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# Matched Relationships and Mechanisms of Water and Land Resources in Karst Mountainous Areas: A Review

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**Abstract:** The matching relationship between water and land resources in the karst mountains is closely related to regional ecological and environmental security, human well-being, and high-quality socio-economic development. Based on a massive literature review, this review systematically summarizes the research overview, development process, and matching mechanism of karst water and land resources. The results show the following: (1) Since 1990, the number of publications on karst water and land resources has shown a steady upward trend, with the journals covering multiple fields, characterized by multidisciplinary and interdisciplinary features. (2) The matching relationship between water and land resources in karst mountainous areas has experienced three stages: "single element–binary matching–multiple coupling". It reveals the evolutionary process from focusing on the single internal system of water and land resources to focusing on the mutual matching relationship between water and land resources, and then to the study of multiple coupling between water and land resources system and other external systems. (3) The internal coordinated development of the water and land resources system in karst mountainous areas depends on the joint interactions of natural, economic, and social factors, while the external matching mainly focuses on the mechanism around the three aspects of water and land resources and agricultural production, ecological environment, and economic and social development. Furthermore, the review proposes that future research should explore the matching of water and land resources in karst mountainous areas through theoretical framework construction, model innovation, scale refinement, and mechanism analysis. The expected results will provide a scientific reference for advancing theoretical research on karst water and land resources and optimizing their management.

**Keywords:** water and land resources; matching relationship; mechanism research; progress; karst mountainous areas

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**Citation:** Pang, X.; Xie, B.; Zhang, X.; Xie, J.; Xiao, J. Matched Relationships and Mechanisms of Water and Land Resources in Karst Mountainous Areas: A Review. *Land* **2024**, *13*, 813. https://doi.org/10.3390/land13060813

Academic Editors: Chunlai Zhang, Fen Huang, Tongbin Zhu and Hui Yang

Received: 26 April 2024
Revised: 31 May 2024
Accepted: 5 June 2024
Published: 6 June 2024



## 1. Introduction

Water and land resources are vital components of natural resources and fundamental conditions for human survival and development. The quantity, quality, and composition of these resources have profound impacts on the economic, political, social, and ecological development of a country or region [1,2]. Since the beginning of the new century, with the growth of the global population and rapid economic development, the increasing demand for water and land resources has exacerbated the contradiction between their growing scarcity, greatly disrupting the dynamic balance of these resources and posing a serious threat to human survival and development [3–5]. Assessment results from the Food and Agriculture Organization of the United Nations (FAO) indicate that the pressure facing land and water resource systems has reached a critical point, with 34% of global land undergoing degradation and 3.2 billion people facing water shortages [6]. Therefore, an in-depth understanding of the coupled characteristics and matching mechanisms of water and land resources can provide important guidance for the formulation of policies for sustainable development.

As early as 1932, Raup identified the mismatch between water and land resources and a series of resulting impacts, explicitly pointing out that land expansion would lead to uncertainty in water resource supply [7]. To effectively address this issue, scholars from fields such as ecology, geography, management, and economics have conducted extensive research and achieved rich theoretical results. Currently, the academic understanding of the connotations of land and water resource matching includes several perspectives: (1) From the perspective of supply and demand, the amount of water supplied should meet the water demand of surface crops to achieve land and water resource matching [8,9]. (2) From the input–output perspective, the efficiency of land and water resource utilization is an important indicator of the degree of land and water resource matching. The higher the utilization efficiency, the better the matching status of land and water [10]. (3) From a systemic perspective, water and land resources constitute an effective whole. Clarifying the mutual influences, constraints, and roles among various elements within and outside the land and water resource system can promote the benign development of land and water resource relationships [11,12]. According to a clear understanding of the concept of water and land resources, scholars have conducted research on the evolution of the spatial-temporal patterns of land and water resource matching relationships. The purpose is to analyze the long-term spatial-temporal changes in water and land resource matching relationships, reveal the evolutionary patterns of these relationships, predict the future trends of land and water resource matching relationships, explore regional spatial consistency and local differences, and conduct rational functional zoning.

Karst is one of the world's major landforms, covering about 15% of the global land area [13]. The term karst is derived from the Classic Karst Area: Istria to Ljubljana districts along the northeastern borders of Slovenia and Italy, and can be summarized as the dissolution of the three major soluble rock types (carbonate, sulfate, and halite) by water (Figure 1), and the resulting landscapes, phenomena, and processes [14]. Its unique hydrogeological environment has attracted the attention of many scholars [15–17]. The rugged topography, rocky outcrops, thin soil layers, fragmented arable landscapes, and large but highly heterogeneous water content in karst mountainous areas are increasingly constraining the spatial development of the region's production, life, and ecology [18–20], and the people may lose the basic conditions on which they depend for their survival [21,22]. However, most studies focus solely on the singular discussion of karst water resources or land resources [23–25], neglecting the internal and external matching relationships and mechanisms of water and land resources. Therefore, this review systematically elaborates the development process and the relationships between internal and external matching mechanisms of water and land resources matching research in karst mountainous areas, summarizes the deficiencies of current research, and puts forward the direction of the future development of karst water and soil resources coupling. It is hoped that it can systematically grasp the contradiction of matching water and land resources in the karst area and provide theoretical support for the efficient and sustainable utilization of karst water and land resources and high-quality socio-economic development.

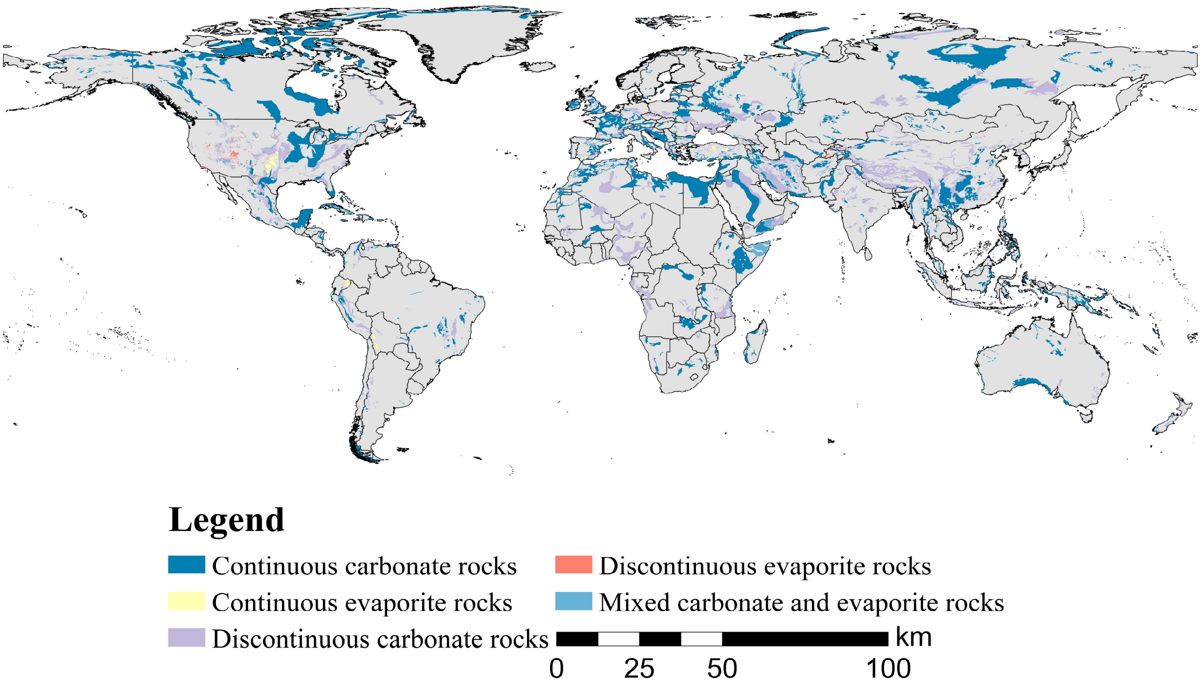


**Figure 1.** Global distribution map of carbonate rocks.

## 2. Methods and Data Sources

The data for this study primarily derive from the Web of Science (WOS) core journal database. Utilizing scient metric visualization software such as VOSviewer 1.6.20.0, a statistical analysis was conducted. To enhance the scientific rigor and authority of the literature, various thematic keywords and combinations were employed in the database search. After multiple trials, the keywords “karst”, “water”, and “land or soil” were selected for the topic search. The document types were limited to articles or reviews, covering the period from 1990 to 2023. To ensure the accuracy of the selected literature, a manual verification process was employed to individually confirm the search results. This process involved the exclusion of irrelevant documents such as book reviews, conference notices, and advertisements, resulting in a final dataset of 3289 relevant records.

## 3. Result Analysis

### *3.1. General Characteristics of the Research on Water and Land Resources in Karst*

Since 1990, the number of publications related to karst water and land resources has shown a steady upward trend (Figure 2a). By the end of 2023, the number of publications had increased approximately 26-fold compared to 1990, indicating a growing scholarly interest in karst water and soil resources. Notably, the top five regions in terms of publication volume are China, the USA, Germany, Italy, and Spain. In terms of journals, relevant studies have been predominantly published in journals such as the *Journal of Hydrology*, *Environmental Earth Sciences*, and *Science of The Total Environment* (Figure 2b). The variety of publication venues highlights the expanding research perspectives on karst water and land resources, encompassing fields such as Environmental Sciences, Agronomy, Atmospheric Sciences, Civil Engineering, and Plant Sciences. This underscores that research on karst water and land resources is inherently multidisciplinary, intersecting various academic domains like environmental science and geography.

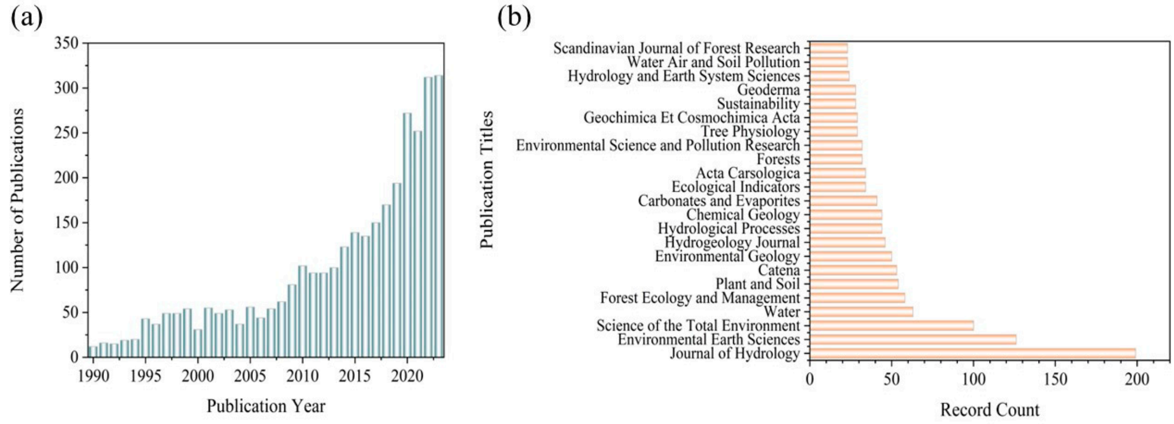


**Figure 2.** (**a**) The number of published articles related to karst soil and water resources since 1990. (**b**) Top 25 titles of publications.

### *3.2. Research Development History of Single Element-Binary Matching-Multi-System of Karst Land and Water Resources*

Using VOSviewer 1.6.20.0, the clustering analysis of research keywords in karst water and land resources revealed several high-frequency terms, including "karst", "water", "land use", "groundwater", "soil erosion", "soil moisture", "trade-offs", "balance", and "impacts". This indicates that the matching of water and land resources has become one of the prominent research focuses (Figure 3). Combined with the research hotspots, the review further combs through the development processes of karst water and land resources matching research. In general, it can be roughly summarized into three stages: single-element research on water and land resources, research on mutual matching of water and land resources, and research on multiple coupling between water and land resource systems and other external systems (Figure 4).

