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Original Research

Study on the Available Amounts of Rainwater/ Stormwater Resources in Ungauged Basin in Semi-Arid Region of the Loess Plateau

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Abstract

Most basins in the semi-arid region of the Loess Plateau lack gauged data on precipitation and runoff. The degree of water resources security seriously restricts the rapid development of the social economy. To determine the available amounts of rainwater/stormwater resources and the utilization potential in the ungauged basin, this study took Si Jiagou Basin as an example, established a SWAT model based on the gauged basin, analyzed and calculated the model output after calculating, it is found that the total rainwater/stormwater resources in the basin in 30 years was $602.68\times10^4 m^3$, with a considerable utilization potential. The rainy season is the crucial period of rainwater/stormwater resource collection, and the proportion of available utilization is 93.52%. The profit of 2-10mm accounts for 53.81% of the total in the rainy season, which is the water-saving potential area. The resources of 1-2mm account for 15.65% of the total in the rainy season, which is the main point and direction of the utilization level. The higher the precipitation guarantee rate, the more significant the proportion of rainwater/stormwater resources in the non-rainy season. The results can provide essential data and theoretical basis for the construction of facilities for the efficient use of rainwater/stormwater resources in the semi-arid region of the Loess Plateau.

Keywords: available amounts of rainwater/stormwater resources, utilization potential in the ungauged basin, water-saving potential areas, SWAT model, semi-arid region of the loess plateau

Introduction

The semi-arid region of the Loess Plateau is still one of the regions with the most serious soil erosion and the most fragile ecological environment due to its unique natural endowment and the level of economic and social development. The water resources in the region are relatively short, and the supply of water resources seriously restricts the rapid development of social economy [1, 2]. The requirements of ecological protection and high-quality development in the Yellow River Basin make the water resources in the region face new development opportunities and major challenges. In the social and economic development of the semi-

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arid region of the Loess Plateau [3], there is an urgent need for a new energy industry, planting and breeding industry, life and ecology, and the shortage of water resources in the region is difficult to support [4-6]. Therefore, it is necessary to identify the water-saving potential of the basin, determine the available amounts of rainwater/stormwater resources in the basin, and deeply tap the water-saving potential to support the rapid development of social economy. It is worth noting that in the semi-arid region of the Loess Plateau, with the lack of total precipitation and uneven distribution within a year, it is mainly concentrated in the rainy season [7-11]. Exploring the amounts of rainwater/stormwater resources in the rainy season of the basin is the main way to increase the regional available water resources amounts. The availability and utilization period of rainwater/stormwater resources are the basis for building the storage and utilization facilities [12, 13]. It is very important to accurately calculate the available amounts of rainwater/stormwater resources in semi-arid regions. In addition to the main hydrological stations with runoff monitoring information, there are many ungauged areas. The lack of runoff data has brought difficulties and challenges in determining the availability of rainwater/stormwater resources and the potential area for water-saving. It has become a basic constraint factor for the socioeconomic development of the basin and the related industrial planning [14, 15]. To achieve the goal of rapid and high-quality development of the basin, it is necessary to rationally increase the amounts of water supply resources in the basin [16]. Therefore, it is significant to quantify the amounts of rainwater/stormwater resources in the semi-arid region of the Loess Plateau.

The calculation methods for the utilizable amounts of rainwater/stormwater resources mainly include: deduction method [17], inversion algorithm [18], chart method [19], evaluation method [20-23], and model calculation method [24, 25]. Li et al. [26] calculated the available amounts of water resources in the basin based on the water quality constraints. Chandrasasi et al. [27] used the F. J. Mock method, compared with the observed discharge, to determine the potential for water availability and its use in the multisector water needs. Han et al. [28] analyzed the amounts and utilization of rainwater/stormwater resources in the basin according to different climate scenarios in the future. However, these studies were mostly concentrated on areas with observational data. At present, there are relatively few studies on rainwater/stormwater resources, and what is available is of low potential, lacking a spatial-temporal variation process and an available period of the ungauged areas. In the semi-arid region of the Loess Plateau, there is a general shortage of water, and the precipitation is mainly concentrated in the rainy season. To alleviate the regional water resources crisis, effectively improve the water resources supply capacity of the basin and provide water resources support for the regional social and economic development. Therefore, using the SWAT model in the distributed hydrological model to clarify the available amounts of rainwater/stormwater resources in the ungauged basin. At the same time, the potential of water saving should be deeply uncovered, and the level of water resource utilization in the basin should be effectively improved based on the SWAT model calculation results.

The SWAT is a semi-distributed model for simulating water, sediment, and chemical flows in a watershed, considering multiple climatic conditions, soil types, channel characteristics, land use, and different agricultural management practices [29]. The model contains powerful physical mechanisms that can be applied to metered and unmetered areas, making it a valuable tool for assessing water resources. The hydrological process is divided into two main stages: the terrestrial stage and the confluence stage of the water cycle [30, 31]. The SWAT model in the distributed hydrological model can complete the simulation of runoff, sediment, and water quality [32-36], and has specific research basis and advantages in simulating the spatial-temporal dynamics of runoff. Jiao et al. [37] used the SWAT model to complete the calculation of the ecological water recharge in the water shortage basin. Abunada et al. [38] conducted the quality of groundwater vulnerability assessment using the SWAT model in the Gaza Strip. Chen et al. [39] used the SWAT model to simulate the distribution of groundwater and evaluated the water resources in the Jinghe Basin. Therefore, the SWAT model was used to simulate the runoff spatial-temporal characteristics in the basin with observed data. The model results were calibrated to ensure the accuracy of the calculation results of the ungauged sub-basin. Then, the available amounts of rainwater/stormwater resources of the ungauged sub-basin were determined. The research results can provide theoretical basis and foundation for water resources planning, water conservancy projects construction, and the construction of facilities for efficient use of rainwater/stormwater resources in the basin, and provide maximum water resources guarantee for the realization of high-quality, coordinated and sustainable development of the basin [40].

Materials and Methods

Study Area

Si Jiagou Basin is located in the upstream of Jinghe River in the northeast corner of Xifeng District, Qingyang City (35°43′ N, 107°38′ E). The basin covers an area of 13.49 km^2, it is a semi-arid continental climate zone with high temperatures and precipitation in summer, and heavy rains are mostly concentrated in July-August, winter is windy and cold with little rain and snow. The annual average precipitation is about 500 mm, the sunshine hours are 2400 hours, the annual solar radiation is 130 ka/cm^2, and the average temperature is 8ºC. The temperature is high in the south and low in the north, and the accumulated temperature changes are the same as the temperature, which is higher in the river valley, but lower in the highland and forest areas. The accumulated temperature is about 3000 when it is greater than 10ºC. The depth of frozen soil in the basin is about 80 cm, and the depth is about 110 cm in extremely cold years, and the frozen soil time is from November to February. The cultivated land is dominated by black loessial soil, which is slightly alkaline, fertile, and loose, and has strong vertical permeability [41]. The main crops are wheat and corn, and it is the best latitude area for apple cultivation. The per capita water resources in the basin are about 20% of the national data, and the average water resources per hectare is about 10% of the national data. The basin is short of water resources and difficult to use. It is a semi-arid water shortage area. There are still some problems in the development and utilization of water resources, such as lack of total amounts, uneven distribution of runoff between and within the year, the flood control situation being grim, serious soil erosion, rapid growth of water resources demands, and difficulty in development and utilization. Observation data of no runoff and rainwater/stormwater resources in the basin, channel shapes, water collection mode, and development and utilization of water resources in the basin are relatively typical in the semi-arid region of the Loess Plateau. Therefore, Si Jiagou Basin is selected as a typical ungauged basin to analyze and calculate the rainwater/stormwater resources yield and availability of the basin (Fig. 1).

Data Sources

Hydrologic meteorological data from the National Meteorological Information Center China meteorological data network (https://data.cma.cn/). The DEM data information from the SRTM website (http://srtm.csi.cgiar.org/) of the CGIAR. The basin land use data from the Institute of Geographical Science and Resources, Chinese Academy of Sciences (http://www.igsnrr.ac.cn). The spatial distribution of soil data from the Chinese soil database (http://vdb3.soil.csdb.cn/).

Methodology

This study constructed a SWAT model of a basin with observed data in the semi-arid region of the Loess Plateau and used the observed data to calibrate and validate the model so that the model accuracy could meet the requirements. After the sub-basin was divided by the SWAT model of the basin, the output information of the ungauged areas of the sub-basin after the extraction rate was determined, and the runoff spatial-temporal characteristics of the ungauged sub-basin were quantized in detail. The output yield and availability of rainwater/stormwater resources in the semi-arid region were analyzed, and the available rainwater/stormwater resources corresponding to their utilization potential in the ungauged areas were proposed. The building steps of a basin SWAT model mainly include: the construction of the basin attribute database, basin spatial discretization methods, sub-basin and HRU's division, meteorological and hydrological parameters writing, model operation, parameter sensitivity analysis, calibration, and validation. The SWAT model is constructed through the above steps.

The Construction of the Basin Attribute Database

The first step of constructing the SWAT model of the basin was to build an attribute database, which needed to input a large number of underlying surface attribute data such as terrain, soil, land use mode, meteorology, and hydrology [42]. The elevation and slope maps of the SWAT model are obtained by using ArcGIS for projection transformation and mas cutting. The elevation of the basin ranges from 898-2059 m, and the slope

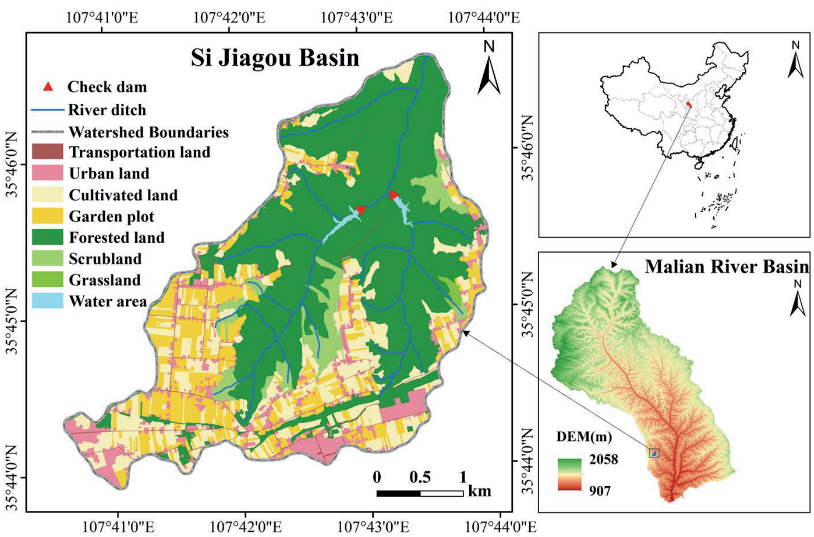

Fig. 1. Research Area: Si Jiagou Basin.

of 15-35° accounted for 47.96% at most in the whole basin, followed by 24.10% when it was greater than 35°, followed by 19.96° when it was 5-15°. The minimum proportion of slopes less than 5 degrees was 7.98% (Fig. 2a and Table 1). The meteorological stations around the basin were Dingbian, Tongxin, Wuqi, Huanxian, Xifeng and Changwu, and the hydrological station for verification of the model was Yuluoping hydrological station downstream (Fig. 2b). According to the accuracy requirements of SWAT model and the national standard classifications of Land Use Status Classification (GB/T21010-2017), it was divided to 6 types of cultivated land, forest land, grassland, water area, urban land and bare land (Fig. 2). Grassland occupies the largest area of 9499.54 km^2, accounting for 49.91% of the total basin area. The cultivated land (7362.92 km^2) ranked second, accounting for 38.69% of the basin area, the forest land (1958.44 km^2, 10.29%) accounted for the third, the urban land (179.29 km^2, 0.91%) accounted for the fourth, the water area (38.04 km^2, 0.20%) and the bare land (0.63 km^2, 0.003%) ranked fifth and sixth (Fig. 2c and Table 2). The basin soil map required by the model was obtained by clipping and projection transformation of the soil spatial distribution data. The soil in the basin includes three categories: black loessial soils, cultivated loessial soils, and alluvial soil, mainly cultivated loessial soils. The cultivated loessial soils area was 16285.06 km^2, accounting for 85.56%, accounting for the largest proportion, while the black loessial soils were 1891.21 km^2, accounting for 9.94%, ranked second, and the alluvial soil (855.59 km^2, 4.50%) was the third type of soil in the basin (Fig. 2d and Table 3).

Table 1. Slope classification table of the basin.

Slope	Percent (%)
0-5	7.98
5-15	19.96
15-35	47.96
>35	24.10

Basin Information Extraction and the Sub-Basin Division

Basin topography determines surface runoff and has an impact on the spatial-temporal distribution of precipitation [43]. Therefore, terrain conditions also control the process of runoff production and accumulation on the slope of the basin. The catchment area and other hydrological elements of the basin are automatically generated by the SWAT model through DEM data. When the drainage system is extracted from

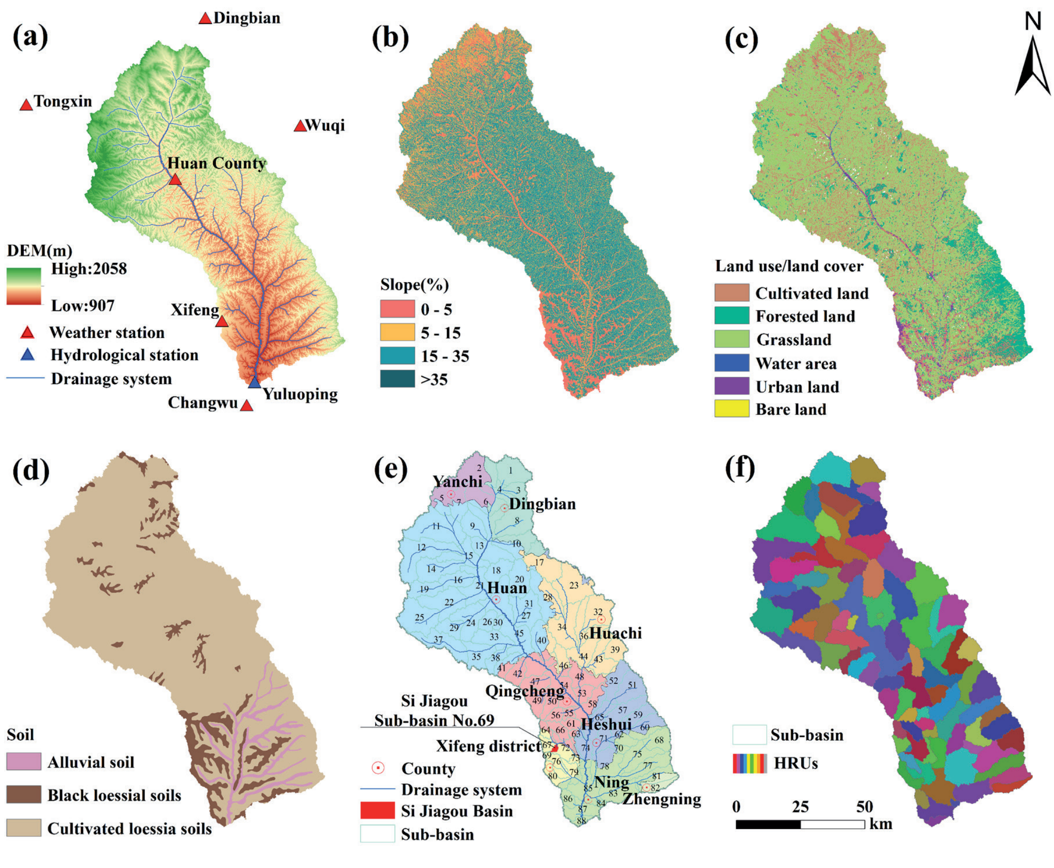

Fig. 2. Construction diagram of basin attribute database.

Table 2. Statistical results of land use types and areas of the basin.

Scenario	Name	SWAT code	Area (km^2)	Percentage of total area (%)
1	Cultivated land	AGRL	7362.92	38.69
2	Forest land	FRSD	1958.44	10.29
3	Grassland	PAST	9499.54	49.91
4	Water area	WATR	38.04	0.20
5	Urban land	URLD	172.29	0.91
6	Bare land	BARR	0.63	0.003

Table 3. Statistical results of soil type area of the basin.

Scenario	Soil type	SWAT code	Area (km^2)	Percentage of total area (%)
1	Black loessial soils	HLuT	1891.21	9.94
2	Cultivated loessial soils	HMianT	16285.06	85.56
3	Alluvial soils	XJiT	855.59	4.50

DEM, the D8 algorithm is adopted, the threshold of the catchment area is 1200 ha, and the basin is divided into 88 sub-basins with a catchment area of 19031.86 km^2 (Fig. 2e).

Division of Hydrological Response Units

The Hydrological Response Unit (HRU) is the smallest unit of SWAT model operation, and the division of the hydrological response unit is a process of reclassification and superposition analysis of underlying surface conditions [44], so as to determine the underlying surface conditions in each sub-basin. The SWAT model divides HRU into two types: (1) Select the largest land use, soil type, and slope range in the sub-basin and combine the whole sub-basin as a hydrological response unit; (2) Perform spatial overlay analysis of land use, soil, and slope, and define multiple HRUs in sub-catchments. According to the actual situation of the Malian River Basin, the study adopted the second method, and the threshold values of land use, soil area, and slope grade were all set at 5%. The model finally divided the basin into 1521 hydrological response units (Fig. 2f). In order to spatially parameterize the HRU scale physical attributes of the Malian River Basin, the parameters required for HRU calculation are written into the corresponding text file, that is, each HRU is assigned. At the same time, other parameters required for Malian River Basin calculation, including sub-basin calculation, are written to prepare for model calculation. Refer to the SWAT Operation manual [45] for the detailed establishment process of the SWAT model. The hydro-meteorological data selected for the SWAT model of the Malian River Basin were from January 1st, 1960 to December 31st, 2017, with 1981-1995 as the regular period and 1996-2016 as the validation period. The SWAT model of the Malian River Basin was simulated at a daily scale and the simulation results at a monthly scale were output.

Model Sensitivity Analysis

The sensitivity analysis of the relevant parameters of the basin SWAT model is based on the SWAT-CUP public program. SWAT-CUP can perform model sensitivity analysis, calibration, validation, and uncertainty analysis, while also providing independent operation, visualization, and diversification of objective functions. Swat-cup contains a large number of multi-objective optimization functions. The sensitivity and result uncertainty analysis of the SWAT model in the Malian River Basin uses the SUFI-II algorithm, which is based on the parameter estimation optimization method developed by Abbaspour KC et al. The sensitivity of the model to the parameters was analyzed by multiple linear regression between the parameters generated by Latin hypercube sampling and the objective function. The range of parameters after calibration was visualized by a 95PPU diagram of the simulated and measured values. The factors used by the SUFI-II algorithm to measure the effectiveness of sensitivity/uncertainty analysis of model parameters are R-factor and P-factor. The degree to which R-factor is close to 0 and P-factor is close to 1 is used to judge the sensitivity of model parameters [46]. After uncertainty analysis, the parameters recommended by SWAT-Cup to affect the results of the SWAT model mainly include: the number of runoff curves, the effective water content of the soil, the hydraulic conductivity of the main river, and the groundwater lag coefficient.

As shown in Fig. 3, the P-Value values of runoff curve number, soil effective water content, hydraulic

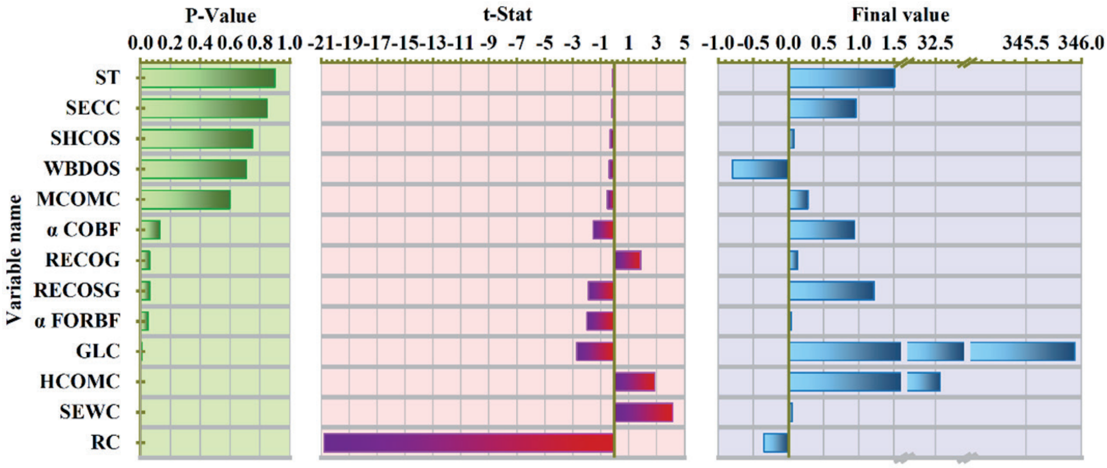

Fig. 3. SWAT model parameter sensitivity analysis of the basin. (ST, SECC, SHCOS, WBDOS, MCOMC, α COBF, RECOG, RECOSG, α FORBF, GLC, HCOMC, SEWC, and RC denote the Snowfall temperature, Soil evaporation compensation coefficient, Saturated hydraulic conductivity of soil, Wet bulk density of soil, Manning coefficient of main channel, α coefficient of basal flow, re-evaporation coefficient of groundwater, re-evaporation coefficient of shallow groundwater, α factor of riverbank basal flow, groundwater lag coefficient, hydraulic conductivity of main channel, soil effective water content, and runoff curve number, respectively).

conductivity of main channel, groundwater lag coefficient, α factor of riverbank basal flow, re-evaporation coefficient of shallow groundwater, re-evaporation coefficient of groundwater and α coefficient of basal flow are all less than 0.15. And the absolute values of t-Stat are all greater than 1.50. This indicates that the sensitivity of these 8 parameters to the SWAT model in the Malian River Basin is relatively high, while the sensitivity of the other 5 parameters is weaker than the above 8 parameters. Among these parameters, the runoff curve number is the most sensitive and significant, and the larger the value is, the stronger the impermeability of the soil and vegetation combination is, and the greater the surface yield and discharge.

Results and Discussion

Calibration and Validation of SWAT Model

The optimal parameters of SWAT-CUP simulation were selected, and assigned to the SWAT model for the calculation of hydrological elements, such as output yield. The monthly scale runoff depth value of the outlet section of the Malian River Basin in the calibration period and validation period was obtained [47, 48]. At the same time, the monitoring data of the outlet section was compared with the hydrological station in Fig. 4. The established SWAT model can basically simulate the monthly scale runoff process, reflect the monthly scale characteristics of runoff from 1981 to 2011, and accurately identify the relationship between main precipitation and runoff in the basin. However, the uncertainty analysis also showed that the monthly

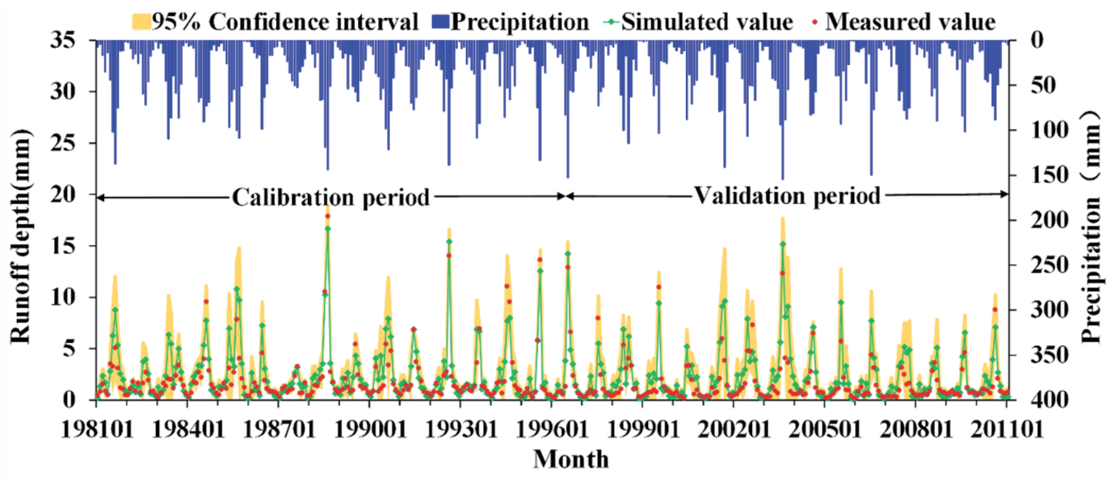

Fig. 4. Comparison of simulated and observed runoff during calibration and validation.

runoff has a large uncertainty at the peak and low-value months, and further simulation and parameter adjustment were still needed.

The scatter plot of simulated monthly runoff and observed values in the calibration period, validation period, and the whole study period of the SWAT model were drawn. It was found that the scatters were basically distributed around the trend line, and the slopes of the trend lines in the calibration period and validation period were all greater than one. Indicating the simulated values in these two periods were slightly higher than the observed values (Fig. 5). Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Coefficient of Determination(R^2) were used to evaluate the simulation accuracy of the model (formula (1)(2)(3)) [49-53]. The calculated results are shown in Table 4. The R^2 of both periods was higher than 0.77, indicating that the corresponding relationship between the simulated value and the observed value is high and the correlation is good. In the calibration period and validation period, the PBIAS of the model is -18.60% and -28.69%, indicating that the precision of the model simulation is fair. According to the results of the model's calibration period and validation period, the NSE is 0.75 and 0.71 respectively, and the simulated value of the SWAT model in the Malian River Basin slightly overestimates the observed value (Fig. 5). Overall, the R^2 of SWAT model in Malian River Basin is 0.79, the PBIAS is -22.31% and the NSE is 0.73. According to the discrimination limit of simulation accuracy proposed by Moriasi et al. [54], the simulation accuracy of the SWAT model in the Mlian River Basin can reach the standard and has the prediction function.

$$NES = 1 - \frac{\sum_{t=1}^{n}(Q_{ot} - Q_{st})^2}{\sum_{t=1}^{n}(Q_{ot} - Q_{a})^2} \tag{1}$$

$$PBIAS = \left(\frac{\sum_{t=1}^{n}(Q_{ot} - Q_{st})}{\sum_{t=1}^{n} Q_{ot}} \right) \times 100 \tag{2}$$

$$R^2 = \frac{\left[\sum_{t=1}^{n}(Q_{ot} - Q_{a})(Q_{st} - Q_{sa})\right]^2}{\sum_{t=1}^{n}(Q_{st} - Q_{sa})^2 \sum_{t=1}^{n}(Q_{ot} - Q_{a})^2} \tag{3}$$

where Q_{ot}, Q_{st}, Q_a, and Q_{sa} represent the actual runoff at time t (m^3/s), the simulated runoff at time t (m^3/s), the average actual runoff at all times (m^3/s), and the average simulated runoff at all times (m^3/s).

After constructing, simulating, and verifying the SWAT model of the Malian River Basin, the results show that the average annual runoff depth of the basin is 27.78 mm (1981-2011). The average annual water resources yield is 5.29×10^8 m^3, the runoff depth in the rainy season is 20.00 mm, and the water resources yield is 3.81×10^8 m^3. The self-produced water resources of the basin are large. Which should be used efficiently, which can greatly increase the water supply resources in the basin [55].

Study on Available Amounts of Rainwater/Stormwater Resources in Ungauged Areas

Si Jiagou Basin is located in the northeast corner of Xifeng District, and there is basically no observation equipment and data such as runoff and rainwater/stormwater resources. The simulation accuracy of the SWAT model in the Malian River Basin can meet the requirements, and the Si Jiagou Basin completely overlaps the sub-basin No. 69 of the Malian River Basin. Therefore, to analyze and calculate the amounts of rainwater/stormwater resources in the ungauged Si Jiagou Basin, the calibrated and validated SWAT model of the Malian River Basin can be adopted, through

Table 4. Model performance based on monthly river discharge.

Period	R^2	PBIAS	NSE
Calibration (1981.01-1996.01)	0.82	-18.60%	0.75
Validation (1996.01-2011.01)	0.77	-28.69%	0.71
Study period (1981.01-2011.01)	0.79	-22.31%	0.73

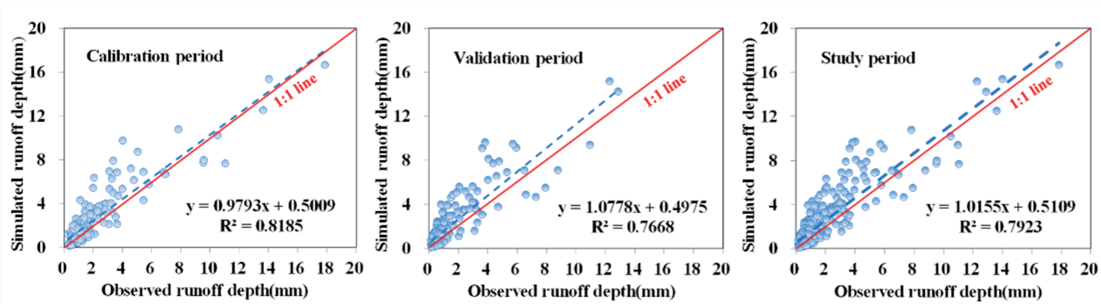

Fig. 5. Scatter of the simulated and observed runoff during calibration and validation.

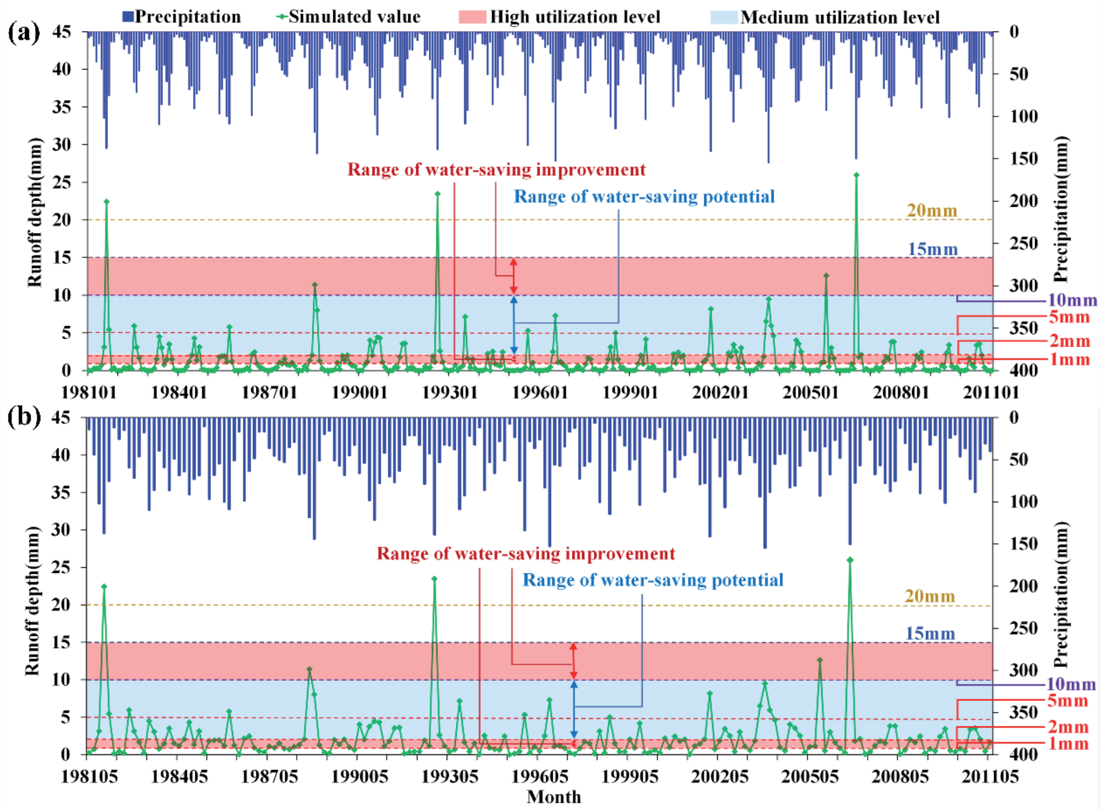

Fig. 6. Yield chart of rainwater/stormwater resources in Si Jiagou Basin. (a is the whole year; b is the rainy season).

the runoff depth data output from the sub-basin. Solve the problem that the output yield of the rainwater/stormwater resources in ungauged areas is difficult to quantify (Fig. 2 and 6a) [56].

The precision of the calibrated and validated model can meet the requirements and predict the runoff depth of the ungauged sub-basin [57]. In this yield chart, the water-saving potential area refers to the area where 2-10 mm runoff (rainwater/stormwater resources) is produced, which is the main component of stormwater resources in the basin, and has great potential for collection and utilization. Water-saving improvement area refers to the area where 1-2 mm and 10-15 mm runoff (rainwater/stormwater resources) are generated. These resources in this part are less than those in the water-saving potential area and are composed of small path flow and large flood volume, which can be collected and utilized to improve the space. After analyzing the output results of sub-basin No. 69 of the SWAT model, it is found that the monthly runoff distribution of sub-basin No. 69 basically matches the variation of monthly precipitation. Indicating that the runoff data output by the model is reasonable and can be applied in the Si Jiagou Basin. The results show that the total amount of rainwater/stormwater resources in the basin in the past 30 years is 602.68×10^4 m^3, and the utilization potential is large. During the 30 years from 1981 to 2011, large runoff was generated after precipitation in the basin, with the depth of runoff exceeding 20 mm for 3 times (1981.08, 1992.08, and 2006.07) and exceeding 15 mm for 3 times (1981.08, 1992.08, and 2006.07). A flood greater than 15 mm inside the basin is considered a major flood, accounting for 16.09% of the basin's output yield, and mainly concentrated in July and August. Flood control work should be done in these crucial months to ensure the safety of the basin. There were two times (1988.07 and 2005.07) when the runoff depth was between 10-15 mm, accounting for 5.37% of the runoff yield in the basin. There were 11 times (Fig. 6a) when the runoff depth was between 5-10 mm, accounting for 16.78% of the runoff yield in the basin. This part of the flood is difficult to utilize and should be stored and utilized on the basis of preventing flood disasters and ensuring safety.

