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Status and Ponder of Climate and Hydrology Changes in the Yellow River Basin

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Status and Ponder of Climate and Hydrology Changes in the Yellow River Basin

Abstract

The Yellow River is known as China's Mother River, which fosters the great and profound Chinese civilization. However, the frequent flood and drought disasters have also brought serious disasters to the people who live in the Yellow River Basin. At present, significant changes have taken place in the climate and hydrological processes of the Yellow River Basin due to global warming and human activities. The warming and drying climate and increase of human water use in the Yellow River Basin have led to an increase in hydrological drought. Although the Grain for Green program has greatly improved the vegetation coverage on the Loess Plateau and effectively inhibited severe soil erosion, but also enhanced the soil desiccation and enlarged the dry soil layers in this area. These phenomena are not only the major challenges for ecological protection and high-quality development in the Yellow River Basin, but also the basic scientific issues which related to the coordinated development of climate-water-ecology-society.

Keywords

the Yellow River Basin; warming and drying climate; decreased streamflow; human water use

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Status and Pondering of Climate and Hydrology Changes in the Yellow River Basin

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Abstract: The Yellow River is known as China's Mother River, which fosters the great and profound Chinese civilization. However, the frequent floods and droughts have brought serious disasters to the people who live in the Yellow River Basin. At present, significant changes have taken place in the climate and hydrological processes of the Yellow River Basin due to global warming and human activities. The warming and drying climate and increase of human water use in the Yellow River Basin have aggravated the hydrological drought. Although the Grain for Green program has greatly improved the vegetation coverage on the Loess Plateau and effectively inhibited severe soil erosion, it enhanced the soil desiccation and enlarged the dry soil layers in this area. These phenomena are not only the major challenges for ecological protection and high-quality development in the Yellow River Basin but also the basic scientific issues which related to the coordinated development of climate–water–ecology–society.

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Editor's note: The Yellow River is known as China's Mother River, which fosters the great and profound Chinese civilization. Protection of the Yellow River is crucial to the great rejuvenation and sustainable development of the Chinese nation. General Secretary Xi Jinping has stressed that the Yellow River Basin is an important ecological barrier, an important economic zone, and an important region to win the fight against poverty, which plays a pivotal role in economic development and ecological security of China. Governance of the Yellow River Basin should focus on protection. Ecological protection and high-quality development of the Yellow River Basin is a complex and systematic project, which requires in-depth study and scientific demonstration of some major issues. *Bulletin of Chinese Academy of Sciences* invited Researcher Ma Zhuguo at the Key Laboratory of Regional Climate-Environment for Temperate East Asia, Chinese Academy of Sciences and Reseacher Zhang Wenzhong at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences to seek thinking and support for the control of the Yellow River from the perspectives of ecological protection and high-quality development.

On September 18, 2019, General Secretary Xi Jinping delivered an important speech at the Symposium on Ecological Protection and High-Quality Development of the Yellow River Basin. He points out that protecting the Yellow River is essential to the great rejuvenation of the Chinese nation, emphasizes the ecological protection and high-quality development of the Yellow River Basin as a national strategy, and proposes the necessity of in-depth study and scientific demonstration of major issues. The Yellow River is a vital water source in Northwest and North China. As of the end of 2018, the total population of the nine provinces through which the Yellow River flows reached 420 million, accounting for 30.3% of the national population. Besides, the gross regional product in this region was CNY 23.9 trillion, accounting for 26.5% of the total in the country [1]. Xi Jinping's speech raises the ecological protection and high-quality development of the Yellow River Basin to the level of national strategy, which demonstrates the important role of the Yellow River Basin in national security.

The Yellow River Basin, accounting for 2.2% of China's streamflow, is responsible for watering 15% of the arable land and supplying water for 12% of the population in China [2,3]. As the main energy base, the Yellow River Basin boasts 70% of the total coal resources and 50% of the total petroleum reserves in China. Large-scale energy development requires abundant water resources. At present, the human demand for water resources has far exceeded the carrying capacity of water resources in the basin, resulting in the overuse of surface water and the overexploitation of groundwater. Water use has significantly changed the water