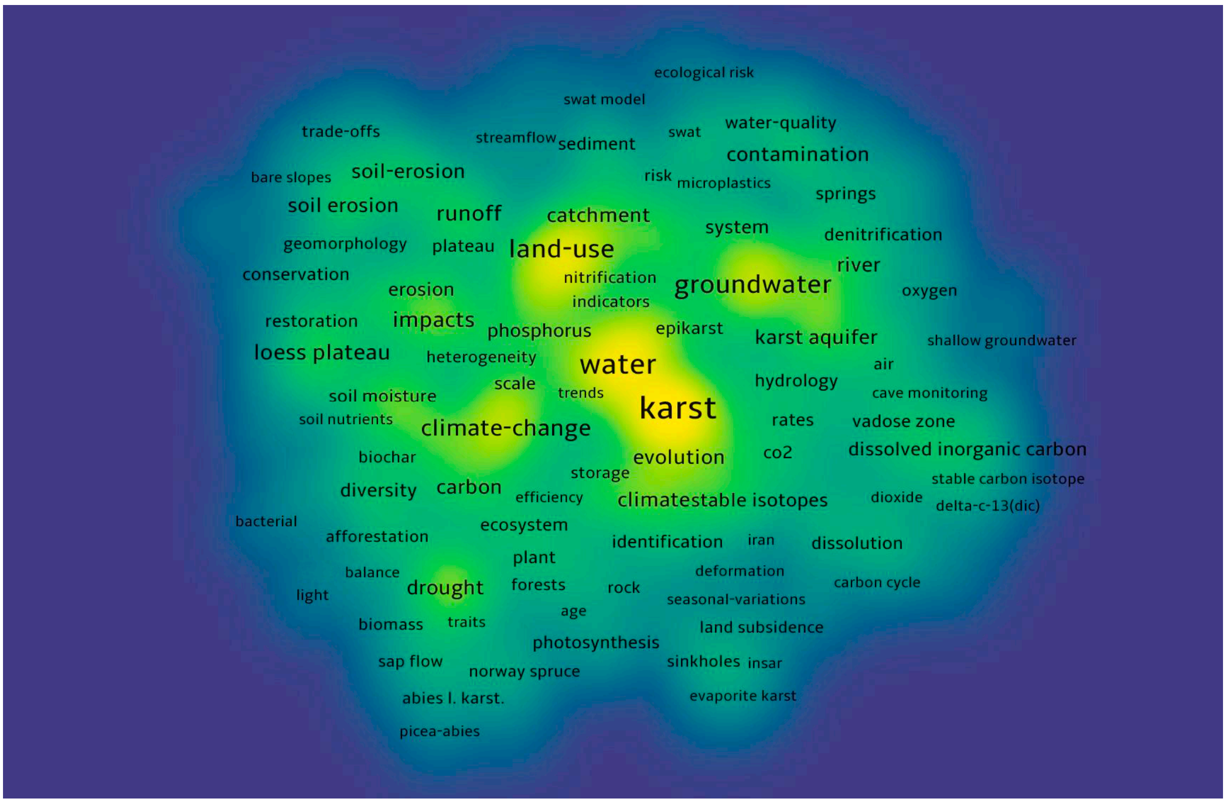


**Figure 3.** Hotspot atlas of karst water and land resources from 1990 to 2023 based on keywords.

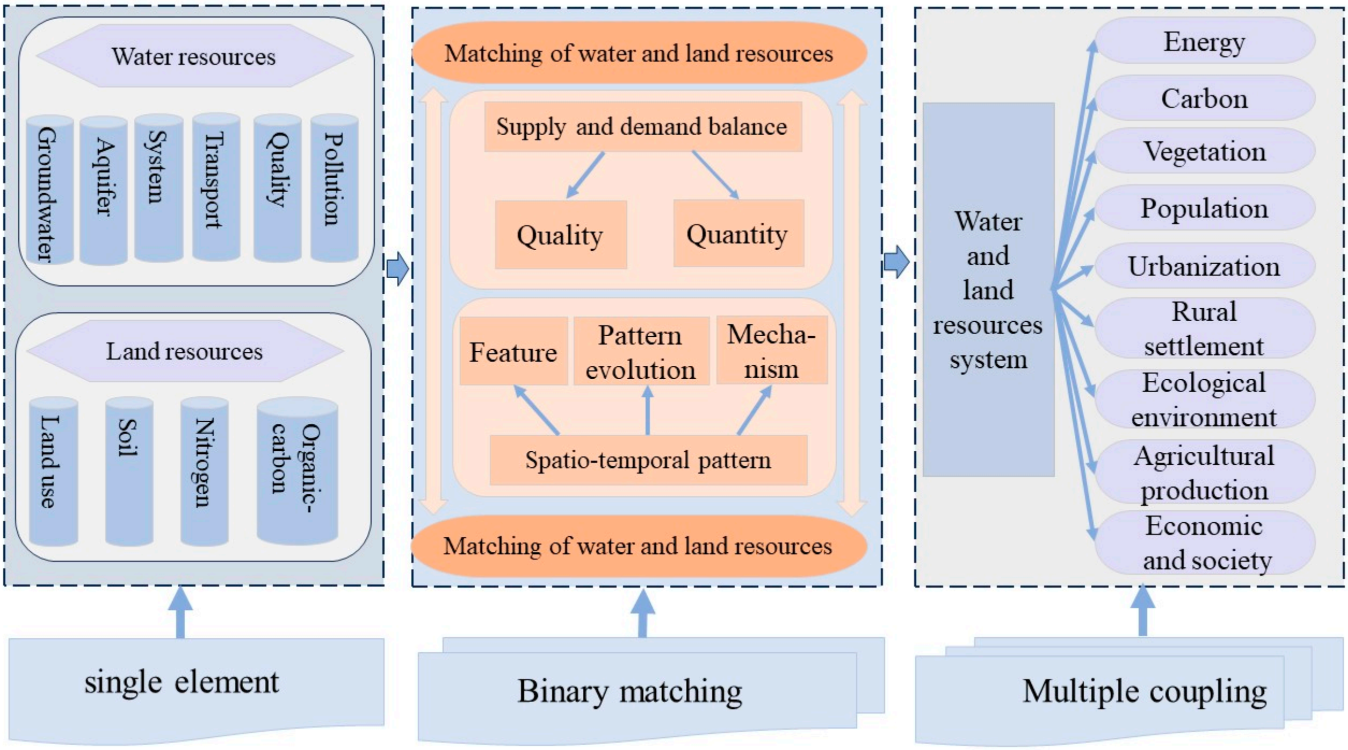


**Figure 4.** Stages of development of research on matching relationships between water and land resources in the karst region.

