Article

Joint Optimal Dispatch of Complex Urban Raw Water Supply: A Case Study of Lanxi City, Zhejiang Province, China

Lingjie Li, Leizhi Wang, Xuan Gao, Xin Su, Yintang Wang and Rui Gao

Abstract: Water resources play a vital role in supporting urban economic and social development and ecological and environmental protection. Water shortage is a key factor that restricts the high-quality development of cities, while the coordinated and optimized allocation of urban raw water is an important measure to alleviate the water supply–demand imbalance. The current research on urban water supply issues and their underlying causes still needs to be further strengthened. Similarly, the formulation of rules for multi-source and cross-district water supply should pay more attention. This paper proposes a general analytical process consisting of four main stages: problem identification, system generalization, rule formulation, and model construction and solution for the joint optimal scheduling of raw water in a complex urban water supply system. This study investigates the significant water resource wastage and structural water shortage in the reservoirs of Lanxi City. The optimal scheduling plan is proposed by formulating rational rules for inter-area water supply and establishing a multi-source and multi-objective joint optimization scheduling model. Compared to the current independent scheduling scheme and multi-water source joint dispatching scheme based on the current dispatch diagram, the optimal scheduling plan effectively reduced the cumulative water shortage by 68.04 million m$^3$ and 29.72 million m$^3$, respectively, and increased the urban water supply guarantee rate in all districts of the city to over 90%. This study offers valuable insights to urban water resource managers, empowering them to develop optimal multiple water source supply rules that align to the specific characteristics of other case studies.

Keywords: urban raw water; multi-water source joint dispatching scheme; inter-area water supply regulation; reservoir scheduling diagram

1. Introduction

Water resources play a crucial role in ensuring the effective functioning of cities. With accelerated climate change, urbanization, and the increment of urban population, the demand for water in urban systems is constantly increasing for daily life, production, and ecological purposes. The contradiction between the supply and demand of water resources for many cities is gradually becoming evident [1]. To ensure the safety of urban water supply, it is crucial to implement a range of strategies, including strengthening water conservation [2], exploiting the potential of local water sources, utilizing water diversion [3], and optimizing collaborative scheduling [4]. These measures will enhance the support capacity of water resource elements for economic and social development.

The urban water supply system comprises raw water sources, water treatment facilities, and transmission facilities with complex hydraulic connections [5]. Raw water refers to the water resources provided by natural water, such as reservoirs, rivers, and lakes, which are located at the beginning of the water supply chain. The raw water is transported to...
the water treatment plant through tunnels and pumping stations. After purification treatment, the water is distributed to end-users through the municipal water supply network. Water sources in various cities exhibit diverse spatial distribution patterns influenced by geographical and climatic conditions. Water resource conditions exhibit uneven temporal and spatial distribution [6]. Furthermore, numerous cities encounter structural challenges, such as inadequate local water supply capacity or subpar water quality, that fail to meet the water demand. Therefore, these cities have implemented inter-basin and regional water diversion projects [7,8]. For example, cities such as Beijing and Tianjin utilize the South–North Water Diversion Project to transport water resources [9]. These projects have become important supplementary sources for urban water supply systems and, in some cases, have even assumed a leading role, further complicating the raw water system. Moreover, water-stressed cities have integrated unconventional water resources such as recycled water and desalinated seawater into their urban water supply systems, along with the implementation of diverse water supply schemes [10–12]. In a context characterized by increasing water source diversity, spatial dispersion, varying spatiotemporal distribution patterns, and a stronger focus on water users, the optimization of raw water allocation and adjustment of water resource distribution in time and space to meet the water demand of different areas in the city poses a highly complex scientific problem.

Scholars have recently conducted studies on joint optimal scheduling concerning multiple water sources and objectives. Roozbahani et al., developed a water resources optimization configuration model encompassing five objectives while simultaneously considering social, economic, and ecological benefits, validated in Iran’s Sefidrud basin, demonstrating its rationality and feasibility [13]. To address the challenge of multi-reservoir scheduling in inter-basin water transfer projects, Guo et al., proposed a bi-level model that can simultaneously consider water transfer and water supply. The first-level solver is used to optimize the rule curve for water allocation to achieve a spatial allocation of water resources across river basins, while the second-level solver determines the optimal water supply quantity by optimizing the hedging rule curve [14]. Liu et al., investigated the water supply issue in the Sanjiang Plain of China using a two-stage regional allocation model. The researchers addressed the optimal allocation scheme for multiple water sources, such as surface water, groundwater, and transboundary water, to supply water resources to the residential, agricultural, and industrial sectors during various hydrological years [15]. Yu et al., constructed a three-layer water supply system network topology of “water source–water plant–zoned users” by analyzing the network topology of the system and established the optimal scheduling of the urban water supply system by considering the two scheduling objectives of social benefit and water supply cost of the whole water supply system [16]. Zhang et al., focused on the primary control nodes and pipelines within the water network topology, developed a sophisticated water resource allocation model, and applied it to the allocation of water resources in Tianjin City in 2020 [17]. Ji et al., proposed a two-stage stochastic programming model considering uncertainty to investigate the impact of future water demand in Tianjin by generating a series of representative scenarios. The research findings revealed the impacts of different scenarios on water allocation patterns, water scarcity, overall benefits, and the cost of water supply systems [18]. Zhang et al., developed a refined water allocation model with different frequencies of encounter probabilities and multiple water sources. Additionally, a quantitative analysis to investigate the correlation between the uncertainty of water inflow from multiple sources and the regional water security rate was conducted using Tianjin as a case [19]. Song et al., conducted a systematic review of the changing trends of optimizing urban multi-source water supply and explored the possible reasons behind these trends. They summarized the modeling methods for the optimal allocation scheme, which included defining topology relationships, constructing mathematical models, solving for the optimal solution, and finally, discussing current emerging challenges [20].

The generalization model of the urban water supply system, based on previous studies, which categorizes the system into three levels of water source, water plant, and users, has
been widely recognized by scholars and adopted as a standard practice. The core content of most research mainly focuses on exploring the objective function, constraints, and solution methods [16–20]. However, it is important to note that each city has unique water resource conditions and faces distinct water scarcity issues, which vary in their manifestations and underlying causes. Therefore, to successfully implement joint scheduling, it is crucial to precisely identify the current challenges associated with water resource allocation and scheduling. