

Original Paper

Water Conservation Mechanism and the Function Improvement of the Ecosystem in Karst Desertification Control

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Abstract

Water source conservation (WSC), as one of the most important ecosystem services (ES), plays a critical role in promoting the restoration of ecosystem structure. Severe soil erosion in karst regions has led to the continuous degradation of soil conservation services. Understanding the current research status and evolutionary trends in this field is crucial for establishing a theoretical foundation for future rocky desertification control in karst areas. This study collected 175 articles on WSC based on the Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) databases. Through systematic reviews and qualitative analyses, this paper summarizes research progress, achievements, and development trends from multiple dimensions, and employs spatial visualization and analytical tools (such as SATI and Gephi) to present the research findings visually. It addresses key scientific issues and future trends in existing water source conservation measures, aiming to enhance water source conservation capacity in rocky desertification areas. This study provides significant guidance for optimizing the layout of ecological engineering projects and rocky desertification control in karst regions.

Keywords

karst desertification, water conservation, ecosystem services, soil physicochemical properties

1. Introduction

Karst refers to a unique geomorphic and hydrological system shaped by dissolution and the coupled processes of groundwater and surface water in soluble rocks (dominated by carbonate rocks). It is typically characterized by well-developed structures such as fissures, caves, underground rivers, and dolines, and exhibits a typical “surface–subsurface dual water cycle” (Jiang et al., 2014; Sweeting,

1995). However, karst ecosystems are also renowned for their remarkable ecological fragility. A fragile rock–soil interface, thin and discontinuous soil layers, intense water leakage, combined with historical irrational human disturbances, readily lead to severe soil erosion, bedrock exposure, and even rocky desertification, making it a typical ecologically fragile region where “the local environment cannot sustain the local population” (Hartmann et al., 2014). To address this severe challenge, China has implemented large-scale comprehensive rocky desertification control projects in karst areas. The core goal of governance is not only to curb bedrock exposure but also to rebuild healthy and stable ecosystems (Liu et al., 2007). Among these, enhancing the water conservation function of ecosystems is regarded as a key link in restoring eco-hydrological balance, strengthening regional drought resistance, and ensuring water security, which is achieved through engineering and biological measures such as forest and grass vegetation restoration and soil improvement (Xiong, 2012). Therefore, this study takes karst rocky desertification control areas as the research object, focuses on the “structure–process–function” chain of ecosystem water conservation, reveals its formation mechanisms, and proposes operational pathways for function enhancement and value realization.

Karst is not only a unique landscape but also a globally critical aquifer system that provides basic domestic and productive water sources for hundreds of millions of people (Ford & Williams, 2007). Nevertheless, this system is inherently fragile, marked by “thin soil layers, poor water storage capacity, rapid runoff convergence, and high spatial heterogeneity” (Ford & Williams, 2007). Once precipitation enters the developed karst fissure and conduit network, rapid water infiltration and runoff concentration coexist, easily triggering surface drought and soil erosion (Kalhor et al., 2019). In southwest China’s karst regions, long-term intensive human activities (e.g., steep-slope reclamation, overgrazing, fuelwood harvesting, and engineering development) have superimposed on the inherently fragile geological background, triggering severe soil loss and bedrock exposure, leading to the spread of rocky desertification and a vicious cycle of “soil erosion–ecosystem degradation” (Jiang et al., 2014). Thus, the fundamental goal of rocky desertification control goes far beyond achieving surface “greening”; it lies in systematically reconstructing the “vegetation–litter–soil” continuum to effectively enhance the ecosystem’s water conservation function, enabling it to truly “store water, retain soil, and support sustainable industries” (Brauman et al., 2007). Against this backdrop, in-depth exploration of the mechanisms of ecosystem water conservation in karst rocky desertification control areas and the proposal of scientific and effective pathways for function enhancement are not only of great scientific value but also an urgent practical need for regional ecological security and sustainable development.

Water conservation is a core issue in ecosystem stability and restoration, and also the key to solving ecological degradation in southwest rocky desertification areas (Wang et al., 2022). Land use changes can alter soil conditions by increasing soil erosion and disturbing the underlying surface, affecting hydrological processes such as infiltration, evapotranspiration, soil water retention, and surface runoff, thereby influencing water conservation functions (Chen et al., 2023b). This study provides theoretical support for realizing the advocated transformation pathway of “lucid waters and lush mountains”: ①It