3.2.1. Single-Element Research on Water and Land Resources

The karst mountainous region is one of the most complex hydrogeological environments on Earth [26]. Owing to its unique geomorphological structure, the natural and socioeconomic attributes of its water resources, as well as their utilization and management, exhibit significant differences compared to other regions [27,28]. Over the years, researchers have conducted extensive research on the unique hydrology of karst mountainous regions, primarily focusing on aspects. The research hotspots are primarily concentrated in the following areas: (1) Studies on karst groundwater variations. This encompasses the mutual constraints and interactions between groundwater and human activities, the impacts on hydrological ecosystems, and the hydrological responses to climate change. It has been shown that water quantity in 80% of karst mountainous areas has been on a continuous downward trend over the past decades [29]. Some scholars propose that water scarcity in karst areas is an engineering problem that can be addressed through the construction of hydraulic facilities [30], such as reservoirs for collecting precipitation. However, engineering practices show that the permeability of limestone makes the construction cost of water storage projects in karst mountainous regions prohibitively high [31], with site selection posing a significant challenge [32]. (2) Research on water resources management and conservation. These studies primarily focus on the mechanisms of the water cycle. Due to the inherent characteristics of aquifers in karst regions and their complex hydrodynamic features, groundwater is susceptible to severe pollution, and pollutants easily migrate and diffuse through karst fissures [33–35]. Previous studies have highlighted the increasingly prominent issues of water quality pollution and deterioration in many karst mountainous regions, particularly in areas with extensive population and industrial development [36]. In many countries where karst landforms are prevalent, karst aquifers play a crucial role in their socioeconomic development, necessitating monitoring and management of water quality and quantity [37]. (3) Research on water resource environmental carrying capacity. The study of the environmental carrying capacity of water resources is a further deepening of water resources security and protection and is one of the core studies for figuring out the potential of karst resources. It mainly focuses on the concept, connotation, evaluation index system, quantitative model, and method [38,39]. The research methods are diverse, including artificial neural network models, principal component analysis, entropy weight method, fuzzy comprehensive evaluation, projection methods, and ecological footprint models [40,41]. Additionally, the efficiency of water resource utilization in karst regions [42] and sustainable use [43], water use prediction, and development [44] are also areas of significant interest.

Research on land resources in karst regions primarily focuses on the following aspects: (1) Microscopic soil studies. Due to the scarcity as well as the porous and permeable nature of karst soils, they are thin and have low fertility. A large number of studies have been conducted on its soil nutrients such as nitrogen [45,46]. For example, studies have investigated soil nitrogen cycling patterns [47–50], nitrogen transformation, nitrogen deposition, and the changes in soil nitrogen following vegetation restoration in karst areas [51,52]. However, some scholars have pointed out that excessive nitrogen use can have negative consequences, such as accelerating soil acidification [53]. The second is to study soil issues around other environmental elements or anthropogenic perspectives. For example, the response characteristics of soil are analyzed in terms of vegetation succession, ecological restoration, and changes in management patterns. (2) Land use/cover change (LUCC) and its driving mechanisms. Land use and land-use/land-cover change (LUCC) directly reflect the interaction between human activities and regional systems, a crucial consideration for the environmentally fragile karst mountainous areas [54–56]. Rapid population expansion and irrational exploitation of resources have led to an increasingly fragile environment in karst mountainous areas, characterized by declining recovery and self-purification capacity of the environmental system, leading to issues such as soil erosion and land desertification. To address the challenges faced by land resource systems in karst mountainous regions, much of the current research on land use in these areas adheres to the pattern–process–mechanism paradigm. Many scholars have approached the exploration of the spatio-temporal change pattern of the karst landscape as the starting point. They then analyze the causes, hazards, and governance pathways of rock desertification [57,58]. Subsequently, they conduct more in-depth analysis by integrating natural factors (e.g., temperature, precipitation, slope) with anthropogenic factors (e.g., population growth, agricultural development, urbanization, and national policies) [59]. (3) Land ecological restoration and land carrying capacity. As the concept of sustainable development has evolved, numerous scholars have put forward specific solutions to address the ecological challenges in karst mountainous regions [60]. For instance, initiatives like reforestation projects have led to a notable increase in vegetation cover. Consequently, the protection and restoration of karst ecosystems have yielded incremental progress [61,62].

#### 3.2.2. Coupled Studies of Water and Land Resources Systems

As research progresses, researchers have realized that studying land resources or water resources separately has significant limitations and may even lose practical guiding significance to some extent, as there is evident coupling between water and land resources systems. Consequently, research methods have gradually shifted from static to dynamic, from qualitative to a combination of qualitative and quantitative approaches, and from single- element analysis to multi-system analysis [11,63,64]. The unique environmental evolution background of karst mountainous areas results in water and land resources scarcity and lack of coordination within the region. Water resources mainly consist of groundwater, which is challenging to develop and utilize; soil resources are sporadically distributed, with thin soil layers prone to erosion, leading to a series of ecological environmental problems. This extreme matching condition has attracted numerous scholars to research the matching of water and land resources in karst mountainous areas, focusing mainly on the following two perspectives (Table 1):

**Table 1.** Research perspectives on matching water and land resources in karst regions.

| Study Type | Study Area | Study Content | Methods | Source |
|---|---|---|---|---|
| Matching supply and demand | Polje karst | Land use supply limitations | Experimental analysis | [65] |
| | Global karst | State of utilization of karst aquifers | Literature analysis | [18] |
| | Karst aquifers in Mediterranean areas | Hydrologic response under soil cover | Experimental analysis | [66] |
| | Guizhou | Ecological supply and demand balance of cultivated land | Ecological footprint | [67] |
| Space–time pattern matching | Karst region of Southwest China | Spatial and temporal coupling and regulation model of water and land resources | Coupling co-ordination degree | [68] |
| | Guizhou | The spatial-temporal matching pattern of agricultural water and land resources | Water and land resources matching coefficient, Gini coefficient | [69] |
| | Karst mountainous areas of China | The matching degree and pattern change of agricultural water and land resources | Water and land resources matching | [70] |
| | Guizhou | Optimum allocation of water and land resources | Bibliometrics | [71] |
| | Huize County | Coupling relationship between water and land resources | Coupling co-ordination degree | [72] |
| | Karst mountains | Coupling relationship between water and land resources and its causes | Coupling index of water–land elements | [73] |

