on the spatial and temporal scale. Accurate calibration of the hydrological

process and appropriate selection of influencing factors can ensure that the evaluation results of rainwater resources utilization and driving force are credible.

(2) The RRU and RRUR in the Zuli River Basin have a positive correlation with precipitation on the spatial and temporal scale. The annual average value of the RRUR is 0.44, and the average value of the RRU is 164 mm. The RRUR in the upper and middle reaches of the basin are relatively high and it shows a decreasing trend overall. The LAI is the greatest driving factor of rainwater utilization.

(3) The four self-designed scenarios of watershed management are evaluated by the model in the basin. The annual average RRUR of forest rehabilitation and cropping rotations increased by 0.1 compared with the original state. The RRUR of grassland rehabilitation has been reduced by 15%, and the increase of RRUR is not significant after taking the parallel terrace measurements. The assessment model based on SWAT and GTWR provides a strong spatial and temporal evaluation function of rainwater utilization, and it also inherits their advantages and disadvantages.

In this paper, the spatial scale of assessment model verification is relatively large, and smaller-scale studies can be conducted in the future to explore the performance of the model (for example, on the hydrological response unit). At the same time, based on the planned river basin management measures, considering potential negative impacts, further discussions the changes and impacts of regional flood control, agriculture, and social-economy can be carried out through the assessment model to comprehensively study rainwater utilization in arid and semi-arid regions.

Declarations

Ethical Approval

The authors declare that the submitted manuscript is original and unpublished elsewhere, and that this manuscript complies with the Ethical Rules applicable for this journal.

Consent to participate

All the authors consent to participate in this research work.

Consent for publication

All the authors consent to publish this work.

Authors Contributions

F. Li and X. Yuan contributed to the study conception and design. Analysis was performed by F. Li and X. Zhang. The first draft of the manuscript was written by X. Zhang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Competing Interests

The authors declare no conflict of interest.

Availability of data and materials

Data and materials are available upon request to the corresponding author.

Code availability

Code is available upon request to the corresponding author.

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