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Simulation and Optimal Scheduling of Water Quality in Urban and Rural Water Supply Systems: A Case Study in the Northwest Arid Region of China

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Abstract: The Northwest Arid Region faces the most serious resource-based water shortage in China, with challenges from engineering-, structural- and management-based water shortages. This water scarcity critically limits the socio-economic development of the region. Rational allocation of scarce water resources to achieve sustainable development of the ecological environment and economy has become a key issue in water resources research in the Northwest Arid Region. South-Central Ningxia, part of the Northwest Arid Region, exemplifies these challenges. This paper examines the urban and rural water supply projects in South-Central Ningxia. The current scheduling scheme focuses primarily on the distribution of water demand, with inadequate attention paid to water-quality requirements. Localized exceedances of water-quality standards indicate the existing scheduling scheme has failed to effectively control water-quality issues while ensuring water quantity. This study is the first to systematically evaluate the impact of the South-Central Ningxia Water Supply Project on water quality alongside field surveys and data analysis and propose an optimized scheduling scheme that addresses both water quantity and quality needs. The main findings are as follows: 1. Overall water quality is good, except for consistently high total nitrogen levels. 2. The optimized scheme significantly reduced total nitrogen levels, achieving a maximum reduction rate of 78.81%, and met all Class III standards.

Keywords: water quantity and quality; scheduling; water transfer projects; environmental impact assessment; optimal allocation of water resources

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1. Introduction

Effective and equitable water distribution is an important means for ensuring the sustainable use of water resources [1], and for achieving overall regulation of a basin's water cycle [2]. As water resource shortages and environmental pollution intensify globally, a water resource model focused solely on water quantity allocation no longer meets the needs of society. The integrated allocation of water quantity and quality has become a major concern for the sustainable use of water resources in various countries [3]. However, compared to single-objective dispatching, this combined allocation approach is more complex and requires a comprehensive consideration of water distribution, the assimilation capacity of water functional areas, and the improvement of water efficiency, thereby unifying the mechanisms and joint optimization of water consumption and pollutant capacity [4].

Regarding water quantity and quality evaluation prediction and optimal scheduling, two primary methods are currently used: field monitoring and numerical simulation. Masse first proposed the issue of reservoir optimization scheduling in the 1940s, aiming to achieve a rational allocation of water resources [5]. With advances in computer technology, water resource system analysis, optimization, and simulation technologies have rapidly developed [6]. By 1971, Marks had introduced linear programming for water resource systems, promoting the widespread application of mathematical programming and simulation techniques in water resource optimization scheduling [7]. In 1978, Shafer and Labadie proposed a watershed management model [8], marking a significant breakthrough in the technical application of water resource management. The water resources management model developed by the Canadian Inland Waters Centre, one based on linear programming and network flow algorithms, was successfully applied to the Ottawa River Basin and the Great Lakes region in 1982 [9]. In the late 1980s, research on water resource allocation began incorporating hierarchical theory and gradually shifted towards multi-objective optimization [10]. In 1987, Willis et al. [11] used linear programming to accurately simulate the joint scheduling of surface water, groundwater, and reservoirs and solved the integrated management problem of a single reservoir and its underlying aquifer using the SUMT algorithm. Percia et al. [12] developed a multi-source integrated scheduling model that includes the utilization of groundwater, surface water, and recycled wastewater, aiming to maximize economic benefits. In the 1990s, the application of visualization technology and decision support systems promoted the development of multi-user, multi-objective water resource allocation models [3]. To achieve visualization of water resources decision analysis, Camara et al. [13] developed a multidimensional simulation decision model based on logical relationships and vector calculations. Hamalalnen et al. [14] investigated multi-criteria water resource management and Multi-Stakeholder Decision Support systems. At the end of the 20th century, further development was made in water resources allocation. In 2000, Rosegrant et al. [15] combined hydrological models with economic models to assess the benefits of optimizing water resource allocation and applied this approach to the Maipo River Basin in Chile. In 2002, McKinney et al. [16] proposed a framework for simulating watershed water resource allocation based on Geographic Information System (GIS) technology. The application of GIS technology enabled managers to better understand and analyze the spatial distribution and trends of water resources, leading to decisions which were more scientific. These studies made meaningful attempts at optimizing water resource allocation, applying emerging optimization techniques to water resource system models and providing additional tools and methods for achieving rational water resource allocation and management.

In the early stages of water resource optimization, excessive emphasis was placed on rapid economic and social development, neglecting the crucial attribute of water quality, which led to a failure to address the diverse water-quality requirements of different users and the impact of wastewater discharge on the water environment within the social water cycle [17]. With the advancement of theoretical theories in water resource management, studies on water resource optimization have evolved from solely analyzing water quantity allocation to models integrating both water quantity and quality and have shifted from pursuing economic optimization to seeking overall benefit optimization while paying more attention to the coordinated development of ecology and economy [18]. By 1990, Pingryd et al. [19] had developed a joint water quantity and quality scheduling Decision-Support system to address issues related to water resource allocation and water pollution treatment balance. In 1992, Mehrez [20] employed a nonlinear programming model to establish a multisource water supply system, incorporating various regional reservoirs and groundwater wells. That same year, Afzalet al. [21] used linear programming models to determine irrigation strategies for each crop based on differentiated water quality. In 1997, Avogadro et al. [22] created a water resource planning decision procedure that, considering water-quality constraints, simulated both water quantity and quality. This procedure analyzed the extent to which different allocation schemes met the temporal and spatial water-quality targets and pollutant reduction progress goals within a watershed, thereby determining the optimal water resource allocation scheme. To manage the combined use of surface water and groundwater, Wong [23] incorporated measures to prevent groundwater degradation within a two-step nonlinear optimization model. By 2002, Campbell et al. [24] had coupled the HEC-5C water-quality model with the MODSIM water quantity model to study the impacts of surface water and groundwater diversion mixing and dilution on water quality, and examined the results under different scenarios.

The Northwest Region of China, despite possessing the majority of land and mineral resources, faces severe water scarcity due to poor water resource combination, which constrains its economic development [25]. The increasing population, coupled with rising water demands from industrial and agricultural sectors, exacerbates water pollution and results in the irrational exploitation and utilization of water resources. Consequently, there is a substantial shortfall in socio-economic water use, and the ecological environment in the arid northwest has become increasingly fragile [26]. Ningxia, part of this Northwest Arid Region, exemplifies these challenges. The current water supply projects in Ningxia have significant deficiencies, leading to water-quality exceedances that hinder the region's development. To address these issues, this paper conducts a study on the optimization of the water allocation scheme based on water quantity and quality demand for the South-Central Ningxia Urban and Rural Water Supply Project to ensure regional water security and provide a reference for developing and implementing optimal water resource allocation schemes in other regions.

2. Materials and Methods

2.1. Research Area and Project Overview

The South-Central Ningxia Urban and Rural Water Supply Project (Figure 1) is a water resource optimization and allocation project that transports abundant surface water from the Jing River basin on the eastern slopes of the Liupan Mountains in the south to the arid and water-scarce regions in the central and northern parts of Guyuan. The first intake point of the project is the Longtan Reservoir, located in the source area of the Jing River, a first-order tributary of the Wei River. The project's average annual water intake is 39.8 M m^3, with seven intake points distributed along the route. The main regulating reservoir, Zhongzhuang Reservoir, is located 10 km south of Guyuan in a primary tributary of the Qingshui River. The auxiliary regulating reservoir, Nuanshui River Reservoir, is situated at the outlet of the Qinjia Valley.

