Postprint of the Scientific Assessment of Ecological Effectiveness of the National Heihe River Basin Comprehensive Management Project

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Abstract

The Heihe River is the second largest inland river in northwestern China, and in 2001 the state implemented a comprehensive management project for this basin. Based on research findings and stage-specific understanding of water cycling, water processes, and ecological and environmental changes in the Heihe River basin’ s natural-economic system over the past decade, this article provides a scientific assessment of ecological governance effectiveness and its environmental impacts. Overall, water resources in the Heihe River basin are primarily influenced by the westerlies, with runoff mainly generated in mid-high mountain areas. The past decade and century constitute a wet period both since instrumental records began and on a millennial scale, providing strong water resource security for water allocation and comprehensive management; however, the continuously growing water demand pressure from the socio-economic system constitutes the primary root cause of conflicts between the middle and lower reaches and between economic development and ecological water use. With surface water utilization effectively controlled in the middle reaches, the water use structure of the socio-economic system in this region has undergone significant changes; however, limitations on surface water resources and continuous expansion of cultivated land area in the middle reaches have led to declining trends in local groundwater levels and storage, and the area faces severe water resource overloading during dry periods. Water volumes reaching the lower reaches approximate planning requirements, and the deteriorating trends in the water system and ecological environment of the lower reaches have been effectively curbed, but have not yet fully recovered and exhibit substantial spatial heterogeneity. Continuously increasing cultivated land converted from riparian forest land places greater pressure on the allocation between ecological and productive water use in the lower reaches, requiring more refined spatiotemporal water resource management and regulation measures. Water resource management under the objective of socio-economic-ecological sustainable development in the basin will face even greater challenges in future potential dry periods.

Full Text

Scientific Assessment of Ecological Effects of the National Integrated Management Project in the Heihe River Basin

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Abstract

The Heihe River is the second largest inland river in northwest China. In 2001, the Chinese government implemented a comprehensive management project for this watershed. Based on research findings and periodic understanding of the water cycle, hydrological processes, and ecological-environmental changes in the Heihe River Basin’ s natural-economic system over the past decade, this paper provides a scientific assessment of the ecological management effects and their environmental impacts.

Overall, the basin’ s water resources are primarily influenced by the westerly belt, with runoff mainly generated in mid-to-high altitude mountainous areas. Both the past decade and the past century represent high-flow periods in the instrumental record and on a millennial scale, providing a robust water resource foundation for water allocation and integrated watershed management. However, the continuously growing water demand pressure from the socioeconomic system constitutes the root cause of conflicts between water use in the middle and lower reaches and between economic development and ecological water requirements. Under effective control of surface water utilization in the middle reaches, the water use structure of the socioeconomic system has undergone significant changes. Nevertheless, limited surface water resources and continued farmland expansion have led to declining local groundwater levels and storage, posing severe water resource overload problems during low-flow periods.

The volume of water reaching the lower approaches meets planning requirements, and the deteriorating trend of the water system and ecological environment has been effectively curbed, though comprehensive recovery has not yet been achieved and substantial spatial heterogeneity persists. Farmland converted from riparian forests continues to increase, intensifying pressure on water allocation between ecological and agricultural uses in the lower reaches, which requires more refined spatiotemporal water resource management and regulation measures. The sustainable development goals for society-economy-ecology in the basin will face even greater challenges in water resource management during future potential low-flow periods.

Keywords: Heihe River Basin, watershed integrated management, ecological effects, scientific assessment, problems and countermeasures

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The Heihe River, the second largest inland river in northwest China, flows through extremely arid regions in its middle and lower reaches where water resources cannot meet the needs of local economic development and ecological balance. Historical water conflicts have been particularly acute. Since the 1960s, increasing population, economic development, and excessive exploitation of water and land resources have gradually reduced water flow to the lower reaches, exacerbating ecological problems such as dried-up rivers and lakes, large-scale forest die-off, grassland desertification, and rampant sandstorms, while intensifying inter-provincial and upstream-downstream water disputes [1].

In 1999, the Yellow River Conservancy Commission of the Ministry of Water Resources established the Heihe River Basin Administration to implement unified water allocation. On August 3, 2001, the State Council approved the *Recent Management Plan for the Heihe River Basin* (hereinafter referred to as "the Plan") through Document No. 86 [2001]. The Plan aimed to achieve the State Council-approved *Heihe River Mainstream Water Allocation Scheme* (Document No. 496 [1997]) within three years, gradually forming an ecosystem comprehensive management and protection system centered on rational water resource allocation to curb ecosystem degradation and lay a solid foundation for gradual improvement of the local ecosystem.

