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Solutions to Difficult Problems Caused by the Complexity of Human–Water Relationship in the Yellow River Basin: Based on the Perspective of Human–Water Relationship Discipline

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Abstract: The human–water relationship in the Yellow River Basin is extremely complex, and the human–water relationship discipline is a powerful tool to solve difficult problems caused by the complexity. This study firstly analyzes the historical evolution of the human–water relationship in the Yellow River Basin. Secondly, we summarize some representative problems in dealing with the human–water relationship. Then, on the basis of discussing the main contents of the human–water relationship discipline, the possible solutions to the difficult problems are discussed. Taking the Yellow River water distribution dilemma as an example, we carry out a detailed application. Finally, the possibility of applying human–water relationship discipline to complex basin research is analyzed, and the future research prospects of the discipline are put forward. Results reveal that: (1) River diversion and unreasonable human activities are the main driving factors for the ecological evolution of the Yellow River Basin. In addition, the basin is currently in the "Protective coordination stage". (2) The complexity of the human–water relationship is the root of many difficult problems, and forming a sound disciplinary system of human–water relationship discipline is the key to breaking through these difficult problems. (3) The Yellow River water distribution scheme based on human–water relationship discipline is consistent with the current water use pattern of the basin. (4) The theory and method system of human–water relationship discipline is also feasible and universal for other complex basins.

Keywords: human–water relationship discipline; the Yellow River Basin; complexity of human–water relationship; solutions to difficult problems; water distribution scheme; human–water relationship science

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1. Introduction

Water is a valuable resource indispensable for human survival and development. With the progress of society and the improvement in human production level, the relationship between human and water is becoming more and more complicated. Human–water relationship refers to the complex interaction between "human" (human system) and "water" (water system). In addition, human–water relationship discipline is an interdiscipline that studies human–water relationship. Both human system and water system themselves are very complex systems, and the human–water system formed by their coupling is a more complex system [1]. On 1 January 2016, the 2030 Agenda for Sustainable Development was officially launched worldwide [2], and countries have taken active actions to achieve the 17 Sustainable Development Goals (SDGs) [3]. Among them, the realization of sustainable development goals such as clean drinking water, climate action, marine environment, and terrestrial ecology requires comprehensive and in-depth research on human–water relationship. In March 2021, based on the UNESCO World Water Assessment

Program project, FAO released the "2021 World Water Development Report: Focus on "Water Value" [4]. The report explicitly calls for an in-depth study of the water system from multiple dimensions to illustrate different aspects of "water value". The Yellow River is the mother river of the Chinese nation, giving birth to splendid Chinese culture. However, with the rapid expansion of economic and social scale, a series of human–water relationship problems have emerged in the Yellow River Basin [5]. In 2019, "Ecological protection and high-quality development in the Yellow River Basin" has become a major national strategy of China, and solving the difficult problem of human–water relationship has become the key to the successful implementation of the strategy [5]. The 2022 China Water Conservancy Work Conference also clearly calls for maintaining the healthy life of the Yellow River and realizing the harmonious coexistence of the human–water system. It can be seen that the coordination of human–water system in the Yellow River Basin is necessary to achieve high-quality development of the basin, and is an important need of the times. Therefore, it is of profound theoretical and practical significance to sort out the difficult problems of human–water relationship in the Yellow River Basin, propose possible solutions from the perspective of human–water relationship discipline, and analyze the feasibility of human–water relationship discipline applied to other complex river basins.

The research of human–water relationship can be summarized in both broad and narrow senses. In a broad sense, the research of human–water relationship can be considered as all relevant research involving human and water. From the thought of water control to production practice, from the prevention of water disaster to the protection of water ecology, all can be brought into the study of human–water relationship in the broad sense. Up to now, many scholars have carried out extensive research on human–water relationship in the broad sense, and a large number of high-quality research results have emerged. For example, research on the development, utilization and protection of water systems by human society (including water resources development and utilization [6], water environmental protection [7], water system management [8], etc.); research on the support and restraint of water system on human society (including the supply of water resources to human system [9], the value of water energy to economic development [10], the damage of floods and droughts to human system [11], etc.). The research of human–water relationship in a narrow sense can be considered as the research that is specifically focused on human–water relationship. Compared with the research in the broad sense, there is less research on human–water relationship in the narrow sense. Nevertheless, there are still some representative research results. For example, Wang et al. [12] analyzed the human–water relationship in China from 722 BC to 1911 AD from the perspective of contradiction and coevolution. Bao et al. [13] analyzed the spatial and temporal variation of human–water relationship in northwest China based on the water constraint intensity index. In addition, since 2007, starting from the definition of human–water system and human–water relationship, Zuo has carried out a series of research on the evolution process of human–water relationship, identification of influencing factors, evaluation of harmonious relationship, and harmonious regulation [1]. In 2021, the research framework of human–water relationship discipline was summarized [14]. From the current research, the research content of human–water relationship science is very rich, and it is necessary to form a stable research direction and discipline system, as well as a scientific theory and method system, to guide the research and application practice of human–water relationship.

The research on the human–water relationship science in the Yellow River Basin has a long history, involving many aspects of natural science and social science. Related research mainly focus on the allocation and regulation of water resources [15], the regulation of water-sediment relationship [16], flood and drought disaster prevention [17], water distribution scheme formulation [18], water conservancy project construction and its ecological impact [19], etc. Since the major national strategy for the Yellow River was proposed in 2019, the human–water relationship in the Yellow River Basin has once again become a new research hotspot, and the research directions are expanding. Difficult issues such as urbanization and ecological security assessment [20], quantification of water use

efficiency [21], water-energy-food system evaluation [22], and driving force analysis of precipitation change [23] are explored in more depth. For example, Qiu et al. [20] explored the correlation between urbanization and ecological security in the Yellow River Basin. Wu et al. [23] analyzed the characteristics of precipitation and temperature variability in the upper Yellow River. At present, no research has been conducted to systematically sort out the historical evolution of human–water relationship in the Yellow River Basin. In addition, many difficult problems caused by the complexity of human–water relationship need to be analyzed from the perspective of human–water relationship discipline.

Based on the above background, combined with historical facts, this study conducts a systematic analysis of the ecological evolution of the Yellow River Basin and its driving factors, and delineates the evolution stages of human–water relationship. On this basis, the difficulties in dealing with human–water relationship in the Yellow River Basin are discussed. Combined with the framework of human–water relationship discipline, the solutions to these difficult problems are discussed from the perspective of human–water relationship discipline, and an application example is carried out. Finally, this study analyzes the possibility of applying human–water relationship discipline to the research of other complex basins and presents future research perspectives of the discipline. Unlike many studies on the human–water relationship in the Yellow River Basin, this study aims to achieve the following objectives: (1) reveal the historical evolution and complexity of human–water relationship in the Yellow River Basin; (2) summarize the difficult problems caused by the complexity of human–water relationship in the Yellow River Basin, and propose solutions from the perspective of human–water relationship discipline; (3) clarify the possibility of applying human–water relationship discipline to complex basin research and future research prospects.

The rest of this study is structured as follows: Section 2 is an analysis of the factors driving the ecological evolution and a delineation of the stages of evolution of the human–water relationship in the Yellow River Basin. Section 3 is a summary of the difficult issues in dealing with human–water relationship in the Yellow River Basin. Section 4 is an overview of the main contents of human–water relationship discipline, as well as an analysis of the possible solutions to these difficult problems from the perspective of the human–water relationship discipline. In addition, an application example in the Yellow River Basin is provided. Section 5 is the feasibility analysis of the application of human–water relationship discipline to other complex basins, and the outlook for future research. Section 6 is the main conclusion.

2. The Historical Evolution and Complexity of Human—Water Relationship in the Yellow River Basin

2.1. Overview of the Yellow River Basin

The main stream of the Yellow River is 4564 km long and flows through nine provinces in China (Figure 1), according to statistics, the Yellow River Basin involves 69 cities and 329 counties. From ancient times to the present, the Yellow River has undertaken the high-intensity water supply pressure of economic and social development in northern China, the per capita water resources in the basin are 905 cubic meters, which is only 33% of the national per capita water resources. The Yellow River with less than 2% of China's river runoff to support 12% of China's population and 17% of the arable land water demand [20], for the areas along the river and even Hebei, Tianjin, Jiaodong Peninsula and other areas outside the basin of people's lives and production to provide a basic water supply guarantee. Therefore, the Yellow River is regarded as the mother river of the Chinese nation.

The Yellow River also plays an important ecological corridor function. The Yellow River channel is not only a natural carrier of water resources, but also undertakes the important task of maintaining the stability of water ecological functions and recharging groundwater along the Yellow River area. The basin connects many important ecological function areas, such as the Three River Source Grassland Meadow Wetland Ecological Function Zone, the Loess Plateau Hilly Gully Soil and Water Conservation Ecological

Function Zone, constituting an important ecological barrier in northern China. The Yellow River Basin mostly belongs to arid or semi-arid areas, and the role of Yellow River water in maintaining ecosystems is self-evident. The source area of the upper Yellow River is an important part of the "China Water Tower". The ecological stability of the Loess Plateau in the middle reaches maintains the downstream flood control security. The lower estuarine delta contains the most complete wetland ecosystem in the warm temperate zone of China. Therefore, the Yellow River Basin also provides a strong support for China's ecological security, and plays a key role in China's economic development layout and ecological civilization construction pattern.

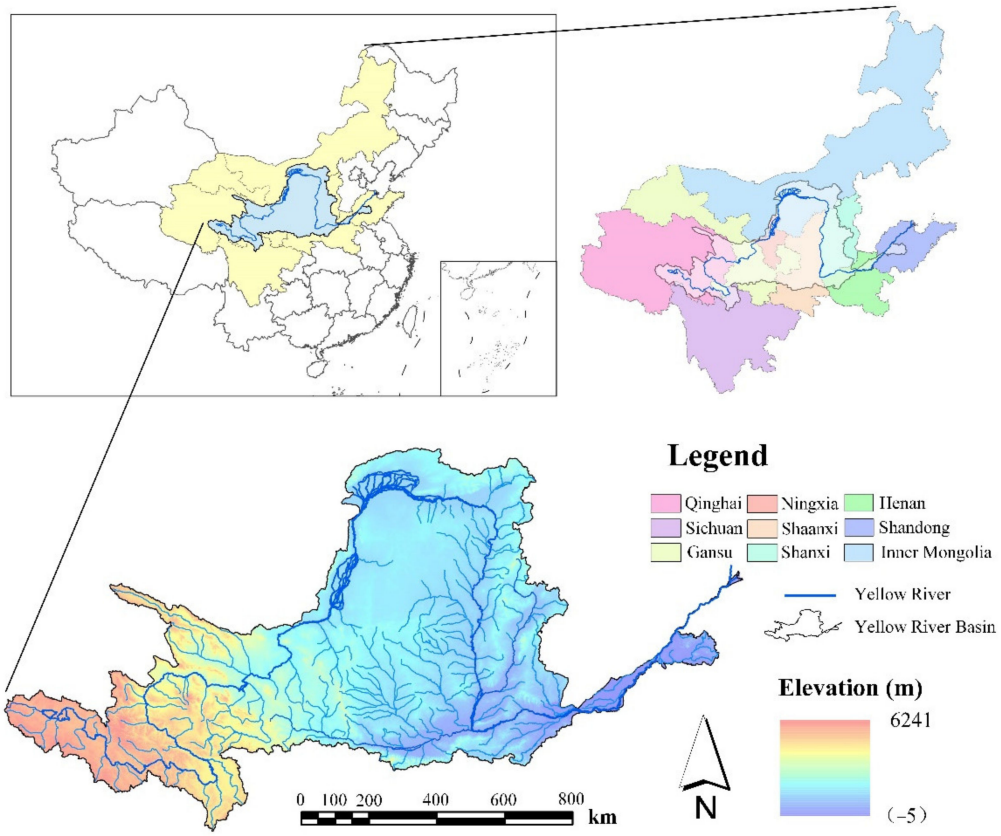

Figure 1. Schematic view of the Yellow River Basin and elevation distribution. (based on the standard map of the Ministry of Natural Resources of China, the base map has not been modified, the approval number is GS (2019)1822).

2.2. Ecological Evolution of the Yellow River Basin and Its Driving Factors

For a long time, human beings have been deeply involved in the ecological cycle and evolution of the Yellow River Basin in the process of flood disaster control and resource development and utilization [24]. At the same time, the impact of the human system on the water system of the basin will also be subtly fed back to human beings from many aspects. Human activities affect the water system, and the water system and its changes will also restrict the development of the human system. This is the most basic feature of the human–water relationship—the principle of interaction. Combined with the development history of the Yellow River Basin, the main driving factors for the ecological evolution can be summarized into two aspects: river diversion and irrational human activities.

Historically, the lower reaches of the Yellow River have overflowed more than 1500 times, and there have been more than 20 major diversions. The large-scale overflow and diversion of the main stream of the Yellow River will directly lead to drastic changes in the water system pattern and disorder of the ecological system, and then bring ecological disaster. Therefore, river diversion is an important driving factor of ecological evolution in the

Yellow River Basin. Historically, there are two main reasons for the diversion of the Yellow River. On the one hand, due to topographical conditions, the main stream in the lower reaches of the Yellow River is frequently diverted, and the Yellow River oscillates violently on the Huang-Huai-Hai Plain with Zhengzhou as its apex for many times. For example, in 1855, the Yellow River burst at Tongwaxiang in Henan and diverted its course to the north, flooding in southern Hebei and southwestern Shanxi for 20 years. Frequent diversions have led to the demise of historically famous lakes and wetlands, such as Ying Ze, Pu Tian Ze and Da Ye Ze. On the other hand, the human-induced diversion of the Yellow River. For example, during the Southern Song Dynasty, the Yellow River has occupied the Huaihe River for more than 700 years, resulting in serious damage to the ecological balance of the Huaihe River Basin.

Irrational human activities can also cause serious damage to basin ecosystems. According to records such as "Yellow River Chronicles", the vegetation coverage rate of the ancient Loess Plateau was as high as 50%. In the late Warring States period, the population of the Loess Plateau continued to increase, the farming area gradually expanded, the forests began to suffer destruction, and the sand content of the Yellow River increased. Since the Western Zhou Dynasty, due to the impact of wars, the consumption of wood has increased sharply, and a large number of forests on the Loess Plateau have been destroyed. From the Western Han Dynasty to the late Qing Dynasty, the population of the Loess Plateau increased dramatically, further intensifying the destruction of vegetation. Until the founding of New China in 1949, the coverage rate of secondary forests on the Loess Plateau was only 6%. The soil erosion on the Loess Plateau caused by the destruction of vegetation has become the main source of sediment problems in the lower reaches of the Yellow River. In the 1970s, the development and utilization of water resources in the Yellow River exceeded its capacity. In 1972, the lower Yellow River began to dry up. In the following 28 years, there were 21 years of dry-flow at Lijin Station. In the 1980s, pollution discharges caused rapid deterioration of the water quality of the Yellow River. According to the 1998 Yellow River Water Resources Bulletin, the proportion of river lengths with water quality at or below Class IV is as high as 71%. The degradation of water quality due to pollution discharge further aggravates the degradation of water ecological functions in the basin.