breaks through the limitations of traditional macro-assessment or single-factor analysis. From an integrated “structure–process–function” framework, it systematically analyzes the synergistic regulation mechanisms of vegetation restoration (e.g., canopy structure, evapotranspiration regulation), litter retention, and soil structure improvement (aggregates, pore networks) on water movement, constructs a mechanistic interpretation model applicable to karst governance areas, and compensates for the deficiency of insufficient mechanistic attribution in current research (Brauman et al., 2007). ②Closely adhering to the core characteristics of strong spatial heterogeneity and rapid hydrological response in karst environments, it identifies the key control links and potential thresholds for water conservation function formation by comparing different ecosystem governance stages and vegetation restoration models, providing empirical support for developing region-specific ecosystems (Hartmann et al., 2014). ③Actively responding to the national strategic orientation of establishing and improving mechanisms for enhancing water conservation functions, it attempts to link the formation mechanisms of water conservation functions with monitorable indicator systems, promoting the shift of water conservation from “qualitative description” to “quantitative contribution” (Ouyang et al., 2020), and providing theoretical support for further research on mechanisms for enhancing water conservation functions.

2. Materials and Methods

2.1 Literature Acquisition Source

Based on the CNKI Information Resource Database of China National Knowledge Infrastructure (<https://www.cnki.net/>) Web of Science and Foreign Journal Resource Service System (<https://www.webofscience.com/>) Conduct literature search on the core database, with the search deadline being December 31, 2025, the maximum time frame that can be searched. Firstly, in CNKI, use “title” as the search term and “ecosystem+water conservation” as the search term. A total of 121 articles were obtained, including 92 journal articles, 17 master’s theses, 3 doctoral theses, and 4 conference papers. Enter the search terms “Ecosystem+water conservation/ecological system+water yield” in the Web of Science core database for retrieval. A total of 92 articles were obtained, including 88 in journals, 2 in conferences, and 3 in reviews. In the end, CNKI and WOS obtained a total of 213 references. Finally, visual screening and duplicate data deletion were performed through literature titles and abstracts, resulting in 175 articles, including 100 Chinese articles and 75 English articles (Figure 1).

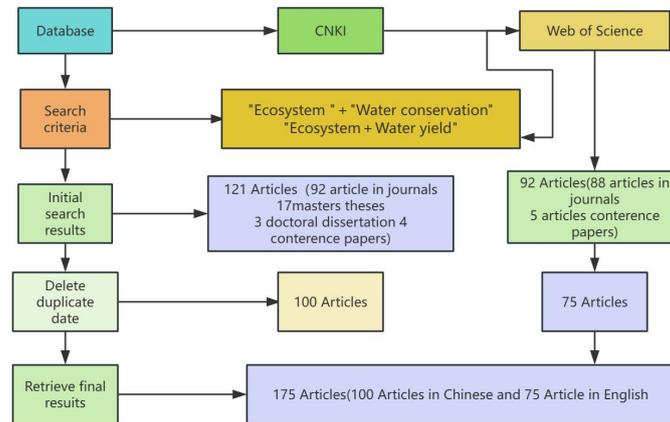


Figure 1. Literature Search and Screening Process

2.2 Literature Statistics Analysis

The data collected from WOS and CNKI databases were screened and further analyzed bibliometrically. In addition, we analyzed and plotted the data using Microsoft Excel 2020 and Origin 2021. Co-occurrence analysis was conducted using SATI and Gephi software. Closely related keywords are grouped into one category to form a clustering network, and the clustering results are visualized to directly display the position and size of each knowledge node in the knowledge structure network. Nodes represent specific keywords. Labels and nodes are proportional to the frequency of keyword occurrence, while the co-occurrence frequency is reflected in the thickness of the connecting lines.

3. Results

3.1 Bibliometric Analysis

3.1.1 Annual and Distribution of Literature

According to the annual distribution map of literature (Figure 1-10), research on ecosystem water conservation began in 2002 and reached its peak in 2020, which can be roughly divided into three stages. The first stage was from 2002 to 2013, and there was relatively little research on ecosystem water conservation, with a total of only 23 articles, known as the budding stage. The second stage is from 2013 to 2020, and the number of literature shows a fluctuating growth trend, which is 11.3 times that of the first stage. In addition, there have been relevant articles on the study of karst ecosystems in this stage, but the number of literature is limited and will be referred to as the development stage. The third stage is from 2020 to 2025, and the number of literature is in a slow growth stage, which is 4.12 times more than the second stage. However, there are only 32 articles on water conservation in rocky desertification control ecosystems. From the overall development trend, the number of articles on this topic will continue to increase in the future (Figure 2).

