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Research on the Impact of Reservoir Regulation on Groundwater Level Changes in Guangxi

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Abstract

To investigate the impact of reservoir regulation on groundwater level changes in Guangxi, based on hydrological cycle theory and regional hydrogeological characteristics, this study systematically analyzes the mechanisms by which reservoir regulation affects groundwater levels, as well as the unique impacts of Guangxi's karst landforms and subtropical monsoon climate. The study reveals that reservoir regulation affects groundwater levels through three core pathways: direct recharge from reservoir water seepage, indirect drive from river flow regulation, and regional hydrological cycle reconfiguration. The development of karst caves and fissures in Guangxi's karst region exacerbates the spatial heterogeneity of seepage, and the monsoon climate causes the impact of reservoir regulation on groundwater levels to exhibit a "rainy season overlap, dry season dominance" pattern. Human water demand further complicates the dynamic relationship between the two. Based on this, theoretical strategies are proposed, including differentiated regulation schemes, multi-source combined regulation, and ecological water level threshold control, to provide theoretical support for the coordinated management of reservoir regulation and groundwater resources in Guangxi.

Keywords: reservoir regulation, groundwater level, karst landform, hydrological cycle

1. Introduction

1.1 Research Background

The Guangxi Zhuang Autonomous Region, located in southwestern my country, has a subtropical monsoon climate. Precipitation distribution is extremely uneven in both time and space—the rainy season (April to September) accounts for over 70% of the annual precipitation, while the dry season (October to March) receives very little, leading to a significant imbalance between water supply and demand. To alleviate this problem, Guangxi has built thousands of reservoirs of various types. Reservoir regulation has become a key means of regulating surface runoff, ensuring urban and rural water supply, and ensuring agricultural irrigation. However, reservoir regulation disrupts the balance of the natural hydrological cycle, profoundly interfering with the groundwater system through seepage and runoff regulation, resulting in significant temporal and spatial variations in groundwater levels.

Groundwater is a key water source in Guangxi, especially in its karst regions. Karst landforms, characterized by the development of caves and fissures, form a unique karst water system that not only supports water for domestic use and agricultural production but also maintains the stability of fragile ecosystems such as springs and cave vegetation. In recent years, Guangxi's economic and social development has driven an annual increase in groundwater extraction, yet a systematic theoretical understanding of the impact of reservoir regulation on groundwater levels has yet to be established. In some areas, excessively high groundwater levels due to reservoir storage have led to reservoir bank instability, while insufficient water release has exacerbated groundwater overexploitation in other regions. Therefore, clarifying the relationship between reservoir regulation and groundwater levels in Guangxi is of great theoretical and practical value.

1.2 Current Research Status

Domestic and international scholars have conducted extensive research on the relationship between reservoir regulation and groundwater levels, but the focus has been significantly biased towards specific regions. Studies in arid basins in northern China have shown that reservoir regulation directly alters groundwater levels through seepage recharge. Under normal storage levels, the maximum groundwater level increase can reach 1.5 meters, with the impact extending as far as 12 kilometers downstream. Research on reservoirs in the eastern plains has focused on the role of reservoir bottom stratum permeability in controlling seepage, confirming that lithologic differences are the core factor influencing the magnitude of groundwater level fluctuations. These studies have established a basic theoretical framework for the "leakage-water-level response" model, but they primarily focus on homogeneous aquifers and fail to consider the unique hydrogeological conditions of the southern karst region.

Related research in the southern karst region remains weak: due to the complex leakage pathways resulting from the development of karst caves and fissures, existing studies are often limited to calculating leakage from a single reservoir, lacking a systematic analysis of the impact of storage and regulation processes on groundwater levels. Guangxi, as the core region of karst landforms, suffers from a subtropical monsoon climate, further complicating the issue. The combined effects of rainy season precipitation infiltration and reservoir leakage, as well as the synergistic effects of dry season water release and irrigation infiltration, have not been systematically addressed at the theoretical level, making it difficult to support coordinated reservoir-groundwater management at the regional level.

1.3 Research Significance and Content

Based on the regional characteristics of Guangxi, this study focuses on the theoretical mechanism of "reservoir regulation-groundwater level" and integrates the dual characteristics of karst hydrogeology and monsoon climate to reveal the unique patterns of reservoir regulation affecting groundwater levels in Guangxi, thereby addressing the gaps in theoretical research on the southern karst region. The research results can provide a theoretical basis for optimizing reservoir regulation schemes and protecting groundwater resources in Guangxi, and also provide a reference for research on similar karst regions around the world.

The research focuses on four aspects: (1) sorting out the general theoretical basis of reservoir regulation affecting groundwater levels; (2) analyzing the specific mechanism of reservoir regulation affecting groundwater levels in Guangxi; (3) analyzing the special regulatory effects of karst landforms and monsoon climate on the relationship between the two; (4) proposing a reservoir regulation optimization strategy based on groundwater level protection.

2. Theoretical Basis of Reservoir Regulation Affecting Groundwater Levels

2.1 The Core Connotation of Reservoir Regulation

The essence of reservoir regulation is to achieve multiple goals such as flood control, water supply, and ecology through artificial intervention in the temporal and spatial distribution of surface runoff. It is specifically divided into two stages: "storage-release": during the storage period, the reservoir water level is raised by intercepting upstream water to store redundant water; during the release period, water is released according to demand to lower the reservoir water level. Both phases interact with the groundwater system through different pathways. During the impoundment phase, rising reservoir water levels create a head difference, driving reservoir water to seep into the aquifer. During the release phase, downstream river water levels fluctuate, altering the intensity of river recharge to groundwater, ultimately affecting the groundwater level.

2.2 Driving Logic of Groundwater Level Changes

The dynamic balance of groundwater levels is determined by the "recharge-discharge" relationship: when recharge exceeds discharge, the water level rises; when it does not, it falls. Under natural conditions, groundwater recharge primarily comes from precipitation infiltration, river leakage, and lateral runoff, while discharge includes evaporation, spring overflow, lateral outflow, and artificial extraction. Reservoir regulation, as an artificial intervention, becomes a key driver of groundwater level change by directly altering recharge (e.g., increasing reservoir leakage) and indirectly regulating discharge (e.g., reducing groundwater extraction demand).

2.3 Common Pathways of Relationship

From a theoretical perspective, reservoir regulation affects groundwater levels through three pathways: First, direct recharge. After a reservoir is filled, water seeps into the aquifer through the reservoir bottom and banks, directly increasing groundwater recharge. Second, indirect regulation. Reservoirs regulate the water level and flow of downstream rivers. During the dry season, water is released to maintain river recharge through seepage, while during the wet season, water is stored to reduce flood infiltration, altering the spatiotemporal distribution of groundwater recharge. Third, the circulation reconfiguration pathway. Reservoir regulation alters surface runoff distribution, indirectly affecting precipitation infiltration (e.g., increased evaporation in the reservoir area alters local precipitation) and irrigation infiltration (e.g., water releases ensure irrigation and increase field recharge), resulting in indirect effects on groundwater levels.

3. Mechanisms of Reservoir Regulation Affecting Groundwater Levels in Guangxi

3.1 Direct Recharge Effects of Reservoir Leakage

After a reservoir is filled, a significant head difference forms between the reservoir water level and the surrounding groundwater level. Reservoir water seeps into the aquifer through pores or fissures in the reservoir bottom strata and reservoir bank rock mass, becoming a direct source of groundwater recharge. The impact of this recharge on the groundwater level exhibits a "spatial attenuation and temporal synchronization" effect: spatially, areas close to the reservoir experience greater leakage, leading to a significant groundwater level rise. However, with increasing distance, the leakage rate decreases, and the amplitude of the water level fluctuation gradually decreases. Temporally, during the impoundment period, rising reservoir water levels drive increased leakage, leading to a simultaneous rise in groundwater levels. During the release period, falling reservoir water levels reduce leakage, slowing the rise in water levels and even causing a slight decline. Regional differences in dam foundation lithology in Guangxi further amplify the spatial heterogeneity of this effect: Clastic rock areas have uniform stratum permeability, stable seepage recharge, and a gradual rise in groundwater levels. Karst carbonate rock areas, however, exhibit a "polarized" pattern due to the development of caves and fissures. If well-connected underground rivers or large caves exist, reservoir water rapidly seeps into the ground, causing a significant rise in groundwater levels within a short period of time. If caves are filled with clay or contain impermeable interlayers, seepage is minimal, and the impact on groundwater levels is negligible.

3.2 Indirect Driving Effect of River Flow Regulation

Reservoirs regulate downstream river flow, indirectly influencing groundwater levels by altering river seepage intensity. This effect exhibits significant seasonal variation in Guangxi. During the dry season (October-March), natural river water levels are low and flows are minimal. River seepage recharge to groundwater is limited, leading to a potential drop in groundwater levels due to evaporation and extraction. During this period, reservoirs release water to maintain a reasonable water level in downstream rivers, significantly increasing river seepage and becoming the core source of groundwater recharge during the dry season, effectively mitigating the downward trend in water levels.

During the rainy season (April-September), natural river floods are frequent, with high water levels and large flows. This should significantly increase the amount of groundwater recharge from seepage. However, reservoirs store water to intercept some of the floodwater, reducing the volume and water level of downstream rivers. This reduces the intensity of river seepage recharge during the wet season and prevents a sharp rise in groundwater levels due to excessive recharge. Furthermore, during the irrigation season (spring), reservoirs release water in concentrated amounts to ensure farmland irrigation. This maintains high downstream river water levels during this period, which, in synergistically with infiltration from irrigation fields, further raises groundwater levels, creating a dual recharge model of "river-farmland."

3.3 Restructuring the Regional Hydrological Cycle

Reservoir regulation has a more complex indirect impact on groundwater levels by restructuring the regional hydrological cycle. On the one hand, reservoir storage expands the reservoir area, increasing local evaporation and air humidity, potentially altering precipitation distribution under microclimatic conditions. Increased precipitation around the reservoir area can increase infiltration recharge, indirectly driving up groundwater levels. On the other hand, reservoir regulation ensures water supply stability, reduces groundwater overexploitation caused by water shortages, and alleviates the pressure on groundwater levels caused by artificial drainage.

At the same time, reservoir regulation alters the natural transformation relationship between surface runoff and groundwater: water that previously flowed down through the river and seeped into the groundwater is intercepted by the reservoir and then recharged through seepage at the reservoir bottom, resulting in a shift in the spatial location of recharge. During the dry season, reservoir releases maintain the ecological base flow of the river, avoiding interruptions in groundwater recharge caused by natural dry-ups and ensuring continuous recharge. This "restructuring of the transformation relationship" further exacerbates the spatiotemporal complexity of groundwater level fluctuations.

4. The Unique Impact of Guangxi's Regional Characteristics on the Relationship Between the Two

4.1 Heterogeneous Regulation of Karst Hydrogeology

The core characteristics of Guangxi's karst landforms—the development of caves, fissures, and underground river systems—significantly alter the logic of reservoir regulation's impact on groundwater levels. First, the heterogeneity of seepage pathways leads to spatially fragmented groundwater level fluctuations: in areas with interconnected underground rivers, reservoir seepage is rapidly transmitted through the underground rivers, causing a simultaneous rise in groundwater levels across a large area. In areas with less developed fissures, reservoir water seeps only slowly through the matrix pores, limiting groundwater level fluctuations to a few hundred meters around the reservoir area. Secondly, the dual porosity of karst water systems (matrix pores and fracture-cavern systems) exacerbates the variability in water-level responses: the matrix pores have low permeability, resulting in gradual groundwater-level rises due to reservoir leakage. However, the fracture-cavern system has high permeability. Once reservoir water enters this system, the hydraulic head pressure is rapidly transmitted, potentially causing sudden rises and falls in groundwater levels. These fluctuations not only have wide-ranging impacts but can also alter the flow direction of underground rivers, further disrupting regional groundwater-level distribution patterns.