In order to further improve the utilization level of rainwater/stormwater resources in the basin, the resources of 1-2 mm during the rainy season accounting for 15.65% of the total, are the most easily utilized parts of rainwater/stormwater resources except the resources of 2-10 mm, so it is the main utilization point and direction. The resources above 15 mm are floods, with large sediment content and poor quality, which only occurred 3 times in the 20 years from 1981 to 2011, and could not be directly utilized due to large sediment contest, poor water quality, and low frequency of occurrence. The main stable water-producing months (62 months) of the basin between 2-10 mm accounted for 51.36% of the basin's water yield discharge. The rainwater/stormwater resources in this part are the largest and most stable, mostly distributed in the rainy season, indicating

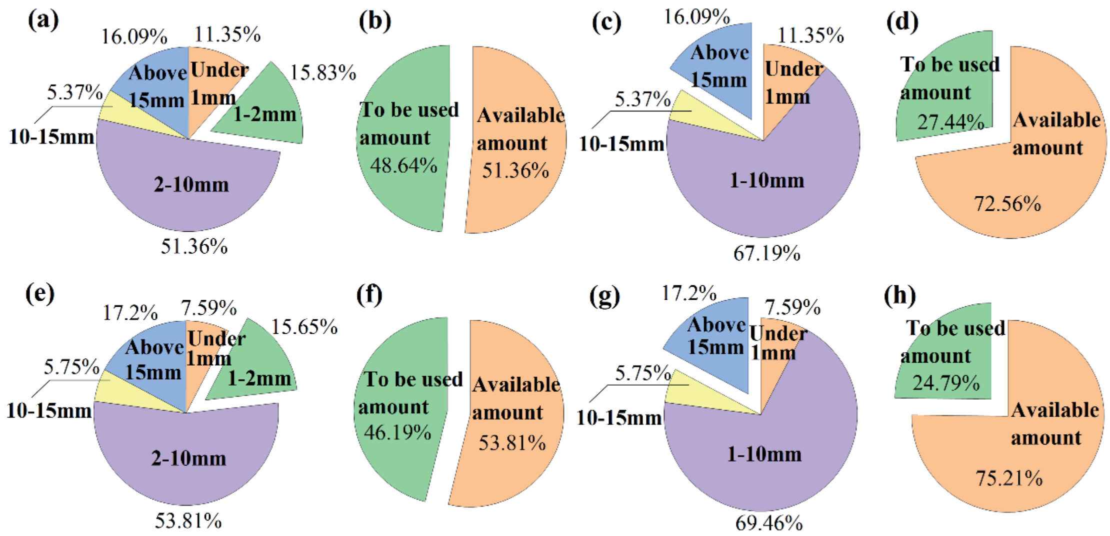

Fig. 7. Analysis chart of rainwater/stormwater resources yield and available amounts in Si Jiagou Basin. (a, b, c, and d denote the rainy season and non-rainy season; e, f, g, and h denote the rainy season).

that the rainy season is the crucial period for efficient utilization of the rainwater/stormwater resources in Si Jiagou Basin [58]. Si Jiagou Basin belongs to the gully region of the Loess Plateau in eastern Gansu Province. Composed of various topography and landforms, such as plateaus, gullies, and valleys. Its special landforms and topography determine the utilizable characteristics of rainwater/stormwater resources of different millimeters, and not all the precipitation in the basin is effective utilizable rainwater/stormwater resources. The output of rainwater/stormwater resources in the rainy season is the main component of the basin, accounting for more than 90% of the annual output of rainwater/stormwater resources. The rainwater/stormwater resources of 2-10 mm during flood season are easy to form stable surface runoff, and the stormwater resources are the largest and most stable, accounting for 53.81% of the total. Under normal circumstances, these parts of rainwater/stormwater resources can be collected, so it is the range of water-saving potential [59, 60].

Under the medium utilization level of the rainwater/stormwater resources in the basin, the resources of 2-10 mm depth are utilized (Fig. 7a and b). The available rainwater/stormwater resources are 51.36% of the total, which can reach 309.52×10^4 m^3, and nearly 40% are the resources to be utilized (293.17×10^4 m^3). If the basin can use this part of self-produced water resources, it will increase the effective water supply and mitigate the water resources crisis. In order to further improve the utilization level of the rainwater/stormwater resources in the basin (Fig. 7c and d), the main point and direction is the part utilization depth increased to 1-15 mm, and the runoff yield within 1-2 mm (15.83%). If this part can be utilized to realize efficient management and utilization in the basin, the utilization of rainwater/stormwater resources can be increased by 21.2%. The available rainwater/stormwater resources in the basin can reach 72.56% (437.33×10^4 m^3) of the runoff yield, which is a considerable amount. It can provide strong support for the high-quality development of the semi-arid region and the mitigation of water resources crisis [61, 62].

The Available Amounts of the Rainwater/Stormwater Resources in the Basin During Rainy Season

In the ungauged Si Jiagou Basin, the yield of rainwater/stormwater resources in the rainy season reached 93.52% of the total. The utilization potential of rainwater resources is great and concentrated in the rainy season [63, 64]. It is necessary to analyze the available potential of rainwater resources in the rainy season in detail [65-67]. Fig. 6b) shows the output curve of rainwater/stormwater resources during the rainy season from 1981 to 2011. In the past 30 years, all the resources with a depth of more than 20mm (1981.08, 1992.08, and 2006.07) in the basin occurred in July and August of the rainy season. Those with a depth of more than 15 mm occurred also in these three times, accounting for 17.20% of the rainwater/stormwater resources in the rainy season. In July and August, the amounts of them are greater, and the flood control pressure is greater. In the rainy season, there were two (1988.07 and 2005.07) floods with the depth between 10-15 mm, accounting for 5.75% of the total runoff yield in the rainy season; there were 11 greater floods with the depth between 5-10 mm, accounting for 17.95% of the runoff yield in the rainy season. This part of the rainwater/stormwater resources can be properly utilized on the basis of ensuring safety. The amounts of 2-10 mm rainwater/stormwater resources account for 53.81% of the whole rainy season. Therefore, this part of water resources is the main part of the efficient utilization of the rainwater/stormwater resources in the basin. The construction

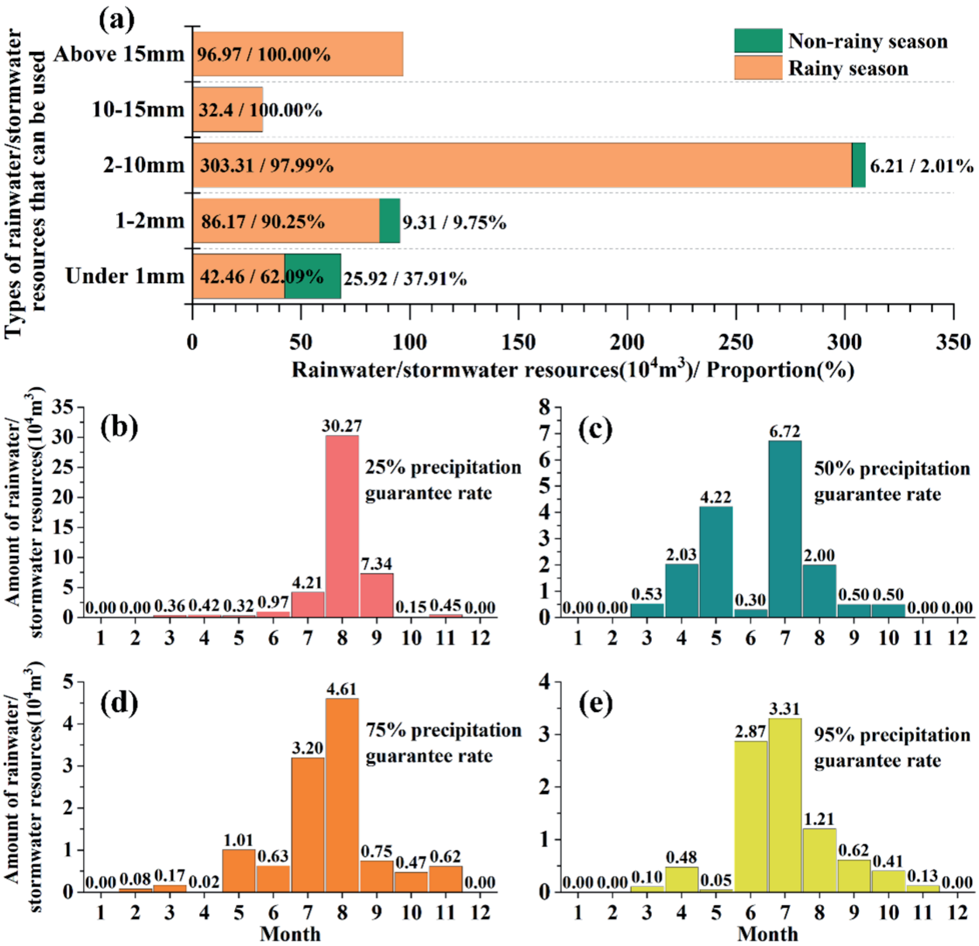

Fig. 8. Comparison chart of rainwater/stormwater resources yield in Si Jiagou Basin. (a is the rainy season and non-rainy season; b, c, d, and e are the different precipitation guarantee rates).

of the rainwater/stormwater resources efficient utilization facilities should also take this part as the design basis. At the same time, the amounts of the rainwater/stormwater resources in the rainy season are 563.61×10^4 m^3, and the runoff yield of 2-10 mm is mostly distributed in this period. The rainwater/stormwater resources yield in the rainy season is the main component of the basin. A detailed quantification of the rainwater/stormwater resources yield in the rainy season, the characteristics of generation time, and reasonable determination of available amounts are important bases for the efficient utilization of these resources in the basin.