How effective has the ecological project been? Can it achieve sustainable development? How should subsequent projects be implemented? These are critical questions for national decision-makers. Conducting scientific assessments of major ecological engineering effectiveness is essential for comprehensively and timely understanding the ecological effects of major ecological management projects, recognizing evolution patterns of ecology and environment in arid northwest China, revealing environmental response processes during ecological restoration, analyzing major problems, and proposing solutions and further countermeasures. This is also a prerequisite for ensuring project effectiveness and scientifically deploying follow-up ecological projects.

Effectively providing authoritative scientific evidence to policymakers represents a major challenge for the scientific community. Extracting consensus-based scientific assessments from numerous research findings and perspectives is a powerful tool to address this challenge [2]. A series of international, global, and regional assessment reports have continuously developed and refined this methodology, such as those from the Intergovernmental Panel on Climate Change (IPCC), Millennium Ecosystem Assessment (MA), Arctic Climate Impact Assessment, Baltic Sea Basin Climate Change Assessment, Comprehensive Report on Environmental Evolution in Western China, and the Second National Climate Change Assessment Report [2].

Since the latter half of the 20th century, water scarcity-induced problems in production, living, and ecology have attracted international attention. Governments and scientific communities worldwide have actively conducted research on regional hydrological processes and their resource-environmental effects to provide scientific basis for rational water resource planning and utilization, gradually forming watershed science with the watershed as the research object and establishing watershed-based water resource management institutions, such as the Tennessee River Basin in the United States, the Murray-Darling Basin in Australia, and the Rhine River Basin in Europe. However, after more than half a century of development, international watershed management remains largely experience-based and engineering-oriented [3].

From the perspective of scientific development needs, some countries have established large-scale observation networks and corresponding research programs. The “European Network of Experimental and Representative Basins (ENERB)” and the U.S. “Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA)” represent recent advances in ecohydrological observation research. These large-scale observation and research programs have laid important scientific foundations for understanding and solving complex watershed resource-environment problems [4].

In response to severe water-ecology issues in China’ s inland river regions, and to understand the processes and mechanisms of ecosystem-hydrology system interactions in inland river basins, ultimately providing basic theories and scientific support for national water security, ecological security, and sustainable economic development in inland river basins, the National Natural Science Foundation of China launched the major research program “Integrated Study of Eco-hydrological Processes in the Heihe River Basin” in 2010. Since its implementation, the program has established an integrated “remote sensing-monitoring-experiment” watershed ecohydrological observation system and corresponding data platform, preliminarily revealing the coupling mechanisms of important ecohydrological processes such as glaciers, forests, and oases in the basin, understanding the water system characteristics of first-level ecohydrological units, and laying a scientific foundation for watershed water cycle and water balance. The program has calculated the ecological water demand of the lower Heihe River, defining important constraints for optimal water resource management [3]. Based on this, Cheng et al. [1] reviewed the comprehensive research progress on the eco-hydrology-economy system in the Heihe River Basin over the years and proposed theoretical and practical frameworks for basin-wide coordinated sustainable development and integrated eco-economic management. The above research findings and periodic understanding of hydrological processes, ecological-environmental changes, and natural-economic system water cycles provide a scientific basis for systematic assessment of the ecological management project implementation effects and their environmental impacts.

1. Water System Changes Driven by Climate Change and Water Allocation

1.1. High Flow Period in Recent Century Dominated by Warm-Season Westerly Moisture Precipitation in Mid-High Altitude Mountains

Isotopic studies of different water bodies show that summer precipitation in the Qilian Mountains of the upper Heihe River originates primarily from westerly moisture transport, with additional influence from polar air masses in winter. The southern mountainous region experiences moisture input from June to September, with the lower atmosphere serving as the moisture input layer that contributes to surface runoff mainly from mid-June to mid-September, while winter runoff is primarily supplemented by base flow [5]. The northern desert region of the basin experiences moisture output and transit throughout the year, with the middle-lower atmosphere as the main moisture output layer. Precipitation in the southern mountains, at landscape scales, shows that alpine cold scrub-meadow, cold desert, and ice-snow zones above 3,000 m (accounting for over 78% of the mountainous area) contribute more than 85% of the basin' s total water yield [6]. Using isotopic tracer technology, model simulation, and 18O analysis of outlet river water, Wang et al. [7] identified areas above 3,600 m as the main runoff-producing zones in the Heihe mountainous region, generating over 80% of the outlet runoff. He et al. [8] studied the hydrological processes in mid-low mountain forest-grassland areas (below 3,200 m) and found that forest zones produce very low runoff (12 mm, 3.5%), with precipitation (374 mm) largely consumed by forest evapotranspiration, and even additional consumption of runoff from high-altitude mountainous areas due to water deficits in forested areas (approximately 14 mm).