4.2 Seasonal Intervention of the Subtropical Monsoon Climate

The core characteristic of Guangxi's subtropical monsoon climate—seasonal variations in precipitation—results in a "rainy season overlap, dry season dominates" pattern in the impact of reservoir regulation on groundwater levels. The rainy season (April-September) is a critical period for natural groundwater recharge, with concentrated precipitation. During this period, reservoirs enter their impoundment phase, and reservoir water leakage and precipitation infiltration create a synergistic effect. In areas surrounding the reservoir, direct recharge from reservoir leakage dominates, leading to a significant rise in groundwater levels. Further away from the reservoir, precipitation infiltration becomes the dominant factor, overshadowing the impact of reservoir regulation.

During the dry season (October-March), with scarce precipitation and insufficient natural groundwater recharge, reservoir regulation becomes the dominant driver of groundwater level fluctuations. Reservoirs release water to maintain downstream river levels, with river leakage accounting for over 60% of total groundwater recharge. Furthermore, irrigation water provided by these releases increases field infiltration, which, in tandem with river leakage, prevents the continued decline of groundwater levels due to evaporation and extraction. This "dry season-dominant" nature makes reservoir regulation a key means of maintaining stable groundwater levels in Guangxi during the dry season.

4.3 The Cumulative Effect of Human Activities

Regional differences in human activities and water resource demand in Guangxi further complicate the relationship between reservoir regulation and groundwater levels. In major agricultural production areas (such as the Nanning and Yulin Basins), large amounts of water are released from reservoirs during the spring irrigation season. This raises downstream river levels, driving seepage recharge and significantly increasing field irrigation infiltration. During this period, groundwater levels exhibit a cyclical pattern of rapid rise followed by a gradual decline. During the non-irrigation season, reservoir releases decrease, and groundwater levels rely primarily on natural recharge, with the fluctuations significantly reduced.

In densely populated urban areas (such as Nanning and Liuzhou), industrial and domestic water demand is high, while groundwater extraction is high, creating a dynamic "recharge-extraction" balance. If reservoir releases are sufficient, surface water supplies stabilize, groundwater extraction decreases, and the decline in groundwater levels is mitigated. If reservoir regulation is insufficient, surface water shortages force groundwater extraction to increase, accelerating the decline in groundwater levels. In some areas, reservoirs and groundwater extraction wells overlap, leading to direct extraction of groundwater recharged by reservoir leakage, resulting in groundwater level rises far below theoretical values, further highlighting the impact of human intervention.

5. Guangxi Reservoir Regulation and Storage Strategy Based on Groundwater Level Protection

5.1 Differentiated Regulation and Storage Plan

Based on the differences in hydrogeology and water resource demands across Guangxi, differentiated regulation and storage rules are formulated: Karst seepage-sensitive areas require strict control of storage levels to prevent abnormal increases in seepage caused by excessively high water levels. Monitoring of seepage channels should be strengthened, and the storage schedule should be adjusted promptly if anomalies are detected. Non-karst plain areas can dynamically adjust the regulation and storage plan based on the groundwater level. When the groundwater level is low, dry season water releases can be increased to replenish groundwater through river seepage and irrigation backseepage. When the groundwater level is high, storage time can be shortened to reduce seepage recharge. Optimize storage and regulation objectives for reservoirs with different functions: Water supply reservoirs prioritize ensuring water supply during the dry season while maintaining appropriate water levels in downstream rivers to ensure seepage recharge; flood control reservoirs must balance flood interception and groundwater recharge, avoiding excessive reductions in precipitation infiltration during rainy season storage;

ecological reservoirs prioritize maintaining stable groundwater levels and develop a "low-level storage, low-flow release" regulation model based on the water level requirements of ecological targets such as springs and wetlands.