By comparing the yield of rainwater/stormwater resources in the rainy season and non-rainy season (Fig. 8a), it is found that the amounts of the rainwater/stormwater resources over 10 mm is 129.37×10^4 m^3, which is concentrated in the rainy season, and the flood accounts for 74.96%, is difficult to use. The collectible yield of 2-10 mm rainwater/stormwater resources in the rainy season is 303.31×10^4 m^3, accounting for 97.99% of the total year, and is an important part of the collection and utilization of resources in the rainy season. The rainwater/stormwater resources of 1-2 mm in the rainy season account for 90.25% of the total year, the recoverable amounts are 86.17×10^4 m^3, and 62.01% of the total amounts are less than 1 mm. However, they are not available for collection and utilization. More than 90% of the rainwater/stormwater resources that can be collected in Si Jiagou Basin are in the rainy season. Therefore, it is more meaningful to carry out the analysis of the rainwater/stormwater resources in the rainy season.

The available amount and the to-be-used amount were determined according to the utilization level, the amount of runoff, whether they were concentrated in flood season, and the degree of utilization difficulty of rainwater/stormwater resources. When the water resources utilization level is moderate, the rainwater/stormwater resources of 2-10 mm account for 51.3% of the annual total, and 97.99% of them are distributed in the flood season. The output of this part of rainwater/stormwater resources is relatively full, concentrated, and easy to use, so it is defined as the available amounts of stormwater resources. Rainwater/stormwater resources less than 2 mm and more than 10 mm are defined as the to-be-used amount of rainwater/stormwater resources at the medium level of water resources utilization because of their small output yield and greater difficulty in utilization. In the case of high utilization levels, rainwater/stormwater resources at the depth of 1-2 mm and 10-15 mm are added to the available amount due to the improvement of water resources utilization level. Therefore, rainwater/stormwater resources at a depth of 1-15 mm are defined as the available amount. Stormwater resources below 1 mm and above 15 mm are still defined as the to-be-used amount due to the difficulty of utilization.

Under the condition of medium utilization level of the rainwater/stormwater resources in the rainy season, the rainwater/stormwater resources with a depth of 2-10 mm can be utilized (Figs. 7e and f), and the available amounts are 303.31×10^4 m^3, accounting for 53.81% of the total amounts in the rainy season. The available amounts of rainwater/stormwater resources of 2-10 mm account for 97.99% of the whole year, which are an important part of the available amounts of the rainwater/stormwater resources in the basin. The rainy season is the crucial period for the utilization of the rainwater/stormwater resources in the basin, and their annual collection amounts can be calculated according to the rainy season. In the case of high-level utilization of the rainwater/stormwater resources in the basin (Figs. 7g and h), the utilization depth increased to 1-15 mm. The rainwater/stormwater resources with a depth of 1-2 mm (15.65%) were the main utilization level increase and main utilization direction, while the proportion of 10-15 mm accounted for 5.75% of the total amounts should also be paid attention to. Under the condition of high utilization level, the available rainwater/stormwater resources reached 75.21% (437.33×10^4 m^3) of the output yield. The available utilization increased by 21.4%, which provided strong support for the high-quality development of the semi-arid region and the mitigation of water resources crisis. Besides, under the condition of high utilization level, the available amounts of rainy season, the rainwater/stormwater resources account for 96.93% of the whole year. Therefore, the yield of rainy season rainwater/stormwater resources in the semi-arid region of the Loess Plateau is the main component of the basin. In the design stage of rainwater/stormwater resources collection and utilization can be taken as the design basis of the available amounts of rainy season [68].

Available Amounts of the Rainwater/Stormwater Resources in Different Precipitation Guarantee Rates

The available amounts of the rainwater/stormwater resources in the basin are an important reference for the construction of efficient utilization. However, in the semi-arid region of the Loess Plateau, the recoverable amounts of the rainwater/stormwater resources are greatly affected by precipitation conditions. Therefore, while analyzing the total available amounts of rainwater/stormwater resources, the available amounts of them under different precipitation guarantee rates should be quantized in detail. Only in this way can we provide a reliable theoretical basis for the efficient utilization of rainwater/stormwater resources in semi-arid regions. The precipitation data from 1960 to 2010 in Xifeng District were selected to make the cumulative frequency curves of precipitation and the theoretical frequency curve of precipitation (P-III curve) in Xifeng District, as shown in the reference [69]. Then, according to the precipitation under different precipitation guarantee

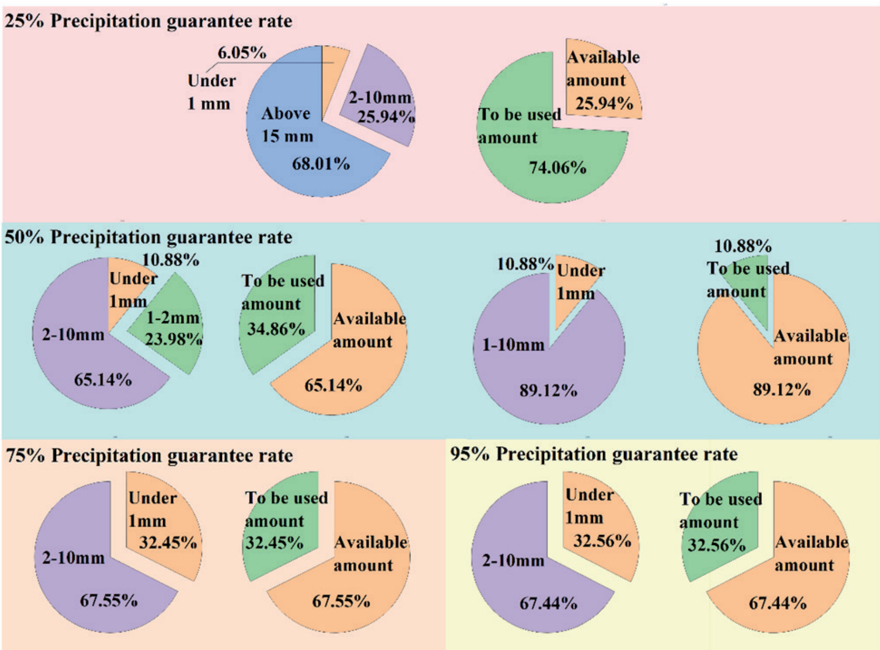

Fig. 9. Analysis chart of rainwater/stormwater resources yield and available amounts under different precipitation guarantee rates in Si Jiagou Basin.

rates, to analyze the availability of rainwater/stormwater resources in the whole year and rainy season, selected years with similar precipitation as typical years under the guarantee rates. The typical years with precipitation guarantee rates of 25%, 50%, 75%, and 95% were selected to analyze the availability of rainwater/stormwater resources in the basin, which were 1981, 1998, 2009, and 1986. The available amounts of the rainwater/stormwater resources under different precipitation guarantee rates were calculated through the output of the SWAT model of the ungauged areas (Fig. 8e). When the precipitation guarantee rate of the basin was 25%, the collectible amounts of the rainwater/stormwater resources for the whole year were 44.51×10^4 m^3, and the collectible amounts is 16.79×10^4 m^3 when the guarantee rate is 50%. When the guarantee rate is 75%, the collectible amounts are 11.55×10^4 m^3, and when the guarantee rate is 95%, the collectible amounts are 9.17×10^4 m^3. The collectible amounts of the rainwater/stormwater resources in drought years are only 20.60% of the abundant years, and the collectible amounts of the rainwater/stormwater resources vary significantly under different precipitation guarantee rates.