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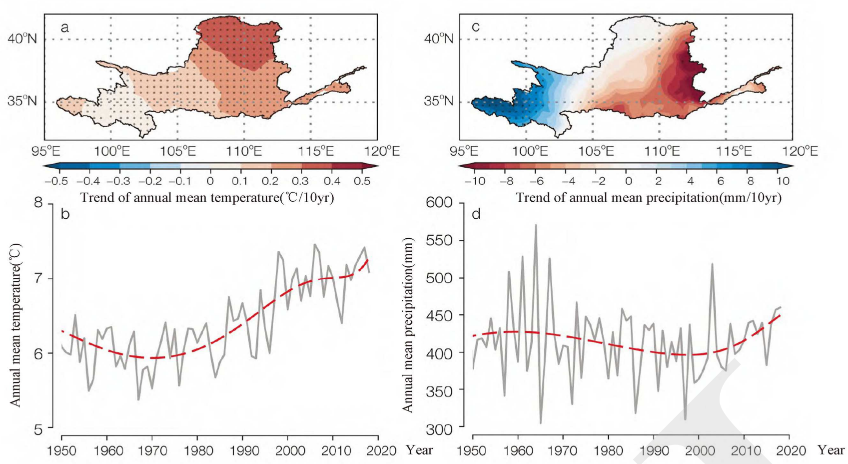

Figure 1 Trend of annual mean temperature and precipitation in the Yellow River Basin from 1951 to 2018.

(a) Trend of annual mean temperature; (b) Annual mean temperature in the basin; (c) Trend of annual mean precipitation; (d) Annual mean precipitation in the basin.

cycle and water resources pattern in the basin [4]. Most areas of the Yellow River Basin are in arid and semi-arid zone and extremely sensitive to climate change. In recent years, the warming and drying climate is one cause of the visual reduction in the streamflow of the Yellow River Basin [5–7]. Under the dual influence of climate warming and human activities, the imbalance between the supply and demand of water resources in the basin has become increasingly prominent, which made the basin one of the areas with scarce water resources in China [3,4]. Moreover, this region will continue to face the challenge of severe water shortage in the following 10–30 years.

What is the impact of the combination of disorderly water use and climate change on the regional water cycle of the Yellow River Basin? Will the water cycle be sustainable in the future? The Grain for Green program has markedly improved the vegetation coverage of the Yellow River Basin. What is the impact of such improvement on the streamflow in the basin? The core of the above questions is the collaborative mechanism of climate–water–ecology–society, and the answers to these questions are the scientific basis for ensuring the ecosystem health of the Yellow River Basin. We analyzed the changes in the climate and hydrology of the Yellow River Basin in the past half century and found that climate warming and human activities had affected the water resources of the Yellow River Basin. According to the results, we pointed out the problems in the ecological protection and high-quality development based on the current status of water resources in the basin.

1 Changes of climate and water resources in the Yellow River Basin

Most areas of the Yellow River Basin are located in arid and semi-arid zone, with a complex and diverse climate and the annual precipitation below 500 mm. With global warming, the climatic elements of the basin have also undergone significant changes in recent years.

1.1 Climate change

As shown in Figure 1a and 1b, the annual mean temperature in the Yellow River Basin has significantly increased from 1951 to 2018, with obvious regional differences. Hetao region had the most significant temperature increase, followed by the middle and lower reaches and the upper reaches. The annual mean temperature has increased by 1.39 °C, while the mean annual precipitation has decreased by 10 mm, which means that the Yellow River Basin has tended to warm and dry in the past 68 years. The annual precipitation in the upper reaches of the Yellow River significantly increased, while that in the middle and lower reaches showed the opposite trend (Figure 1c and 1d). From 1951 to 2018, the annual mean temperature and the annual precipitation have increased by 0.82 °C and 33 mm, respectively, in the upper reaches; the annual mean temperature has increased by 1.67 °C while the annual precipitation has decreased by 31.6 mm in the middle reaches. Precipitation concentration degree is an effective indicator characterizing precipitation process. A large precipitation concentration degree indicates frequent extreme precipitation events, which plays a role in the generation of streamflow, as the same precipitation results in different streamflow due to different precipitation processes. As shown in Figure 2, the precipitation concentration degree in most areas, especially in the middle and lower reaches, showed an increasing trend from 1951 to 2018, meaning that the extreme precipitation events in the Yellow River Basin tended to increase.

In the whole basin, the climate showed a trend of warming and drying, while the extreme precipitation events tended to increase. These phenomena would significantly impact the water resources system of the basin.