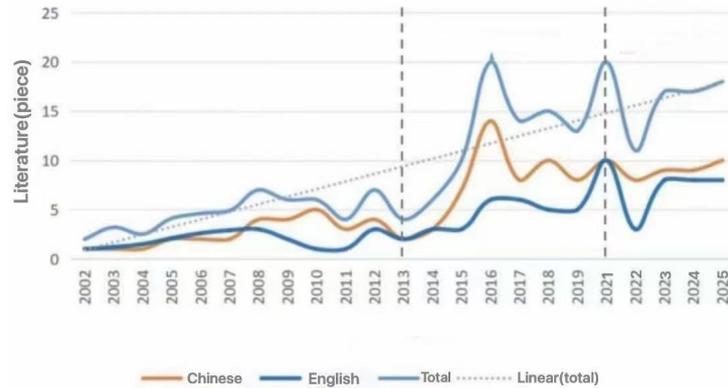


Figure 2. Annual Distribution of the Number of Published Documents

3.1.2 National and Regional Distribution

The research footprint on ecosystem water conservation and functional enhancement covers 110 countries worldwide, indicating the widespread attention and importance of this issue on a global scale. The research distribution has obvious regional characteristics, manifested in the concentration and imbalance of research forces. Most studies are focused on some tropical and subtropical countries, especially Brazil, India, and southern parts of China. Due to the hot and rainy climate conditions, vegetation grows rapidly but the ecosystem is relatively fragile. Taking the Amazon rainforest in Brazil as an example, as the world’s largest tropical rainforest, its water conservation function is of great significance in regulating the global climate and maintaining the water cycle. In temperate regions, such as some mountainous areas in the United States, the Alps in Europe, and Northeast China, they are also research hotspots. The ecological system in the western mountainous areas of the United States is complex, with forests, grasslands, and alpine lakes intertwined, playing a crucial role in the water supply to surrounding areas. These countries account for over 80% of the total research literature in this field. In the face of global climate change, soil degradation and other issues in the future, from a holistic perspective, research on improving the water conservation function of ecosystems will receive increasing attention from countries around the world. Firstly, the research scope will be further expanded to cover more countries and regions, in order to have a more comprehensive understanding of the dynamics and response mechanisms of water conservation in different regional backgrounds; Secondly, interdisciplinary and cross disciplinary cooperation will become the norm, breaking down disciplinary barriers and integrating interdisciplinary perspectives such as ecology, hydrology, and engineering to jointly explore solutions to complex ecological and hydrological problems; Thirdly, international cooperation and exchanges will become more frequent and in-depth, reaching new heights, and jointly addressing the challenges brought by global climate change through forms such as sharing research results and joint research projects (Figure 3).

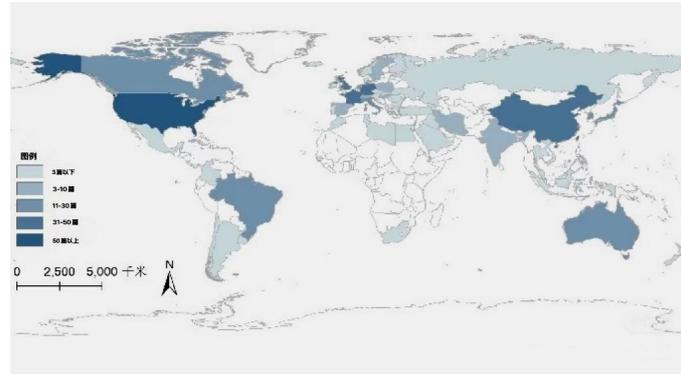


Figure 3. Distribution of Document Units

3.1.3 Distribution of Units and Authors

Network visualization analysis was conducted on authors and their affiliated institutions who have published 2 or more articles. From the global institutional cooperation chart, it can be clearly observed that current research on ecosystem water conservation is mainly focused on universities and research institutions, Chinese Academy of Sciences、University of Chinese Academy of Sciences United States、Beijing Forestry University The institution is the main research institution in this field, and its research results have a wide influence internationally, providing important academic support for the sustainable development of this field. Through the visualization of the global author collaboration network, it was found that complex collaborative relationships have also formed between authors from different countries and regions, and these collaboration networks exhibit obvious clustering characteristics (Figure 1-6), indicating that researchers often tend to collaborate with peers from the same region or with similar research interests. Among them, Richardson, David M, Rouget, Mathieu, Xie Gaodi, Asbjornsen, Heidi, Belinda, Reyers and other scholars constitute the core research team and academic leaders in this field (Figure 4, Figure 5).

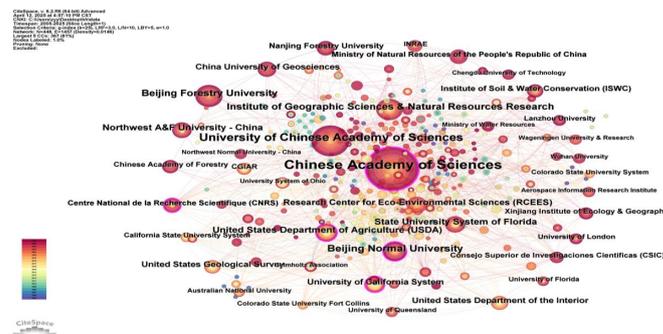


Figure 4. Distribution of Global Units of Ecosystem Water Conservation and Functional Enhancement

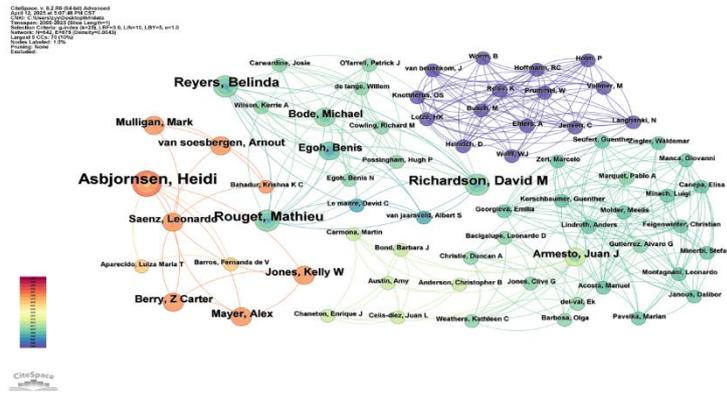


Figure 5. Distribution of Domestic and Foreign Authors

3.1.4 Hotspots and Trend Distribution

To grasp the current academic frontier and predict future development directions, the retrieved literature was imported into the CiteSpace analysis software to generate a hotspot trend map of related literature. Nodes corresponding to terms such as water conservation, soil conservation, litter, ecological restoration, and land use are relatively large and prominent, indicating higher frequency and popularity of these keywords, which are research hotspots in the field of ecosystem water conservation. Keywords connected to the core term “water conservation” include ecological function, soil erosion, forest land, stand structure, and karst, suggesting emerging trends in karst rocky desertification governance and ecosystem water conservation (1-8). Figure (1-9) displays the top 25 keyword burst maps. The overall burst intensity of these keywords is high, with significant variations in intensity. The highest intensity term is “water yield” (4.53), while the lowest is “land use” (4.53). The burst period of these keywords primarily spans 2016-2023. The most intensely burst terms include “rainfall” (4.99), “tree forest” (4.63), and “water source” (4.53), indicating that water yield, land use, water resources, and tree forests are key research areas in water conservation. The term “land use” first appeared in 2022 and persisted until 2025, highlighting its focus in recent years within water conservation research (Figure 6).

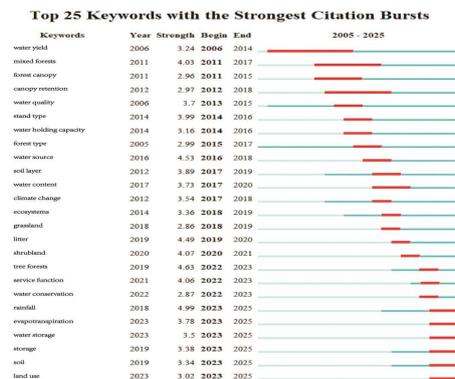


Figure 6. International Water Conservation Research Hotspots Highlighted by Chinese Keywords

3.2.2 Research Phase Division

In the 1960s, the concept of forest water conservation was introduced to China from the Soviet Union. Molchanov et al. argued that water conservation refers to the impact of forests on river runoff. Oki Toshihiro et al. proposed that the function of water conservation primarily involves the influence of forests on the increase or decrease of river flow (Oki et al., 1990). Sun Lida et al. began focusing on the precipitation interception function of forests based on previous research. By 2000, domestic understanding of forest water conservation functions mainly included the effects of forests on precipitation, evapotranspiration, runoff, and water quality. Zhang Biao et al. expanded the connotation of water conservation functions into broad and narrow senses, encompassing both the narrow function of precipitation interception and river runoff regulation, as well as the broad comprehensive manifestation of hydrological effects (Zhang et al., 2009). Lü Yihé et al. conducted an in-depth analysis of the concepts of water conservation and hydrological regulation, noting that the confusion between the two is widespread and may adversely affect research on ecohydrological processes and ecosystem services (Lü et al., 2015). Zhou Jiawen et al. incorporated climate regulation and erosion reduction into the scope of water conservation functions, further generalizing the definition of water conservation functions (Zhou et al., 2022). Liu et al. summarized the forest water conservation function as the interception, storage, and spatiotemporal regulation of precipitation by forest ecosystems through vegetation layers, litter layers, and soil layers, along with the derived comprehensive effects of regulating climate, erosion, and water quality (Table 1).