2.3. The Complexity and Evolution Stages of Human—Water Relationship in the Yellow River Basin

The Yellow River is a river of civilization with a long history. In China's more than 5000 years of civilization history, the Yellow River Basin has been the political, economic, and cultural center of the country for about 3400 years. The Yellow River has profoundly influenced China and is revered as the "head of the hundred waters" of China [25]. However, the Yellow River is also an unruly, complex, and difficult river of distress. The Yellow River is recognized as one of the most difficult rivers in the world to manage, and the human–water relationship is extremely complicated. The complex evolution of the human–water relationship in the Yellow River Basin can be basically divided into five stages (Figure 2):

(1) Low-level harmony stage. From the primitive society period to the early feudal society, the level of human productivity was low, and the impact on the water system was small. The water system plays an absolute leading role in human–water relationship, and this relationship in the Yellow River Basin is in a low-level harmony stage. At this stage, the human system and the water system adopt a simple interaction way. Humans have explored some measures to control the Yellow River. For example, Dayu used the method of channelization to dredge the Yellow River and divert floods, which alleviated the flood threat to some extent. However, due to the limitation of the level of productivity, human beings do not have the ability to resist the floods of the Yellow River. China's millennia-long "Yellow River sacrifice" originated from this stage.
(2) Exploratory development stage. From the early stage of feudal society to the end of feudal society, social civilization and productivity in the Yellow River Basin continued to improve. The role of the human system in the human–water relationship is gradually increasing, and this relationship is in the stage of exploratory development. In

this stage, the human system is more closely linked to the water system, which shows the ability to govern and develop the water system from shallow to deep. During the Western Han Dynasty, Jia Rang, a strategist for the governance of the Yellow River, proposed the "Three Strategies for River Management", which advocated diversion and consolidation of dikes at the same time. During the Eastern Han Dynasty, Wang Jing, an expert in water conservancy, opened a new channel, which formed a flood route of the Yellow River with smooth water flow and strong sand transport capacity. Pan Jixun, an expert on river management in the Ming Dynasty, advocated "using embankments to restrain water and attacking sand with water". This idea of water control had a profound impact on the subsequent governance of the Yellow River. Compared with the previous stage, the subjectivity of human system to water system has been fully developed in this stage. The complexity of human–water relationship in the Yellow River Basin is deepening in the process of exploratory development.

(3) Dysfunctional deterioration stage. From the end of feudal society to the end of the 20th century. With the rapid development of industrial civilization, the effect of human system on water system is further enhanced. In addition, it occupies a dominant position in the human–water relationship in the Yellow River Basin. However, it also brings a series of serious problems for the water system, and the human–water relationship is in the stage of dysfunctional deterioration. At this stage, the Yellow River Basin enters the peak demand for water resources utilization, and the intensity of human exploitation of water system is unprecedentedly high. However, the Yellow River has gradually entered a vicious circle of coexistence of floods and dry-flow, and deterioration of water ecology. In the 1970s, the Yellow River experienced a long-term dry up. In 1997, the Henan section of the Yellow River was cut off for 226 days, and the river ecosystem was on the verge of collapse. At the end of the 20th century, more than 70% of the Yellow River's water body basically lost its ability to purify itself. Compared with the previous stage, the human system showed a predatory development trend for the water system in this stage. In addition, various conflicts among human–water system appeared successively. The human–water relationship in the Yellow River Basin continues to deteriorate during this unsustainable development process.

(4) Protective coordination stage. From the end of the 20th century to the 2030s, with the change of river management ideas, the development and utilization mode of the Yellow River water resources has undergone a transition from "resource water conservancy" to "ecological water conservancy". The human system began to pay attention to the protection of the water system, the contradiction among human–water system has been alleviated to a certain extent. In addition, the human–water relationship is in the stage of protective coordination. A series of water disasters at the end of the 20th century provided new impetus for coordinating human–water relationship in the Yellow River Basin. After entering the 21st century, the Chinese government has taken many effective measures to regulate human–water relationship. In 2001, human–water harmony was formally incorporated into China's modern water conservancy system [26]. In 2013, the State Council of China approved the "Comprehensive Plan for the Yellow River Basin (2012–2030)", which clearly requires the human–water harmony, and the comprehensive maintenance of the healthy life of the Yellow River. In 2019, the ecological protection and high-quality development in the Yellow River Basin officially became China's major national strategy, opening a new chapter for the human–water relationship. Compared with the previous stage, the human system in this stage presents a protective development state to the water system. Under the subjective regulation of the human system, the human–water relationship has been greatly improved. According to the current development trend, by the 2030s, the human–water relationship in the Yellow River Basin will basically achieve preliminary coordination. However, there are still many difficult problems to be solved.

(5) High-quality harmony stage. With reference to two important documents, "Comprehensive Plan for the Yellow River Basin (2012–2030)" and "Outline of the Plan for Ecological Protection and High-Quality Development in the Yellow River Basin", 2030 is regarded as the dividing point between the high-quality harmony stage and the protective coordination stage. After the 2030s, the utilization and protection of water resources in the Yellow River will change from "ecological water conservancy" to "intelligent water conservancy". The human system will be able to carry out the development and protection of the Yellow River Basin under the premise of protecting the health of water system. The contradiction between human and water will be basically resolved, and the human–water relationship is in a high-quality harmony stage. Compared with the previous stage, human beings will be able to make full use of modern information technology to carry out water resource utilization and protection work. The theory, methodology and application of human–water relationship discipline will also accumulate fruitful results. Based on rich experience in water resources utilization and protection, supported by advanced information and cyberspace technology, and guided by the principle and methodology of human–water relationship discipline, the traditional difficult problems of human–water relationship will be gradually solved. The Yellow River Basin will realize the harmonious coexistence between human system and water system.

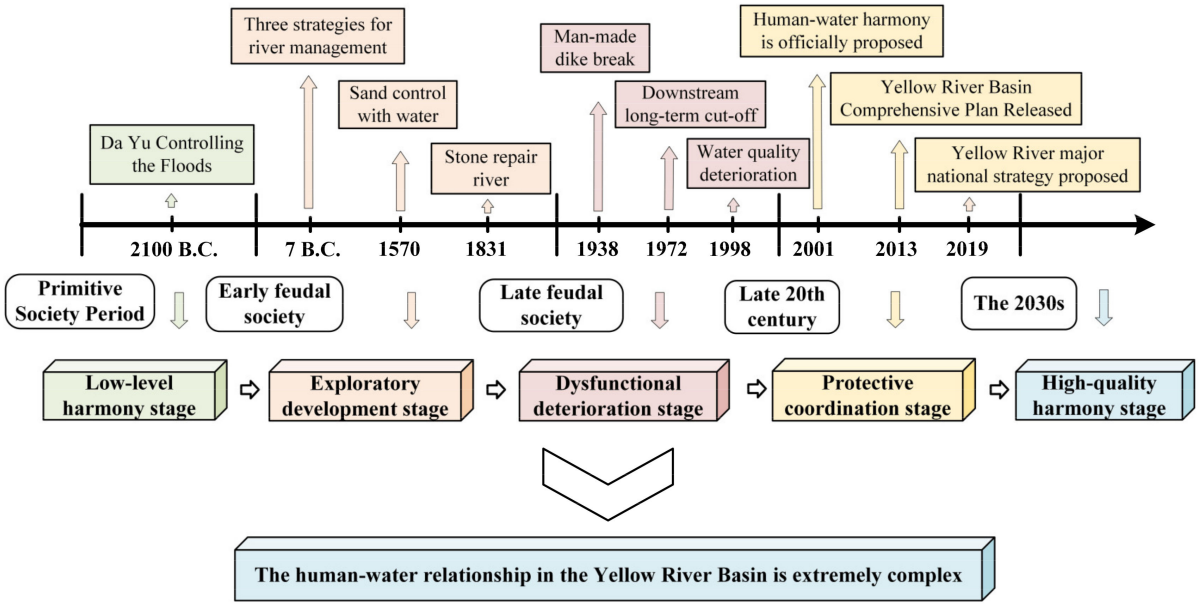

Figure 2. Historical evolution and representative events of human–water relationship in the Yellow River Basin.

The complexity of the human–water system can be clearly seen from the historical evolution of human–water relationship in the Yellow River Basin. It is also the complexity of the human–water relationship that has brought a series of intractable problems to the basin. Since ancient times, the Chinese people have made arduous efforts to coordinate the human–water relationship. The complicated evolution of human–water relationship in the Yellow River Basin is also a microcosm of the development history of entire human–water relationship in China.

3. Difficult Problems in Dealing with Human—Water Relationship in the Yellow River Basin

3.1. Difficult Problems Caused by the Complexity of Human—Water Relationship

The harmony and stability of the human–water relationship in the Yellow River Basin plays a vital role in China's future development. Therefore, solving the difficult problem of

human–water relationship is the only way to achieve high-quality development. There are still many difficult and cutting-edge problems that need to be solved urgently. For example, the demonstration of the west route of the South-to-North Water Diversion Project, the water distribution problem of the Yellow River, the construction of large water conservancy projects, and the prevention and control of flood and drought disasters [27], etc.

