Evaluation of National Rainwater Development and Utilization Potential Based on Geoclimatic Zoning

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Abstract. In response to the fact that it is not strong of systematic evaluation of rainwater utilization potential, and lack the results of rainwater utilization potential for the whole country and different levels of climate zones, this paper defines and divides suitable rainwater harvesting and utilization areas based on the differences of geography, climate and geological conditions in China, and also describes the rainwater development and utilization potential from the perspective of "appropriate" development and utilization of unconventional water resources and constructs a calculation model to evaluate the rainwater development and utilization potential in China based on geological and climatic dimensions. The results show that China's rainwater harvesting and utilization area is divided into core area and general area, in which the core area is divided into Loess Plateau hilly area and Karst area. In 2025, China's potential of rainwater development and utilization is 117.14 billion m^3, while the rainwater development and utilization rate is only 0.7%, so there is a large potential and space for development and utilization of rainwater resources in the future, and we can vigorously develop and utilize the rainwater in places where there is demand.

Keywords: Rainwater Utilization Potential; Geoclimatic Zoning; Evaluation; Appropriate.

1 Introduction

With the global worsening situation of drought and the increasing scarcity of water resources, rainwater has become a new way to solve the water crisis in water-scarce countries and regions. Rainwater is the most fundamental source of water resources and rainwater resource potential is the basis for ensuring the sustainable economic and social development and guaranteeing that rainwater resources can be exploited sustainably[1].Rainwater harvesting has a high potential to promote agricultural development[2]. In recent years, the evaluation of rainwater resources utilization potential is a popular topic of research by scholars at home and abroad, and Li proposed a model for calculating the target potential of rainwater resources utilization in watersheds based on the defining of theoretical[3],realistic and target potential of rainwater resources utilization. Zhao used GIS technology to establish a quantitative evaluation model of rainwater

P. Xiang et al. (eds.), *Proceedings of the 2023 5th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2023)*, Atlantis Highlights in Engineering 26,
https://doi.org/10.2991/978-94-6463-398-6_26

resources utilization potential[4],and evaluated the potential of rainwater resources utilization in the region of the Loess Plateau area. Sara analyzed the endogenous resource potential of urban rainwater runoff, using a campus in Barcelona as an example [5]. Meanwhile, the application of SCS-CN method, NRCS-CN method, set-pair analysis method, and gray correlation theory [6~9] has broadened the diversity of evaluation methods for rainwater resources utilization potential. Summarizing the previous studies, the rainwater resources utilization potential has gradually changed from the initial theoretical research and qualitative analysis to quantitative research, and some achievements have been made. However, the evaluation of rainwater resource potential is concentrated in certain regions and drainage basins, and the evaluation of rainwater resources utilization potential is not systematic, and the understanding of the driving and constraining mechanisms of rainwater development and utilization and its regional differences is not deep enough and comprehensive, and the results of rainwater resources utilization potential of the whole country and different levels of climate zones are lacking. Therefore, it seems very necessary to explore the evaluation method for evaluating the rainwater resource potential in China. This paper defines the suitable area for rainwater utilization from the geological, geographical and climatic scale, defines the rainwater development and utilization potential from the perspective of appropriateness, evaluates the national rainwater development and utilization potential by ArcGIS and Thiessen Polygons, innovates the evaluation theory and method of "appropriateness" development and utilization of unconventional water resources, makes the development and utilization of unconventional water resources in China more scientific and reliable at the macro and micro levels, providing technical support for the macro decision making and planning design of unconventional water resources control and allocation in China.

2 Principle and framework of rainwater harvesting and utilization area division

2.1 Principle of project construction suitability

Rainwater harvesting and utilization projects are generally suitable for construction in areas with precipitation above 250 mm, and they can be implemented in areas with precipitation around 200 mm when special needs arise[10].In this paper, the areas with precipitation lower than 200 mm are first excluded, and Beijing, Hebei Province, Shanxi Province, Inner Mongolia Autonomous Region, Anhui Province, Jiangxi Province, Shandong Province, Henan Province, Hubei Province, Guangdong Province, Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province, Guizhou Province, Yunnan Province, Shanxi Province, Gansu Province, Qinghai Province and Ningxia Hui Autonomous Region, where rainwater utilization projects are concentrated, are adopted as the basic research areas.

