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Ecological Flow Guarantee Mechanisms in the Modernization of Irrigation Districts

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Abstract: The modernization of irrigation districts is of great significance for improving irrigation efficiency and ensuring food security, while ecological flow is a fundamental prerequisite for maintaining the stability of surrounding ecosystems and ensuring the sustainable utilization of water resources. However, in some modernization projects, excessive emphasis has been placed on irrigation while ecological considerations have been neglected, resulting in insufficient ecological flows and frequent ecological problems. This paper expounds the concepts of irrigation district modernization and ecological flow, and clarifies their interrelationship. It further analyzes the engineering, management, and climatic–environmental factors affecting ecological flows, and constructs an ecological flow guarantee mechanism by defining objectives, accounting methods, and multi-dimensional safeguard measures. The results indicate that a sound guarantee mechanism can achieve synergy between irrigation benefits and ecological benefits, providing practical reference for ecological flow protection in irrigation districts.

Keywords: Modernization of irrigation districts; ecological flow; guarantee mechanism

Introduction

Irrigation districts are an important foundation for agricultural development, and their modernization is a key measure for enhancing comprehensive agricultural production capacity. However, during the modernization process, the issue of ecological flow protection has become increasingly prominent. Ecological flow is closely related to the stability and sustainable development of irrigation districts and their surrounding ecosystems. If its protection is neglected, a series of ecological problems may arise. Therefore, in-depth research on ecological flow guarantee mechanisms in the modernization of irrigation districts, and proper coordination between agricultural irrigation water use and ecological water demand, are of great importance for achieving sustainable water resource utilization and high-quality development of irrigation districts.

1. Basic Concepts and the Relationship between Irrigation District Modernization and Ecological Flow

1.1 Connotation and Objectives of Irrigation District Modernization

The modernization of irrigation districts is a systematic project based on traditional irrigation districts that

integrates engineering, technological, and managerial measures to comprehensively upgrade irrigation facilities, water supply systems, and management models, with the aim of achieving high-quality development. Its connotation encompasses five dimensions: modernization of facilities, technology, management, water use, and ecology. This approach breaks away from the traditional model of "emphasizing construction while neglecting management" and "prioritizing irrigation while overlooking ecology," and instead balances multiple objectives. The objectives of modernization can be summarized as follows. First, to enhance irrigation security capacity by rehabilitating and upgrading aging and damaged facilities, optimizing water supply systems, and meeting the water demand of large-scale agricultural production. Second, to promote efficient and water-saving use by popularizing water-saving technologies, improving metering and control systems, and reducing irrigation quotas. Third, to realize coordinated ecological development by integrating ecological protection throughout the entire modernization process, ensuring ecological flows, restoring surrounding environments, and promoting positive interactions between agricultural irrigation and ecological protection, thereby achieving the unity of economic, social, and ecological benefits.

1.2 Definition and Importance of Ecological Flow

Ecological flow, also known as environmental flow, refers to the minimum flow or flow regime required to maintain the structural integrity and functional stability of aquatic ecosystems, protect biodiversity, and ensure their normal operation. Its core lies in safeguarding the natural recovery capacity and sustainable development of ecosystems. The determination of ecological flow should take into account factors such as water body type and ecological function. Although requirements vary across regions and ecosystem types, all ecological flow standards aim to maintain essential ecological functions. Ecological flow is of critical importance to irrigation districts and surrounding ecosystems. It helps maintain riverine ecological balance and prevents water quality deterioration caused by flow interruption; protects biodiversity by providing suitable habitats for various organisms; supports the restoration of wetland ecosystems and prevents wetland degradation; and ensures the sustainable utilization of water resources by coordinating conflicts between irrigation water use and ecological water demand, thereby avoiding ecological crises resulting from excessive exploitation [1].

1.3 Relationship between Irrigation District Modernization and Ecological Flow

The modernization of irrigation districts and the guarantee of ecological flow are interdependent and mutually reinforcing, jointly serving the goals of sustainable water resource utilization and high-quality development. Ecological flow guarantee is an important prerequisite and a core component of irrigation district modernization. Modernization aims to achieve the coordination of multiple benefits; neglecting ecological flow protection can damage the environment and, in turn, constrain agricultural development. Proper guarantee of ecological flow can facilitate environmental restoration, enhance water conservation capacity, and provide a stable foundation for irrigation water supply. At the same time, irrigation district modernization provides strong support for ecological flow guarantee. By optimizing water supply systems, promoting water-saving technologies, and improving management systems, modernization enhances water use efficiency and reduces competition with ecological water demand. In addition, the construction of supporting ecological water replenishment facilities improves regulation and control capacity, enabling the scientific allocation of water between irrigation and ecological uses, and ultimately promoting coordinated advancement of both objectives.

2. Analysis of Factors Influencing Ecological Flow in the Modernization of Irrigation Districts

2.1 Engineering Factors

Engineering factors are the core elements affecting ecological flow during the modernization of irrigation districts. These factors span the entire process of design, construction, and operation, directly impacting the effectiveness of ecological flow security. First, the irrational modification of irrigation and drainage facilities. Some irrigation districts excessively expand irrigation channels and water diversion projects to increase the irrigated area but fail to build synchronized ecological replenishment facilities. This results in a massive diversion of water resources for irrigation, which encroaches upon ecological water and leads to a shortage of ecological flow. Second, the

improper operation of hydraulic structures. Following modification, some barrages and intake gates prioritize irrigation security. The lack of dedicated ecological release facilities—or release patterns that do not align with ecological needs—extends the duration of downstream river desiccation, threatening ecological stability. Third, channel hardening projects. Lining channels with impermeable materials severs the recharge pathways between surface water and groundwater. As a result, surrounding wetlands and vegetation degrade due to water scarcity, indirectly destabilizing the ecological flow. Fourth, substandard construction quality. If the quality of the engineering construction fails to meet standards, leakage during water conveyance exacerbates water resource scarcity, further undermining the system's capacity to guarantee ecological flow.

2.2 Management Factors

Management factors represent significant human-driven variables. Incomplete management systems and inadequate oversight often prevent security measures from being implemented effectively. First, an incomplete management system. In some irrigation districts, irrigation and ecological management are separated, lacking a unified coordination body. This lack of synergy leads to a prioritization of agricultural needs over the maintenance of ecological flow. Second, loose water consumption control. Following modernization, if water metering facilities remain incomplete, excessive irrigation and water waste by some users will continue to encroach upon ecological water shares. Third, ambiguous accountability for ecological flow security. When the responsibilities of relevant departments are not clearly defined, it often leads to a "passing of the buck" when problems arise. Fourth, lagging management technology. The absence of advanced monitoring and regulation technologies makes it difficult to acquire real-time data and perform precise allocation of ecological flow. Fifth, insufficient publicity and guidance. A lack of awareness regarding ecological protection among personnel leads to the neglect of reasonable ecological flow safeguards [2].

2.3 Climate and Environmental Factors

Climate and environmental factors are natural variables that influence ecological flow. Due to their inherent uncontrollability, they directly impact the supply of water resources and ecological flow. First, climate change. Global warming leads to uneven precipitation and increased evaporation within irrigation districts. Frequent droughts and reduced rainfall result in a deficit of total water resources, intensifying the conflict between irrigation and ecological water use, which makes securing ecological flow increasingly difficult. Furthermore, the rise in extreme weather events disrupts water resource allocation, leading to significant fluctuations in ecological flow. Second, disparities in water resource endowment. In water-scarce irrigation districts, ecological water is often over-appropriated to meet irrigation demands. Conversely, even in water-abundant districts, irrational allocation can lead to inadequate ecological flow security. Third, water quality pollution. Excessive pollution from surrounding industrial and agricultural activities means that contaminated water bodies cannot sustain ecological health, thereby undermining the effectiveness of flow security measures. Fourth, degradation of the surrounding ecological environment. Destruction of vegetation and shrinking of wetlands reduce the area's water conservation capacity, further exacerbating the tension surrounding ecological flow.

3. Construction of Ecological Flow Security Mechanisms in the Modernization of Irrigation Districts

3.1 Objectives and Principles of Ecological Flow Security

The objectives for securing ecological flow serve as the core guidance for modernization efforts. These must be formulated by comprehensively considering the water resource status, ecological functions, and agricultural irrigation requirements. These objectives cover three levels: First, the fundamental security objective. This aims to provide a stable supply of core ecological flow to surrounding rivers, lakes, and wetlands, preventing channel desiccation and wetland shrinkage while maintaining basic ecosystem functions. Second, the quality and efficiency improvement objective. This focuses on gradually enhancing ecological flow regulation capabilities, optimizing flow processes, improving water quality, and promoting ecosystem restoration and biodiversity enhancement. Third, the synergistic development objective. This involves the scientific allocation of water between agricultural

irrigation and ecological needs, promoting the synchronized advancement of irrigation, economic, and ecological benefits to ensure the sustainable utilization of water resources.

The security of ecological flow must adhere to four key principles: First, the principle of "ecology first while balancing benefits." This requires prioritizing ecological flow requirements before rationally allocating agricultural irrigation water to achieve synergy between the environment and agriculture. Second, the principle of "scientific rationality and local adaptation." Security measures must be formulated based on the specific water resource characteristics and ecological functions of the irrigation district, avoiding a "one-size-fits-all" approach. Third, the principle of "overall planning and coordinated control." This involves coordinating irrigation supply with ecological replenishment while strengthening collaboration between different departments and operational stages. Fourth, the principle of "long-term stability and dynamic optimization." This focuses on building long-term security mechanisms and dynamically adjusting measures based on climate shifts, ecological changes, and the developmental needs of the irrigation district.

3.2 Methods and Standards for Ecological Flow Accounting

Scientific and accurate accounting of ecological flow is a prerequisite for the effective operation of the guarantee mechanism. Accounting methods and standards should be selected in accordance with the actual conditions of irrigation districts. The chosen methods should balance scientific rigor and operational feasibility. Four categories of methods are commonly used. The historical flow method determines minimum ecological flow by analyzing long-term historical flow data of surrounding rivers and wetlands. This method is simple and easy to apply, and is suitable for irrigation districts with long-term monitoring records. The ecological demand method calculates the minimum flow required to maintain the survival of aquatic organisms and vegetation based on their ecological requirements, placing emphasis on actual ecological needs. The water balance method considers total water resources, irrigation water consumption, evaporation, seepage, and other factors to estimate the volume of water available for ecological replenishment, thereby achieving a balance between water supply and demand. The comprehensive analysis method integrates multiple approaches and comprehensively considers ecological, agricultural, and economic factors to determine scientifically sound and reasonable ecological flow levels [3]. At the same time, clear accounting standards should be established. Ecological flow thresholds for different seasons and water bodies should be specified, with a distinction made between core ecological flow and suitable ecological flow. Differentiated standards should also be formulated for different periods, such as drought seasons and flood seasons, to ensure that accounting results are targeted and operable, thereby providing a reliable basis for ecological flow regulation and protection.

3.3 Engineering Guarantee Measures

Engineering guarantees constitute the core support for ecological flow protection in the modernization of irrigation districts. In combination with modernization projects, it is necessary to construct supporting facilities related to ecological flow protection, optimize engineering operation modes, and enhance the overall capacity for ecological flow guarantee. During the renovation of water diversion, conveyance, and drainage systems in irrigation districts, ecological water replenishment gates, channels, and related facilities should be constructed simultaneously. Clear ecological water replenishment pathways should be defined to ensure that surrounding rivers and wetlands can receive timely ecological flows during peak irrigation periods. Existing structures such as diversion weirs and intake gates should be upgraded by adding ecological flow release facilities. Release periods and discharge volumes should be clearly specified to ensure stable downstream ecological flows and to prevent artificial flow interruption. Channel renovation should be planned rationally to avoid full cross-section hardening. In suitable areas, eco-friendly channel construction models should be adopted, with the preservation of riparian vegetation and the maintenance of recharge pathways between groundwater and surface water, thereby enhancing water conservation capacity and indirectly safeguarding ecological flows. Water resources allocation projects should be constructed in irrigation districts with uneven water resource distribution. Cross-regional and cross-reach water transfer and allocation projects can be implemented to optimize water resource configuration. During periods

of water scarcity, water resources should be coordinated and allocated with priority given to ecological flow demands. In addition, water quality purification projects should be improved through the construction of wastewater treatment facilities and ecological purification wetlands to treat industrial wastewater and agricultural non-point source pollution around irrigation districts. By improving water quality and ensuring that ecological flows meet relevant standards, the ecological protection function of ecological flows can be fully realized.