The first perspective is from the perspective of water and land resources supply–demand balance. To explore the relationship between water and land resources supply and demand, scholars conduct studies on balanced optimization of regional agricultural irrigation water demand, urban–rural production and living water demand, and ecological water demand, in comparison with the available supply of water and land resources in the region [65,67,74]. As critical elements of production input, the maximum efficiency of water and land resource utilization can be achieved only when the demand for water by production, living, and ecological land reaches its maximum. The degree of balance in the matching status of water and land resources depends not only on the quantity of water and land resources but also closely relates to the quality of regional water and land resources. Existing research mainly focuses on two aspects: (1) The influence of inherent environmental characteristics of karst mountainous areas on water and land resources. Firstly, from the perspective of the micro-environment of karst soil–water molecules [75,76], the presence of bare karst rocks alters the surrounding soil moisture microenvironment. In addition, soil properties, rock fragment content, and soil texture are the three main soil properties that affect soil moisture content [77]. Due to the spatial heterogeneity of soil distribution in these areas, the distribution of water also exhibits high heterogeneity [78]. In shallow karst soils, the shortage of soil volume, poor soil quality, strong permeability [79], and generally poor water storage capacity often lead to soil–water mismatch and frequent soil droughts, resulting in serious negative impacts on plant growth [80]. In the karst mountainous areas, especially in the peak-clustered depression areas, precipitation is generally abundant. Under the action of erosion and infiltration by flowing water, the dissolution rate of limestone is much higher than that in non-karst mountainous areas, leading to fragmented terrain and serious surface water leakage, resulting in a lack of surface water. Moreover, most areas consist of hard rock mountains such as limestone, with fewer plains, scarce soil resources, severely insufficient arable land, and per capita arable land area far lower than that in plain areas. Additionally, most of the arable land is sloping, with large differences in terrain and topography, unsuitable for agricultural cultivation, resulting in a mismatch between surface water and arable land. Furthermore, the uneven distribution of precipitation in time and space is an important natural factor causing inappropriate matching of water and land resources in karst mountainous areas, while improper development and utilization measures of water and land resources reduce the level of regional matching of water and land resources, which is a key social factor aggravating the contradiction between water and land. (2) The interaction between land use changes in karst mountainous areas and water resources. The research on the matching of water and land resources is mostly based on the specific interactions between physical processes such as precipitation, soil water, and surface runoff, and different types of land. Among them, the influence of land use on water resources is mainly reflected in its impact on water quality. The karst groundwater system is closely related to surface changes, and surface land types can quickly change under human activities, making karst aquifers particularly susceptible to land use changes [32,81]. From 1992 to 2020, the total area of karst landforms globally experiencing land use changes was 1.3 million $km^2$, accounting for nearly 4.85% of the total area [82]. With the development of the economy, increase in population, and expansion of cultivated land, the pressure on karst aquifers in terms of groundwater quality and quantity will gradually increase [83,84].

The second perspective is from the perspective of spatial-temporal pattern matching of water and land resources. The spatial-temporal mismatch of water and land resources in karst mountainous areas is mainly manifested as "places with water lack soil, while places with soil lack water". Current research on the spatial-temporal pattern matching of water and land resources mainly revolves around three aspects: the division of matching characteristics, the study of pattern evolution, and the analysis of driving factors. The division of matching characteristics often involves spatial division based on three levels of matching: good, moderate, and poor, or extreme coordination, high coordination, moderate coordination, low coordination, and maladjustment and decline [85]. Further exploration of spatial-temporal variation patterns is conducted through remote sensing, GIS spatial analysis, and other means. Due to factors such as altitude and climate, the matching of water and land resources in karst mountainous areas shows strong regional differences. For example, the matching degree of agricultural water and land resources in the mid-low altitude areas of karst mountainous areas tends to be good, while that in high-altitude areas is weaker [86,87]. The coupling coordination degree of water and land resources also shows a negative correlation with the spatial distribution of land desertification, that is, the higher the degree of desertification, the lower the coupling coordination degree [68]. Research also indicates that the fundamental problem of water and land resources in karst lies not in the insufficient quantity of resources but in the uneven spatial-temporal distribution of water and land resources, which determines the large spatial differences in the matching degree of water and land resources [70]. In the research on the matching of water and land resources, methods such as the Gini coefficient, matching coefficient, equivalent coefficient, and coupling coordination degree are widely used. Scholars continue to expand and improve the application of the Gini coefficient in the matching of water and land resources, further broadening its application scope [88]. However, in practical research, the Gini coefficient can only reflect the overall consistency characteristics of resources in the research area, and the matching results may be significantly biased due to the influence of unit division range. After the introduction of the agricultural water and land resources matching coefficient, its application is also widespread [89]. Considering the differences in resource endowments in different regions, the concept of the equivalent coefficient is introduced to describe the matching of agricultural water and land resources and the relative relationship with local natural water and land resources endowments. However, from a microscopic perspective, further discussion is needed on the distribution characteristics of the consistency of basic resources and the degree of variation with other factors in the analysis of matching coefficient methods [90,91]. The spatial scale is mostly at the middle and micro levels, and the research areas include provinces, cities and counties, and special karst environmental groups. Further refinement of the research scale still needs to be supplemented [69,71,72,92].

#### 3.2.3. Research on the Coupling between Land and Water Resource Systems with Other Systems in Karst Mountainous Areas

With the depletion of Earth's resources and the continuous deterioration of the ecological environment, people's understanding of the coupling of water and land resources is no longer limited to simple water–land relationships. Gradually, attention has turned to the interaction patterns and coupling relationships between external systems and water–land resource systems [93]. The optimization of water and land resources involves not only two natural resources but also a complex system composed of economics, society, ecology, environment, resources, and population. Especially after the implementation of sustainable development strategies, the demand for water and land resource allocation is increasing, pursuing the unity of ecological, economic, and social benefits [71]. Water and land resources matching, as well as how various systems based on water and land resources can achieve sustainable development, has become a new research focus. These systems include water and land resources and energy [94], water and land resources and agricultural production [95], water and land resources and socio-economics [96], water and land resources and carbon [97], water and land resources and vegetation [98], water and land resources and population [99], water and land resources and urbanization [100], water and land resources and rural settlements [101], water and land resources and ecological environment [102], and so on. Current research mainly focuses on quantitative evaluation, constructing evaluation indicator systems from aspects such as water resource utilization subsystems, land resource utilization subsystems, ecological environment subsystems, and socio-economic development subsystems. Research in the karst mountain area currently focuses more on aspects such as water and land resources and the ecological environment, water and land resources and agricultural production, and water and land resources and socio-economic development, with relatively less emphasis on coupling studies with other systems such as carbon and heat resources [103]. In terms of indicator selection, compared to other non-karst mountain areas, the karst mountain areas highlight indicators such as rocky desertification and soil erosion (Figure 5) [104]. In the exploration of the mutual matching of water and land resources systems with other systems, the coupling coordination model is widely used, such as using the coupling coordination model to explore the coupling coordination status, regulation mechanisms, and coordination degree of the three systems of water and land resources utilization and the ecological environment. Although the coupling coordination method has been proven to be useful, the interaction between water and land resources systems and other systems involves natural processes and human activities, considering the intricate relationships between all resources involved in this process. Therefore, a multi-objective optimization model for sustainable management has been proposed [105,106].