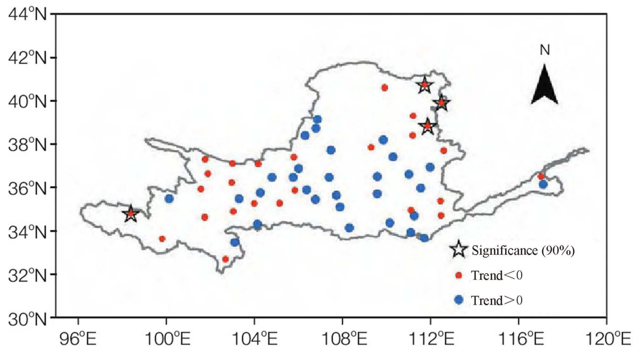

Figure 2 Trend of precipitation concentration degree in the Yellow River Basin from 1951 to 2018

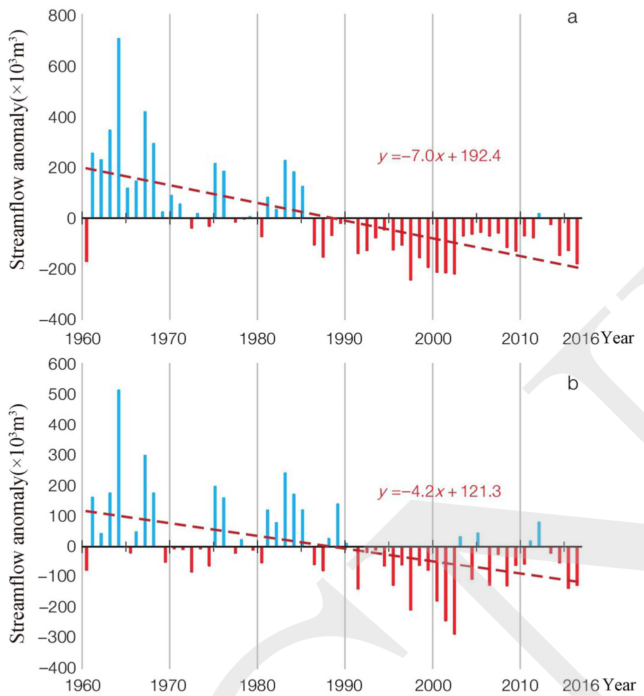

Figure 3 Changes in measured (a) and natural (b) streamflow in the Yellow River Basin

1.2 Changes of water resources and human water use

The Yellow River Basin, located in the arid and semi-arid zone with intense human activities, is extremely sensitive to climate change and human activities. The warming and drying climate and the increase in vegetation coverage have caused significant changes in the water resources of the basin. We analyzed the status of human water use in the basin based on the changes in streamflow.

Both the measured streamflow and the natural streamflow in the Yellow River Basin showed an obvious downward trend from 1961 to 2016 (Figure 3). The downward trend of natural streamflow was associated with the warming and drying climate during this period, especially the decrease in precipitation. Moreover, the increase in temperature accelerated the evapotranspiration in the basin, which was not conducive to the generation of streamflow. The substantial reduction in measured streamflow was associated with not only the warming and drying climate in the middle and lower reaches of the basin but also the overuse of surface water by humans.

The Yellow River Basin is China's main food base and energy base, where the imbalance between water supply and demand is particularly prominent. Agricultural water accounts for more than 60% of the water supply in the entire basin. As shown in Figure 4, the proportion of human water use in the total surface streamflow has risen from less than 20% in the 1950s to more than 85% recently, far exceeding the warning line (40%) of healthy rivers.

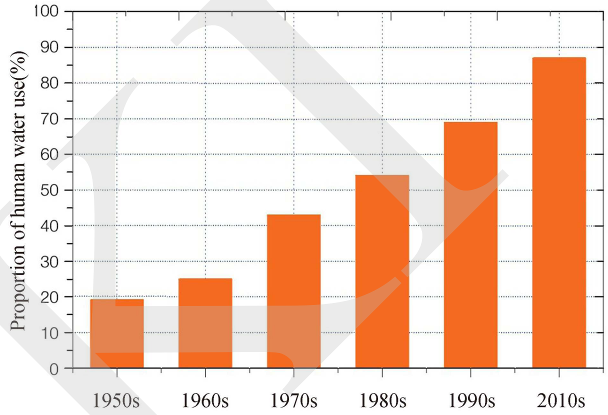

Figure 4 The proportion of human water use in natural streamflow in the Yellow River Basin since the 1950s