Table 1-1 Research Phase Division

Research Development	Stage	Research Development	Stage	Research Development	Stage	Research Development	Stage
Budding stage (2002-2013)		The relevant theoretical research at home and abroad is still in its infancy, and lacking systematic		The relevant theoretical research at home and abroad is still in its infancy, and lacking systematic		The research is based on qualitative analysis,	
Slow development stage (2014-2020)		With the development of the economy, domestically		Diversified methods, and Mainly utilizing		research gradually expanding spatial	
						To verify the results	

	Ecosystem	water	
	conservation		
Rapid development stage (2021-2024)	Rapid development, scientific research isis further clarified, and gradually advancing	researchThe mechanism of water conservation in ecosystems assessment party	Water conservation
	Cross fusion research isis further clarified, and gradually advancing	quantitative and qualitative research systems	Diverse laws and
	Increased number,	research is gradually	Present the paradigm of

3.2 Main Progress and Landmark Achievements on Soil Conservation

3.2.1 Research on the Mechanism of Ecosystem Water Conservation

The core support of ecological theory: Ecology focuses on the structure and function of ecosystems, providing a fundamental framework for research on water conservation. By analyzing vegetation community structure, species composition, and biodiversity, the contributions of different plant types to precipitation interception, transpiration, and soil improvement can be clarified (Li et al., 2019). Research has found that the canopy interception capacity of multi-layered vegetation structures (such as trees shrubs grasslands) is significantly stronger than that of single vegetation types. Complex ecosystem structures help to mitigate the direct impact of precipitation on the surface and prolong water infiltration time. Hydrology starts with processes such as precipitation, runoff, and evaporation to quantify the water flux in water conservation. Through hydrological methods, the proportion of precipitation intercepted by the canopy, surface runoff, and soil infiltration in forest ecosystems can be calculated, revealing the regulatory mechanism of hydrological processes on water conservation (Yohannes et al., 2021). Soil science focuses on studying the physical and biological properties of soil, providing a basis for understanding water storage and transport. The pore structure, texture, and organic matter content of soil directly affect water infiltration and water holding capacity. Soil rich in organic matter can significantly increase its water storage capacity by improving its pore structure.

In some complex terrain and landform areas, such as karst regions, high mountain canyon areas, etc., the mechanism of water conservation is unique. Taking karst areas as an example, their unique karst topography leads to uneven soil distribution and complex conversion of surface water and groundwater, making traditional water conservation theories and models difficult to accurately apply. Therefore, it is necessary to conduct in-depth mechanism research on these special terrain and landform conditions, reveal their unique mechanisms of water transport, storage, and regulation, and provide theoretical basis for water resource protection and ecological restoration in these areas. In complex terrain areas such as mountains and plateaus, the influence of factors such as topography, slope, and aspect on various aspects of water conservation mechanisms was studied. It was found that the water infiltration and runoff processes on slopes were significantly different from those on flat land, and the vegetation transpiration and soil evaporation on shaded and sunny slopes were also different.

3.3.2 The Process of Ecosystem Water Conservation Mechanism

Land use change is a key driving factor behind changes in ecosystem service functions, as it can affect the attributes, processes, and components of ecosystems (Dai et al., 2018). Changes in land use can alter soil conditions by increasing soil erosion and disturbing underlying surfaces, affecting hydrological processes such as infiltration, evapotranspiration, soil moisture retention, and surface runoff, thereby affecting water conservation functions (Li et al., 2021). The increase in water capacity is beneficial for enhancing the water storage capacity of regional forest and grassland vegetation and soil layers, reducing flood flow, and decreasing the difficulty of water resource development and utilization during floods. However, the reduction in soil water capacity can easily exacerbate regional drought disasters. Li Yingying's study on the water conservation capacity of the Ziwuling Ecological Function Zone in Shaanxi Province showed that shrubs have the strongest water conservation capacity due to their good precipitation interception ability and small transpiration; However, due to vigorous transpiration and the fact that most of the precipitation intercepted by the canopy is used for evaporation and cannot be accumulated, the water conservation capacity of forests is slightly lower than that of shrubs; Grassland and farmland cover areas where precipitation is easily lost, resulting in poor water conservation capacity and minimal contribution to the total water conservation of the region (Li et al., 2015). Li Qinglan's study on the impact of land use change on water conservation function in the Taihang Mountains showed that there were significant differences in water conservation function among different land types, with the order of grassland>forest land>mixed farming forest land. Forest land and cultivated land show a significant positive correlation with water conservation function, while grassland and unused land show a significant negative correlation with water conservation function (Li et al., 2023).