2.2 Principle of rainwater resource demand

China's geography and geological conditions vary greatly from east to west and from north to south, and the geographical characteristics of rainwater harvesting and utilization are obvious, which are mainly concentrated in the hilly areas of the Loess Plateau and Karst areas where water use is difficult in mountain areas. Loess plateau area is one of the poorest areas with the most serious soil erosion, more prominent ecological and environmental problems, and backward socio-economic development in China[11]. With an arid climate, scarce precipitation with uneven distribution within the year, and low utilization of rainfall, 60%-70% of rainfall lost as surface runoff and ineffective evaporation [12], this region is the most water-stressed area in China, with extreme difficulties in domestic water use and harsh conditions for agricultural production. Although the Karst area has abundant rainfall, less evaporation capacity and rich surface and ground water resources, surface water is not easily stored and groundwater is buried deep and not easily exploited, thus forming an arid water-scarce area under humid climate, resulting in prominent contradiction between supply and demand of water resources in local mountains and difficulties in water supply for domestic production and agricultural irrigation. Rainwater resources are the most important water resources in Loess Plateau area and Karst area.

Therefore, considering the different natural geology, topography and geomorphology characteristics, the Loess Plateau hilly areas with serious resource-based water shortage and the Karst areas with serious seasonal water shortage are classified as the core area of rainwater harvesting and utilization, and other areas as the general area of rainwater harvesting and utilization according to local conditions.

2.3 Principle of climate zoning

Climate conditions are the key factor to determine rainwater resources, different climatic zones have different rainfall and different degree of rainwater utilization. Therefore, the core area and general area of rainwater harvesting and utilization are overlaid with Agro-climatic layers and divided into smaller climatic zones so as to calculate rainwater development and utilization potential more reasonably and accurately.

The dividing framework of rainwater harvesting and utilization area is shown in Figure 1.

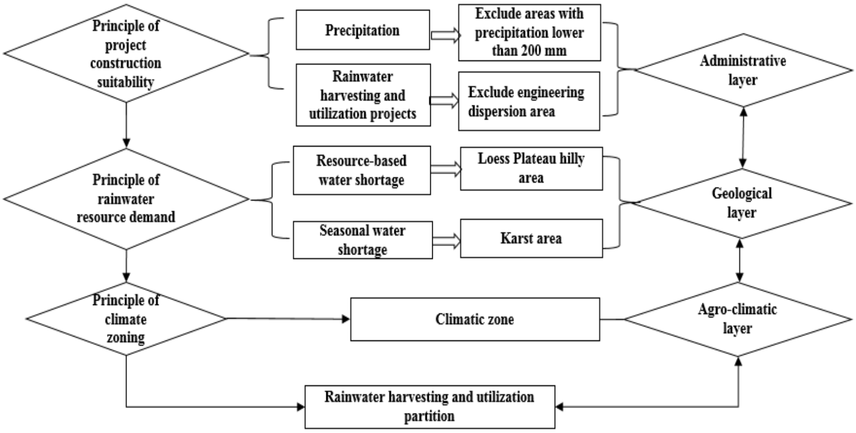


Fig. 1. The dividing framework of rainwater harvesting and utilization area

3 Basic concept and potential evaluation method for rainwater development and utilization

3.1 Basic concept of rainwater development and utilization

Rainwater harvesting and utilization is a form of rainwater utilization and also a form of water resources development. All forms of water resource on Earth come from rainwater. In this sense, rainwater utilization is the utilization of rainwater in its original state or the utilization of rainwater at the initial transformation stage, and as for other forms of water resources formed by rainwater after multiple transformations, such as the utilization of runoff in rivers with large drainage basin areas and groundwater extraction, they should not fall into the category of rainwater utilization [13]. Through such means as changing the microscopic shape of the ground surface, regulating the infiltration capacity of the soil, the rainwater harvesting and utilization could effectively change the distribution of rainwater on the ground surface and the way of surface runoff collection, extend the time of surface runoff, or change the path of surface runoff movement, thus achieving the local collection of runoff and serving the purpose of rainwater harvesting and utilization. China's rainwater harvesting and utilization mainly includes on-site utilization, off-site utilization and overlapping utilization methods.

Rainwater resources utilization is a new concept proposed in recent years, and the basic connotation of rainwater resources utilization lies in a process of emphasizing the evaluation and utilization of rainwater as a resource, and through planning and design, taking corresponding engineering measures to transform rainwater into a usable water source [14], and finally producing its value. The rainwater resources utilization potential refers to the maximum capacity of developing and utilizing rainwater resources under certain technical and economic conditions, in a specific area and within a certain period of time [15-16]. Rainwater utilization potential reflects the connotation of appropriateness, so we define rainwater resources from the perspective of "appropriateness".