The agricultural water consumption has decreased by $3.474\ 1 \times 10^9$ m^3 from 2002 to 2018, and the industrial water consumption has reached a record high of 6.55×10^9 m^3 in 2011 (Figure 5). From 2002 to 2018, the agricultural and industrial water consumption has increased steadily ($+1.451 \times 10^8$ m^3), while the domestic and ecological water consumption has increased by 1.459×10^9 and 1.94×10^9 m^3, respectively. Among the human water use in the Yellow River Basin, agricultural water consumption accounted for the highest proportion, reaching 72% on average during 2002–2018. In 2012, the total supply of surface water and groundwater was 5.246×10^{10} m^3 (accounting for 68% of the water resources of the Yellow River Basin), while the agricultural water supply and consumption were $3.467\ 2 \times 10^{10}$ m^3 and $2.809\ 9 \times 10^9$ m^3, respectively, equivalent to an increase of 35 mm in mean evaporation per unit area, which significantly changed the evapotranspiration of the basin [8]. Due to the serious shortage of surface water supply, the groundwater of the Yellow River Basin was seriously over-exploited. In 2010, the shallow groundwater storage of the Yellow River Basin decreased by 1.63×10^8 m^3 compared with that in the last year, forming 12 cones of depression. Statistical data showed that the groundwater volume in the plain area of the Yellow River Basin was 1.546×10^{10} m^3, and the mean amount of extracted groundwater was 1.323×10^9

m^3 in recent years, far exceeding the reproducible amount of groundwater and surface water in the region ①. In addition, more than 20 large-scale reservoirs have been built along the main branches of the Yellow River, with the total storage capacity of more than 7×10^{10} m^3, which far exceeded the streamflow of the river. Besides, the increases in reservoirs and storage capacity have led to the rapid expansion of surface water bodies in the entire basin in the last 10 years. Human water use (including groundwater extraction and surface water utilization) has changed the distribution pattern of water resources and can affect the local hydrological cycle and regional climate in the Yellow River Basin. For example, farmland irrigation increased soil moisture and evaporation, which affects atmospheric precipitation and its supply to groundwater, influencing the conversion of atmospheric precipitation, surface water, and groundwater [8,9].

2 Effect of vegetation change on the regional water cycle in the Yellow River Basin

2.1 Vegetation change

As a fragile area of the ecosystem, the Yellow River Basin has undergone significant changes in the vegetation coverage, especially after the implementation of Grain for Green program in recent years. As shown in Figure 6a, the vegetation coverage in most areas of the Yellow River Basin has been improved since 2000, particularly in the middle and lower reaches. As shown in Figure 6b, the leaf area index (LAI) of the entire Yellow River Basin has increased by 36.6% since 2000. Specifically, the LAI has increased by 22.8% in the upper reaches (catchment area upstream of Lanzhou Station) and 43.9% in the middle and lower reaches from 1982 to 2017. From 1982 to 2017, the annual mean temperature and the annual precipitation increased by 0.82 °C and 33.0 mm, respectively, in the upper reaches; the annual mean temperature has increased by 1.67 °C and the annual precipitation has decreased by 31.6 mm in the middle and lower reaches. The increase in vegetation coverage in the upper reaches was mainly attributed to the increased temperature and precipitation. The warming and drying climate in the middle and lower reaches was unfavorable for plant growth, whereas the increase in vegetation coverage in the middle and lower reaches was about twice of that in the upper reaches. It can thus be inferred that the vegetation increase was attributed to the climate change in the upper reaches while the Three-North Shelter Forest program and the Grain for Green program in the middle and lower reaches.

