# Quantitative Assessment of Hydrological Alterations Induced by the Panzhihua Irrigation Project and an Adaptive Ecological Restoration Strategy in the Dry-Hot Valley of the Jinsha River

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**Abstract:** Large-scale irrigation infrastructure in arid and semi-arid river valleys frequently induces hydrological regime shifts that compromise river connectivity, degrade aquatic habitats, and threaten endemic biodiversity, thereby necessitating rigorous quantitative impact assessment and site-specific adaptive management frameworks to reconcile water-resource development with ecosystem resilience. The Panzhihua Irrigation Project in the ecologically fragile dry-hot valley of the Jinsha River exemplifies these challenges. In this study, the ecological impact of the Panzhihua irrigation project on the dry and hot valley of Jinsha River is analysed with the help of Indicators of Hydrologic Alteration (IHA), Lindeman-Merenda-Gold (LMG) variance partitioning and complementary multi-source monitoring methods, and the impact of water diversion is relatively small, only 8.6%.The discharge of downstream rivers has increased by 3.2% to 32%, and the runoff of receiving rivers has increased by 0.1% to 11%.From the local point of view, the connectivity between rivers has declined, vegetation has been damaged, and the habitat of endemic fish has been lost. The main driving factors are fish passage (16.5%), water intake (38.2%) and hydrological change (25.7%). It is necessary to implement adaptive management, design fishways, build ecological flow regulation projects and set up buffer zones for native vegetation, which is conducive to the restoration of fragile ecosystems.

## 1. Introduction

Global water-infrastructure development must balance human water security with ecological integrity, particularly in arid and semi-arid river valleys where hydrological alterations can trigger cascading biodiversity losses and habitat fragmentation. In the dry-hot valley of the Jinsha River, the Panzhihua Irrigation Project exemplifies the tension between regional irrigation demands and the maintenance of fragile riverine ecosystems. Although worldwide ecological restoration experience is extensive, formulating context-specific strategies for dry-hot valleys remains challenging because of unique climatic extremes, low baseline vegetation cover, and high endemism [1]. Recent quantitative studies have documented significant declines in vegetation net primary production and carbon storage under combined hydropower and irrigation pressures, as well as dam-induced connectivity losses for endemic fish, underscoring the urgency of integrated hydrological-ecological assessments [2-4]. The present study utilises field data collected between 2020 and 2024 to quantify project-induced hydrological and ecological impacts through the Indicators of Hydrologic Alteration (IHA) and Lindeman-Merenda-Gold (LMG) methods, thereby constructing a monitoring-informed restoration framework that advances sustainable water management in similar arid-valley contexts [5].

## 2. Study Area and Methods

### 2.1 Study Area Characteristics

The research area is located in the middle reaches of Jinsha River, within the ecologically fragile dry-hot valley section of the Panzhihua Irrigation Project, as shown in Figure 1. The climate here belongs to dry-hot monsoon climate, with annual rainfall of 600-800 mm, annual evaporation of more than 2000 mm, and annual average temperature of 20-25 ℃. The vegetation coverage rate is only 30%, and the soil is easy to be eroded. The tributaries here are dry in the dry season, and the connectivity of the river is related to the survival of many endemic fish, including Coreius guichenoti. The irrigation system here has a complex canal network, including Renhe Reservoir and other reservoirs. Spatiotemporal analyses confirm that vegetation and carbon-storage dynamics in this basin are particularly sensitive to land-use and hydrological perturbations [1,2].

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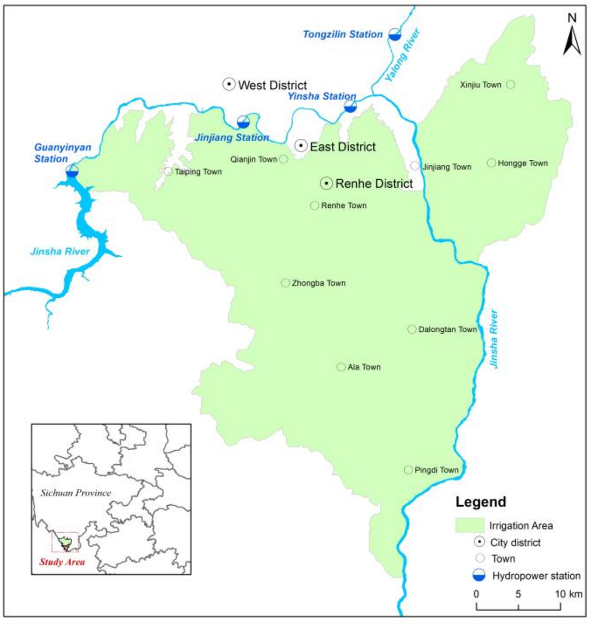