Tree-ring reconstructed annual runoff sequences for the Yingluoxia station on the Heihe River mainstream [9] indicate that over the past 1,500 years (AD 575-2006), the Heihe River' s average runoff ranged from 1.111 to 1.364 billion m^3, lower than the instrumental period (1958-2006) average of 1.573 billion m^3, with differences existing under different guarantee rates. The instrumental record period represents one of three high-flow periods in the past 1,500 years at the centennial scale. Influenced by climate change, glacier/permanent snow area in the upper Heihe River has continuously decreased over the past two decades, while increased precipitation has led to a significant upward trend in outlet runoff. This provides favorable water resource conditions for watershed water allocation, greatly alleviating water conservation and allocation pressures in the middle reaches.

The total water resources (precipitation) in the upper mountainous region of the Heihe River Basin are primarily affected by climate change, while human activities concentrated in areas below 3,500 m, including mineral development, grazing, afforestation, reservoir construction, and rain-fed agriculture in shallow mountainous areas, mainly affect hydrological processes of precipitation conversion to runoff (surface and subsurface), interception, and utilization. In the upper mountainous region, particularly the expansion of large-scale artificial afforestation and cool-agriculture irrigation areas in shallow mountainous zones, changes in land use patterns (from desert grassland to agricultural land) may intercept and utilize portions of outlet runoff. Therefore, determining reasonable scales and thresholds for forests, grasslands, and rain-fed agriculture is essential to ensure stable outlet runoff.

Based on long-term climate change cycle analysis, at the interdecadal scale, the basin’ s runoff will likely transition to a low-flow stage within the next 10-20 years [9]. In other words, future water resources will be insufficient to support the average 950 million m^3 allocated to the lower reaches and the continuously expanding oasis in the middle reaches. Consequently, countermeasures should be formulated promptly to control or even reduce farmland area in the middle and lower reaches and adjust the industrial structure and internal structure of the primary industry (agriculture) to adapt to normal or low-flow water resource conditions.

1.2. Changes in Watershed Water Resource Allocation Process Under Human Control Over the Past 60 Years

Hydrological records indicate that the past decade has been a high-flow period in the instrumental record stage. Since 1945, the multi-year average annual runoff at the Yingluoxia station (outlet) has been (1.587±0.274) billion m^3, while at the Zhengyixia station in the lower reaches it has been (1.059±0.257) billion m^3. During 2000-2012, the annual runoff at these two stations was (1.753±0.291) billion m^3 and (1.019±0.209) billion m^3, respectively. The multi-year average runoff at the outlet during 2000-2012 was 13.25% higher than during 1945-1999, while the lower reach Zhengyixia station was 4.54% lower.

Comparing the theoretical discharge at Zhengyixia (calculated according to the “97 Water Allocation Scheme” [State Council 1997 water allocation scheme]) with measured runoff shows that, except for the dry year of 2004, all other years had lower actual discharge than theoretical discharge. Before the 1980s, actual discharge exceeded theoretical discharge. During the 1980s, they were basically equal; starting in the 1990s, actual discharge became consistently lower than theoretical discharge, marking the stage of overall environmental deterioration in the lower reaches.

Cumulative curve data for water allocation between middle and lower reaches show that since 2000, total runoff at the Yingluoxia outlet has been 22.794 billion m^3, with 13.254 billion m^3 discharged at Zhengyixia. However, compared to the theoretical discharge, there is a cumulative deficit of 1.5 billion m^3, particularly since 2006 when a paradox emerged: "the more water comes, the more debt accumulates." According to the extended water allocation curve in the "97 Water Allocation Scheme," when upstream inflow at Yingluoxia exceeds 1.58 billion m^3, each additional 1 m^3 of water corresponds to 1.18 m^3 discharged at downstream Zhengyixia, representing a paradox in scheme implementation. Therefore, the water allocation quota above this threshold requires further optimization.

Except for 150 million m^3 allocated to Dingxin and Dongfeng field areas, the remaining discharge at Zhengyixia flows into the Ejina Oasis and East Juyan Lake via the Langxinshan East-West Rivers and the East Juyan Lake dedicated canal. Before 1990, discharge below Langxinshan was 592 million m^3, decreasing to 350 million m^3 in the 1990s, and recovering to 542 million m^3 since 2000. The water allocation ratio between East and West Rivers is basically 7:3.

Since the first water delivery to East Juyan Lake in 2002, the multi-year average inflow has been 50 million m^3, with cumulative inflow reaching 548 million m^3. Since 2004, the lake has maintained year-round water presence, with area fluctuating around 40 km^2 and reaching a maximum surface area of 42.3 km^2 in 2011.