The origin of these difficult problems can be regarded as the complexity of human–water relationship (Figure 3). However, at the same time, it also exposed the serious deficiency of human's understanding of the human–water relationship science. There is a lack of systematic understanding of the core issues of the human–water relationship, such as the interaction of the human–water system, the adaptive utilization of water resources, the balance of human–water system, and the harmonious evolution of human–water relationship. In addition, the human–water relationship in the Yellow River Basin involves many disciplines, and it is difficult to solve only from the perspective of a single discipline. At present, a complete set of human–water relationship discipline system and mature theory and method system have not been formed, which is the key to breaking through these difficult problems of human–water relationship.

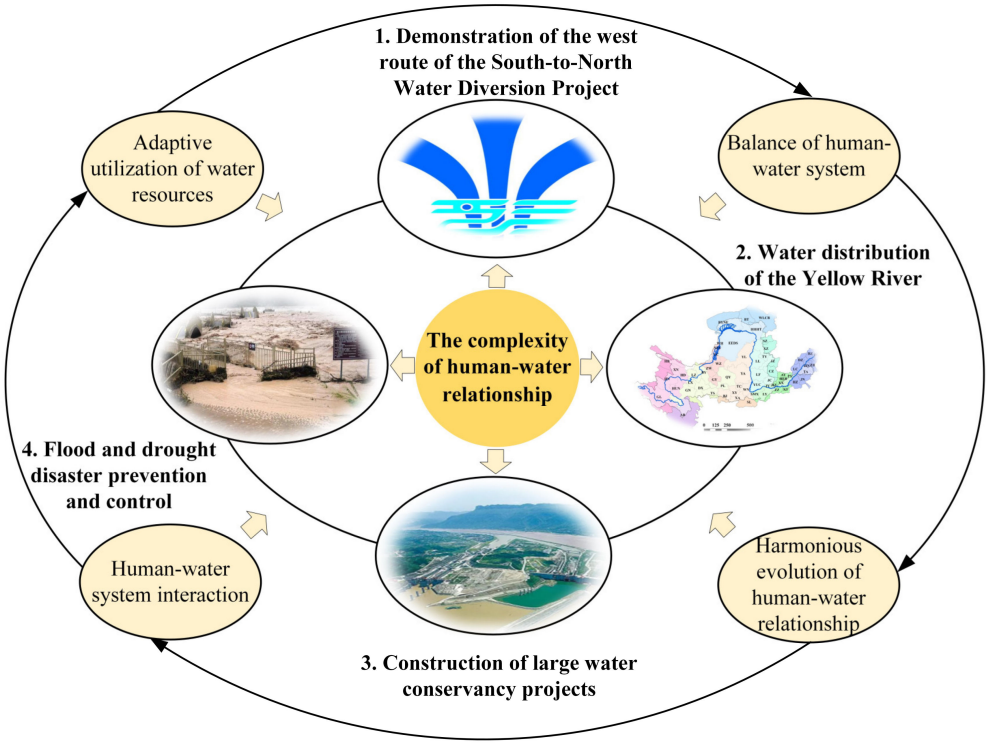

Figure 3. The difficult problems and essence of human–water relationship in the Yellow River Basin.

3.2. Demonstration of the West Route of the South-to-North Water Diversion Project

The west route of the South-to-North Water Diversion Project is a major inter-basin water transfer project to alleviate the water supply contradiction in northwest China. However, if the demonstration is not sufficient, it may bring about major problems in planning, design, construction and operation. The following problems often arise in the demonstration of inter-basin water transfer projects. (1) Most of the demonstration work focuses on emphasizing the necessity of water transfer projects and desalinating the adverse effects on the region. The voice of the beneficiary is louder, and the voice of the disadvantaged is weaker. (2) Judging from the funding situation, there are no or very few counter-argumentation topics for special research. The starting point of professional argumentation or industry funding has been biased toward supporting water transfer from the beginning, while opponents have less support channels. (3) Inter-basin water transfer projects involve many aspects, and it is difficult to analyze from a systematic perspective

with general research depth and limited financial support. Because of the complexity of the argument, decisions may be made without the depth of the argument.

3.3. Water Distribution of the Yellow River

The Yellow River spans nine provinces and is a typical transboundary river, and there are inevitably disputes over water distribution. In 1987, the Chinese government promulgated the Yellow River Water Distribution Plan (i.e., the Yellow River "87" Water Distribution Scheme). After more than 30 years, the state of the river and the external environment have undergone great changes, and it is imperative to redefine the water distribution scheme of the Yellow River. However, because of its difficulty, no new water distribution scheme has been formulated so far. For the water distribution of the Yellow River, the following problems often occur. (1) Based on the analysis of water supply and demand, the optimal allocation of water resources is carried out to determine the water distribution of the river. The general idea is correct, but the actual operation is difficult to carry out. Because the amount of water resources in the Yellow River is extremely limited, if the water demand of the nine provinces is strictly followed, the water resources in the Yellow River will definitely not be enough. (2) From a favorable point of view in a certain region, formulate a water distribution scheme for the Yellow River. Such distribution schemes often lead to tensions between upstream and downstream and ultimately lead to disorderly river development. In a tense relationship, nature's water needs are easily overlooked.

3.4. Construction of Large Water Conservancy Projects

The construction of large-scale water conservancy projects, such as the Xiaolangdi Water Conservancy Project on the Yellow River, provides convenience for human beings to utilize water resources. However, at the same time, it has also greatly changed the connectivity of the river, with a series of adverse effects on the water system of the basin [28]. The following problems often occur in the demonstration and construction of large water conservancy projects. (1) Overly optimistic, that is, actively advocating the construction of large-scale water conservancy projects on rivers. This view holds that the impact of water conservancy projects on the water system can be solved through a series of engineering measures. However, the fact is, any human activity is a perturbation of nature, and the threshold of permissible perturbation is difficult to determine. (2) Too negative, that is, strongly vetoing the construction of water conservancy projects. This view holds that the construction of water conservancy projects will bring irreversible effects on the water ecosystem. However, it ignores the self-restoring function and self-adaptive capacity that nature itself has. How do we find a balance between human needs and the needs of nature? There are still major difficulties.

3.5. Flood and Drought Disaster Prevention and Control

Floods and droughts are still a prominent threat to the Yellow River Basin. If the main rain area of Zhengzhou's "7.20" rainstorm in 2021 is in the Yellow River Basin, the peak flow at Huayuankou will exceed 20,000 m^3/s. The severe drought in the upper reaches of the Yellow River in 1973 and the severe drought in the middle reaches of the Yellow River in 1980 brought serious disasters to the basin. Although human beings have accumulated rich experience in the long history, there have been problems in the attitude toward flood and drought disasters. (1) Attempt to completely control or eliminate the disaster. However, numerous facts have proved that floods and droughts are universal natural disasters, and it is impossible for human beings to completely eliminate the existence of natural disasters. (2) It is customary to treat flood and drought disasters as independent disaster events to respond to. In fact, floods and droughts are both a node in the water cycle process and are not isolated events. The likelihood of droughts tends to increase after floods. (3) It is customary to respond to floods and droughts as sudden disasters. Although there are well-developed emergency measures, systemic response capabilities such as daily risk prevention and early warning forecasting are insufficient.

4. Solutions to Difficult Problems Caused by the Complexity of Human—Water Relationship: Human—Water Relationship Discipline

4.1. Overview of the Proposition and Main Contents of Human—Water Relationship Discipline

The human–water relationship in the Yellow River Basin is complex and diverse, involving knowledge in different fields such as physics, chemistry, geography, resource science, environmental science, economics, and management science. Some difficult problems require the joint research of multiple disciplines. Human–water relationship discipline involves 10 sub-disciplines of water science (hydrology, water resources, water environment, water security, water engineering, water economy, water law, water culture, water information, and water education) and has the outstanding advantage of human–water relationship research. Therefore, the theory and method system of human–water relationship discipline is a powerful tool to solve the difficult problems of human–water relationships in the Yellow River Basin.