5.2 Joint Regulation of Multiple Water Sources

Establish a joint regulation system for "reservoir surface water and groundwater" to coordinate the development and utilization of both. During peak water supply periods, prioritize the use of reservoir surface water, reduce groundwater extraction, and alleviate pressure on declining groundwater levels. When reservoirs are fully stocked, appropriate water releases are used to increase river seepage and irrigation infiltration, replenishing groundwater reserves and establishing a "high-water-to-low-water" water resource allocation model. Furthermore, establish a joint monitoring network to monitor groundwater level dynamics in real time and adjust reservoir regulation and regulation plans based on feedback from water level changes. For karst underground river systems, special consideration must be given to the hydraulic connection between reservoirs and underground rivers. In areas with well-developed underground rivers, the magnitude of reservoir water level increases should be reduced to prevent sudden underground river water level surges and karst collapse. During the dry season, reservoir water release should be used to increase underground river recharge, maintain the ecological flow of underground rivers, and safeguard the stability of the karst water system.

5.3 Ecological Water Level Threshold Control

Ecological groundwater level thresholds—the water level ranges that maintain ecological safety and geological stability—have been defined for different regions in Guangxi. Karst springs and cave vegetation areas must maintain water levels above the "ecological critical value" to prevent spring flow interruption and vegetation withering. Low-lying, flood-prone areas must maintain water levels below this critical value.

The ecological water level threshold is incorporated into the reservoir operation constraint conditions to establish an early warning mechanism: when the water level approaches the upper limit of the threshold, water storage is reduced and water release is increased; when the water level approaches the lower limit of the threshold, water release is increased to supplement the supply. The control status of the ecological water level threshold is clarified through legal means, and it is used as the core indicator for the approval of reservoir operation plans to ensure that the operation plan takes into account both water resource utilization and ecological protection, and realizes the sustainable coordinated development of Guangxi reservoir operation and groundwater resources.

6. Conclusion

6.1 Research Conclusion

(1) Reservoir operation affects groundwater level through three paths: "direct seepage recharge, river runoff regulation, and regional hydrological cycle reconstruction". Direct seepage is the short-term dominant factor, while river regulation and cycle reconstruction have long-term regional impacts. The three together constitute the core relationship between Guangxi reservoir operation and groundwater level.

(2) The heterogeneity of Guangxi's karst hydrogeology leads to "spatial fragmentation" in groundwater level changes, and the leakage volume in areas with developed caves and fissures is prone to abnormal fluctuations; the subtropical monsoon climate makes the impact of regulation and storage on groundwater levels present the characteristics of "rainy season superposition and dry season dominance", and reservoir water release in the dry season becomes the key source of groundwater recharge.

(3) Regional differences in human activities and water resource demand further superimpose the regulation and storage effect: agricultural irrigation causes groundwater levels to show seasonal cyclical changes, and urban water supply forms a "recharge-exploitation" dynamic balance, which together constitute a complex picture of the impact of reservoir regulation and storage on groundwater levels in Guangxi.

(4) Strategies such as differentiated regulation and storage plans, multi-source joint regulation, and ecological water level threshold control can effectively coordinate Guangxi's reservoir regulation and storage and groundwater level protection, providing theoretical support for the sustainable use of regional water resources.

6.2 Research Prospects

Further research can be deepened in three aspects: (1) conducting empirical research based on typical reservoirs in Guangxi to quantify the magnitude and impact range of groundwater level changes under different storage and regulation schemes and verify the applicability of the theoretical mechanism; (2) constructing a numerical model that takes into account the characteristics of karst caves and fissures to simulate the dynamic impact of long-term storage and regulation on groundwater levels and provide precise technical support for scheme optimization; (3)

incorporating climate change scenarios to analyze the impact of future changes in precipitation patterns on the "reservoir storage-groundwater level" relationship and enhance the foresight of research results.

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