2.2. Methodologies

This study evaluates the water quality of the South-Central Ningxia Urban and Rural Water Supply Project and simulates an optimized scheduling scheme based on water quality and water-quantity standards.

2.2.1. Water-Quality Analysis Methods

From 2019 to 2022, intake points were monitored every six months for fluoride, pH, sulfate, dissolved solids, and total hardness, with focused monthly monitoring from March 2020 to February 2021 for 29 factors including temperature, pH, permanganate index, dissolved oxygen, ammonia nitrogen, chloride, and nitrate. Zhongzhuang Reservoir was monitored monthly during the same period for the same 29 factors, providing a comprehensive four-year water-quality assessment. Monitoring sections were set up at each intake point (Table 1), with water quality monitored according to China's "Environmental Quality Standards for Surface Water" (GB3838-2002) [27]. Table 2 outlines the specific testing methods used to monitor various water-quality parameters. All of the data are provided by the Liupanshui Water Authority in Ningxia.

Table 1. Surface water quality monitoring sections at intake points.

Section Name	River	Section Property
Longtan Reservoir	Jing River mainstream	Reservoir Center
Shi Ju Zi	Cedi River mainstream	Intake Point
Hongjia Canyon	Jing River branch	Intake Point
Qingjia Gully	Nuanshui River mainstream	Reservoir Front
Baijia Gully	Nuanshui River branch	Intake Point

Table 1. *Cont.*

Section Name	River	Section Property
Qingshui Gully	Jie River branch	Intake Point
Woyang Valley	Jie River mainstream	Intake Point
Longtan Reservoir	Jing River mainstream	Reservoir Center

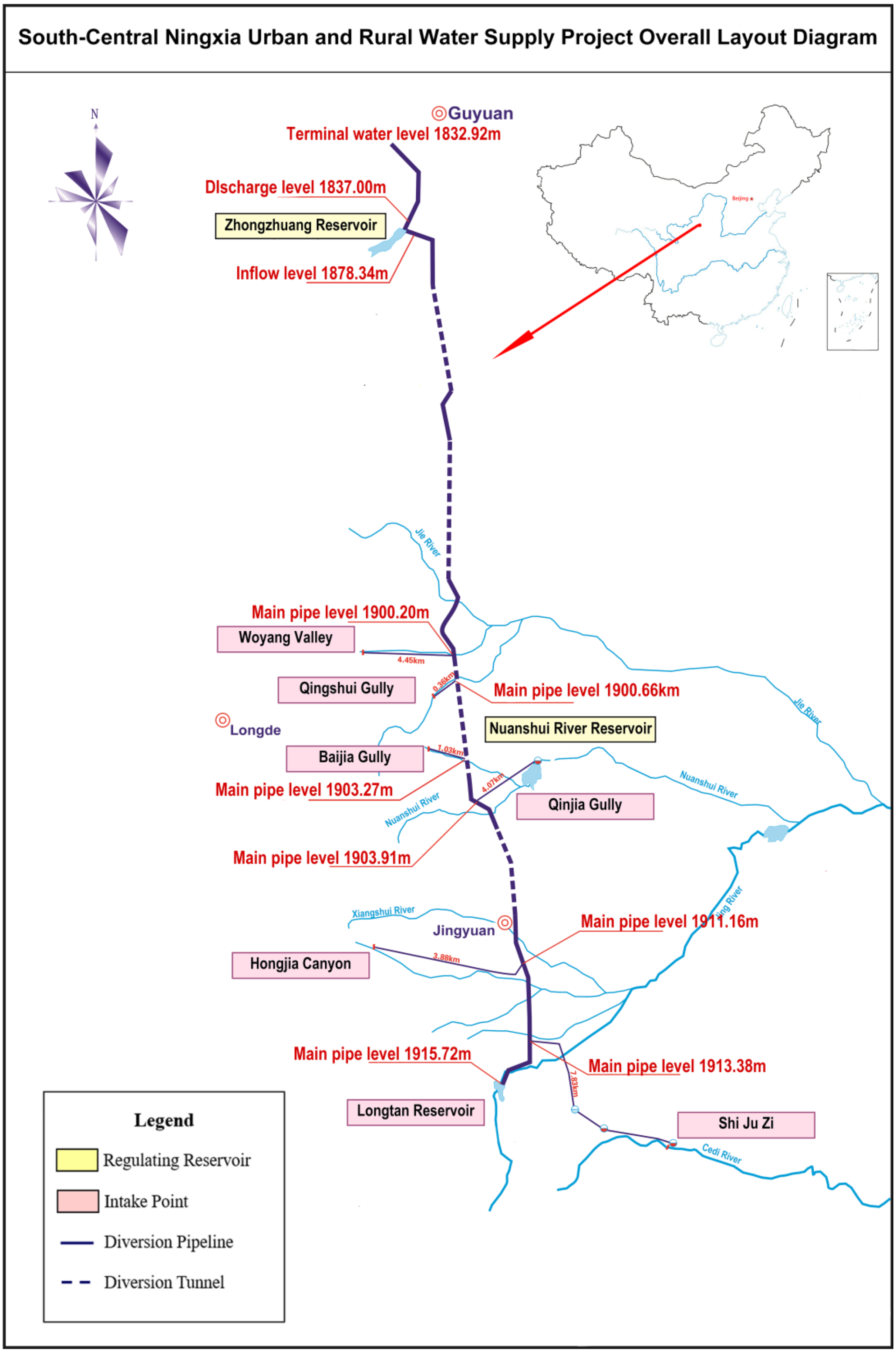

Figure 1. Engineering site location map.

Table 2. Water quality parameters and corresponding testing methods.

Data Type	Testing Method
Permanganate Index (mg/L)	Acid Process
Bio-chemical Oxygen Demand (BOD5, mg/L)	Dilution and Inoculation Test
pH	Glass Electrode Method
Fluoride (mg/L)	Fluoride Reagent Spectrophotometry
Ammonia Nitrogen (mg/L)	Nessler's Reagent Spectrophotometry
Total Phosphorus (mg/L)	Molybdate Spectrophotometry
Nitrate (mg/L)	Phenol Disulfonic Acid Spectrophotometer
Sulfate (mg/L)	Ion Chromatograph
Chloride (mg/L)	Silver Nitrate Titration
Chemical Oxygen Demand (COD)	Dichromate Titration
Total Hardness	EDTA Titration

The equipment used included an Atomic Absorption Spectrophotometer (A3, Shimadzu, Kyoto, Japan); Ion Chromatograph (ICS-90, Dionex, Sunnyvale, CA, USA); Gas Chromatograph (Agilent 7890B GC, Agilent Technologies, Santa Clara, CA, USA); Electronic Balance (BSA224S-CW, Sartorius, Göttingen, Germany); Electro-Optical Analytical Balance (TG328A, Shimadzu, Kyoto, Japan); Spectrophotometer (UV751-GD model, Shanghai Metash Instruments Co., Ltd., Shanghai, China); Spectrophotometer (721 model, Shanghai Analytical Instrument Factory, Shanghai, China); Spectrophotometer (722S model, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China); Infrared Oil Meter (IR-200A, Infralyt, Berlin, Germany); pH Meter (PB-10 model, Sartorius, Göttingen, Germany); Conductivity Meter (DDS-307A, Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China); Atomic Absorption Spectrophotometer (4530F, Beijing Ruili Analytical Instrument Co., Ltd., Beijing, China).