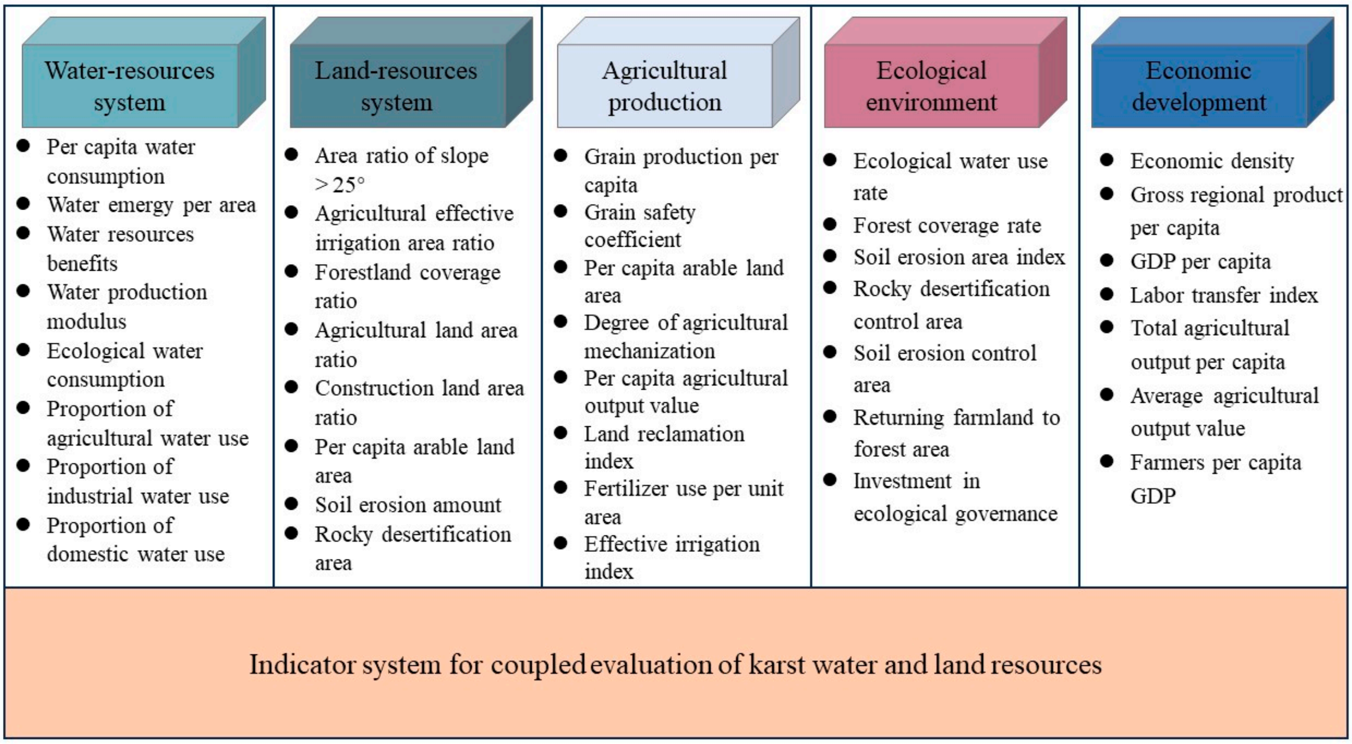


**Figure 5.** Indicator system for matching water and land resources in karst regions.

### 3.3. Matching Mechanisms of Water and Land Resources Systems in Karst Mountainous Areas

According to the relationship between the systems, the mechanism of matching water and land resources in karst mountainous areas can be elaborated from two aspects: internal and external matching. Internal matching refers to the relationship between water resources and land resources within the karst region. Natural, economic, and social factors collectively influence the matching relationship of karst water and land resources. Among them, natural factors mainly include landforms, topography, changes in groundwater levels, and vegetation cover types. Economic factors mainly involve the influence of human activities, such as economic development and industrial restructuring. Social factors mainly manifest in achieving optimal allocation and common utilization of water and land resources through continuous technological innovation or policy regulation. External matching primarily refers to the interaction between the overall system of karst water and land resources and other external systems. Currently, research in karst mountainous areas often involves external systems such as ecological environment, agricultural production, and socio-economic development. Therefore, this review focuses on exploring these three external systems. Rational external matching can promote stable development of agricultural production, sustainable economic growth, and healthy development of the ecological environment, providing important guarantees for achieving sustainable development goals (Figure 6).