The unique geological and geomorphological types of karst give soil a rich pore structure, which can be divided into macropores, mesopores, and micropores. Pores of different sizes play different roles in water storage and transport processes. Large pores can quickly allow rainwater to infiltrate, while mesopores and micropores can store water, like sponges, absorbing and storing water during rainfall and providing water sources for plant growth during drought periods. The vegetation canopy can intercept rainfall. The root system of vegetation is also crucial for water conservation. In karst areas, plant roots can penetrate deep into rock crevices, dissolve rocks through root growth and secretions, and increase soil porosity. These pores can store water like small reservoirs, and the roots can enhance the soil's resistance to erosion, reduce soil erosion, and indirectly help conserve water sources. The litter covering the ground can absorb some of the rainfall and slow down the flow rate of rainwater on the surface. During the decomposition process, litter can improve soil properties, increase soil organic matter content, and further enhance soil's water conservation function. From the perspective of ecosystem integration, vegetation, soil, and litter layer interact with each other. Soil provides water and nutrient support for vegetation growth, and its good structure depends on the combined action of vegetation roots and litter; The litter plays a transitional role between soil and vegetation, and together

they constitute the water conservation mechanism of the karst rocky desertification control ecosystem.

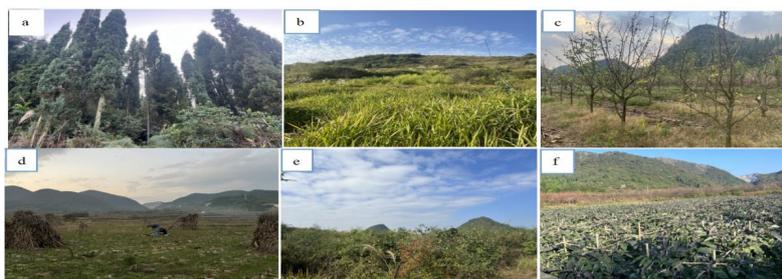


Figure 7. Different Land Use Types (a: Arboreal Woodland, b: Grassland, c: Mixed Agroforestry, d f: Cropland, e: Shrubland)

3.3.3 Analysis and Evaluation of Water Conservation Capacity

The water conservation capacity is a quantitative expression of the size of the water conservation function. The measurement methods for water conservation capacity are divided into field experiments and model simulations (Wang et al., 2021; Jia et al., 2022). The field testing methods specifically include traditional methods such as comprehensive water storage method, water balance method, canopy interception method, soil water storage method, precipitation storage method, annual runoff method, and underground runoff method. Since the 1980s, numerous scholars have conducted a series of field experiments on water conservation in the Huodi Tang forest area of the Qinling Mountains and other regions. For example, Lei Ruide considered the comprehensive benefits of different ecological layers and quantified the water conservation capacity of different forest types in the Huodi Tang forest area of the Qinling Mountains based on the principle of water balance. The study found that the mixed forest of pine and oak had a more significant water conservation function than the *Pinus armandii* forest. Chen et al. (2012) and Lu et al. (2012) conducted studies on the canopy layer and soil layer, respectively. The former found that the canopy layer plays a role in redistributing and delaying precipitation. The canopy interception and stem flow of natural secondary *Pinus tabulaeformis* forests in the Qinling Mountains accounted for 33.2% and 4.4% of the total precipitation, respectively; The latter found that the soil water holding capacity, water storage capacity, and soil permeability coefficient of mixed coniferous and broad-leaved forests were significantly better than those of deciduous broad-leaved forests, which can provide guidance for local afforestation. To guide forestry production practice, Meng Qingxu et al. (2016) found that thinning mainly improves the water conservation function of forest areas by increasing soil water storage capacity. The comparison showed that 20% is the optimal thinning intensity for the Huashan pine forest in the Xunyangba forest area of Qinling Mountains.