Seasonal water allocation in the lower Heihe River is completely influenced by agricultural activities in the middle reaches. During April-June and October-November, when the middle reaches enter peak agricultural water use periods, surface runoff below Zhengyixia reaches minimum values, with inflow to the lower reaches occurring only during the non-agricultural period of January-March. Analysis of monthly runoff data from key control hydrological stations shows that Yingluoxia station exhibits a clear "single-peak" distribution across decades, with runoff peaking in June-September and reaching maximum in July. Zhengyixia station shows an obvious "double-peak" or "triple-peak" distribution, with runoff troughs in May and November and peaks in March, July, August, and September. Before the 1950s, the maximum runoff at Zhengyixia occurred in August; in the 1960s and 1980s in July; and in the 1970s, 1990s, and first decade of the 21st century in September. Except for the 1980s, the interdecadal runoff during flood seasons at Zhengyixia showed a continuous decreasing trend from 1950-1999, rebounding in the first decade of the 21st century with great variability.

Before 1950, the Ejina River in the lower reaches generally flowed for 8-10 months, flowing year-round in wet years. The 1960s were similar to the 1950s but with greatly reduced runoff. After the 1970s, the flow period shortened to about 5 months, concentrated in spring and autumn, with dry conditions from April-September and only 10-20 days of flow in winter-spring during dry years. The East and West Rivers of Ejina showed clear "double-peak" distributions in the 1990s and first decade of the 21st century, with peaks in February-March and September, and basically dry conditions in April-June and November. After watershed water allocation implementation, monthly runoff in the East River has generally increased, particularly in July-September, with minimal flow even maintained in April-June.

1.3. Water Resource Development and Engineering Control Measures Have Profoundly Altered Watershed Water Cycles at Different Scales and Regions

Since implementation of the watershed ecological management project, water storage projects in the middle reaches increased from 2000 to 2012, with high-tech water-saving area increasing by 460,000 mu, channel lining increasing by nearly 400 km, and irrigation water use coefficient increasing from 0.48 in 2000 to 0.53 in 2012. On the other hand, irrigated farmland area increased by 350,000 mu, with irrigation water use increasing by over 200 million m^3. According to water conservancy census data, groundwater exploitation increased by over 100 million m^3 annually. Therefore, increased water consumption from expanded irrigation area has basically offset or even exceeded water savings achieved through water-saving society construction.

Overall, from 1985-2013, groundwater depth in the middle reaches increased by an average of 1.0-3.0 m, with a maximum of 17.4 m. Although groundwater levels rebounded during 2005-2013, the cumulative trend over the past 30 years still shows regional decline, with groundwater volume remaining in deficit. Since water allocation, the middle reaches have experienced continuous groundwater level decline in the upper and middle parts of the piedmont alluvial fan zone, though the rate has slowed, while groundwater levels in the lower part of the alluvial fan and in fine soil and valley plains have basically stabilized or shown upward trends [10]. Under current irrigation levels, middle reach groundwater storage will continue to decrease at a rate of 100-200 million m^3/a. To maintain stable groundwater volume in the middle reaches, current irrigation water use must be reduced by 20%.

Isotopic and hydrochemical research results also indicate that under water allocation constraints and water-saving systems, the well-canal mixed irrigation area in the middle reaches has begun extensively exploiting deep groundwater, accelerating and altering regional deep-shallow and surface-subsurface water cycling processes and spatial patterns. Tritium (T) concentrations in shallow groundwater in the middle reaches have gradually decreased, indicating that deep groundwater with lower T concentrations from irrigation return seepage is strongly mixing with and recharging the original shallow groundwater. In the lower reaches, groundwater around populated and agricultural concentration areas in Ejina Banner shows high total dissolved solids (TDS), indicating that the final convergence and discharge area of groundwater has shifted from former terminal lake areas to Dalai Kubu Town and the area between East Juyan Lake [11].

The surface-groundwater conversion process from the outlet at Yingluoxia to the terminal lake involves multiple transformations: outlet runoff mostly recharges river surface water above Zhengyixia, after which channel runoff seeps to recharge groundwater in the desert alluvial plain. It is estimated that groundwater discharge to recharge river runoff in the upper middle reaches is about 1.075 billion m^3; in the lower section, surface water recharges groundwater by 1.913 billion m^3. River recharge to groundwater from the outlet to Zhangye accounts for about 27% of outlet runoff, while from Zhangye to Zhengyixia it accounts for about 69% of river runoff in that section [12]. Based on these hydrological processes, the current middle reach hydrological regime can support an inland river in arid regions achieving spatiotemporal water resource needs between middle and lower reaches through a "steady flow" approach.

The Huangzangsi Water Conservancy Project, a key storage project on the Heihe River mainstream identified in both the *Recent Management Plan for the Heihe River Basin* and the *Heihe River Water Resources Development, Utilization and Protection Plan*, is designed with a storage capacity of 405 million m^3. In October 2013, the project proposal passed NDRC review. The proposal suggests the project could control 80% of inflow above Yingluoxia on the Heihe River mainstream, directly regulate the inflow process at Zhengyixia, shorten the closure time in the middle reaches, and increase discharge at Zhengyixia and Langxinshan by 103 million m^3 and 118 million m^3, respectively. This directly controlled water conveyance and distribution process may simplify and alter middle reach water cycling processes, shorten cycling chains, reduce water resource reuse rates, and further intensify groundwater environmental problems in the middle reaches.