2.2.2. Simulation of Water Supply System Optimization Model

The optimization of the water supply system was simulated using the Storm Water Management Model (SWMM Version 5.1), which is specifically designed to simulate urban hydrological and hydraulic conditions. SWMM effectively handles various flow scenarios such as surface runoff, infiltration, pipe network flow, and river flow [28]. In this model, the drainage system is represented by a network of nodes and connecting pipes, in which each node can serve as an inflow point, confluence point, or outflow point. The model accurately tracks and simulates the quantity and quality of runoff generated by each sub-basin across different time steps, as well as the flow and water-quality changes within pipes and tunnels.

Pipe Network Water Quantity Model

SWMM simulates water flow movement based on the Saint-Venant equations for unsteady free-surface flow, which conserves mass and momentum [29]:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f = 0 \tag{2}$$

A is the cross-sectional area of flow; t is the time coordinate; Q is the flow rate; x is the spatial coordinate; H is the hydraulic head; S_f is the friction angle; g is the gravitational acceleration.

Nodes in the system are categorized into non-storage types (such as junction nodes) and storage types (such as ponds and tanks). The model ensures flow conservation at system nodes using the node continuity equation, where the total area of a node is composed of its storage surface area and the surface area contributions of connected pipes [30]. The change in the hydraulic head at a node is approximated by the following equation [31]:

$$\frac{dH}{dt} = \frac{\sum Q_{in} - \sum Q_{out}}{A} \tag{3}$$

where Q_{in} and Q_{out} are inflow and outflow rates, and A is the total area of the node.

The model uses the surface areas of the node and connected pipes in a finite difference computation with an iterative method, solving implicit solutions at a set time step. Outflow boundary conditions are user-defined and can be constants, time-series extractions, or based on critical or normal flow depths [32].

Pipe Network Water-Quality Model

In the SWMM model, the concentration change of dissolved components along the pipe is simulated through the mass conservation equation:

$$\frac{\partial c}{\partial t} = -\frac{\partial (uc)}{\partial x} + \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) + r(c) \tag{4}$$

c is the constituent concentration (ML^{-3}); u is the longitudinal velocity (LT^{-1}); D is the longitudinal dispersion coefficient; and $r(c)$ is the reaction rate term.

Boundary conditions in SWMM are defined by the water-quality concentration at the end nodes of the transport network [31]. For non-storage nodes, the concentration is the flow-weighted average of inflow and outflow masses. For storage nodes, complete mixing is assumed, and concentrations are updated using a simplified mixing equation based on the mass conservation equation:

$$c(t+\Delta t) = \frac{c(t)V(t)e^{-K_1\Delta t} + C_{in}Q_{in}\Delta t}{V(t) + Q_{in}\Delta t}. \tag{5}$$

$V(t)$ is the water volume in the reactor and $e^{-K_1\Delta t}$ is the decay factor, with K_1 being the first-order reaction rate constant.

Model Calibration Validation

The model was calibrated using data collected from the water source intake points on 8 April 2020. Calculations were performed to determine the water volumes and pollutant distributions at various depths and concentrations along different pipelines over the corresponding period. The simulation results show an average relative error of only 3.8% compared to the measured data.

Further validation, using monitoring results from 9–17 April 2020, showed an average error of just 1% (Figure 2). These results indicate that the model has high precision and reliability and can be used for joint optimization and scheduling simulation of water quantity and water quality.

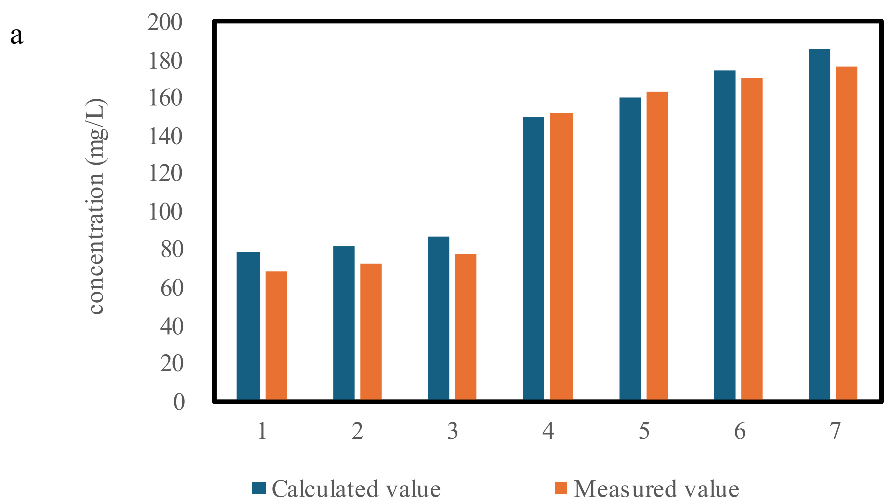

Figure 2. *Cont.*

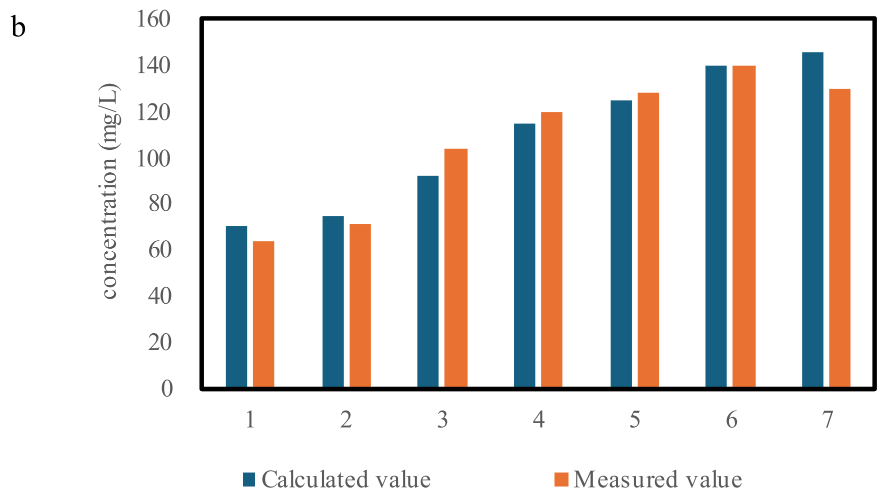

Figure 2. Model calibration and verification at intake points: (**a**) calibration results and (**b**) validation results.

3. Results and Discussion

3.1. Overall Water Quality

Figure 3 illustrates the basic water-quality parameters along the project route. Monthly monitoring data were collected from each intake point of the water supply project and the Zhongzhuang reservoir from March 2020 to February 2021. The water temperature ranged from 1 °C to 24.2 °C, with a median of 12.0 °C. Dissolved oxygen levels were between 6.15 mg/L and 11.01 mg/L (median: 8.4 mg/L). The permanganate index varied from 0.73 mg/L to 3.54 mg/L (median: 1.25 mg/L), while biochemical oxygen demand (BOD) was from 0.03 mg/L to 2.44 mg/L (median: 0.82 mg/L). The pH values ranged from 6.99 to 9.37, with a median of 8.33. For total phosphorus and fluoride, some sections and periods showed values below detection limits, with medians of 0.03 mg/L and 0.23 mg/L, respectively. Ammonia nitrogen concentrations ranged from 0.01 mg/L to 0.68 mg/L (median: 0.1 mg/L). Total nitrogen levels were between 0.33 mg/L and 6.08 mg/L (median: 1.30 mg/L). Nitrate concentrations varied from 0.2 mg/L to 5.92 mg/L (median: 1.135 mg/L). Chloride levels ranged from 6 mg/L to 157 mg/L, with a median of 15 mg/L, and sulfate levels ranged from 8 mg/L to 741 mg/L, with a median of 124.5 mg/L.