**Figure 1.** Location of irrigation area

### 2.2 Integrated Environmental Monitoring System

Hydrological and water-quality parameters were recorded at 10 of the 12 monitoring stations (the remaining two stations did not record these two parameter categories) [6]. The assessment scope covered the entire irrigation district, including the southern bank of the Jinsha River in Yinjiang Town (outside the Guanyinyan diversion irrigation area) and the southern bank of the Jinsha River in Renhe District (outside the Guanyinyan diversion irrigation area), with focused evaluation on the water-source reservoirs (Renhe pumped-storage upper reservoir and the proposed Renhe Reservoir), the seven retreat rivers (Naluo River, Mosuo River, Yanyang River, Bala River, Dahe River, Xiaohe River and Dazhu River), and the three regulating reservoirs (Pingdi, Yuejin and Shengli). Water-quality monitoring included 30 items (24 routine parameters plus sulfate, chloride, nitrate nitrogen, iron, manganese and chlorophyll a) and was conducted quarterly for three years during the operation period (four times per year). Hydrological monitoring comprised daily mean water levels of the regulating reservoirs, monthly runoff and water-resource quantities [7].

To characterise terrestrial ecology within the assessment area, field surveys were conducted in May–June 2021, October–November 2021, March–April 2022, September–October 2022, and April 2023, each lasting 7–9 days. Surveys employed 3S technology, line transects, quadrat sampling, and community interviews, following the Ministry of Environmental Protection’s Biodiversity Observation Technical Guidelines (HJ 710.1, HJ 710.3–6). A total of 44 terrestrial plant quadrats covering 14 vegetation formations and 50 animal line transects spanning various habitat types were established.

For aquatic ecology, two systematic surveys were carried out in April and July 2021 across six transects: one in Renhe Reservoir (source reservoir) and five in the three regulating reservoirs (Pingdi, Yuejin, Shengli) and two retreat rivers (Dahe and Naluo). Surveys assessed phytoplankton, zooplankton, benthic animals, aquatic vascular plants, fish species composition, biomass, and important habitats.

Data analysis was performed using the Indicators of Hydrologic Alteration (IHA) method combined with the Mann-Kendall trend test to evaluate hydrological alterations, the Lindeman-Merenda-Gold (LMG) variance-partitioning method to identify driving factors, and scenario simulation to assess restoration efficacy.

IHA followed the Range of Variability Approach (RVA) and examined four core parameters derived from project documentation: (1) design-level-year irrigation supply﹣demand balance before and after implementation; (2) multi-year average reservoir discharge (e.g., Renhe Reservoir) pre- and post-operation; (3) multi-year average runoff change in main receiving rivers; and (4) water-level and flow comparisons across wet, normal, and dry periods in the three key regulating reservoirs (Pingdi, Yuejin, Shengli).

The single-indicator alteration degree is given by Equation (1)

$$\boldsymbol{D_i} = \frac{\boldsymbol{N_e} - \boldsymbol{N_o}}{\boldsymbol{N_e}} \times \mathbf{100\%} \qquad (1)$$

where $\boldsymbol{N_e}$ is the expected number of years exceeding the RVA threshold under natural conditions and $\boldsymbol{N_o}$ is the observed number post-project; the overall alteration degree is calculated by Equation (2) with classification thresholds of light.

$$\boldsymbol{D_o} = \frac{\mathbf{1}}{\boldsymbol{n}} \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} |\boldsymbol{D_i}| \qquad (2)$$

LMG method was used to partition variance and determine relative contributions of drivers. Input variables included: irrigation water withdrawal volume (calculated from intake-hub flow and water-level data); hydrological regime change (quantified via IHA spatial-temporal variability); fish passage facility adequacy (via improved barrier coefficient method and migration blockage rate); riverbed sedimentation depth and vegetation coverage percentage (derived from UAV remote sensing and field transects).

## 3. Results

### 3.1 Hydrological Regime: Overall Improvement with Localized Alteration

The impact of water withdrawal on the source flow is relatively small, and the impact on the source flow of the Renhe Reservoir is also relatively small. The discharge of downstream water has increased by 32% to 39%, and the flow of seven rivers has increased by 1% to 11%, which can effectively alleviate the water stress in the dry season. However, the water level and velocity in the intake area have changed, which has a negative impact on the surrounding habitat [7, 8]. IHA analysis confirmed an overall low alteration degree (8.6%) at the basin scale, consistent with RVA thresholds (Figure 2).