3.3.4 Research on the Enhancement of Ecosystem Water Conservation Service Function

There are differences in the effectiveness of water conservation among different tree species and grass species. Generally speaking, tree species with deep roots, dense tree crowns, and abundant dead

branches and leaves have better water conservation capabilities. The soil structure has a significant impact on the infiltration and storage of water. By implementing measures such as deep plowing and deep loosening, the bottom layer of the plow can be broken, increasing the deep porosity of the soil, which is beneficial for water infiltration and storage. A reasonable land use structure is crucial for enhancing the water conservation function of ecosystems. Grasslands can regulate regional climate through transpiration, promote water cycling, and have a certain positive effect on water conservation. Especially in the gentle slopes of some karst mountains, grasslands can play a good role in maintaining soil and water conservation and conserving water sources. Forests have good water conservation capabilities. The canopy layer can intercept precipitation, reduce direct erosion of the ground by rainwater, and delay runoff generation. The layer of dead branches and leaves under the forest can increase soil organic matter content, improve soil structure, increase soil porosity, enhance soil infiltration capacity, and allow a large amount of water to seep into the ground, forming underground runoff and playing a role in conserving water sources. In karst areas, forests can also retain soil through root systems, reduce soil erosion, and further ensure the function of water conservation.

The land use types in karst areas mainly include forests, grasslands, cultivated land, mixed forest land, etc. Forests play an important role in regional ecosystems due to their complex vegetation structure and rich biodiversity; Grasslands are widely distributed and serve as the foundation for many animal husbandry industries. Grasslands have high vegetation coverage and well-developed root systems, which can effectively fix the soil. Its interception effect on precipitation is relatively weak compared to forests, but the root system of grasslands can improve soil aeration and permeability, and increase soil water storage capacity. In addition, arable land is the main site for human agricultural activities; With the acceleration of urbanization, the construction land area is also constantly increasing. Different land use types in karst areas have a significant impact on water conservation capacity. Forests and grasslands have obvious advantages in water conservation. In order to achieve ecological sustainable development in karst areas, it is necessary to pay attention to the rational planning and management of land use types, take effective measures to enhance water conservation capacity, protect water resources in the region, and maintain ecological balance.

4. Discussion

4.1 Key Scientific Issues to Be Addressed and Prospects

4.1.1 Research on Ecosystem Water Source Conservation Mechanisms

In response to the key scientific problem of inconsistent concepts and calculation methods in water conservation, it is urgent to unify concepts and understanding, and solve research limitations and difficulties caused by inconsistent connotations; Karst has significant differences in geomorphological features, soil characteristics, and ecosystem types. When calculating water conservation, it is necessary to revise parameters and relevant empirical values based on actual conditions to ensure the scientific and accurate calculation results.

There are many methods for calculating water conservation capacity, but these methods have certain advantages and limitations. In practical applications, it is necessary to flexibly choose and modify the model parameters according to specific situations. The trend in future research is to conduct regional applicability evaluations of commonly used measurement methods for water conservation, effectively integrate various methods, and apply them effectively to practical accounting. At the same time, according to policy requirements, new methods for measuring the forest water conservation function that are in line with the actual situation of the research area should be explored to further improve the accuracy and effectiveness of the assessment. In terms of dynamic assessment, the main focus is on long-term factors such as climate and human activities, as well as the feedback effect of forest vegetation on climate. Long term dynamic evaluation should take into account the impact of time scale effects during the simulation process, using secondary precipitation events as a benchmark and extending to seasonal, annual, or multi-year scales through scaling. The interception amount of forest ecosystems at different levels during the next precipitation event will be mostly evapotranspiration on a seasonal and long-term scale. In terms of time scale, this evapotranspiration should be considered to improve the simulation accuracy of the model. At present, existing models have taken into account dynamic evaluation, such as the InVEST model for different scenario assessments and the BEPS TerrainLab model for dynamic simulation of vegetation (Govind A et al., 2009). Long term dynamic simulation and evaluation are the mainstream direction for future research on ecosystem water conservation function.

4.1.2 Mechanism of Ecosystem Water Conservation Processes

(1) To address the scientific challenge of optimizing ecosystem water conservation functions, this study analyzes driving factors across different ecological types to elucidate their impact mechanisms. The unique karst topography in limestone regions leads to uneven soil distribution and complex surface-groundwater interactions, rendering traditional water conservation theories and models inadequate for accurate application. Therefore, in-depth mechanistic research is essential to uncover distinctive water storage and regulation mechanisms tailored to these specific geomorphological conditions.