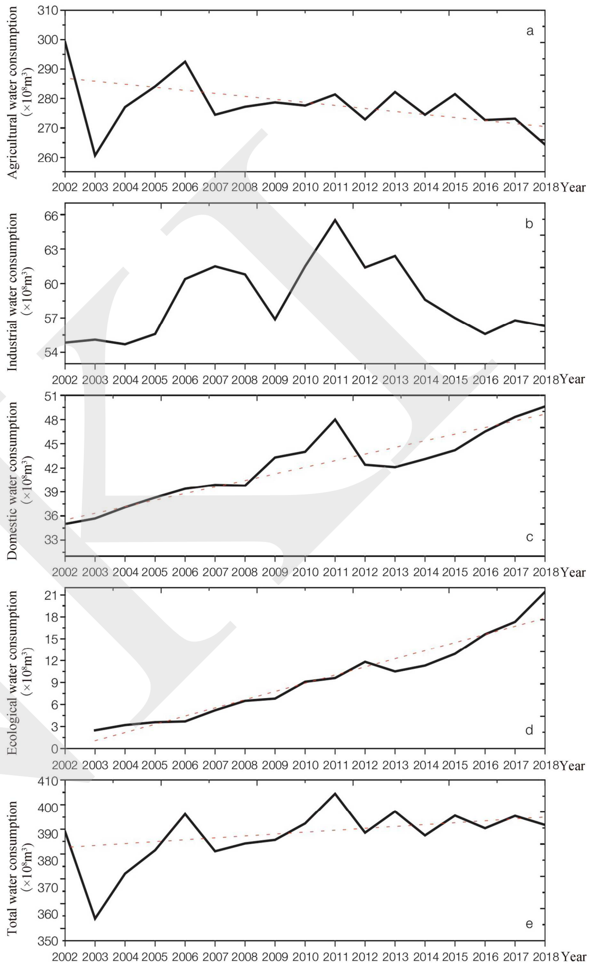

Figure 5 Changes in human water use in the Yellow River Basin in 2002–2018.

(a) Agricultural water consumption; (b) Industrial water consumption; (c) Domestic water consumption; (d) Ecological water consumption; (e) Total water consumption.

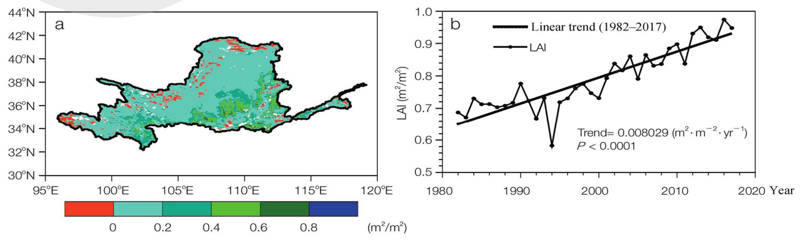

Figure 6 Changes in vegetation of the Yellow River Basin from 1982 to 2017

(a) The difference between mean $LAI_{2000–2017}$ and mean $LAI_{1982–1999}$. (b) Changes in mean LAI in the whole Yellow River Basin from 1982 to 2017.

① http://www.yellowriver.gov.cn/other/hhgb/2011/index.html.

2.2 Effect of vegetation change on water cycle

Climate change and human activities are two major factors that affect the water cycle of a river basin. Due to the regional differences in topography and climate change between different river basins, the diversity of climate, as well as the difference in human activities, the water cycle and its influencing factors are unique to different river basins, forming a complex system of water–soil–climate–ecology interactions involving both the nature and human. The research on water cycle change in a basin is indispensable for the exploration of these interactions. The available studies merely consider the interaction between single influencing factors and the water cycle [12], ignoring the relative contribution and comprehensive impact of various factors affecting the water cycle. The main problems can be summarized into two aspects. ① Unidirectionally driven hydrological model cannot objectively describe the interaction of climate change or human activities with the water cycle, and does not systematically consider the complete coupling of atmosphere–vegetation–hydrology. ② The comprehensive effects of climate change and human activities as well as the relative contribution of influencing factors are ignored. The relevant studies on the Yellow River Basin also have the above problems.

As mentioned above, since the implementation of the Grain for Green program in 1999, the vegetation coverage of the Yellow River Basin has increased significantly. How will such significant vegetation changes affect the water cycle of the entire basin? Is the current rapid decrease in streamflow of the Yellow River Basin related to changes in vegetation coverage? The underlying mechanism remains to be explained from the perspective of physics. For example, precipitation (being abundant) counts little for the sharp decline in sediment discharge in the Loess Plateau in recent years. Instead, human activities have changed the vegetation coverage of the underlying surface, and the increase in vegetation coverage has curbed the soil erosion caused by precipitation and reduced the sediment input into the river [21]. At the same time as the drastic reduction of sediment, the streamflow generation in the basin has also been sharply reduced, leading to the unique water–sediment imbalance of the Yellow River Basin [3,22,23]. Besides, the increase in vegetation coverage enhances the transpiration of underlying surface, which further causes the decrease in soil moisture and the thickening of dry soil layer, thereby leading to the imbalance between the supply and demand of soil moisture [24]. In addition, the source area of the Yellow River, which accounts for 35% of streamflow generation in the entire basin, is located on the Qinghai-Tibet Plateau with complex underlying surface and sensitive to climate warming. The temperature and precipitation, the changes in snow, frozen soil, and vegetation, as well as their impacts on local hydrological processes and water resources, are significantly different in different regions [25–27]. In the context of warming and drying climate, rapid reduction in streamflow, and increasing human water use, how to clarify the mechanisms underlying the above-mentioned scientific problems is a major challenge for achieving ecological protection and high-quality development of the Yellow River Basin.