3.4 Management Guarantee Measures

Management guarantees are the key to ensuring that ecological flow protection measures are effectively implemented. It is necessary to establish a sound management system, strengthen regulation and control, clarify the division of responsibilities, and achieve refined management of ecological flows. First, the management system should be improved by establishing a unified institution for irrigation district water resources allocation and ecological flow management. Relevant functions such as irrigation management and ecological protection should be integrated to realize coordinated allocation and unified management of irrigation water and ecological water, thereby avoiding management fragmentation. Second, responsibilities should be clearly defined by specifying the duties of relevant departments and units in ecological flow accounting, regulation, monitoring, and supervision. Ecological flow protection should be incorporated into the performance assessment system of irrigation district modernization, with an accountability mechanism implemented to ensure that all measures are effectively carried out. Third, water use control should be strengthened by improving water metering facilities in irrigation districts, achieving precise measurement of irrigation water use, strictly controlling total irrigation water consumption, and promoting quota-based irrigation. Excessive irrigation and water waste should be strictly prevented, so as to free up more water resources for ecological flow protection. Fourth, a coordinated supervision mechanism should be established by enhancing collaboration among water resources, agriculture, and ecological environment departments. Routine supervision of ecological flows should be conducted to promptly identify and address issues such as insufficient ecological flow and water pollution.

Fifth, publicity and guidance should be strengthened through multiple channels to disseminate the importance of ecological flow protection, enhance the ecological awareness of farmers and management personnel, and guide the whole society to participate in ecological flow protection efforts.

3.5 Technical Guarantee Measures

Technical guarantees are a key support for improving the scientific basis and precision of ecological flow protection, and require the promotion of advanced technologies and the improvement of supporting systems.

(1) Promotion of monitoring technologies. Flow and water quality monitoring equipment should be installed at key locations such as rivers and wetlands surrounding irrigation districts to establish a real-time monitoring network, enabling real-time monitoring, data collection, and analysis of ecological flows and water quality, and timely grasp of flow variations.

(2) Application of intelligent regulation technologies. By leveraging big data, the Internet of Things, and related technologies, an intelligent ecological flow regulation platform should be established. By integrating data on water resources, irrigation water use, and ecological demand, precise allocation and dynamic regulation can be achieved, allowing discharge flows and replenishment timing to be automatically adjusted according to ecological needs.

(3) Promotion of water-saving irrigation technologies. During irrigation district modernization, technologies such as drip irrigation, sprinkler irrigation, and pipeline irrigation should be widely applied to optimize irrigation modes, improve irrigation efficiency, reduce irrigation quotas, and alleviate the pressure of agricultural irrigation on ecological water use [4].

(4) Strengthening research and application of ecological restoration technologies. In accordance with the ecological characteristics of irrigation districts, technologies such as vegetation restoration and wetland rehabilitation should be promoted to enhance water conservation capacity, improve the ecological environment, and increase ecosystem resilience to flow fluctuations.

(5) Establishment of a technical support system. Cooperation with scientific research institutes and universities should be strengthened to carry out

research on ecological flow accounting and regulation, promote mature and advanced research outcomes, and improve the overall technical level of ecological flow protection.

Conclusion

Ecological flow protection in the modernization of irrigation districts is a complex and long-term systematic endeavor. By clarifying protection objectives and principles, scientifically accounting for ecological flows, and implementing comprehensive engineering, management, and technical measures, the capacity for ecological flow protection can be effectively enhanced. In the future, continued attention should be paid to the impacts of climate change and ecological environmental changes on ecological flows, and protection mechanisms should be continuously optimized to meet new demands arising from irrigation district development. In this way, a win–win outcome between agricultural irrigation and ecological protection can be achieved, laying a solid foundation for the sustainable development of irrigation districts.

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