The theoretical utilization of rainwater resources is the total amount of precipitation in the drainage basin or region. The amount of rainwater resources that can be utilized under the constraints of the current economic conditions and the level of science and technology is the amount of rainwater resources available. Under the current engineering conditions of rainwater collection, storage and utilization, the amount of rainwater resources that have been realized is the current utilization amount of rainwater resources. Rainwater development and utilization potential is the difference between the amount of rainwater resources available and the current utilization amount of rainwater resources.

3.2 Evaluation method of rainwater development and utilization potential

3.2.1 Rainwater development and utilization potential model construction.

Based on the definition of rainwater development and utilization potential, Equations (1) and (2) are constructed:

$$W_e = 10^3 \sum_{i=1}^{n} \lambda_i P A_i \tag{1}$$

$$\mathrm{W} = W_e - W_y \tag{2}$$

Where: W_e is the available amount of rainwater resources, in m^3; P is the annual precipitation under the designed frequency, in mm; A_i is the area of different catchment surfaces, in km^2; λ_i is the catchment coefficient of different catchment surfaces which is also determined in Equations(4)and(5); W is rainwater development and utilization potential, in m^3; W_y is the current amount of rainwater resources utilization, in m^3.

3.2.2 Calculation method of annual design precipitation under climate zoning scale.

Factors such as uneven temporal and spatial distribution of precipitation across the country and large seasonal fluctuations have caused a large amount of rainwater resources to be lost, and the interception and storage of runoff resources is the main way to solve the water shortage problem. Large-scale evaluation of rainwater development and utilization potential requires the division of precipitation units on the basis of geomorphological zoning. The data of precipitation come from the actual measurement data of weather stations, and the precipitation observed by weather stations can only represent the rainfall in a smaller area around that weather station, and the distribution is uneven. Therefore, this paper uses the Thiessen Polygons of ArcGIS to calculate the designed annual rainfall after excluding the invalid precipitation in a certain area. The calculation of regional average precipitation is below:

$$\bar{x} = \frac{f_1 x_1 + f_2 x_2 + \cdots + f_n x_n}{f_1 + f_2 + \cdots + f_n} = \frac{1}{F} \sum_{i=1}^{n} f_i x_i = \sum_{i-1}^{n} A_i x_i \tag{3}$$

Where: x_i is the amount of precipitation at the precipitation observation point, in mm; f_i is area of the Thiessen polygon, in km^2; n is the number of precipitation observation points or Thiessen polygons in the region; F is the total area of the region, in km^2; A_i is Weight coefficient of precipitation station.

3.2.3 Statistical method of underlying surface area for rainwater harvesting and utilization.

In terms of the current level of rainwater harvesting and storage technology, the only way to use rainwater resources is off-site utilization. Through construction of small catchment fields and a certain number of water storage facilities, the precipitation in a certain area will be gathered, stored and used for other areas of rainwater utilization. So the rainwater development and utilization potential is the potential of rainwater utilization under the off-site utilization model. At present, urban land, rural settlements, rural roads, highway land, other construction land, bare land, bare rocky land can collect, store and utilize rainwater by building small catchment fields or small water storage facilities, and such area is classified as off-site utilization area.

3.2.4 Method of determining annual rainfall catchment coefficient.

By analyzing the rainfall process line of multi-year average precipitation at typical stations, the annual rainfall catchment of the underlying surface is calculated from the single-site precipitation and the number of rainfall sites, and the relationship between the annual precipitation and the catchment coefficient is deduced, and then the rainfall catchment coefficient is obtained.

The catchment coefficient of single-site rainfall is the area occupied by the rainfall meter that should be taken when calculating the unit precipitation. It should be calculated according to the actual effective area based on the following formula:

$$\lambda_0 = \frac{P_0 * 10^5}{A_0 * \mathrm{P}} \tag{4}$$

Where: λ_0 is the single catchment coefficient; P_0 is the actual net precipitation; A_0 is the effective catchment area; P is the single precipitation amount.

The catchment coefficient for the whole year is calculated by the following formula:

$$\lambda = \sum P_i * \lambda_i / \sum P_i \tag{5}$$

Where: λ is the year-round catchment coefficient; P_i is the precipitation amount for each rainfall event during the year; λ_i is the catchment coefficient of each rainfall site, which is calculated according to the rainfall and rain intensity of each rainfall site.

The values of catchment coefficients are different for different catchment surfaces, and the catchment coefficients are different for different climatic zones. The catchment coefficient takes into account the catchment discount due to topography, infiltration, and the retention effect of surface soil and water conservation measures [17].