Water source conservation is a complex process involving multiple spatiotemporal scales. At the microscale, it is essential to thoroughly understand the mechanisms of water adsorption, transport, and storage by soil particles and plant root systems. At the macroscale, research must focus on water resource cycles and balance at watershed, regional, and even global scales (Lu et al., 2012; Liu et al., 2016). The key challenge lies in applying microscopic mechanisms of water movement within soil pores to hydrological models at watershed scales through appropriate scale transformation methods, thereby enabling more accurate prediction and interpretation of watershed water source conservation functions (Xing et al., 2022). Human activities such as land use changes and water resource development have profoundly impacted water source conservation mechanisms. It is crucial to clarify how different patterns and intensities of human activities alter ecosystem structures and functions,

subsequently affecting water source conservation processes (Xu et al., 2023). For instance, large-scale urbanization increases impermeable surfaces, alters precipitation-runoff relationships, and impacts groundwater recharge; meanwhile, irrational agricultural irrigation practices may lead to soil moisture imbalance, compromising vegetation growth and water source conservation capacity. In-depth research on these mechanisms is vital for formulating scientific water resource management and ecological conservation policies.

4.1.3 Analysis and Evaluation of Water Source Conservation Capacity

(1) Regarding the scientific challenges of multi-factor coupling effects on water source conservation functions, the integration and coordination across studies at different scales remain inadequate. Establishing a unified cross-scale theory and model that effectively combines micro-level processes with macro-level phenomena remains an urgent priority. Given the inherent fragility of karst ecosystems in structural stability, functional capacity, and disturbance resistance, scenario modeling and coupling effect studies are essential to identify the root causes of water source conservation changes, pinpoint key influencing factors, develop targeted enhancement measures and technologies, and formulate scientific strategies to address climate change impacts and soil degradation challenges.

The hydrological cycle of ecosystems is not isolated. Dynamic changes in vegetation growth, structure, and function significantly influence water conservation capacity. Therefore, it is essential to dynamically assess key factors such as phenological patterns, structural variations, and succession processes in forest vegetation to achieve dynamic monitoring of water conservation functions (Wang et al., 2013). By adopting a holistic perspective across ecological levels and considering driving factors like precipitation, latent evapotranspiration, and land use, this study elucidates the impacts of climate change and human activities on water conservation in the Qinling Mountains. The research aims to establish systematic evaluations of water conservation mechanisms, enhance the authenticity and comprehensiveness of ecosystem service assessments in karst regions, and advance the development of sustainable forest ecosystem services.

The karst regions in southern China are typical ecologically fragile areas, where ecological issues such as soil erosion and rocky desertification pose serious threats to the ecological security and socio-economic development of southern China. The evaluation model for karst ecosystem services should be modified based on soil formation rates to assess soil and water conservation functions, and based on karst geology to adjust climate regulation functions. Due to incomplete information on karst ecosystem services, large measurement errors, and prominent human-land conflicts, it is both urgent and challenging to evaluate the benefits of karst ecosystem services using multiple ecosystem service models. Human activities play a significant role in altering karst ecosystem services. In regions with relatively scarce existing datasets and difficulties in estimating ecosystem services, satellite imagery and novel methods should be employed to develop scientific equipment for studying karst water source conservation, storage capacity, and runoff generation. Continuous monitoring of ecosystem service changes through appropriate methods and reliable multi-scale datasets is essential to ensure regional

sustainable development (Bai et al., 2023).

5. Conclusions

This study conducted an analysis and review of 175 papers indexed in WOS and CNKI databases. Key findings include: (1) Water source conservation has garnered significant attention, with a surge in related publications since 2014. (2) Keywords such as water source conservation, soil conservation, litter, ecological restoration, and land use demonstrate prominent prominence, indicating high frequency and relevance in research, making them focal points in ecosystem water conservation studies. (3) Leading research institutions including the Chinese Academy of Sciences, University of Chinese Academy of Sciences (USA), and Beijing Forestry University have produced internationally influential research outcomes, providing crucial academic support for sustainable development in this field. (4) High-frequency keywords including “rainfall” (4.99), “tree forest” (4.63), and “water source” (4.53) highlight that water yield, land use patterns, water resources, and forest ecosystems remain central themes in water source conservation research.

This study summarizes several key scientific challenges and their implications in rocky desertification regions: (1) Coordination difficulties in water source conservation assessment parameters; (2) Over-reliance on single-function evaluation methods for water source conservation; (3) Research limitations confined to single analytical scales; (4) Neglect of above-ground and underground dual-structure dynamics; (5) Improvement measures primarily based on single-vegetation management strategies; (6) Transition from historical data analysis to current status assessment in conservation studies; (7) Lack of systematic research on water supply-demand relationships. Future research should expand methodologies by integrating karst region-specific soil conditions and refining conservation frameworks according to diverse decision-making dimensions.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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