Wetland construction and artificial water replenishment in the middle reaches have promoted local groundwater recharge to some extent but have altered natural water cycling paths and patterns under natural geological structures, potentially causing local hydrological geological hazards, such as the local groundwater level rise in Ganzhou District, Zhangye City during 2005-2007 [14]. Under current water shortage conditions, high groundwater exploitation intensity in the Ejina Basin will intensify negative groundwater balance and shift it spatially toward areas with strong human activities, ultimately affecting healthy development and stability of human settlements and surrounding areas.

1.4. Groundwater Level in Lower Reaches Gradually Recovering and Water Quality Freshening

Overall, influenced by ecological water conveyance, groundwater levels along riverbanks in recharge areas such as the East River, West River, and Middle Gobi have generally risen compared to pre-allocation periods. By 2014, groundwater mineralization showed a decreasing trend due to mixing, dilution, and dissolution of Ca^2 , Mg^2 and other minerals in soils, with the natural hydrochemical field generally evolving toward freshwater. In the East and West Gobi areas on the oasis periphery, less affected by water conveyance, concentration and evaporation continue to increase mineralization, with the hydrochemical field still evolving toward salinization.

The time required for Zhangye Basin groundwater formation is: upper reaches < middle reaches < lower reaches. Groundwater renewal simulation results show that deeper groundwater formation and transformation often takes 4,000-6,000 years or more; shallow groundwater can be renewed in relatively short time through surface water replenishment after extraction, while exploiting deep groundwater tens of thousands of years old would overdraw water resource sustainability [13]. The youngest phreatic water in the Ejina Basin occurs along the Heihe River channel, indicating strong groundwater renewal capacity along the river and demonstrating that the most important groundwater recharge source in the lower Heihe River’ s Ejina Basin comes from river channel seepage, where groundwater-surface water interaction is most active.

Over more than a decade of ecological water conveyance, areas with decreased TDS mainly occurred in the middle-lower East River section from Jirigelangtu to Juyan Lake, Guaizi Lake, and Ceke, with most areas transitioning from saline to brackish water. Areas with increased TDS appeared in the upper East River section from Langxinshan to East River Bridge, the Juyan Delta, and East-West Gobi areas. Trends in the West River and Middle Gobi are less obvious.

In terms of hydrochemical types, compared to pre-allocation, Cl type water bodies decreased significantly by 2014, with salt content declining. Spatially, freshwater distribution areas expanded in river-affected zones, but brackish and saline water remain widely distributed. In 2014, freshwater distribution expanded from populated areas in Saihantaolai, Dalai Kubu Town, and upper river Langxinshan along the East River to the terminal lake area, middle-lower West River, and the ancient oasis Heicheng area.

Overall, groundwater system water volume changes are developing favorably for ecological restoration of the groundwater basin, but this results from consecutive high-flow years in recent years. How the groundwater system will change during consecutive dry or low-flow years in the future requires further research. Therefore, when utilizing Heihe River water resources, river water and rapidly renewable shallow groundwater should be used rationally, while deep groundwater, especially confined aquifers with long formation times, must be strictly limited in exploitation. Regional, seasonal, and interannual artificial groundwater recharge systems should be established based on partitioned groundwater system renewal and utilization intensity to achieve groundwater extraction-recharge balance and maintain healthy and sustainable development of basin and watershed groundwater systems.

1.5. Changes in Socioeconomic System and Water Use Structure in Middle Reach Agricultural Oasis Under Water Allocation Constraints

Over the past 20 years (1994-2013), Zhangye’ s GDP and per capita GDP have grown rapidly at an average annual rate of about 14%. The economic structure has been optimized at different levels, with the proportion of primary, secondary, and tertiary industries shifting from 50:25:25 in 1994 to 26:35:39 in 2013. Within agriculture, the ratio of crop production to forestry-animal husbandry-fishery output value changed from 69:31 in 1994 to 64:36 in 2013. From a water use perspective, total water consumption in Zhangye increased at an average annual rate of 0.24% over 20 years, with water use structure showing declining proportions in high water-consumption sectors and rising proportions in relatively low water-consumption industries. Within the main water-use sector of agriculture, farmland irrigation water showed a declining trend while forestry-animal husbandry-fishery water use increased slightly [15].