3 Pondering of ecological protection and high-quality development of the Yellow River Basin

Under the combined influences of global warming and human activities, the climate and hydrological processes of the Yellow River Basin have undergone significant changes. The warming and drying climate, substantial reduction in streamflow, increase in extreme climate events, improvement of vegetation and the accompanied reduction in soil moisture and the continuous thickening of dry soil layer in the middle and lower reaches have become the main problems facing the ecological protection and high-quality development of the Yellow River Basin, is a multi-disciplinary issue. However, available studies cannot provide a scientific basis to support this issue. The speech of Xi Jinping on September 18, 2019 has already endorsed the ecological protection and high-quality development of the Yellow River Basin as a national strategy, with the core goals of (1) strengthening ecological protection, (2) guaranteeing the long-term stability, (3) promoting the economical and intensive use of water resources; (4) promoting the high-quality development, and (5) protecting, inheriting, and promoting the culture of the Yellow River. To realize these goals, we should conduct research in the following five aspects.

(1) To establish a collaborative monitoring network of water–soil–climate–ecology in the Yellow River Basin and realize data sharing. In the past, a large number of observational experiments and studies were conducted in the Yellow River Basin, such as the water–soil–climate–ecology observation experiment in the source area of the Yellow River and the observational experiment on small river basin in the Loess Plateau, which have accumulated a wealth of data. However, most of these studies are independent and fail to build a long-term national comprehensive monitoring network of water–soil–climate–ecology interaction in the Yellow River Basin. Thus, it is difficult to realize the sharing of data between different disciplines, which limits the progress of related scientific research and causes a waste of scientific and technological investment. It is therefore urgent

to study and establish the monitoring network of water–soil–climate–ecology in the Yellow River Basin for realizing data sharing.

(2) To develop a high-resolution climate–water–ecology–society coupling model. In the past, rich results and considerable progress have been achieved in the research on the Yellow River Basin, whereas the multi-layer interaction is still not fully studied from the perspective of earth system science, and the regional high-resolution earth system model has not been well studied and applied at the basin scale. Therefore, developing the high-resolution climate–water–ecology–society coupling model based on the new understanding of water–soil–climate–ecology interaction will provide effective tools for the research on the system in the Yellow River Basin.

(3) To study the coordinated development of climate–water–ecology–society. The core of ecological protection and high-quality development in the Yellow River Basin is the coordinated development of climate–water–ecology–society. The coordinated development necessitates the quantitative assessment and comprehensive analysis based on the high-resolution water–soil–climate–ecology model, which can clarify the coordination mechanism between different processes and give the optimal scheme.

(4) To predict climate change and its impact on the Yellow River Basin in the next 10–50 years. On the basis of the full understanding of climate–water–ecology–society coordination mechanism and the optimal scheme, scenario prediction of climate change in the following 10–50 years with the application of a well-developed coupling model is not only an important scientific basis for formulating the strategic plan for the ecological protection and high-quality development of the Yellow River Basin but also an effective way to actively respond to climate change.

(5) To explore the dynamic water distribution plan and the key technologies for the economical and intensive utilization of water resources in the Yellow River Basin. The warming and drying climate are unfavorable for the sustainable use of water resources in the basin. The large interannual variations of water resources and the remarkable decline in streamflow expose the necessity of exploring the dynamic water resources management plan for coping with the serious imbalance between water supply and demand in the basin. In addition, water conservation is an eternal topic. It is recommended to regard the possible scenarios of future water resources as rigid constraints at the climate and time scale, vigorously develop key water-saving technologies, and promote the conversion from extensive to economical and intensive water use to guarantee the most basic and critical water resources for the high-quality development of the Yellow River Basin.

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