When compared with the concentration limits of the Surface Water Environmental Quality Standards, the levels of dissolved oxygen, permanganate index, biochemical oxygen demand (BOD), pH, fluoride, nitrate, and chloride were mostly at Class I levels. Approximately 80% of sulfate measurements were at Class I levels. As for total phosphorus, about 60% of measurements were at Class II levels and 40% at Class I. Ammonia nitrogen was at Class I levels for around 70% of the measurements, with 30% at Class II. Total nitrogen was generally at Class IV levels, but this is typically not used as an assessment indicator. Overall, the water quality over the monitoring period of one year was good, with most key indicators meeting Class II standards or higher.

3.2. Water-Quality Investigation and Evaluation of Zhongzhuang Reservoir

To understand the current water quality of the water source in the project area, a surface-water-quality survey of Zhongzhuang Reservoir was conducted. Monitoring was carried out monthly from 2019 to 2022. The results (Figure 4) indicated that the pH value (8.0), permanganate index concentration (1.20–1.80 mg/L), five-day biochemical oxygen demand (BOD_5) concentration (0.71–1.77 mg/L), ammonia nitrogen (NH_3-N) concentration (0.04–0.21 mg/L), chemical oxygen demand (COD) concentration (3.75–11.03 mg/L), dissolved oxygen concentration (8.00 mg/L), total phosphorus (as P) concentration (0–0.04 mg/L), and sulfate (SO_4^{2-}) concentration (89–125 mg/L) all met the Class III water-quality standards set by the "Environmental Quality Standards for Surface Water". However, the total nitrogen (as N) concentration (0.84–1.40 mg/L) consistently exceeded the standard but showed a fluctuating downward trend, indicating the potential to meet the Class III water-quality standards in the future. Dissolved oxygen concentration exhibited clear seasonal variation, being lower in summer and higher in winter, while the permanganate index and ammonia nitrogen concentrations were higher in summer and lower in winter. Other indicators did not show significant seasonal variations throughout the year.

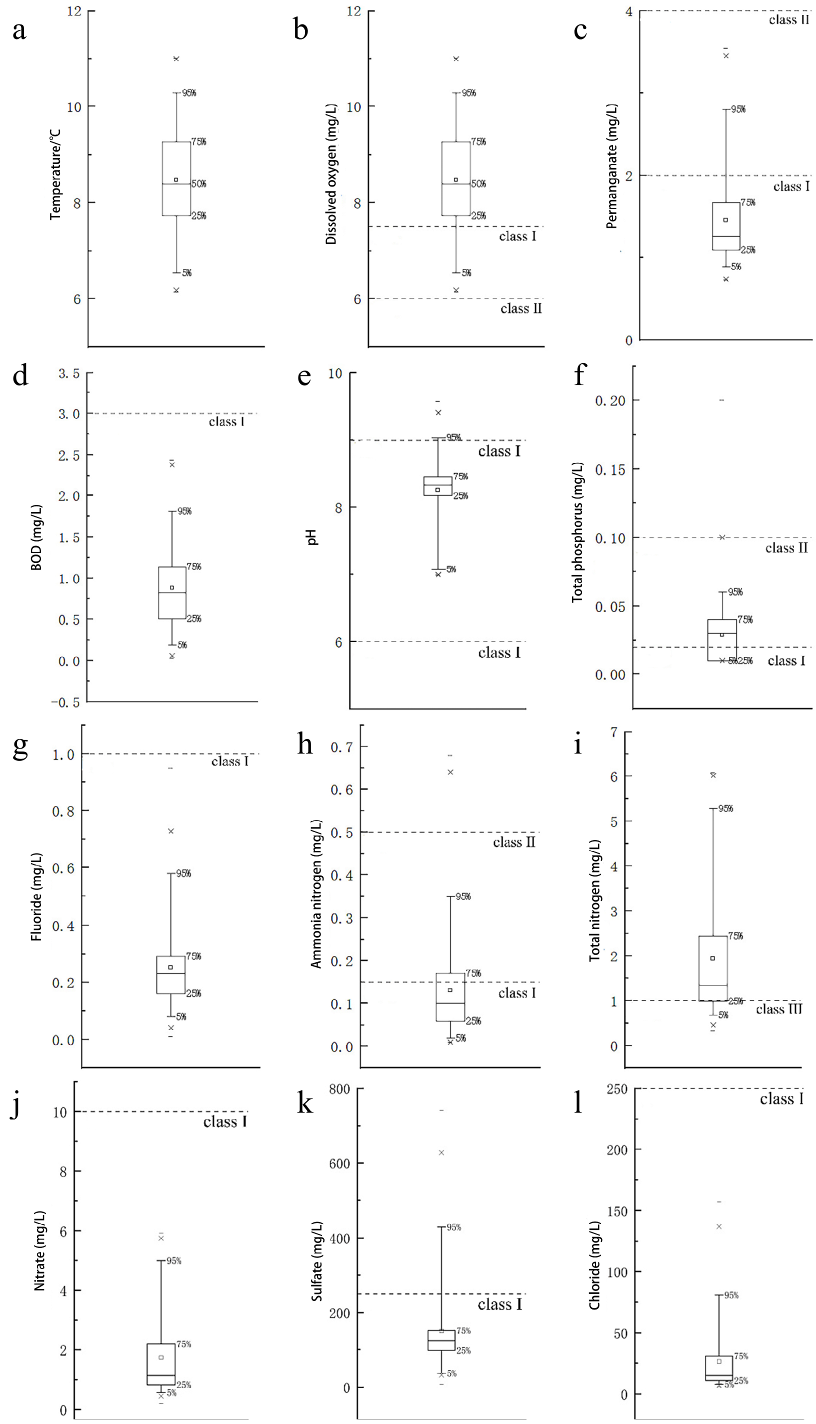

Figure 3. Water-quality parameter comparison: (**a**) Temperature (°C); (**b**) Dissolved Oxygen (mg/L); (**c**) Permanganate Index (mg/L); (**d**) Biochemical Oxygen Demand (BOD5, mg/L); (**e**) pH; (**f**) Fluoride (mg/L); (**g**) Ammonia Nitrogen (NH_3-N, mg/L); (**h**) Total Phosphorus (mg/L); (**i**) Nitrate (mg/L); (**j**) Total Nitrogen (mg/L); (**k**) Sulfate (SO_4^{2-}, mg/L); (**l**) Chloride (mg/L), as compared to standards in the urban and rural areas of southern Ningxia.

Figure 4. Water-quality trends for (**a**) pH Values; (**b**) Permanganate Index; (**c**) Biochemical Oxygen Demand (BOD5); (**d**) Ammonia Nitrogen (NH_3-N); (**e**) Chemical Oxygen Demand (COD); (**f**) Dissolved Oxygen (DO); (**g**) Total Phosphorus; (**h**) Sulfate (SO_4^{2-}); and (**i**) Total Nitrogen at Zhongzhuang Reservoir.

3.3. Water-Quality Investigation and Evaluation of Intake Points

Based on China's "Environmental Quality Standards for Surface Water" (GB3838-2002) [27], water-quality monitoring was conducted at various intake points over four years from 2019 to 2022, with monitoring conducted every 6 months. Additionally, from March 2019 to March 2021, intensive monthly monitoring focused on Total Nitrogen (TN) as a key factor.