3.3 Data source

The data source of annual precipitation, underlying surface area of rainwater harvesting and utilization, catchment coefficient, Loess Plateau hilly area, Karst area and agricultural climatic zoning are shown in table 1.

Table 1. Data source

S/N	Data category	Data source
1	Design annual precipitation	Precipitation observed at key weather stations nationwide from 1984-2015, with invalid rainfall excluded.
2	Underlying surface area of rainwater harvesting and utilization	Land use data interpreted from remote sensing data in 2015, where the road data of underlying surface is obtained from the national road distribution data in 2016.
3	Catchment coefficient	Technical Code for Rainwater Collection, Storage and Utilization (GB/T 50596-2010) and Theory, Technology and Practice of Rural Rainwater Harvesting and Utilization
4	Loess Plateau hilly area	Source from vector data of Resource and Environmental Science and Data Center
5	Karst area	Source from the Karst Science Data Center, obtained by deciphering from a 1: 500,000 geological map.
6	Agricultural climatic zoning	The Source from the Resource and Environmental Science and Data Center, which divides China into 38 agricultural natural regions based on temperature zones and humidities.

4 Results of rainwater harvesting and utilization zoning and potential evaluation

4.1 Rainwater harvesting and utilization area division

In accordance with the principle of rainwater harvesting and utilization area division, China's rainwater harvesting and utilization area is divided into core area and general area considering the different natural geography, geological geomorphology and climate characteristics. The core area is divided into Loess Plateau area and Karst area, and each area is subdivided into seventeen climatic zones according to Agro-climatic zones, as shown in Figure 2.

Loess Plateau region includes all of Shanxi Province, northern Shaanxi, central and eastern Gansu, all of Ningxia, eastern Qinghai, southern Inner Mongolia and the northwest part of Henan, which can be divided into arid middle temperate zone, arid warm temperate zone, warm temperate zone, and plateau temperate zone according to climatic zone, and marked with I1, I2, I3, and I4 respectively in Figure 2. The region involves a total area of 649,300km^2, accounting for 14% of the entire rainwater harvesting and utilization project distribution area.

Karst region includes Sichuan, Chongqing, Yunnan, Guizhou, Hubei, Hunan, Guangxi and Guangdong areas, which can be divided into five climatic regions based on climate zones, that is northern subtropics, central subtropics, southern subtropics, marginal tropics and plateau temperate zones, and marked with K1, K2, K3, K4, and K5 respectively in Figure 2. The region involves an area of about 1,935,100km^2, accounting for 43% of the entire rainwater harvesting and utilization project distribution area.

The general region of rainwater harvesting and utilization includes most parts of Qinghai, southern Shaanxi, Hebei, southeastern Inner Mongolia, Beijing, Shandong, most parts of Henan, Anhui and Jiangxi. Based on the climate zones, it can be divided into eight climate zones, that is cold temperate zone, middle temperate zone, arid middle temperate zone, warm temperate zone, plateau sub-frigid zone, plateau temperate zone, northern subtropical zone, and central subtropical zone, and marked with Y1, Y2, Y3, Y4, Y5, Y6, Y7, and Y8 respectively in Figure 2. The region involves an area of about 1,950,500km^2, accounting for 43% of the entire rainwater harvesting and storage project distribution area.