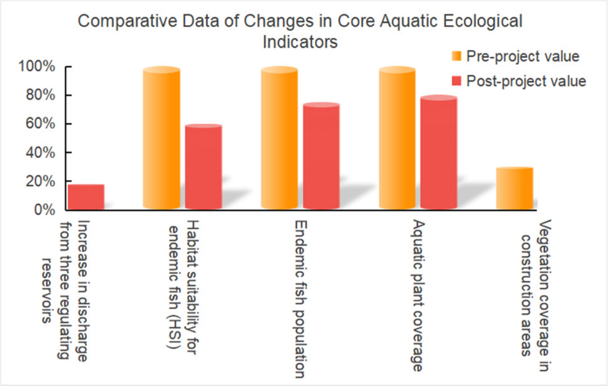

**Figure 2.** Comparative changes in core aquatic ecological indicators before and after project implementation

### 3.2 River Connectivity: A Significant Decline

According to the monitoring data, after the project was built, the regional river connectivity index dropped significantly from 0.87 to 0.62, as shown in Figure 3. The most critical reason for the decline in physical connectivity is the presence of structural barriers—including the water intake structure and channelized reaches that fragment the natural stream network—along with sedimentation (depth: 0.3–0.8 m) caused by construction spoil entering the river. Ecological connectivity has also declined markedly: the absence of functional fish passage facilities has blocked over 65% of migration corridors for endemic fish species, leading to spatial separation of foraging and spawning habitats between upstream and downstream reaches [9].

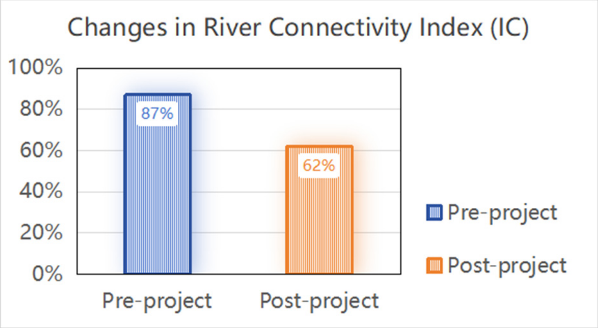

**Figure 3.** Changes in river connectivity index (IC) before and after project implementation

### 3.3 Aquatic Habitat and Biota: Degradation of Critical Habitats

The change of hydrological regime will lead to ecological chain reaction, and the decline of habitat quality is the most obvious, because the flow speed of the river is too slow, the sediment is deposited, the wetland is encroached, and the spawning and foraging habitat of the fish is reduced by 15% to 25%, which is not conducive to the improvement of habitat quality[1]. Land use has a significant impact on the suitability of fish habitats[5]. From the biological point of view, the decline of habitat quality and the existence of migration barriers have reduced the number of fish by 20% to 30%, and the coverage of aquatic plants has declined by 18% to 22%, which weakens the self-purification ability of the water and leads to the collapse of the food chain [9]. These patterns align with recent UAV- and eDNA-based assessments of habitat fragmentation in Jinsha cascade systems [3, 10].

### 3.4 Key Driving Factors Identified by Data

In this study, the LMG method is used to analyze the data, and five key drivers are identified, including the contribution rate of each driver: 38.2% for irrigation water withdrawal, 25.7% for hydrological regime change, 16.5% for fish passage facility adequacy, 10.8% for riverbed sedimentation, and 8.8% for vegetation coverage, as shown in Figure 4. The results obtained in this study can provide a reliable basis for the construction of ecological compensation mechanism, and can also provide reasonable basis for the formulation of compensation standards and the selection of compensation targets[9,5], so as to promote the implementation of ecological restoration measures.

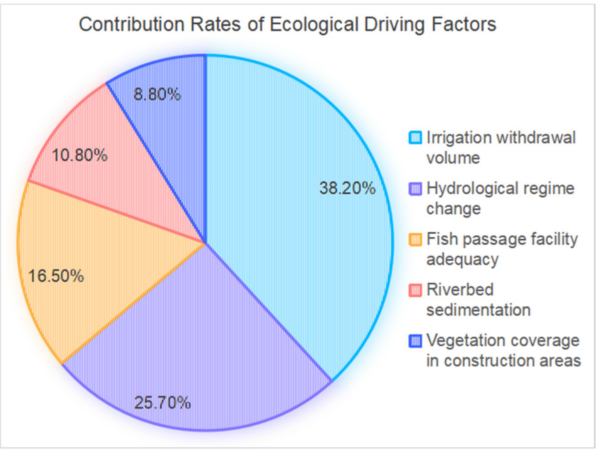

**Figure 4.** Contribution rates of ecological driving factors as determined by the LMG method

## 4. Discussions

Basin-wide hydrological benefits (increased downstream discharge and runoff) coexist with pronounced localised ecological degradation driven primarily by irrigation withdrawal (38.2 %) and hydrological alteration (25.7 %). LMG results further demonstrate that fish-passage barriers (16.5 %) amplify connectivity loss, consistent with recent findings that dam-induced fragmentation outweighs climatic effects for upper-Yangtze endemic fish [3]. Vegetation damage and sedimentation exacerbate habitat degradation, threatening Coreius guichenoti and related taxa. These outcomes extend global ecological-flow restoration principles to dry-hot valley contexts and emphasise the superiority of monitoring-driven adaptive interventions over static compensation measures [1, 2]. Based on the above quantitative results and identified drivers, the following adaptive ecological restoration strategy is proposed.