Analysis of key factors affecting total water consumption shows that economic growth in Zhangye is the main driver of water consumption increase, showing an incremental effect of 3.01 m^3 water per year. Industrial structure adjustment and declining water use intensity show decremental effects of -1.93 m^3 and -0.62 m^3 water, respectively, with their combined decrement slightly less than the incremental effect, consistent with the overall small upward trend in Zhangye' s total water consumption.

Water use constraints have caused structural proportion changes among major water-use sectors. The proportion of water used by high water-consumption industries decreased significantly after water allocation, with agricultural water proportion and farmland irrigation water proportion within agriculture decreasing by 1-2%, while industrial water, service industry water, and forestry-animal husbandry-fishery water proportions within agriculture showed gradual upward trends.

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2. Ecological Effects Under Water System Regulation

2.1. Economic Development and Water Allocation Practices Dominate Watershed Landscape Pattern Evolution

Continuously strengthening regional human activities dominate the allocation pattern of water and land resources in the middle and lower reaches. The upper reaches are dominated by bare rock, meadows, sparse grassland, steppe, and deciduous broadleaf shrub forest, accounting for 24.4%, 20.2%, 19.1%, 17.4%, and 8.1% of the total area, respectively. From 1990-2010, the most obvious land cover change in the upper Heihe River Basin was the continuous reduction of glacier/permanent snow area transforming into bare land, mainly due to climate change. Continuously strengthening human activities are evident in increased industrial land, transportation land, and mining sites. Overall vegetation shows little change. Reservoir/pit pond areas have increased significantly due to reservoir construction.

The middle reaches are dominated by sparse grassland, dryland, bare rock, desert/sandy land, and bare soil, accounting for 41.0%, 20.0%, 11.6%, 5.8%, and 5.2% of the total area, respectively. From 1990-2010, both farmland abandonment and expansion coexisted in the middle reaches, with overall farmland area still showing an increasing trend. Industrial land, transportation land, and residential areas continued to increase, while water-intensive crop planting areas (such as paddy rice along rivers) were controlled.

The lower reaches are dominated by bare soil, bare rock, desert/sandy land, and sparse grassland, accounting for 66.5%, 18.7%, 7.8%, and 3.3% of the total area, respectively. Due to guaranteed water volume and completion of the East Juyan Lake dedicated water conveyance channel, water areas such as lakes and rivers have gradually recovered and stably expanded. Groundwater levels in the lower reaches have gradually risen and water quality has freshened, though with strong spatial heterogeneity, and the overall water environment has improved. On the other hand, continuous increases in farmland, industrial-transportation land, and residential areas place great pressure on current water resources and the groundwater environment. Overall, the lower reach ecological environment has shifted from deterioration before water allocation to gradual recovery and continuous improvement after allocation.

2.2. Desert Riparian Forest Growth Status Generally Improving Under Water System Regulation

Tree radial growth characteristics represent forest health status to some extent, with tree-ring chronologies recording interannual-scale ecological changes of forest decline and recovery at different sample sites. Based on dendrochronology methods and 28 Populus euphratica tree-ring width chronologies from the Ejina Oasis, the growth status of Populus euphratica over the past 50 years and before/after water allocation was evaluated [16]. Overall, the oasis Populus euphratica forest has been in decline over the past 60 years (1954-2010), with 1969 being the year of best growth and 2001 the year of most severe decline. Spatially, growth conditions are better in the upper East River and lower West River sections. Compared to the pre-1990 period (natural stage), 1990-2002 was a decline period for the oasis Populus euphratica forest, with annual inflow to the lower reaches decreasing by nearly 30% and radial growth decreasing by about 23.8% compared to the natural stage. After watershed water allocation (since 2003), Populus euphratica radial growth has gradually recovered, basically returning to pre-1990 average levels after 2007, though spatial differences persist, with non-recovered areas mainly concentrated in the middle-lower East River section.

According to Ejina Banner statistical data (*Ejina Banner Land Use Master Plan 2009-2020*), total farmland area in the banner was 2,910 hm² (43,700 mu) in 2005, increasing to 6,457 hm² (95,200 mu) by 2008. Lower reach farmland has mostly been reclaimed from oasis interior forest land. Groundwater is heavily extracted during the growing season for agricultural irrigation, causing seasonal low water levels that affect riparian forest growth dominated by Populus euphratica and Tamarix. This is one of the main reasons why Populus euphratica forests in the middle-lower East River section, where population and farmland are relatively concentrated, have not fully recovered after water allocation.

Therefore, the oasis dominated by desert riparian forests in the lower reaches requires more refined water resource allocation patterns and management countermeasures. Through studies of spatiotemporal dynamics of groundwater levels and water consumption processes of natural vegetation in the Ejina Oasis, Si et al. [17] proposed that water volumes of 80 million m^3 and 108 million m^3 should be guaranteed during two critical ecological water demand periods: April (when forest and grass begin growing) and August (when Populus euphratica seeds mature and seedlings update). During the main growing season (April-October), 232 million m^3 should be guaranteed in the main oasis area, with at least 156 million m^3 for the East River oasis area, 100 million m^3 for the West River oasis area, and 160 million m^3 for terminal lake areas such as East and West Juyan Lakes.