Since 2007, starting from the definition of the human–water system, Zuo has carried out a series of studies on the evolution process, simulation model and influencing factors of the human–water relationship discipline. In 2021, Zuo summarized the concept and disciplinary system of human–water relationship, and discussed in detail the basic principles and theory system [14]. Human–water relationship discipline is an interdiscipline that respects the natural laws of water systems and economic development, and draws on water science theory and multidisciplinary approaches to study the mechanisms, change processes, numerical simulation and scientific regulation of human–water system. In addition, human system can use these theories and methods to address human–water relationship problems and develop water strategies [14].

A complete disciplinary system includes at least five elements, namely, a clear research object, specific basic principles, a relatively well-developed theory system, a set of methodologies and extensive application practices. Obviously, human–water relationship discipline has these five elements, and the framework of the discipline system is shown in Figure 4.

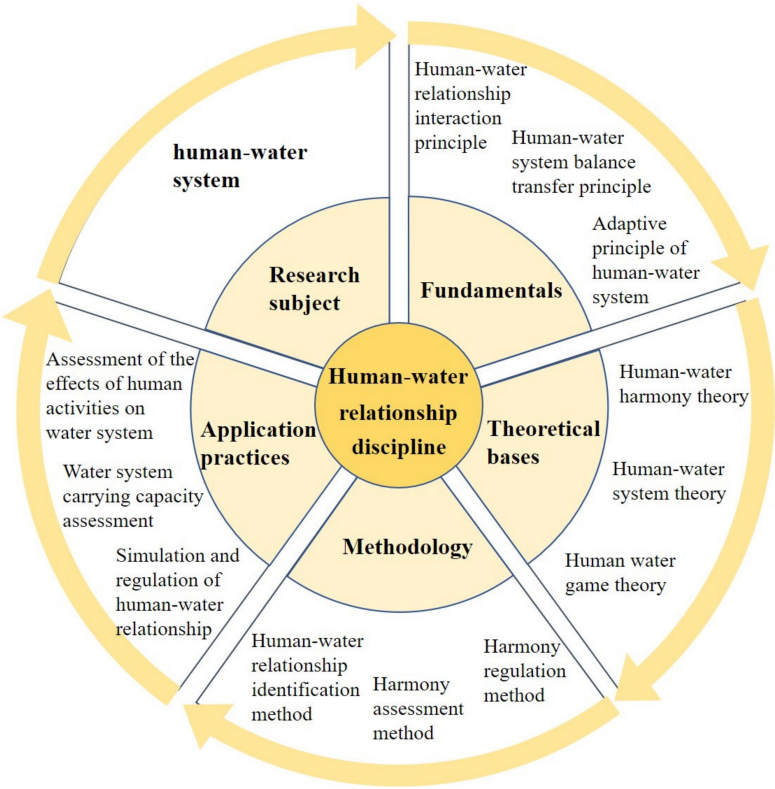

Figure 4. Framework of human–water relationship discipline.

(1) The research object of human–water relationship discipline. The research object of the discipline is very clear, that is, the human–water system.
(2) The basic principles of human–water relationship discipline. The basic principle is the interpretation to the basic laws of the interaction and evolution of the human–water system. According to the internal function relationship of the human–water system, the basic principles of the human–water relationship discipline are summarized, including the human–water relationship interaction principle, human–water system balance transfer principle, and adaptive principle of the human–water system.
(3) The theoretical bases of human–water relationship discipline. Human–water relationship is an interdisciplinary discipline involving water science, sociology, economics, systems science and many other disciplines. Most of the theories and methods from the above disciplines can be applied to the research of human–water relationship discipline. Therefore, these theories are also the theoretical bases of human–water relationship discipline. In addition, there are some theories specifically proposed for the research of human–water relationship. For instance, human–water harmony theory, human–water system theory, human–water game theory, and human–water relationship process theory, etc.
(4) The methodology of human–water relationship discipline. The representative methodology of hydrology, water resources, water environment, water security, water engineering, water economics, water law, water information, as well as sociology, economics, systems science and other disciplines can be applied to the research of human–water relationship. In addition, there are some methods specially proposed for the research of human–water relationship. For instance, human–water relationship identification method, harmony assessment method, human–water relationship simulation method, harmony regulation method, etc.
(5) The application practices of human–water relationship science. Human–water relationship discipline is a subject with wide application. Its representative application practices include: ① Analyze the role of human activities on water systems and assess the impact of human activities. ② Analyze the restrictive effect of the water system on human development, and evaluate the carrying capacity of water system. ③ Establish a simulation model of human–water relationship and analyze the evolution trend of human–water system. ④ Construct a support system for the human–water relationship, respond to water issues, and develop water strategies.

4.2. Solutions to Difficult Problems in the Yellow River Basin Based on the Perspective of Human—Water Relationship Discipline

Human–water relationship discipline has outstanding advantages in solving difficult problems of human–water relationship. A few representative problems in the Yellow River Basin are selected to introduce possible solutions from the perspective of human–water relationship discipline (Figure 5).

(1) Demonstration of the west route of the South-to-North Water Diversion Project. Combined with the simulation method of human–water relationship, it should be simulated and demonstrated from both positive and negative aspects based on the interaction principle of human–water relationship. Forming two academic camps and forming a consensus through discussion will help the government to make more scientific decisions. Based on the thinking of human–water game theory, analyze and demonstrate from a global perspective, and avoid making decisions when the depth of the argument is insufficient.
(2) Water distribution of the Yellow River. Based on the adaptive principle of human–water system, combined with the harmony assessment method, consider the dynamic adaptability of regional human–water system. Then formulate the water distribution calculation method and process, and determine the water distribution of the Yellow River. Based on the human–water system theory to establish the idea of harmonious water distribution, and to ensure the stability of various ecological functions of the

water system and realize the harmonious coexistence of human and nature. Coordinate the relationship between different water-using areas and the relationship between water resources carrying and economic development, so as to promote the harmonious development of the human–water system in the Yellow River Basin.

(3) Construction of large water conservancy projects. To follow the principle of balance transfer of human–water system, and strive to make the human–water system to the benign direction. The construction of large-scale water conservancy projects will inevitably bring about changes in the river water ecosystem, and it is necessary to regulate and demonstrate that the transformed system is acceptable. Based on the theory of human–water harmony, combined with harmonious regulation method, adhere to the concept of harmonious coexistence between man and nature to scientific demonstration and regulation. Encourage some people to stand in the perspective of nature and have a dialogue with engineering demonstrators.

(4) Flood and drought disaster prevention and control. Learn to deal with floods and droughts from the principle of harmonious evolution of human–water relationship. Based on the concept of human–water system theory, combined with harmonious regulation method, build an integrated disaster prevention and relief system. Flood and drought disaster prevention is a systematic project. First of all, the hardware capacity should be improved. Secondly, the popular science education of flood control and drought relief should be strengthened. Finally, a disaster prevention and relief system of "government command, department leadership, and public participation" should be formed.