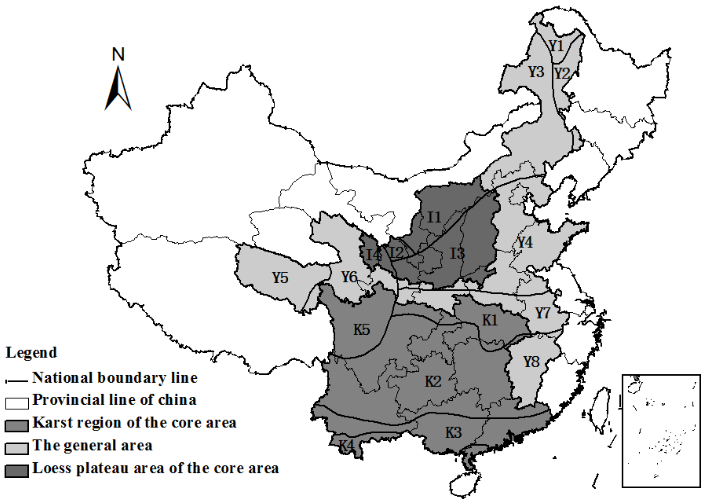


Fig. 2. National rainwater harvesting and utilization zoning map

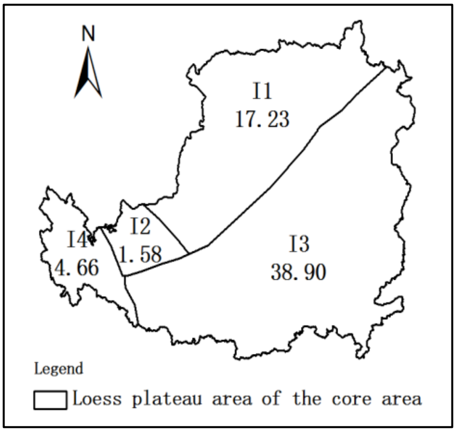
4.2 Potential for rainwater development and utilization in different climatic zones

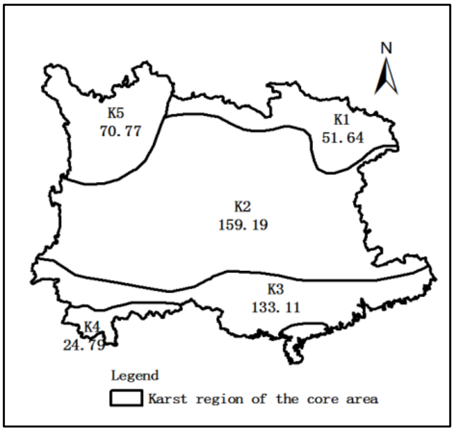
The regional average precipitation is calculated by the Equation (3) in different climatic zones, and according to the Equations (1) and (2) of rainwater development and utilization potential function model, the rainwater development and utilization potential of different climatic zones is calculated, as shown in Figure 3.

The climate of the Loess Plateau hilly area gradually warms from north to south, and the precipitation gradually increases from north to south. When the design frequency is 50%, the size of rainfall is ranked as I3>I4>I1>I2. And another factor that determines the potential of rainwater development and utilization, the underlying surface area for rainwater harvesting and utilization, is the largest in the warm temperate zone (I4) of the Loess Plateau hilly area, with suitable climate, dense population, urban land, rural residential land and highway land, and the integrated underlying surface area of seven types of land utilization types is I3 > I1> I4 >I2. The size of the catchment coefficient is changing with the size of precipitation, therefore, combining the three factors, the warm temperate zone(I3) has the largest potential for rainwater development and utilization, which is 3.890 billion m^3. The arid warm temperate zone(I2) is the smallest, which is 0.158 billion m^3.

The precipitation in the Karst area gradually increases from north to south, and when the design frequency is 50%, the size of precipitation is ranked as K4>K3>K2>K1>K5. Combining the areas of the seven types of land utilization types in the underlying surface, in the Karst zone, the area of the underlying surface is K2> K5>K3>K1>K4. Whereas the rainwater development and utilization potential is the largest in the central subtropics (K2), which is 15.919 billion m^3. The marginal tropical(K4) potential is the smallest, which is 2.479 billion m^3.

The general area of rainwater harvesting and utilization spans a large area, gradually warming from north to south, the precipitation gradually increases from north to south. When the design frequency is 50%, the maximum precipitation is the central subtropical zone(Y8), the annual design precipitation is 1,606mm, and the plateau sub-frigid zone(Y5) is only 291mm. Combining the area of the seven types of land utilization types in the underlying surface, the underlying surface area of the warm temperate zone(Y4) is the largest and the cold temperate zone(Y1) is the smallest. And the rainwater development and utilization potential is the largest in the warm temperate zone(Y4), which is 24.293 billion m^3. The cold temperate zone(Y1) has the smallest potential of 0.034 billion m^3.





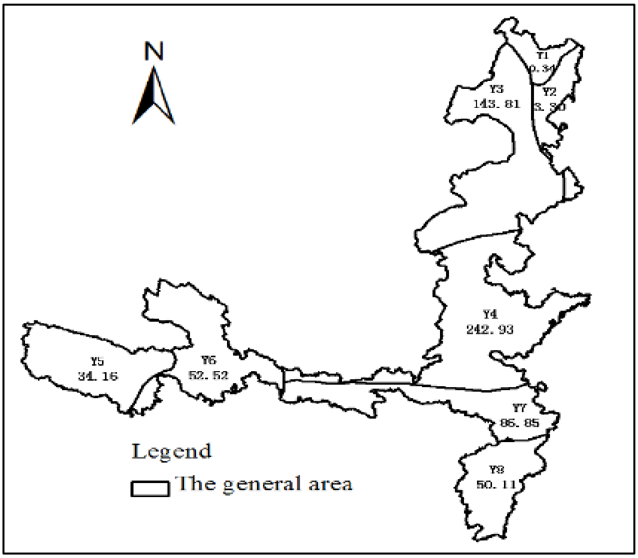


Fig. 3. The map of rainwater development and utilization potential in different climatic zones