3.3.1. Water-Quality Changes from 2019 to 2022

The pH monitoring results (Figure 5a) show that all monitoring points exhibited similar variation patterns, with most results meeting the Class III water-quality standards. Only Shi Ju Zi and Longtan Reservoir sections exceeded the standards, and only for a few months. The pH values peaked and hit their lowest point in April 2020, with Longtan Reservoir reaching its peak and other points, including Baijia Gully, hitting their lowest. Baijia Gully recorded the lowest pH value, at 7.04. Fluoride concentration monitoring results (Figure 5b) indicate that most levels were far below Class III standards, except for the Baijia Gully section in August 2019, where the fluoride levels were close to the upper limit of Class III standards. Dissolved total-solids pollution was relatively severe across the sections (Figure 5c), and these concentrations were generally higher in the autumn across various sections. Baijia Gully section was the most prominent, showing concentrations between 947 and 1586 mg/L, except for the August 2019 measurement, while all other measurements failed to meet Class III standards. Baijia Gully section also exhibited significant total hardness pollution (214–625 mg/L) (Figure 5d) and sulfate concentration pollution (300–621 mg/L) (Figure 5e), while these types of pollution were relatively less severe at other sections.

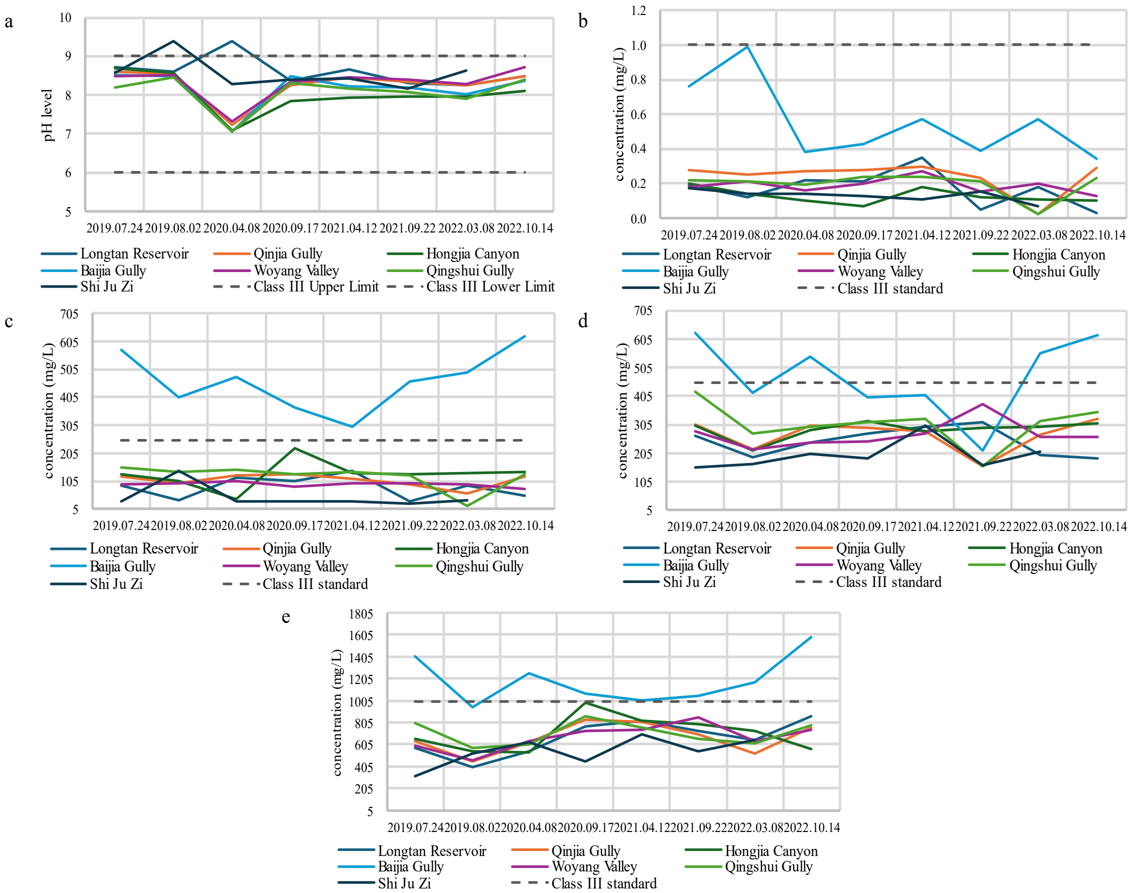

Figure 5. Water-quality trends of (**a**) pH Values; (**b**) Fluoride Concentration; (**c**) Total Dissolved Solid Concentration; (**d**) Total Hardness; and (**e**) Sulfate Concentration at different intake points.

3.3.2. Water-Quality Trend of Key Factor (TN) from 2020 to 2021

Based on the overall water-quality changes, further monitoring and analysis of Total Nitrogen (TN) concentrations were conducted from 2020 to 2021 (Figure 6). The results indicate that, except for the Hongjia Canyon section, most sections exhibited serious TN pollution, failing to meet the Class III water-quality standards set by the "Environmental Quality Standards for Surface Water" (GB3838-2002) [27]. The concentration of total nitrogen showed obvious differences between the different points, and the fluctuation was significant. The Qingshui Gully and Woyang Valley sections were particularly affected, with all measurements falling short of the Class III standards. In contrast, the Hongjia Canyon section showed relatively low TN pollution, meeting the Class III standards in all monitoring results except for June 2020.