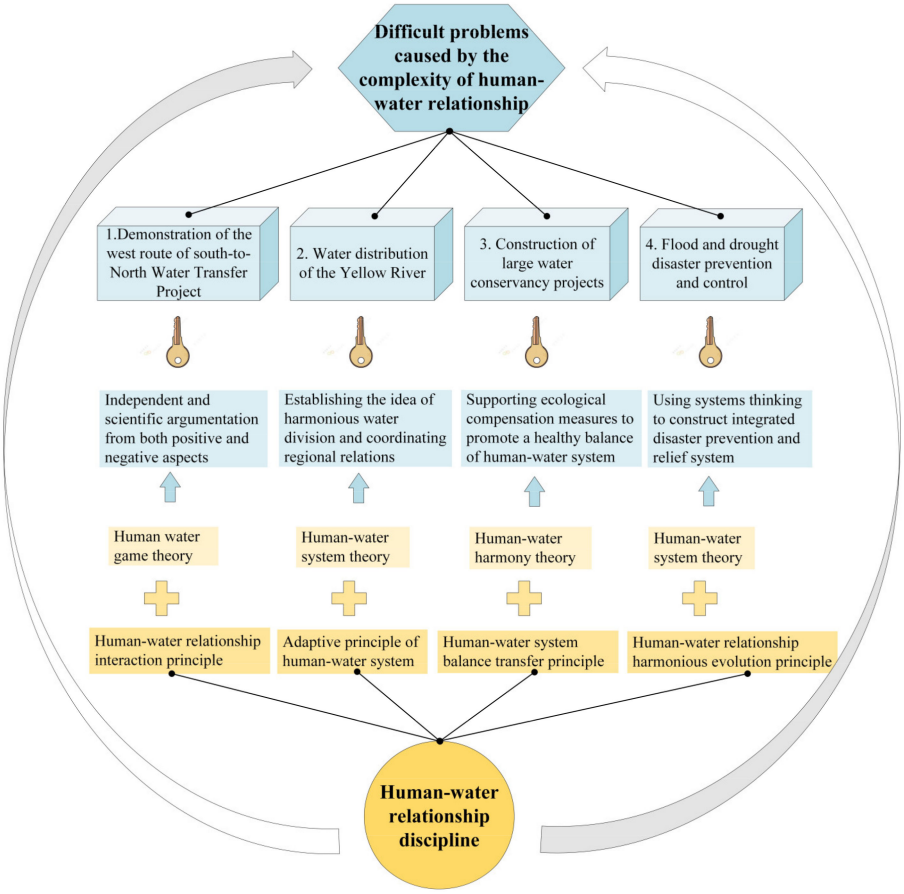

Figure 5. Solutions to the difficult problems caused by the complexity of human–water relationship in the Yellow River Basin.

The solutions discussed above are only a general introduction at the macro level. Only the basic theories and methods of human–water relationship discipline are covered, and no

more in-depth and detailed exploration is carried out at the application level. In order to further verify the ability of human–water relationship discipline to guide the solution of practical problems, the following is a concrete application of its theory and method system, taking the Yellow River water distribution problem as an example.

4.3. A Case Study on the Water Distribution of the Yellow River from the Perspective of Human—Water Relationship Discipline

4.3.1. The Necessity of Further Research on the Water Distribution

The water distribution of the Yellow River has always been a difficult problem of the human–water relationship in the basin. In addition, it is also one of the key issues to be overcome in the implementation of the major national strategy of the Yellow River. Since the 1970s, the interruption of the Yellow River has become increasingly serious. To alleviate the conflict between water supply and demand, the Chinese government approved the Yellow River water distribution scheme in 1987, known as the "87" scheme. The scheme is the first transboundary river distribution scheme in China for large river, which effectively balances the water demand in various regions of the Yellow River Basin.

However, it has been more than 30 years since the implementation of the "87" scheme, and the regions have undergone radical changes. Moreover, the scheme clearly stated that it was based on the actual water consumption in 1980, which did not match the current water consumption pattern. The "87" scheme urgently need to adjust but difficult to carry out. The Chinese government and scientists have been discussing the issue for more than a decade, but no conclusive conclusion has been reached. The Yellow River water distribution problem is ultimately a human–water relationship problem, and needs to be analyzed from the perspective of human–water relationship discipline. How to coordinate the human–water relationship and formulate a feasible new water distribution scheme is very important for the future development of the Yellow River Basin. In this section, the Yellow River water distribution problem is used as an application example to explore a new water distribution scheme from the perspective of human–water relationship discipline.

4.3.2. The Ideology and Principle of the Water Distribution

Human–water relationship discipline emphasizes the harmonious balance between the human system and the water system. Therefore, to deal with the water distribution problem of the Yellow River from the perspective of human–water relationship discipline, the following guiding ideology should be followed. ① Bearable water distribution idea. The water distribution must first ensure the carrying capacity of the water system. ② Harmonious water distribution idea. The intricate human–water relationship of the Yellow River Basin requires a harmonious balance within the human–water system in the process of water distribution. ③ Fair water distribution idea. Water distribution needs to realize the utilization of the water resources in a fair and reasonable way in all regions of the basin. ④ Shared water distribution idea. "Public" is the basic characteristic of water resources. The water distribution scheme needs to form a suitable relationship of mutual benefit and coordinated development in different regions. ⑤ Systematic water distribution idea. The water distribution of the Yellow River is a complex systematic project. The water distribution scheme should be systematically formulated from two perspectives of human system and water system.

From the perspective of human–water relationship discipline, the basic principle of the Yellow River water distribution is analyzed as follows. ① The water system is greatly affected by natural conditions and human activities, so it is necessary to consider these environmental changes and carry out adaptive water distribution. ② The problem of water distribution in the Yellow River is complex. It is necessary to adhere to scientific water distribution ideas and principles, and learn from international successful distribution experience to carry out comprehensive distribution. ③ Through the implementation of the water distribution scheme, to support the living, production and ecological water utilization,

and to realize the stable development of the human system, the healthy circulation of the water system, and finally to realize the harmony of the human–water system (Figure 6).

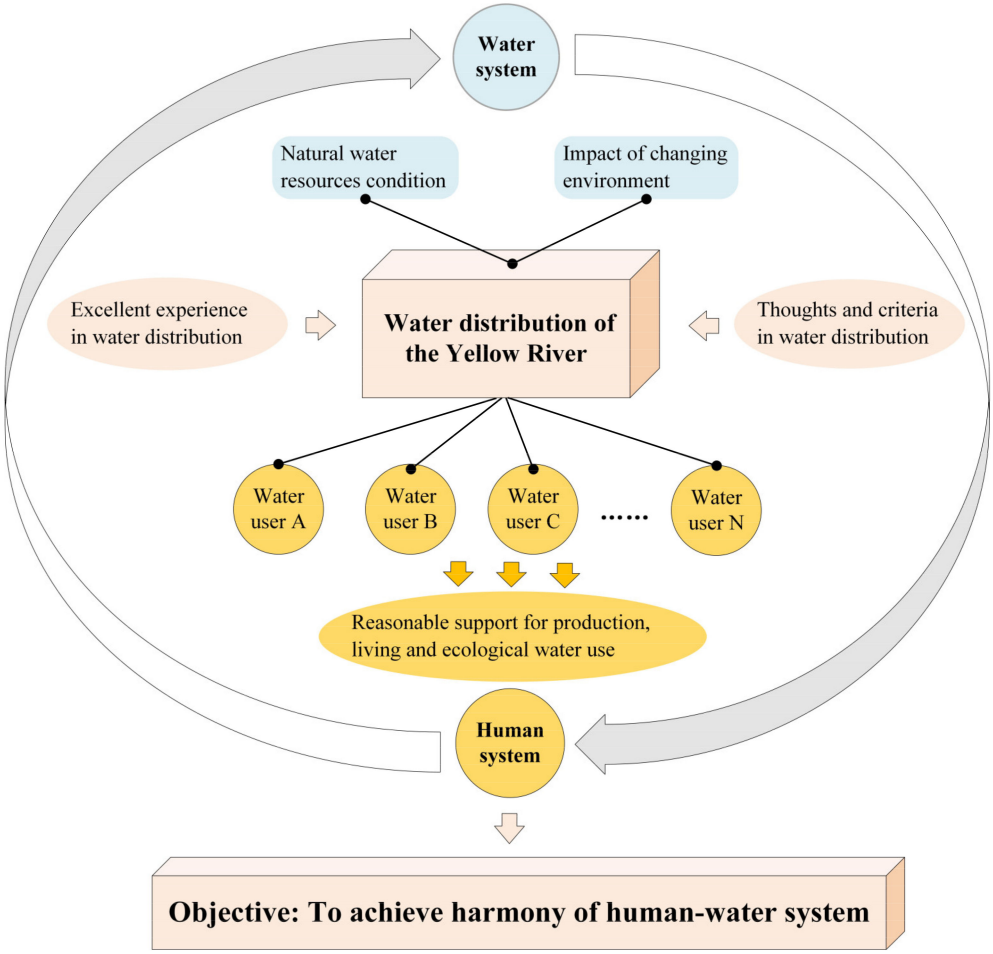

Figure 6. Schematic diagram of the principle of the Yellow River water distribution.