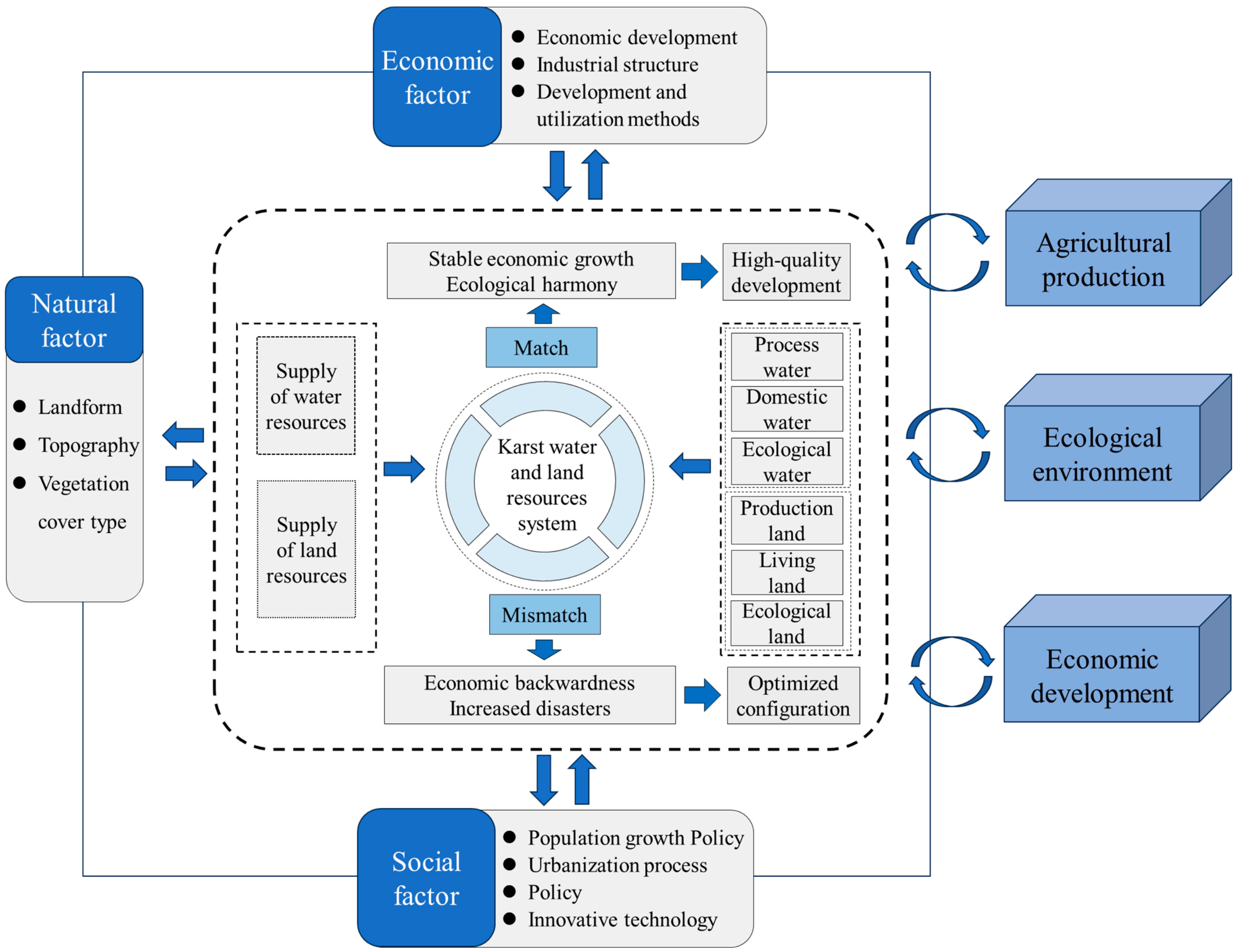


**Figure 6.** The matching mechanism of water and land resources in karst mountain areas.

#### 3.3.1. Internal Matching Mechanisms of Water and Land Resources System in Karst Mountain Areas

The natural environmental characteristics of karst mountainous areas are innate conditions that influence the matching of water and land resources. Natural factors include landforms, groundwater level, topography, vegetation cover types, etc., which affect the distribution of water resources, the formation of groundwater, and the conditions for soil moisture retention and land use, thereby impacting the matching of karst water and land resources [107]. Karst regions are predominantly characterized by karst landforms, with surface rocks mainly composed of soluble rocks such as limestone and gypsum. Due to precipitation rapidly infiltrating into underground rock layers, groundwater is formed, resulting in relatively scarce surface water resources in karst mountainous areas. Therefore, the replenishment of soil moisture mainly relies on groundwater recharge [108]. However, due to significant seasonal variations in groundwater levels, during the rainy season, groundwater levels rise, leading to sufficient soil moisture, while in the dry season, groundwater levels decrease, resulting in reduced soil moisture [109,110]. Additionally, due to the rugged terrain of karst regions, with mountains, hills, basins, and other geomorphic types interspersed, the spatial distribution of water and land resources is uneven. Some low-lying areas are prone to waterlogging, while mountainous areas are susceptible to soil erosion [111]. The surface cover types in karst areas mainly include bare rocks and shrub grasslands. Soil under bare rock cover is prone to erosion and severe soil erosion, while soil under shrub grassland cover is relatively stable [112]. In summary, the interaction of various natural conditions results in poor natural endowment of water and land resources in karst areas, leading to challenges in their supply [113]. Therefore, it is necessary to maximize the potential of water and land resources through scientific water resource management, soil conservation, and land use planning to promote regional sustainable development and ecological environment protection.

Economic conditions are the support for the development and utilization of water and land resources, while water and land resources also provide material guarantees for economic development. The two are closely linked and mutually influence each other. Factors such as rapid economic development, industrial restructuring, and methods of development and utilization of water and land resources are the main reasons for the imbalance between the supply and demand of water and land resources. Rapid economic development and industrial restructuring increase the demand for natural resources such as water and land resources, leading to a widening gap between supply and demand. Correspondingly, the tension in water and land use and the threats of water and land pollution continue to intensify. Issues such as groundwater overexploitation, land subsidence, drinking water safety, soil erosion, and pollution caused by this will become concentrated and manifested, affecting the stability of soil moisture and the benign matching of water and land resources [114].

The influence of social factors on the matching of water and land resources in karst regions is persistent. With population growth and accelerated urbanization, the demand for resources such as arable land and water sources will increase, potentially leading to excessive land reclamation and overexploitation of water resources, exacerbating the matching issues of water and land resources [115–117]. Social policies and regulations play an important role in the management and protection of water and land resources. The formulation and implementation of relevant land use planning, water resource management policies, environmental protection regulations, etc., can regulate social behavior, reduce improper use and destruction of water and land resources, and promote the benign circulation and utilization of water and land resources. In addition, the development of modern innovative technologies also contributes to improving resource utilization efficiency and promoting high-quality development of karst water and land resources systems.

#### 3.3.2. Matching Mechanism between Water and Land Resources System with External System in Karst Mountainous Area

The water and land resources system, in addition to the mutual influence between the two internally, also interacts independently or jointly with other external systems, mainly including agricultural production, ecological environments, and economic development.

Arable land and water resources are two major rigid constraints affecting agricultural production. In the karst agricultural production system, the scarcity and spatial mismatch of water and land resources severely restrict agricultural production. The availability and quality of irrigation water directly affect crop growth and yields. As karst regions mostly rely on groundwater for irrigation, difficulties in accessing irrigation water limit agricultural production. Additionally, the scale of arable land restricts the development of large-scale agriculture in karst areas, mainly due to scattered and fragmented arable land caused by karst landforms, which is not conducive to the mechanization of agriculture. The shortage of input quantities of water and land resources will to some extent slow down the growth rate of the grain industry. The scarcity of input quantities of resources is partly due to the limited endowment of water and land resources in karst regions, and partly due to the relatively limited agricultural output benefits and employment opportunities. This puts agriculture at a disadvantage in resource competition, leading to an increasing trend of resource transfer to non-agricultural industries, resulting in greater constraints on agricultural resources, thus forming a vicious cycle [118].