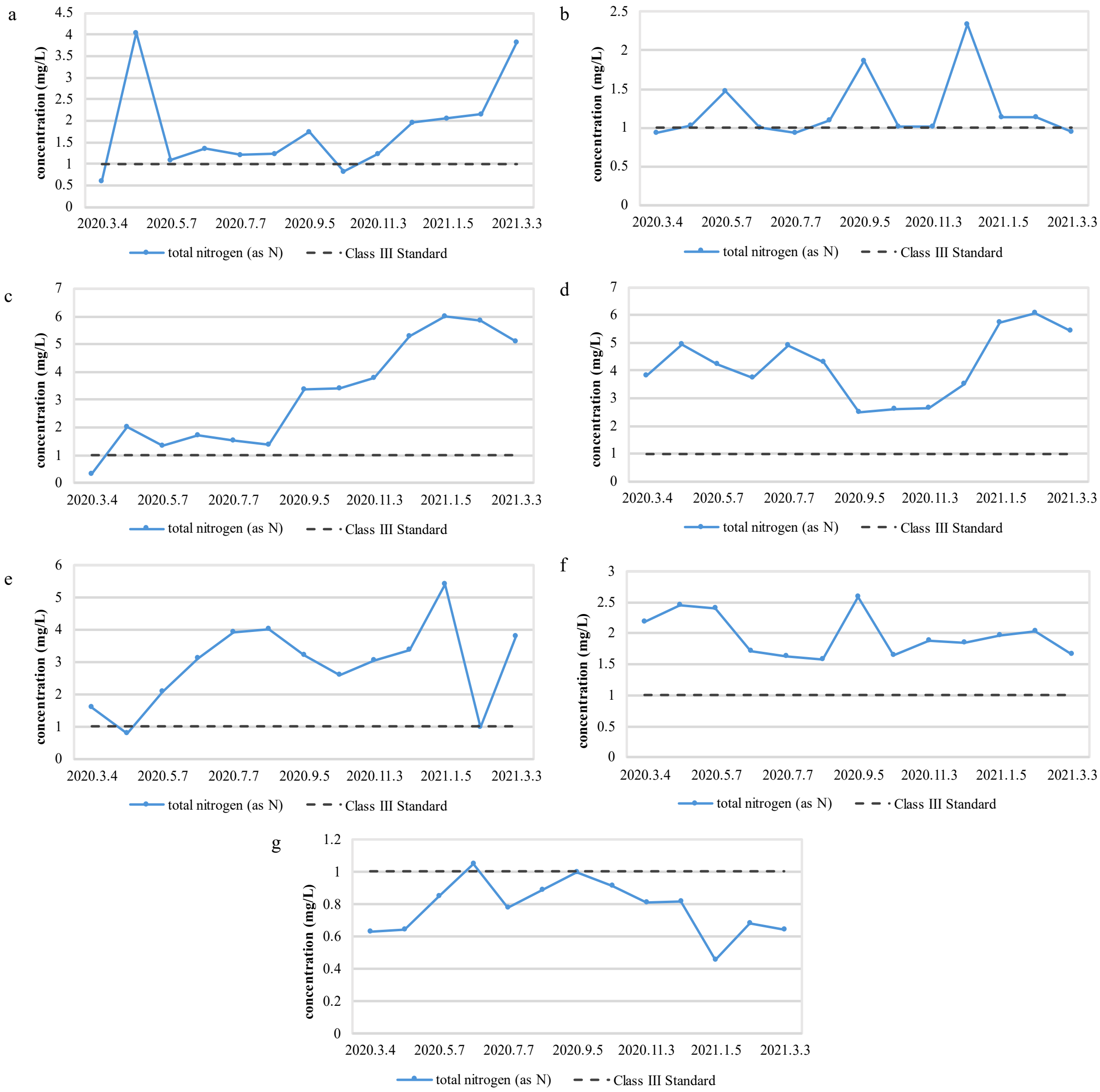

Figure 6. Water-quality trends of total nitrogen (as N) concentration at (**a**) Baijia Gully; (**b**) Longtan Reservoir; (**c**) Qinijia Gully; (**d**) Qingshui Gully; (**e**) Shi Ju Zi; (**f**) Woyang Valley; and (**g**) Hongjia Canyon.

3.4. Optimization Scheduling of the Water Supply System

3.4.1. Design Schemes

The water intake volume determined in the "Preliminary Design of Urban and Rural Drinking Water Safety Source Project 2012" was used as the baseline scheduling scheme. To address issues such as the widespread exceedance of Total Nitrogen (TN) concentrations at some intake points, an optimized scheme was designed by adjusting the water intake volume. The optimization schemes follow the principle of "more water diversion in wet season, less water diversion in normal season, and no water diversion, as far as possible, in dry season", and all intake points and reservoirs give priority to ensuring 10% ecological water quantity in the river and water demand outside the river. According to water-quality monitoring data, when the TN concentration at an intake point exceeds 3 mg/L, water intake at that point will cease, and its flow will be redistributed among other intake points to ensure the total diverted water volume remains unchanged (Optimization Scheme 1). If the TN concentration exceeds 2 mg/L, water intake at that point will cease (Optimization Scheme 2). Although the Class III standard for TN concentration is 1 mg/L, the threshold values of 2 mg/L and 3 mg/L are thought to be responsible for degradation of TN concentrations along the way.

The water intake volumes for the three design schemes are shown in Table 3.

Table 3. Optimization of water intake scheme (m^3/s).

Scheme	Month	Shi Ju Zi	Longtan Reservoir	Hongjia Canyon	Qinjia Gully	Baijia Gully	Qingshui Gully	Woyang Valley	Total
Baseline Scheme	1	28	74	8	42	7	11	5	175
	2	23	54	6	40	7	10	4	144
	3	26	65	7	48	8	13	5	171
	4	47	139	16	42	7	11	4	266
	5	56	195	18	40	6	11	20	345
	6	47	168	17	42	6	13	21	314
	7	59	266	29	66	8	28	35	492
	8	51	288	32	78	9	40	45	544
	9	51	278	33	90	10	52	55	568
	10	33	183	20	78	9	40	43	405
	11	36	142	20	72	10	28	20	327
	12	24	101	13	55	8	17	11	229
	total	481	1950	218	692	96	275	268	3980
Optimization Scheme 1	1	0	74	8	0	7	0	5	94
	2	23	54	6	0	7	0	4	94
	3	0	65	7	0	0	0	5	77
	4	68	139	16	53	0	0	4	280
	5	61	195	18	129	6	0	20	429
	6	0	168	17	119	6	0	21	571
	7	0	313	29	94	8	0	35	479
	8	0	376	32	109	9	0	45	571
	9	0	478	33	0	10	52	55	628
	10	33	271	20	0	9	40	43	416
	11	0	217	26	0	12	44	36	335
	12	0	214	13	0	8	0	11	246
	total	185	2564	225	504	82	136	284	3980
Optimization Scheme 2	1	0	74	8	0	0	0	5	87
	2	23	54	6	0	0	0	4	87
	3	0	65	7	0	0	0	17	89
	4	79	193	22	0	0	0	0	294
	5	68	195	18	131	13	0	0	425
	6	0	192	17	91	14	0	48	362
	7	0	353	34	131	13	0	53	584
	8	0	375	37	144	14	0	66	636
	9	0	539	58	0	13	0	0	610
	10	0	279	29	0	12	0	45	365
	11	0	219	26	0	13	0	36	294
	12	0	0	26	0	14	0	0	40
	total	170	2538	288	497	106	0	274	3980

3.4.2. Simulation Analysis of Scheduling Scheme

Zhongzhuang Reservoir Simulation Results Analysis

The annual Total Nitrogen (TN) concentration simulation results of different scheduling schemes for Zhongzhuang Reservoir are shown in Figure 7, and the monthly average TN concentration simulation results are presented in Table 4. Using the baseline scheduling scheme, the predicted TN concentration in Zhongzhuang Reservoir exceeded the Class III standard for 192 days, with a non-compliance rate of 52.89%. The baseline scheme simulation results display significant TN concentration peaks, particularly in January, September, and December.

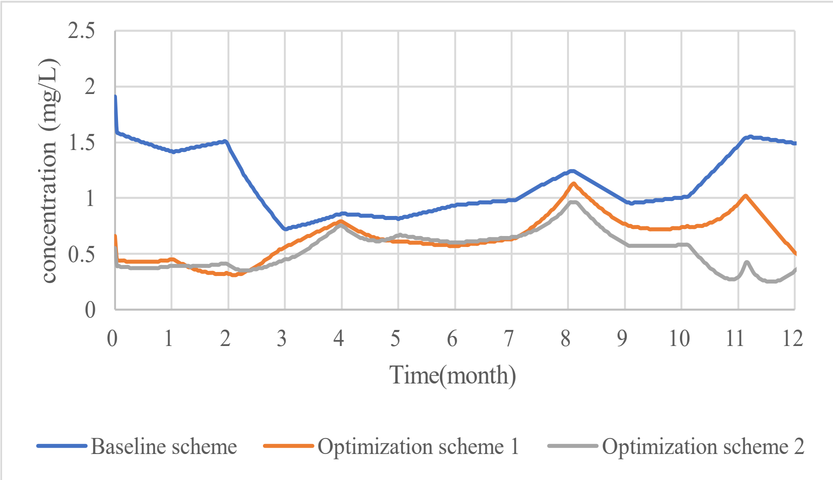

Figure 7. Annual total nitrogen (TN) concentration (mg/L): simulation results for Zhongzhuang Reservoir under different schemes.

Table 4. Monthly average total nitrogen (TN) concentration simulation result (mg/L) for Zhongzhuang Reservoir under different schemes.