4.3.3. The Formulation and Calculation of the Water Distribution Scheme

From the perspective of human–water relationship discipline, the Yellow River water distribution scheme is formulated. The general process is as follows. ① Firstly, consider the water constraints of each region, and the water allocated to the region should meet the minimum water demand for living, production and ecology. ② Secondly, systematically determine water distribution criteria, quantitatively calculate the water distribution schemes under different water distribution criteria. ③ Thirdly, determine the weight of each water distribution scheme. ④ Then, each water distribution scheme will be weighted and calculated to obtain a new water distribution scheme for the Yellow River. ⑤ Finally, dynamically adjust the new water distribution scheme with the change of the amount of water resources.

Taking various factors into consideration and combining with the basic principle and theoretical basis of human–water relationship discipline, the water distribution criteria and specific quantification methods of the Yellow River is summarized.

(1) Water is allocated according to the original water distribution scheme. The original water distribution scheme (The "87" scheme) is based on expert's argumentation and comprehensive coordination, which has high reference value.
(2) Water is allocated according to the current water use pattern and considering the future water demand. This criterion is more realistic and effective in alleviating

water shortage and waste. This is also a common method of water distribution in transboundary rivers. The calculation method is as follows [29]:

$$Q_k = \omega \cdot Q_{kx} + (1 - \omega) \cdot Q_{kw} \quad (1)$$

In Equation (1), Q_k is the water distribution amount in region k, 10^8 m^3; k is the area number, k = 1, 2, . . . , n. ω is the adjustment coefficient of the current water use. Q_{kx} is the current water consumption, 10^8 m^3. Q_{kw} is the future water demand considering the future development scale, 10^8 m^3. Generally, ω = 0.5 is taken, that is, the current water consumption and the future water demand each account for half of the proportion.

(3) Water is allocated according to the proportion of the actual population. Population is one of the main indicators that affect and even determine the scale of water use. This criterion is to allocate water according to the population of each region under the condition of ensuring the ecological protection of the Yellow River. The calculation method is as follows [29]:

$$Q_k = \frac{P_k}{P_z} \cdot Q_{z1} \quad (2)$$

In Equation (2), Q_k is the water distribution amount in region k, 10^8 m^3; P_k is the actual water-using population of region k; P_z is the total actual water-using population in the Yellow River Basin. Q_{z1} is the amount of the allocatable water, 10^8 m^3.

(4) Water is allocated according to the proportion of regional GDP. GDP is an important indicator to characterize the scale of regional economic development. Considering the needs of regional production and development, water can be allocated according to the proportion of regional GDP. The calculation method is as follows [29]:

$$Q_k = \frac{G_k}{G_z} \cdot Q_{z1} \quad (3)$$

In Equation (3), Q_k is the water distribution amount in region k, 10^8 m^3; G_k is the GDP of region k; G_z is the total GDP in the Yellow River Basin.

(5) Water is allocated in proportion to the area of the basin in each region. In order to reflect the contribution of different regions to water production in the basin, it is reasonable and fair to use basin area or water production ratio to divide the water. The calculation method is as follows [29]:

$$Q_k = \frac{S_k}{S_z} \cdot Q_{z1} \quad (4)$$

In Equation (4), Q_k is the water distribution amount in region k, 10^8 m^3; S_k is the basin area of region k; S_z is the total area of the Yellow River Basin.

(6) Water is allocated according to the maximum overall harmony degree (*HD*). The water distribution of the Yellow River should adhere to the idea of harmonious water distribution. The harmony evaluation method in the human–water relationship discipline is adopted. Water is allocated reasonably according to factors such as water use, geographical location, and per capita water consumption so as to achieve the maximum overall harmony degree. The calculation method is as follows [30]:

$$HD = a \cdot i - b \cdot j \quad (5)$$

$$a = \frac{\sum_{k=1}^{n} B_k}{\sum_{k=1}^{n} A_k} \tag{6}$$

In Equations (5) and (6), *HD* is the degree of harmony, which is used to characterize the degree of harmony of the water distribution scheme [1]. a is the uniform degree, which is expressed by the ratio of the water consumption that meets the harmonious goal to the actual water consumption. b is the divergence degree, which indicates the proportion of the harmonious participants who have disagreement with the harmonious goal, $b = 1 - a$. i is the harmony coefficient, reflecting the satisfaction degree of the harmony goal; j is the disharmony coefficient, reflecting the importance of the harmonious participants to the phenomenon of divergence, i and j are generally calculated using the given function curve [30].A_k is the harmonious behavior of region k, that is, the actual water consumption. B_k is the harmonious behavior of region k that conforms to the harmonious rule, that is, the water consumption does not exceed the allocated water quantity.

In this research, the weight of each water distribution scheme was determined by expert consultation methods. A total of 180 valid questionnaires were received, all from experts in related fields. The final weights of the six water distribution schemes were obtained as 0.170, 0.255, 0.130, 0.090, 0.080, and 0.275, respectively.

4.3.4. The Result and Analysis of the New Water Distribution Scheme

According to the "87" scheme, the Yellow River can supply 37 billion cubic meters of water. In this section, the water volume of 37 billion cubic meters is allocated first. If the water volume is adjusted, a new water distribution volume can be obtained according to the dynamic adjustment formula. Six water distribution schemes are obtained according to the above six water distribution criteria. Scheme ② requires future water demand data. The data are obtained according to the total water consumption control target in the "Strictest Water Resources Management System" and in combination with the comprehensive planning of water resources in each region. Scheme ⑥ is based on the water consumption data of the past 10 years, and adjusts the water volume of each region in the water distribution scheme according to the degree of harmony, so as to achieve the greatest overall harmony degree.

In fact, the water supply regions of the Yellow River include not only the nine provinces in the basin, but also Hebei and Tianjin. Therefore, according to Scheme ① and ②, the final water distribution of Hebei and Tianjin is 976 million m^3 (Table 1). Then, the remaining water volume of 36.024 billion m^3 was allocated to the nine provinces according to six schemes (Table 2). Finally, combined with the weights of each scheme, the final water distribution and proportion of each province was calculated (Table 3).

As can be seen from the results of water distribution, the three regions with the largest water distribution are Shandong, Inner Mongolia, and Henan, respectively. Three regions received more than 50% of the total water distribution. The water distribution in Sichuan and Qinghai is less, less than 10% of the total water distribution. Compared with the "87" scheme, it can be seen that under the new scheme, Hebei, Tianjin, Shaanxi, Ningxia, and Shandong have the largest changes in water distribution, and other regions have little change.

Combined with the actual situation of the nine provinces, it can be seen that the water distribution scheme based on the actual water consumption of the region is not suitable for the current development layout of the Yellow River Basin. After in-depth discussion, we believe that from the perspective of the human–water relationship discipline, the new water distribution scheme obtained by considering multiple criteria is more in line with the current water use pattern of the basin and the development orientation of the nine provinces. However, there are also uncertainties in the water distribution scheme. Firstly, the uncertainty of the water distribution criteria. Although we selected as many representative water distribution criteria as possible, the water distribution problem

involves a wide range, and it is difficult to quantify all the water distribution criteria. Secondly, the uncertainty of the weighting scheme. The distribution of weights under different water distribution criteria depends mainly on the subjective perception of experts in this field, which is ultimately a subjective method of determining weights, and the result of weight distribution may be disturbed by subjective factors.

Table 1. Water distribution and weight calculation under two water distribution schemes (10^8 m^3).

Water Distribution Scheme	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shanxi	Shaanxi	Henan	Shandong	Hebei Tianjin	Weight
Scheme ①	14.1	0.4	30.4	40	58.6	43.1	38	55.4	70	20	0.4
Scheme ②	10.92	0.26	26.49	45.04	68.4	39.39	47.55	51.53	77.48	2.94	0.6

Table 2. Water distribution and weight calculation under six water distribution schemes (10^8 m^3).