4.3 Evaluation of national rainwater development and utilization potential

According to the model of rainwater development and utilization potential, the rainwater development and utilization potential is calculated with the climate overlaying administrative division as the unit. As shown in Fig.4.below.

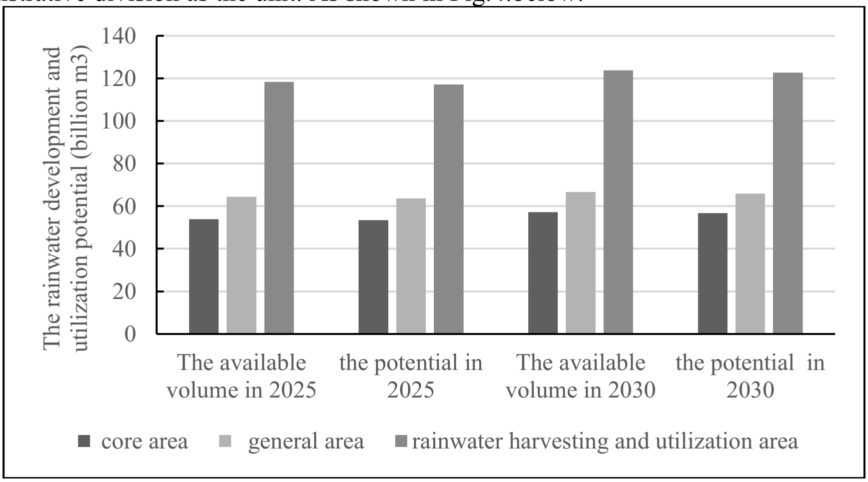


Fig. 4. The rainwater development and utilization potential in 2025and 2030

After calculation and analysis, when the design frequency is 50%, The national rainwater development and utilization potential in 2025 is 117.14 billion m^3, and the rainwater development and utilization potential in 2030 is 122.70 billion m^3. while the utilization amount of rainwater harvesting projects in China is only 0.794 billion m^3, accounting for about 0.7% of the available amount in 2025, it can be seen that at this stage, China's use of rainwater resources is very low, and the scale is small, there is a lot of space for the use of rainwater resources in the future, and it can be developed and utilized vigorously in places where there is demand.

5 Conclusions

China's geographic, climatic and geological conditions vary greatly from east to west and from south to north, and rainwater harvesting and utilization has obvious geographical characteristics. Through the principle of suitable construction of rainwater harvesting and utilization project, the principle of demand for rainwater resources and the climatic conditions of rainwater resources, the national rainwater utilization area is defined and divided. The large scope is divided into core area and general area of rainwater harvesting and utilization, the core area is divided into Loess Plateau hilly area and Karst area according to the geological structure characteristics, each area is further divided into different climatic zones according to the Agro-climatic characteristics, such a hierarchical division breaks through the difficulty of evaluating the rainwater resource potential in a large scope, making the evaluation results more scientific and reliable.

The previous evaluation of rainwater resource potential focuses on small regions, small drainage basins and other scopes, and lacks the results of rainwater development and utilization potential of the whole country and different levels of climatic zones. Based on the definition of rainwater harvesting and utilization zoning, this paper defines the rainwater development and utilization potential from the perspective of appropriateness by analyzing the form of rainwater resource transformation, proposes the theoretical amount of rainwater resources, the available amount of rainwater resources and the current amount of rainwater resources utilization, and analyzes and evaluates the national rainwater development and utilization potential by constructing the evaluation method of rainwater development and utilization potential. The evaluation results show that the current degree of utilization of rainwater resources in China is low and the scale is small, and there is a lot of space for future rainwater utilization, and it is recommended increasing the development of rainwater resources in the Loess Plateau area and Karst area in the core area of rainwater harvesting and utilization.

Acknowledgments

This study was supported by the Gansu Provincial Scientific Research Program for Water Conservancy (2021-71-15; 22GSLK005), Gansu Provincial Science and Technology Program (21JR7RA766), National Key R & D Program of China (2017YFC0403504).

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