Month	Baseline Scheme	Optimization Scheme 1	Optimization Scheme 2	Class Standard III
1	1.51	0.44	0.38	1
2	1.46	0.36	0.39	1
3	1.04	0.41	0.38	1
4	0.79	0.68	0.59	1
5	0.84	0.67	0.65	1
6	0.88	0.59	0.63	1
7	0.96	0.60	0.62	1
8	1.11	0.84	0.76	1
9	1.11	0.99	0.78	1
10	0.98	0.73	0.57	1
11	1.22	0.80	0.39	1
12	1.52	0.76	0.31	1

The simulation results of Optimization Schemes 1 and 2 indicate that by reasonably adjusting the intake volumes and water diversion month at the intake points, the TN concentration in Zhongzhuang Reservoir can be effectively reduced, leading to a more stable annual water quality. Particularly during the autumn and winter seasons, the annual predicted TN concentration shows a more noticeable decrease. Specifically, in Optimization Scheme 1, the annual TN concentration exhibited a noticeable downward trend, with February showing the most significant change, achieving a maximum reduction rate of 78.81%. The predicted maximum reduction rate reached 78.81%, and the monthly average concentration decreased from 1.46 mg/L to 0.36 mg/L, a difference of 1.1 mg/L. However, the reduction during the spring and summer seasons was minimal, with 21 days of TN concentration exceeding the standard in August and September, while the maximum exceedance concentration reached 1.19 mg/L. The average monthly TN concentration in September was 0.99 mg/L, slightly below the standard. In contrast, the average monthly TN concentration under Optimization Scheme 2 was only 0.76 mg/L in September. The predicted maximum annual reduction rate reached 83.66%, and all simulation results met the Class III standard. In critical months like October to December, Optimization Scheme 2 avoided significant TN concentration peaks. In December, the average monthly TN concentration was 0.31 mg/L under Scheme 2, compared to 1.52 mg/L under the baseline scheme. These lower concentrations in the autumn months help reduce the risk of water-quality deterioration during the dry season (January to March), ensuring better management of potential pollution peaks. Therefore, Optimization Scheme 2 is recommended for Zhongzhuang Reservoir to ensure compliance with water-quality standards and sustainable use of the water source.

Simulation Analysis of Water Diversion Tunnels

The simulated section location of the water diversion tunnel is shown in Figure 8. To understand the water-quality distribution along the water diversion system, a simulation analysis was conducted for the water transfer tunnels (Table 5). The simulation results for Optimization Scheme 1 indicate significant water-quality improvements in Tunnels 1, 4, 6, and 8. Compared to the baseline scheme, the number of days exceeding the standard in Tunnel 1 decreased from 317 to 135 days. In Tunnel 4, the exceedance days were reduced to 104, dropping the exceedance rate to 28.57%. For Tunnel 6, the exceedance days decreased to 131, with the rate falling to 35.99%. Tunnel 8, the most downstream, showed a substantial reduction to 46 exceedance days, lowering the rate to 12.64%. Further comparison of the simulation results for Optimization Scheme 2 reveals even more obvious improvements in Tunnels 1, 4, 6, and 8. In Tunnel 1, exceedance days were reduced to 83, with an exceedance rate of 22.80%. For Tunnel 4, the exceedance days dropped to 57, lowering the exceedance rate to 15.66%. In Tunnel 6, the exceedance days were reduced to 34, and the exceedance rate was 9.43%. Finally, in Tunnel 8, the exceedance days significantly decreased to 11, with an exceedance rate of only 3.02%. In summary, Optimization Scheme 1 and Optimization Scheme 2 demonstrated obvious advantages over the baseline scheme in improving water quality, with Optimization Scheme 2 maintaining much lower exceedance rates and demonstrating improvements which were remarkable and more stable.

Table 5. Simulation results for water intake tunnel.

Tunnel Number	Baseline Scheme		Optimization Scheme 1		Optimization Scheme 2	
	Exceedance Days	Exceedance Rate	Exceedance Days	Exceedance Rate	Exceedance Rate	Exceedance Rate
1	317	87.09%	135	37.09%	83	22.80%
4	347	95.33%	104	28.57%	57	15.66%
6	364	100%	131	35.99%	34	9.43%
8	282	77.47%	46	12.64%	11	3.02%

The annual simulation results of the cross-sections of the water diversion tunnels under different scheduling schemes are shown in Figure 9. Optimization Scheme 2 demonstrates a more stable degradation of total nitrogen (TN) along the route, leading to a consistent improvement in water quality. Both the baseline scheme and optimization Scheme 1 exhibit an increase in TN concentration along Tunnel 4, mainly due to the severely high TN concentrations from the Baijia Valley intake point. During October to December, these two schemes experienced water-quality deterioration and a surge in TN concentration, with consistently high TN peaks in September. Optimization Scheme 2 effectively addresses these issues by adjusting the water intake scheme, resulting in a more stable TN degradation along the route and significant improvement in water quality. Compared to the baseline scheme and Optimization Scheme 1, Optimization Scheme 2 achieved more noticeable reductions in TN concentration from upstream (Tunnel 1) to downstream (Tunnel 8) in October to December, indicating that early interventions effectively prevented high-TN water from entering the system, resulting in a more stable water quality across all tunnels. Starting from Tunnel 6 in September, the TN concentration peaks were significantly lower in Optimization Scheme 2. The average monthly TN concentration in September was reduced by 0.47 mg/L compared to the baseline scheme, whereas Optimization Scheme 1 only achieved a reduction of 0.21 mg/L. This indicates that Optimization Scheme 2's overall reduction strategy is robust, with cumulative effects becoming significant downstream. Even if some TN enters the system, it can be effectively managed and reduced as the water flows through each tunnel.