Unreasonable utilization of water and land resources in karst areas has also led to a series of ecological environmental problems [99]. Firstly, excessive land use has led to rapid soil degradation. Excessive input of production factors, such as excessive use of fertilizers and pesticides, disrupts soil structure at the micro level, resulting in a decrease in organic matter content, and it manifests as soil degradation, soil desertification, and soil infertility at the macro level. Secondly, land overuse behaviors such as hillside planting, deforestation, and overgrazing make originally sensitive ecological environments more fragile, exacerbating soil erosion [119]. Agricultural water resources and arable land resources themselves are key elements of the ecological environment, and their development and utilization are also the main driving forces of ecological environmental changes. The methods, structures, and intensities of agricultural water and land resource utilization directly affect soil properties, hydrological processes, nutrient cycles, etc., in the ecological environment system. In order to maintain land yields, large amounts of pesticides, fertilizers, etc., are used in the agricultural production process, causing nutrients to enter lakes and rivers through hydrological cycles, thereby causing harmful substances to accumulate in the ecological environment, leading to deterioration of water quality and imbalance of ecological processes. Similarly, the protection of the ecological environment system has a positive feedback effect on achieving the sustainability of the land resource system and ensuring water resource security. Effective reduction of the use of chemicals such as fertilizers and pesticides while promoting the popularization of green agricultural technologies can reduce pollution in farmland ecological environments, achieve water purification and water conservation, and maintain ecosystem stability.

The endowment of water and land resources is coupled with the sustainable development of regional economy. Karst areas are relatively prone to natural disasters and have difficulties in development and utilization; thus, agricultural economic development is difficult, and rural poverty alleviation pressure is high [55]. With the development of the economy and society and the increase in the material demands of the people, the contradiction between supply and demand of agricultural water and land resources continues to intensify. For example, the implementation of various production and construction projects threatens the quantity of arable land resources, while the sharp increase in industrial and domestic water demand also leads to continuous exploitation of water resources [21]. In addition, the allocation of factors such as funds, policies, technology, and labor directly determine the development direction of the economy and society in karst areas, thereby affecting the development and utilization of water and land resources.

## 4. Conclusions and Further Outlook

### *4.1. Conclusions*

The review systematically summarizes the development history and research hotspots of water and land resources in karst mountainous areas from 1990 to 2023 and clarifies the matching mechanism of water and land resources system internally and externally. The main conclusions are as follows:

The volume of publications on karst land and water resources has gradually increased, the research perspectives have become more abundant, and the cognitive process of scholars on the matching of water and land resources in karst mountain areas has been constantly evolving and developing. Initially, scholars focused on individual internal systems of water and land resources, then progressed to studying their mutual matching, and eventually explored their coupling with external systems. Research on water resources primarily focuses on the changes in karst groundwater, water resources management and protection, and the environmental carrying capacity of water resources. Studies on karst land resources systems mainly concentrate on the micro-level of soil, including soil formation and the nutrient cycling system. The macro level includes land use/cover change (LUCC) and its driving mechanism, as well as land ecological restoration and land carrying capacity research.

The study of the mutual matching of water and land resources is carried out from two perspectives: the balance between supply and demand of water and land resources and the matching of spatial and temporal patterns. The supply–demand balance relationship focuses on the quantity and quality of water and land resources; the spatio-temporal pattern matching is mainly based on quantitative analysis, which is divided into three aspects: matching characteristic division, pattern evolution research, and driving factor analysis. The study of multiple coupling between water and land resources system and other systems pursues the unification of ecological, economic, and social benefits, and karst mountainous areas are more involved in the aspects of the water and land resources and ecological environment system, water and land resources and agricultural production system, and water and land resources and socio-economic development.

The coordinated development of the water and land resources system depends on the joint action of natural factors, economic factors, and social factors. Natural influences mainly include topography, fluctuations in groundwater levels, terrain, and vegetation cover type. Economic factors include rapid economic development, industrial structure adjustment, and water and land resources development and utilization. Social factors include population growth, urbanization, policies, regulations, and innovative technologies.

### *4.2. Further Outlook*

In reviewing the development history of karst water and land resources matching research, initial achievements have been made. However, with the rapid advancement of socio-economic development and scientific technology, there remains a demand for further advancement in the future of karst water and land resources coupling research:

(1) More evaluation indices and research models with karst characteristics should be explored in combination with the characteristics of the region. Due to the uniqueness and regionality of intertwined water and land resources in karst mountainous areas, selecting appropriate evaluation indices for matching characteristics of water and land resources based on a comprehensive understanding of their conditions in karst is the focus of the research. Secondly, in terms of research methods, the quantitative approaches used in the water and land resources matching model are relatively limited and have their advantages, disadvantages, and specific application requirements. Therefore, when selecting and optimizing the model for the optimal allocation of water and land resources, it is imperative to avoid blindly adopting the model and optimization method from other regions and instead seek a model that suitably reflects the characteristics of karst water and land resources based on existing research.

(2) A combination of macro and micro research scales should be used to study the matching of water and land resources in karst. Macro-scale matching of water and land resources mainly grasps the region as a whole, and under the guidance of different focuses and themes, optimization of different industries and water and land resources utilization units in the region can be realized in order to improve the status quo of mismatch between supply and demand of water and land resources in the region. Due to the karst landscape, the cultivated land in the region is mostly fragmented. To propose targeted solutions for the region, it is essential to explore the growth and structure of crops, farming methods, and agricultural irrigation measures at a finer scale in order to improve the matching degree of regional water and land resources.

(3) Expanding linkages between water and land resource systems in karst mountain areas and more external systems. The matching of water and land resources in karst mountainous areas is a dynamic developmental process closely linked to the region's level of economic development, population size, and changes in resource elements. Currently, research on the interaction between karst water and land resources systems and external systems primarily focuses on agricultural production, ecological environment, and economic development. However, integrating research on other external systems such as carbon cycling and energy changes into the study of karst water and land resources is a future research direction.

(4) Exploring systematically the study of internal and external driving mechanisms of karst water and land resources. In analyzing the coupling mechanism of karst water and land resources, although existing studies have initially revealed the driving

mechanism of the internal system, a significant amount of empirical evidence is still needed to supplement the comprehensive and systematic understanding of the matching process of water and land resources. This can focus on regional natural geographic variations or changes in water consumption and land resource demand across different industries. Research on the mechanisms of influence, synergistic response, and driving factors of the karst water and land resources system in relation to external systems is still relatively lacking. In future research on coupled water and land resources, establishing an open integrated system that combines the water and land resources system with related influencing factors for comprehensive analysis will be an important direction for achieving integrated research on coupled water and land resources.

**Author Contributions:** X.P.: conceptualization, methodology, resources, visualization, and writing—original draft. B.X.: funding acquisition, project administration, supervision, and writing—review and editing. X.Z.: software and validation. J.X. (Jianyong Xiao): software. J.X. (Jing Xie): software, and validation. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by National Key R&D Program of China (2022YFF1300705).

**Data Availability Statement:** Data is contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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