### 4.1 Adaptive Ecological Flow Management Based on Real-time Monitoring

The application of an intelligent monitoring system enables automatic alerts and achieves >99 % compliance with dry-season ecological-flow thresholds (simulation-based, in accordance with SL 525 and SL/T 712) [11].

### 4.2 Targeted Connectivity Restoration Focusing on Fish Passage

In the process of fishway construction, we need to analyze the swimming performance of the fish in this area, and optimize the design and construction according to the migratory behavior of the fish. In the empirical study [9], the hybrid configuration is introduced, and the fish ladder is set as a supplement to the vertical slot fishway. Some key parameters need to be calibrated in the process of construction, such as pool length, slot width, flow velocity (0.8-1.2m/s), so as to meet the needs of Coreius guichenoti in terms of swimming and climbing preferences. In the process of setting up the fishway, we should also pay attention to the geometry of the inlet and outlet, and make targeted improvements to the key barriers, so as to enhance the ecological pertinence and improve the efficiency of passage, and achieve the purpose of restoring connectivity[1,9]. Such designs draw on empirical efficacy evaluations of upper-Yangtze fish-passage facilities [3].

### 4.3 Habitat Rehabilitation and Water Quality Enhancement

In the degraded habitat area, the HSI index is used to guide the restoration project. In the study of HSI of endemic fish[1], the following restoration actions are taken: (1) Ecological gravel and artificial fish nests are set up to improve the quality of the substrate; (2) The ecological buffer zone is restored to increase the complexity of the habitat structure; (3) Oxidation ponds and small reservoirs are built along the irrigation channel to deal with agricultural non-point source pollution. The integrated approach can not only improve water quality, but also achieve the purpose of habitat reconstruction[1, 11].

### 4.4 Rapid Vegetation Restoration in Construction Areas Using Native Species

In the dry valley, the recovery of vegetation is inevitably related to the reasonable selection of species and the effective management of water resources. In this study, the strategy of rapid vegetation restoration is adopted, and drought-tolerant species are selected as the core, including Euphorbiaceae and other plants, which are arranged according to the principle of ecology, and shrubs, grass and other species are combined in a multi-level way, and a large number of micro-catchments are built to retain water resources. The aim is to increase the vegetation coverage to more than 50% in 3-5 years. The framework provides a replicable model for balancing irrigation benefits with ecosystem resilience in arid river valleys worldwide.

### 4.5 Long-term Coordinated Monitoring and Adaptive Management

In the process of development, we should establish a perfect monitoring system, which should be maintained for at least 10 years, and the monitoring indicators should be comprehensive, including all the contents involved in this study, and some new parameters should be added. In this regard, we should build a data sharing platform, evaluate the effectiveness of restoration measures every year, and adjust the restoration strategy dynamically according to the evaluation results, so as to form a "monitoring-evaluation-management" framework and improve the scientificity and sustainability [7].

## 5. Conclusions

In this study, the positive impact of the project on the water supply of the region is analyzed, and the impact of the project on the ecological environment is also analyzed, including the adverse effects, such as the degradation of the connection between the waters, the deterioration of the fish habitat, and the disturbance of the vegetation. The analysis of the attribution of the above problems leads to the following conclusions: the key drivers are the change of hydrological regime (25.7%), the withdrawal of irrigation water (38.2%), and the inadequacy of the fishway (16.5%).In the process of restoring the ecological environment, the advantages of multi-source monitoring data are brought into play, combined with the characteristics of the dry-hot valley, the restoration strategy is formulated, and the management framework of "monitoring-evaluation-restoration-protection" is constructed, which includes habitat reconstruction, ecological flow scheduling, fishway optimization and so on. In this way, a reasonable solution is put forward for the Panzhihua water diversion project, and a reference for the construction of similar projects in other countries and regions is provided. This method has a positive impact on the coordinated development of the two, which requires the use of evidence to monitor, restore spatially, and govern adaptively. The framework provides a replicable model for balancing irrigation benefits with ecosystem resilience in arid river valleys worldwide.

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