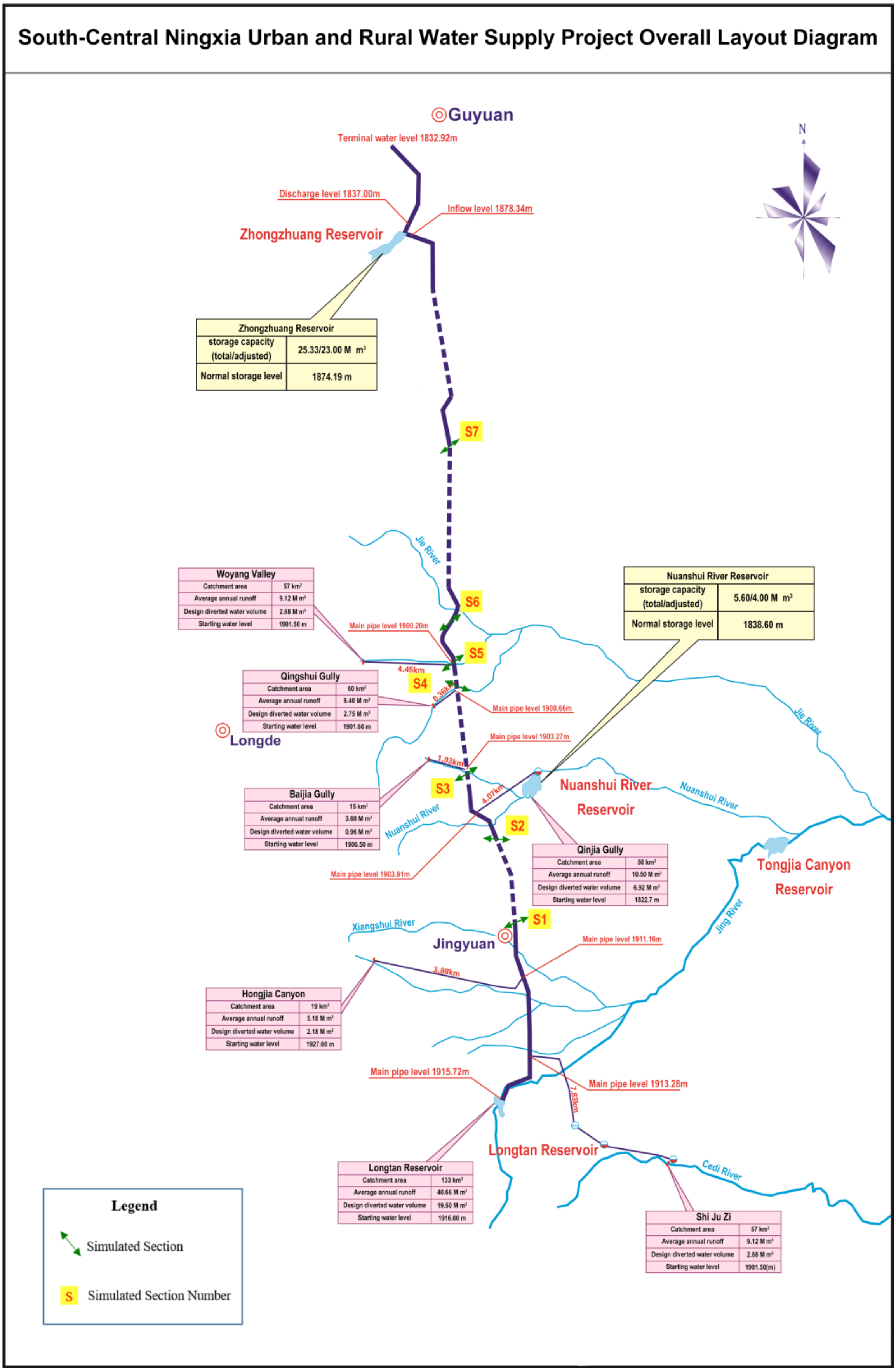

Figure 8. Simulated cross-section location of water intake tunnel.

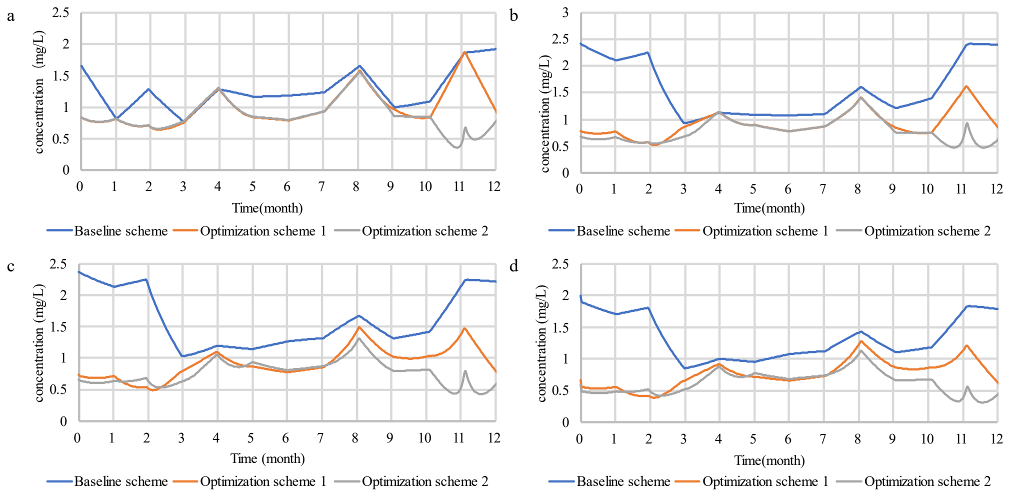

Figure 9. Simulation results for (**a**) No.1; (**b**) No.4; (**c**) No.6; and (**d**) No.8 intake tunnels under different schemes.

The key factors contributing to the superiority of Optimization Scheme 2 include strategic increases in water diversion during critical months and effective redistribution of water in high-TN areas. In August, the TN concentration in Qinjia Gully approached the Class III standard, and Optimization Scheme 2 increased the water diversion from Qinjia Gully (from 109 to 144 m3/s), coupled with a significant increase in diversion in September (from 568 to 628 m3/s). These measures ensured that low-N water diluted the TN concentration, helping to flush out accumulated pollutants and maintain better water quality. These actions ensured that TN levels remained low not only in August and September but also in the following months. This further proves the superiority of Optimization Scheme 2 over Scheme 1, indicating that Optimization Scheme 2 is more suitable as the final optimized scheme to ensure improved water quality and reliable scheduling effects.

In summary, Optimization Scheme 2 provides stable and consistent TN degradation, effectively solving the water-quality decline caused by excessive TN concentrations at the Baijia Valley intake point. However, this study focused solely on the optimization of total nitrogen, without addressing other water-quality indicators. While other indicators generally met quality standards, some monitoring points exhibited short-term exceedances. Future studies should comprehensively consider multiple indicators, including pH, total dissolved solids, and sulfates. Additionally, the improvements in water quality achieved by altering water transfer plans are temporary. Long-term solutions should involve proactive protection of the water source area to prevent water-quality issues from occurring at the source.

4. Conclusions

Using the South-Central Ningxia Urban and Rural Water Supply Project as a case study, this research employs the Storm Water Management Model to develop an optimized scheduling scheme based on water quantity and quality demand, following a thorough evaluation of the water quality at intake points and the water source. The main conclusions are as follows:

1. Water-Quality Evaluation of Intake Points: The results indicate that the overall water quality in the intake area is good, with most indicators meeting Class III water-quality standards. However, there are instances of excessive total nitrogen and sulfate levels, particularly in Baijia Valley, where sulfate and dissolved solids concentrations exceed the standards to a considerable extent. Therefore, further efforts are needed to enhance water environment management and governance.

2. Water-Quality Evaluation of Zhongzhuang Reservoir: The results show that the overall water quality of Zhongzhuang Reservoir is good, except for consistently high total nitrogen levels. Other monitored factors meet Class III water-quality standards. After water from the intake points mixes and degrades along the route, the total nitrogen concentration upon reaching Zhongzhuang Reservoir is close to the Class III standard.
3. Water-Quality Simulation Results: The simulation results reveal that using the design water intake volume specified in the "Preliminary Design of Urban and Rural Drinking Water Safety Source Project 2012," the predicted annual total nitrogen concentration in Zhongzhuang Reservoir exceeds the standards throughout the year, with an over-standard rate of up to 52.89%. After the optimization scheme was adopted, the annual predicted total nitrogen concentration in Zhongzhuang Reservoir significantly decreased, with the maximum reduction rate reaching 78.81% and all simulation results meeting the Class III standards of the "Environmental Quality Standards for Surface Water".

In conclusion, according to the "Technical guideline for delineating source water protection areas" (HJ 338-2018) [33], issued by theMinistry of Ecology and Environment of the People's Republic of China, it is essential to scientifically delineate each intake point and regulate reservoirs as water source protection areas and give them priority protection. Additionally, there is a need to strengthen environmental risk assessments for water sources, which includes screening potential risk sources and identifying potential risk types, as well as assessing their risk levels. Finally, a comprehensive water-quality monitoring and early warning system needs to be established, including regular patrols of water bodies within the protection areas and continuous water-quality monitoring to prevent pollution. Implementing these measures will likely enhance scientific management and scheduling and provide valuable insights for other regions, promoting the sustainable utilization of regional water resources.

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