The availability of the rainwater/stormwater resources under different precipitation guarantee rates was analyzed (Fig. 9). When the precipitation guarantee rate was 25%, the total rainwater/stormwater resources were 44.51×10^4 m^3, among which, the 2-10 mm resources accounted for 25.94% of the total, while the depth of these resources above 15mm reached 68.01%, most of which was flood, which could not be utilized. The available amounts were 11.55×10^4 m^3, 74.06% of the floods were to be used, the available amounts were low in this low guarantee rate, and the flood control pressure was large. When the precipitation guarantee rate was 50%, the total amount was 16.79×10^4 m^3, and when the utilization level of the rainwater/stormwater resources was medium, their utilizable amounts with a depth of 2-10 mm can reach 65.14% of the basin water output yield, and the utilizable amounts can reach 10.98×10^4 m^3, and nearly 35% were the amounts to be utilized (5.85×10^4 m^3). The rainwater/stormwater resources of 1-2 mm account for 23.98% of the total, and there was no volume of more than 15 mm. If the utilization range was 1-10 mm at a high utilization level, the utilizable amounts account for 89.12% of the total, and the utilizable amounts reach 14.97×10^4 m^3, and the utilization potential is large. When the precipitation guarantee rate was 75%, the total amounts of the rainwater/stormwater resources were 11.55×10^4 m^3, and these resources only consisted of 1-10 mm, none of them was above 10 mm. Therefore, the available amounts of the rainwater/stormwater resources from 2-10 mm can be used, and the available amounts were 7.81×10^4 m^3, accounting for 67.55% of the total, other 32.45% were the amounts to be used. However, the amounts were small and dispersed, it was difficult to collect and use, so the utilization potential was not great. When the precipitation guarantee rate was 95%, the total amount of the rainwater/stormwater resources was 9.17×10^4 m^3, and these resources only consisted of 1-10 mm. The 2-10 mm rainwater/stormwater resources can be utilized, the available amounts were 6.19×10^4 m^3, accounting for 67.44% of the total, and the other 32.56% is the amount to be utilized. It can be seen that under the circumstance of a higher precipitation guarantee rate, the utilization range of the rainwater/stormwater resources was 2-10 mm, accounting for more than 67% of the total. It was difficult to increase the collectible amounts, so the utilization efficiency of nearly 70% of the existing rainwater/stormwater resources should be improved. In the years with a low precipitation guarantee rate, the utilization level of rainwater/stormwater resources can be appropriately improved.

It is worth noting that although the collectible utilization of rainwater/stormwater resources varies greatly under different precipitation guarantee rates, the collectible utilization of these resources under a 95%

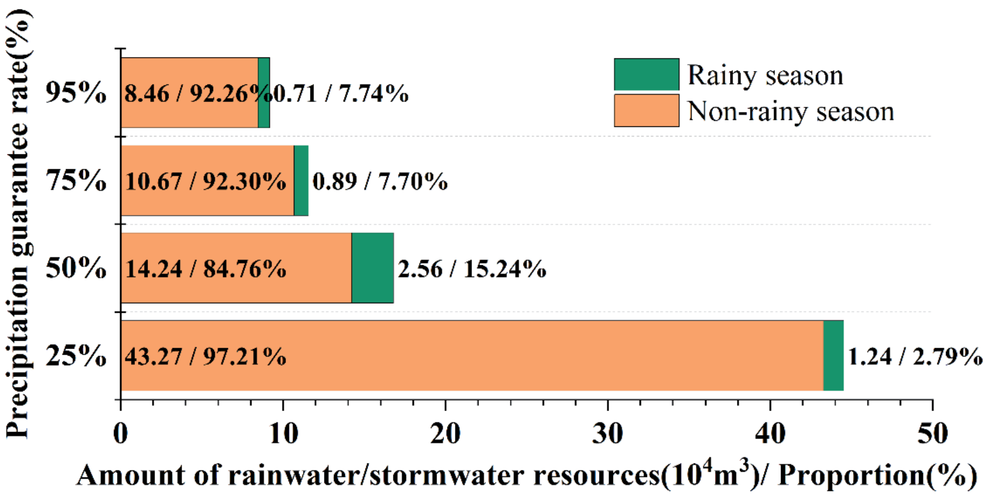

Fig. 10. Comparison chart of rainwater/stormwater resources yield during the rainy season and non-rainy season under different precipitation guarantee rates in Si Jiagou Basin.

precipitation guarantee rate only accounts for 20.6% of the 25% guarantee rate. However, most of the collectible utilization of rainwater/stormwater resources under various precipitation guarantee rates is concentrated in the rainy season (Fig. 10). When the precipitation guarantee rate is 25%, the collectible amount of rainwater/stormwater resources in the rainy season is 43.27×10^4 m^3, accounting for 97.21% of the whole year collectible amount. When the guarantee rate is 50%, the collectible amount is 14.24×10^4 m^3, accounting for 84.78% of the whole year. When the guarantee rate is 75%, the collectible amount is 10.67×10^4 m^3, accounting for 92.31% of the whole year. When the guarantee rate is 95%, accounting for 92.26% of the whole year, and the collection amount is 8.46×10^4 m^3. When Griffiths et al. [67] used the SWAT model to simulate runoff in the Little Zab River Basin (LZRB) between Iraq and Iran, it was found that rainwater and stormwater resources during the rainy season are the main sources of runoff in the basin. In different typical years, the output yield of rainwater/stormwater resources in the rainy season still accounts for more than 85% of the whole year. Therefore, the collectible utilization amounts of rainwater/stormwater resources in the rainy season can be used as the basis for the design of relevant collection and utilization measures.

Available Amounts of Rainwater/Stormwater Resources in Rainy Season Under Different Precipitation Guarantee Rates

Analyzing the depth of rainwater/stormwater resources with different precipitation guarantee rates in the basin (Fig. 11), it is found that these resources with a depth below 1 mm are distributed in each precipitation guarantee rate. Except that the rainwater/stormwater resources with a guaranteed rate of 25% are 53.9% in the rainy season, the collected amounts in other guaranteed rates account for more than 70% of the whole year. However, the rainwater/stormwater resources with a depth below one mm are difficult to collect and utilize. The rainwater/stormwater resources yield of 1-2 mm only exists when the precipitation guarantee rate is 50%, and these resources amounts in the rainy season is 2.03×10^4 m^3, accounting for 50.37% of the whole year. Under all the guarantee rates, the rainwater/stormwater resources of 2-10 mm are generated during the rainy season, which is an important part of the rainwater/stormwater resources in the basin, so the collection and utilization of rainwater/stormwater resources during the rainy season is very critical. Nageswara Rao, (2020) found that the upper Gosthani river basin in India receives a good amount of rainfall, but most of it is lost as surface runoff (nearly 40% of total rainfall) due to rapid overland flow and impermeable rocks [70]. The rainwater/stormwater resources at a depth of more than 15 mm is 30.27×10^4 m^3, which only occurs when the precipitation guarantee rate is 25%, and all exist in the rainy season. This part of resources is difficult to use as rainwater/stormwater resources. Storage and utilization of these resources can be attempted to further improve the availability and utilization level of the rainwater/stormwater resources in the basin under the condition of ensuring safety.

According to the separate analysis of the rainwater/stormwater resources in the rainy season (Fig. 12), it is found that when the precipitation guarantee rate is 25%, the total rainwater/stormwater resources is 43.27×10^4 m^3, among them, 2-10 mm accounts for 26.69% of the total. The depth of rainwater/stormwater resources above 15 mm reaches 69.96%, most of them are floods that cannot

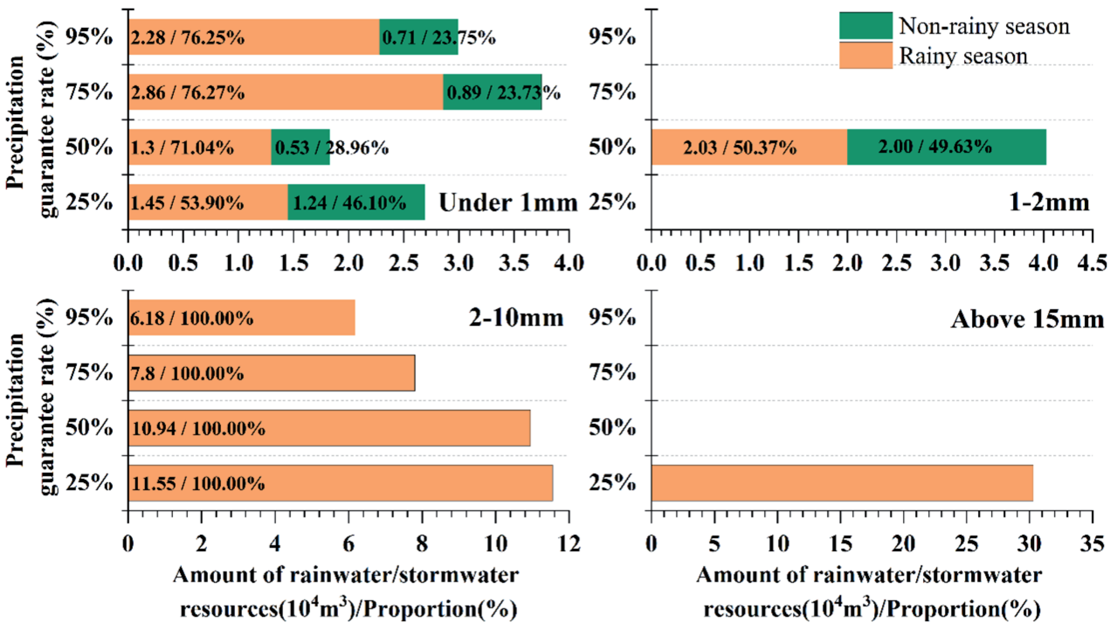

Fig. 11. Yield analysis chart of rainwater/stormwater resources during the rainy season and non-rainy season in Si Jiagou Basin.