2.3. Terminal Lake and Wetland Landscape Structure Evolution Under Artificial Water Allocation Management

Changes in terminal lakes and wetland landscapes in arid inland rivers reflect the comprehensive manifestation of watershed water balance under climate change and human activity influences [18]. Based on modern alluvial fan channel distribution and hydrological status in the lower Heihe River, terminal lakes and wetlands can be divided into three categories: (1) Directly connected to modern channels, such as East and West Juyan Lakes and Juyanze; (2) Distributed at alluvial fan margins in the lower reaches, such as the Guri Lake wetland, historically connected by paleochannels at Shaomaying, with hydraulic connections to the main Heihe River channel from Dingxin to Langxinshan and receiving groundwater recharge from the Beishan Corridor through the southwestern edge of the Badain Jaran Desert; (3) Tectonic graben areas, such as the Guaizi Lake wetland, part of a geological period river-lake system that has basically lost groundwater connection with ancient Juyanze. Due to its linear, deeply incised graben structure, it has become the main collection area for groundwater formed by precipitation in the northern hilly Gobi and northern Badain Jaran Desert.

Interpretation of multi-temporal remote sensing images shows that East Juyan Lake had a surface area of 47.56 km^2 in 1975, shrinking to 29.12 km^2 by 1990, and remaining dry in 1995 and 2000 with lakebed saline-alkali land becoming the main landscape type. Since implementation of the Heihe River water allocation plan, East Juyan Lake area reached 39.55 km^2 in 2005 through a dedicated water conveyance channel, and has since been maintained at about 35 km^2 through 2010. Lakeshore grassland landscape area ranges between 11-20 km^2, with shallow marshes existing only when the lake contains certain water volumes.

West Juyan Lake has been dry since the 1960s, with only seasonal water surfaces below 3 km^2 in 1990 and 2005. The main landscape types are lakebed salt crust and saline-alkali land reaching 426 km^2, with lakeshore grassland landscape fluctuating below 4 km². Most of ancient Juyanze is covered by drifting sand, with only small, relatively low-lying wetlands such as Suoyang Pit, Jinsutu Lake, and Swan Lake remaining from south to north, mainly dominated by saline-alkali land and lakeshore grassland landscapes. Before 2005, only the northernmost Swan Lake had water surfaces below 5 km², with lake water levels fluctuating within 1.5 m, mainly recharged by East River groundwater. In 2010, the easternmost tributary of the East River directly flowed into Swan Lake, connecting with the southern Jinsutu Lake and reaching a 25 km² water surface covering previously extensive lakeshore grassland and saline-alkali land types.

Overall, the landscape of Guaizi Lake and Guri Lake wetlands is dominated by saline-alkali land and grassland types, with small shrub forest landscape types, where saline-alkali land and grassland areas change inversely.

3. Blue-Green Water, Virtual Water, and Socialized Water Resource Management Recommendations

In China' s arid inland river basins, green water and blue water have very complex conversion relationships between upstream, middle, and downstream ecological zones. The upstream mountainous area is the blue water (runoff) formation zone, where green water mainly converts to blue water, while in the plain area blue water mainly converts to green water. Both the blue water volume in the upstream and the conversion volume from blue to green water in the middle reach irrigation oasis affect blue and green water utilization in the downstream [19]. Green water spatial heterogeneity is influenced by multiple factors including climate, soil, vegetation, and land management. Therefore, only by analyzing the formation processes and mutual conversion relationships and mechanisms of blue and green water in upstream, middle, and downstream areas can rational water resource management models be established.

From an ecohydrological process and function perspective, the water conservation function of upstream mountainous vegetation in arid regions represents ecological regulation between green and blue water by forests and grasslands [20], with its scale and condition determining the internal water resource cycling process in mountainous areas and the blue water resource volume and spatiotemporal allocation pattern entering the middle reach plain area. Currently implemented national projects such as the Natural Forest Protection Project and Grazing Withdrawal and Grassland Restoration Project will undoubtedly enhance the regulation function of mountainous ecosystems on blue-green water resources and their spatiotemporal allocation, ensuring seasonal and interannual stability of blue water and improving internal green water cycling and utilization efficiency in mountainous ecosystems.