Water Distribution Scheme	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shanxi	Shaanxi	Henan	Shandong	Total	Weight
Scheme ①	14.51	0.41	31.29	41.17	60.32	44.36	39.11	57.02	72.05	360.24	0.17
Scheme ②	10.71	0.25	25.99	44.21	67.13	38.66	46.67	50.58	76.04	360.24	0.26
Scheme ③	9.95	1.56	38.54	11.33	21.04	61.55	53.26	73.1	89.91	360.24	0.13
Scheme ④	7.9	0.88	17.81	10.39	33.34	44.36	57.67	79.35	108.54	360.24	0.09
Scheme ⑤	68.97	7.7	64.89	23.29	68.42	44	60.4	16.4	6.17	360.24	0.08
Scheme ⑥	9.99	0.21	32.94	38.12	74.25	31.88	43.51	53.7	75.64	360.24	0.28

Table 3. Final calculation results of the new scheme with 37 billion m^3 volume (10^8 m^3).

Regions	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shanxi	Shaanxi	Henan	Shandong	Hebei Tianjin	Total
Water distribution	15.47	1.09	32.81	33.03	59	41.68	47.46	55.31	74.39	9.76	370
Ratio	0.042	0.003	0.089	0.089	0.159	0.113	0.128	0.149	0.201	0.026	1
Comparison with the "87" scheme	+1.37	+0.69	+2.41	−6.97	+0.4	−1.42	+9.46	−0.09	+4.39	−10.24	0

5. Possibility and Prospect of Applying the Human—Water Relationship Discipline to the Research of Complex Basins

5.1. Feasibility Analysis of Human—Water Relationship Discipline Applied to Other Complex Basins

From the perspective of the human–water relationship discipline, the solutions to several representative problems of the human–water relationship in the Yellow River Basin are discussed in previous sections. In fact, various countries and major river basins all over the world have different degrees of human–water relationship problems. In this section, three typical complex river basins, including the Yangtze River Basin, Nile River Basin, and Mississippi River Basin, are selected to analyze the feasibility and universality of the human–water relationship discipline in the research of complex river basins.

(1) Feasibility analysis of the application of human–water relationship discipline in the Yangtze River Basin. The Yangtze River is the largest river in China and has an important strategic position in China's regional coordinated development pattern. However, the problems of water ecology and water environment in the Yangtze River Basin are very prominent, which seriously restricts the development quality of the Yangtze River Economic Belt. From the perspective of the human–water relationship discipline, the emergence of the above problems represents that the interaction of the human–water relationship has entered a vicious circle. The human system blindly pursues "me as the center" without considering that destroying the water system will also put pressure on the development of the human system. Based on the thinking of human–water harmony theory, using the method of harmony identification to judge the state of the human–water relationship. Moreover, combining the method of harmony regulation to improve the interaction of the human–water system can alleviate the disharmony between ecological protection and economic development in the Yangtze River Basin to a certain extent.

(2) Feasibility analysis of the application of human–water relationship discipline in the Nile River Basin. The Nile is the most famous international river in Africa. Due to historical reasons and development needs, water disputes among different countries are the most prominent problems [31]. From the perspective of human–water relationship discipline, the contradiction between water supply and ecological problems of Nile River, similar to the problem of water distribution of Yellow River, is caused by the contradiction of water use between nature and humans and the contradiction of water use between different regions. It is necessary to actively explore a win-win water distribution method based on the principle of human–water system adaptability, combined with the idea of human–water system theory. On the premise of ensuring the stability of the ecological function of the basin, the harmonious development of the relationship between humans and water, between regions, and between countries should be realized.

(3) Feasibility analysis of the application of human–water relationship discipline in the Mississippi River Basin. The Mississippi River is the largest river in North America and the most valuable river in the United States. However, in the past hundred years, floods have occurred frequently in the lower reaches of the river [32]. The U.S. government's early "flood control" strategy based on large-scale construction of embankments did not work well. The problem of flood management is the biggest human–water relationship problem on the Mississippi River. With the popularization of the idea of human–water harmony, the flood control measures for the river in the United States have changed from "mainly engineering measures" to "combining engineering and non-engineering measures". The principle of harmonious evolution of the human–water relationship has been embodied in the flood control of the Mississippi River. When dealing with flood and drought disasters, we should not blindly pursue "control", but conform to the natural law of disaster, and use diversified means to achieve harmonious coexistence with floods.

5.2. Prospect for Future Research on Human—Water Relationship Discipline

Human–water relationship discipline is a newly proposed subject, which has a strong application prospect in solving the problem of the human–water relationship. However, the disciplinary system is still in the initial stage of development, and the theories, methods, and applications need to be further enriched. The following discusses the research prospect of the human–water relationship discipline from three aspects.

(1) Prospect of theory research. ① Extensive integration of multidisciplinary theories to further strengthen the theoretical foundation of human–water relationship research. For example, the integration of water cycle theory and social theory, the integration of water environment theory and life and health theory, and the integration of water resources theory and value theory in economics. ② Further carry out theoretical research on the human–water relationship and form the theoretical characteristics. For example, human–water harmony theory, human–water system theory, human–water relationship process theory, etc.

(2) Prospect of method research. ① Promote the cross-application of multidisciplinary methods. Due to the complexity of the human–water relationship, the research on the cross-application of multidisciplinary methods needs to be strengthened. ② In-depth research of the identification method, evaluation method, and regulation method of the human–water relationship. The construction and solution of the harmony regulation model and the development of the regulation system are the key points of the method system of human–water relationship discipline.

(3) Prospect of applied research. ① Further research of the simulation model of the human–water relationship and apply it to the analysis and control of the evolution trend of the human–water relationship. ② Further apply the regulation method of human–water relationship to the practice of water resource planning, management, and dispatching.

③ Further research the support system of the human–water relationship and apply it to the response to water problems and the formulation of water strategies.

6. Conclusions

Based on the historical evolution and complexity of the human–water relationship in the Yellow River Basin, this study summarized the difficult problems of the human–water relationship, discussed the solutions from the perspective of the human–water relationship discipline, and provided an application example. In addition, the possibility of applying human–water relationship discipline to complex basin research was analyzed, and the future research prospects of the discipline were discussed. This study is a framework study focusing on theories and methods. Although it provides an application case analysis, the application of the theory and method system is not comprehensive. Some theories and methods still need to be further verified in practical applications. Finally, some valuable conclusions are as follows:

(1) River diversion and irrational human activities are the main driving factors for the ecological evolution of the Yellow River Basin. The evolution process of human–water relationship in the basin can be basically divided into five stages: low-level harmony stage, exploratory development stage, dysfunctional deterioration stage, protective coordination stage and high-quality harmony stage. The current human–water relationship is at protective coordination stage. With the progress of concept and technology, the difficult problems of human–water relationship will be gradually overcome, and the human–water relationship in the Yellow River Basin will enter a high-quality harmony stage.

(2) The complexity of the human–water relationship in the Yellow River Basin brings many difficult problems. For example, the demonstration of the west route of the South-to-North Water Diversion Project, the water distribution problem of the Yellow River, the construction of large water conservancy projects, and the prevention and control of flood and drought disasters, etc. Forming a sound disciplinary system of the human–water relationship and the corresponding theory and method system is the key to breaking through these difficult problems of the human–water relationship.

(3) Since the development of the human–water relationship discipline, it has basically possessed a clear research object, specific basic principles, a relatively complete theory system, a set of methodology, and extensive application practice. The four difficult problems of the human–water relationship in the Yellow River Basin can be solved from the perspective of the human–water relationship discipline. The new water distribution scheme of the Yellow River based on the human–water relationship discipline is a suitable fit with the current water utilization pattern.

(4) In addition to the Yellow River Basin, other typical river basins also have different degrees of human–water relationship problems. The theory and method system of the human–water relationship discipline is also feasible and universal for the research of other complex basins such as the Yangtze River Basin, the Nile River Basin, and the Mississippi River Basin. As an emerging discipline that takes human–water systems as its research object, the human–water relationship discipline has outstanding advantages in solving the difficult problems of human–water relationship science. However, it is still in the preliminary development stage, and its theory, methodology, and application research need to be further enriched.

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