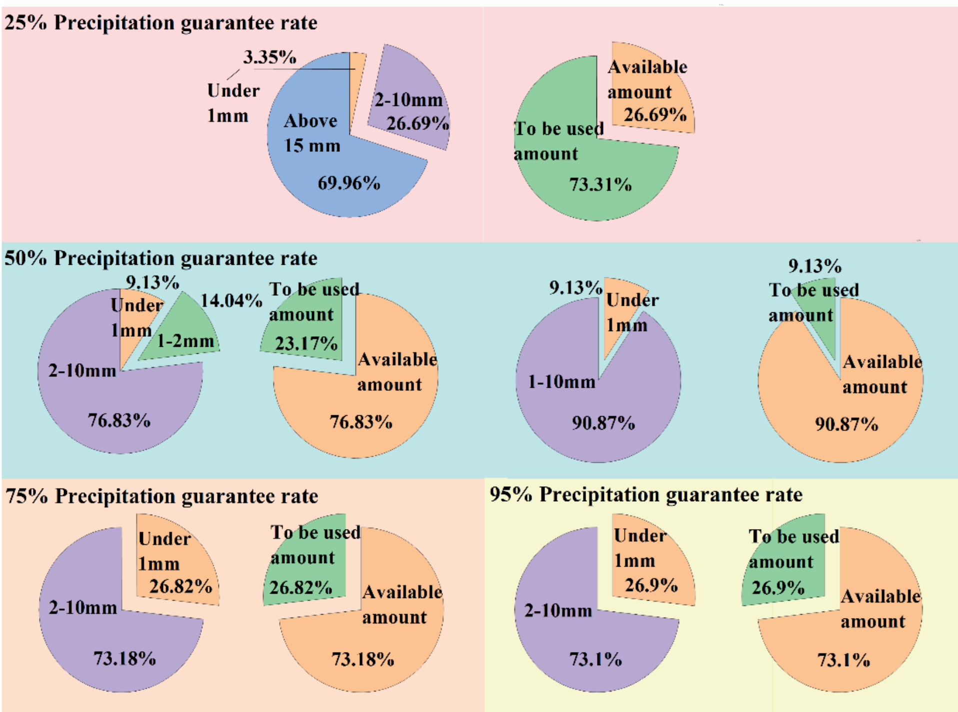

Fig. 12. Analysis chart of rainwater/stormwater resources yield and available amounts during the rainy season under different precipitation guarantee rates in Si Jiagou Basin.

be used, and the available amount is 11.55×10^4 m^3. 73.31% of the flood amounts are to be used. The utilization of rainwater/stormwater resources with a low precipitation guarantee rate is lower, and the flood control pressure is greater. When the precipitation guarantee rate is 50%, the total amounts are 14.24×10^4 m^3. When the utilization level of these resources in the basin is medium, the available amounts of 2-10 mm depth can reach 76.83% of the basin output water yield. The utilization amounts can reach 10.94×10^4 m^3, which is close to 23.17% for the utilization amounts (3.30×10^4 m^3) to be used. The rainwater/stormwater resources of 1-2 mm account for 23.98% of the total, and there are no resources above 15 mm. In the case of high utilization level, the utilization range of rainwater/stormwater resources is 1-10 mm, so the utilizable rainwater/stormwater resources account for 90.87% of the total, and the utilization amounts reach 12.94×10^4 m^3. Therefore, the utilization potential of rainwater/stormwater resources in the rainy season is large. When the precipitation guarantee rate is 75%, the total amount of the rainwater/stormwater resources is 10.67×10^4 m^3, these resources only consist of 1-10mm, and the available amounts range from 2-10 mm, accounting for 73.18% of the total, and the available amounts is 7.81×10^4 m^3. Nearly 1/4 of them are difficult to collect due to the small depth, and the utilization potential is small. When the precipitation guarantee rate is 95%, the total amounts are 8.46×10^4 m^3, and no rainwater/stormwater resources of more than 10mm are generated. These resources only consist of 1-10 mm, and the utilizable amounts of them of 2-10 mm are 6.19×10^4 m^3, accounting for 73.1% of the total amounts, and 26.9% are the amounts to be utilized. In the case of a high precipitation guarantee rate, the utilization range of the rainwater/stormwater resources is 2-10 mm, accounting for more than 73% of the total. It is difficult to increase the collectible amounts, so the utilization efficiency of existing rainwater/stormwater resources should be improved. Under the condition of a low precipitation guarantee rate, the utilization potential of the rainwater/stormwater resources is great. The utilization level of rainwater/stormwater resources should be appropriately improved to further promote the high-quality development of the rainwater/stormwater resources utilization in the basin under the condition of ensuring safety.

Conclusions

This study constructed a SWAT distributed hydrological model for basins with observed data in the semi-arid region of the Loess Plateau, taking the model output which met accuracy requirements as the basis for calculating the available amounts of rainwater/stormwater resources in ungauged sub-basin. By analyzing the output of the calculation model, the utilizable amounts, utilization period, and water-saving potential area of the ungauged sub-basin were obtained. It provides essential support for the efficient utilization of rainwater/stormwater resources and the construction of collection and utilization facilities in the semi-arid region of the Loess Plateau. The main conclusions are as follows:

The established SWAT hydrological model of the Malian River Basin has a certainty coefficient of 0.79 and an NSE of 0.73, and the accuracy of the model is up to the standard, which can describe the hydrological process of the basin and calculate the rainwater/stormwater resources amounts and water-saving potential of the ungauged areas Si Jiagou Basin. The rainwater/stormwater resources distribution of Si Jiagou Basin simulated by the model matches the precipitation change. It is feasible to analyze the rainwater/stormwater resources of ungauged sub-basins through the output of the SWAT model of the gauged basin. Therefore, we can solve the problem that these resources of the ungauged areas are difficult to quantify, and can provide a basis for the construction of facilities for efficient utilization of rainwater/stormwater resources in subsequent basins.

In the semi-arid region of the Loess Plateau, the total amounts of rainwater/stormwater resources in ungauged Si Jiagou Basin in the past 30 years was 602.68×10^4 m^3, which showed great utilization potential. Among them, the 2-10 mm rainwater/stormwater resources amounts are 309.52×10^4 m^3, accounting for 51.36% of the total. This part of rainwater/stormwater resources amounts is the largest and most stable, it is the crucial period and potential area for efficient utilization of rainwater/stormwater resources in the basin. Under the medium water resources utilization level in the basin, this part of rainwater/stormwater resources can be utilized. At the high utilization level, the utilization depth increased from 1-15 mm, the utilization amounts increased by 21.2%, and the available utilization reached 72.56% (437.33×10^4 m^3) of the total, with considerable amounts. The part of the output yield flow in 1-2 mm (15.83%) was the main point and direction of the utilization level of rainwater/stormwater resources.

The output yield of rainwater/stormwater resources in Si Jiagou Basin during the rainy season can reach 93.52% of the total, and 97.99% of these resources of 2-10 mm are distributed in the rainy season, which is the crucial period for efficient utilization of them in the basin. Under the medium level of the rainwater/stormwater resources utilization, their available amounts of 2-10 mm are 303.31×10^4 m^3, accounting for 53.81% of the total in the rainy season. Under the condition of high-level utilization, the available amounts reached 75.21% (437.33×10^4 m^3) of the total, accounting for 96.93% of the whole year, and the available amounts could be increased by 21.4%. The yield of rainwater/stormwater resources in the rainy season is the main component of the total in the river basin. It is an important basis for the efficient utilization of rainwater/stormwater resources in the river basin to quantify the yield of these resources in rainy season, the characteristics of generation time, and reasonable determination of available amounts.

The availability of rainwater/stormwater resources in the basin is greatly affected by the precipitation situation, the availability of a 95% precipitation guarantee rate only accounts for 20.6% of the 25% guarantee rate. The output yield of rainwater/stormwater resources in the rainy season under different guarantee rates accounts for more than 85% of the whole year, and the output yield of these resources in the rainy season can be used as the basis for the design of collection and utilization facilities. Under the higher precipitation guarantee rate, the available range of rainwater/stormwater resources in the basin is 2-10 mm, accounting for more than 67% of the total. In the years with low guarantee rates, the utilization potential and the risk of rainwater/stormwater resources coexist. In order to provide support for the high-quality development of the semi-arid region of the Loess Plateau and the mitigation of water resources crisis, it can be attempted to store and utilize the rainwater/stormwater resources in the condition to ensure safety.

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CRediT Authorship Contribution Statement

Yayu Gao: Conceptualization, Funding acquisition, Formal analysis, Methodology, Visualization, Resources, Writing – original draft, Writing-review & editing. Yupei Hu: Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing. Yu Song: Data curation, Investigation. Jinhua Tian: Data curation, Funding acquisition, Investigation. Rongxiang Hua: Investigation, Visualization.

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Conflict of Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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