The watershed water allocation scheme formulated based on nearly 50 years of instrumental hydrological data primarily relies on mainstream annual runoff data, lacking effective intra-annual spatiotemporal allocation schemes and adjustment strategies under future hydrological scenario changes. Centralized water conveyance, water conservation, and water conservancy project construction (including subsequent control projects under construction) have caused groundwater environment deterioration in the middle reaches and ecological degradation in near-oasis peripheral areas. Artificial oases, especially farmland area, continue to expand, offsetting or even exceeding achievements from water-saving society construction and causing continuously increasing water demand pressure. The lower reach oasis lacks rational water resource allocation planning, and the oasis dominated by riparian forests has not yet achieved effective and comprehensive recovery. The current industrial structure status has led to a sharp outward export trend of virtual water resources.

3.1. Management Recommendations

(1) Conduct comprehensive data surveys to optimize watershed industrial structure status. Socialized water resource management represents the highest level of water demand management. Fully recognizing the social attributes of water resources and using these attributes as the main thread to fully utilize various external resources to alleviate local water scarcity [21]. For the current Heihe River situation, the improvement space for technical water conservation is limited; structural water conservation is also constrained by industrial advantages and location characteristics to some extent, hindering adjustment of primary, secondary, and tertiary industrial structures and thereby affecting progress toward the fourth level of water resource management—socialized water resource management. Currently, watershed water resource management needs to expand traditional water resource evaluation and utilization methods, using watershed precipitation as the basic total water resource amount, comprehensively considering green water resources, constructing a vertical "green" water-centered watershed water cycle simulation and green water resource evaluation system, establishing efficient green water utilization land use patterns in upstream, middle, and downstream areas, and proposing comprehensive watershed-scale water resource management models.

(2) Optimize water resource allocation among watershed water-ecosystem-socioeconomic systems. The implementation of emergency water conveyance and ecological rescue projects in the Heihe River Basin has initially solved water allocation between middle and lower reaches and the ecological restoration of seriously degraded downstream areas. In response to the prominent problems of continuous groundwater system degradation in the middle reaches and ecological degradation of the oasis edge protection system, future attention must be paid to water resource allocation among watershed water-ecosystem-socioeconomic systems to achieve overall ecological health and socioeconomic sustainable development in the watershed.

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4. Summary and Targeted Recommendations for Heihe Ecological Management Effectiveness Assessment

Overall, since implementation of the Heihe ecological management project, the production-living-ecology water use structure in the basin (mainstream) has undergone major changes. The upstream ecology has improved, middle reach surface water has been effectively controlled, water volume entering the lower reaches approaches planning requirements, and the deteriorating trend of the downstream ecological environment has been effectively curbed. However, total water consumption in the middle reaches remains high, facing serious water resource overload problems during low-flow periods. The assessment of ecological effectiveness of China' s Heihe River Basin comprehensive management project can be summarized in three aspects, with corresponding specific recommendations:

(1) Implement comprehensive watershed-wide water resource management. Current Heihe River water resource management is limited to the east branch mainstream area, covering several administrative regions including Ganzhou, Linze, Gaotai, Dingxin, and Ejina Banner. Management of the lower reach Ejina Basin focuses mainly on the core oasis area and East Juyan Lake, while basically ignoring ancient dry lake basins such as the Guri Lake wetland, West Juyan Lake, and ancient Juyanze that are maintained by groundwater recharge. In areas bordering the Badain Jaran Desert, declining groundwater levels and resulting vegetation degradation and weakened protection functions have caused continuous desert expansion. The degraded wetlands and dry lake basins are basically covered by salt crust and saline soil, becoming important sources of salt dust and sand dust for sandstorms along their paths. The newly completed Lin-Ce Railway and under-construction Lin-Ha Railway have suffered multiple sand invasions and track burial incidents in the ancient Juyanze section.

(2) Conduct thorough and detailed data surveys to optimize watershed industrial structure. Water resource socialized management is the highest level of water demand management. It requires full recognition of water resources' social attributes and utilization of various external resources to alleviate local water scarcity [21]. For the Heihe River' s current situation, the improvement potential for technical water conservation is limited, while structural water conservation is constrained by industrial advantages and location characteristics, hindering adjustment of the three-industry structure and thereby affecting progress toward the fourth level—water resource socialized management. Watershed water resource management must expand traditional evaluation and utilization methods, using watershed precipitation as the total water resource base, comprehensively considering green water resources, constructing a vertical "green" water-centered watershed water cycle simulation and evaluation system, estab-

lishing efficient green water utilization patterns across upstream, middle, and downstream areas, and proposing integrated watershed water resource management models.

(3) Optimize water resource allocation among water-ecosystem-socioeconomic systems. The emergency water conveyance and ecological rescue projects have initially addressed water allocation between middle and lower reaches and the restoration of seriously degraded downstream ecosystems. In response to prominent issues of continuous groundwater system degradation in middle reaches and ecological degradation of oasis edge protection systems, future efforts must focus on water resource allocation among watershed water-ecosystem-socioeconomic systems to achieve overall ecological health and socioeconomic sustainable development.

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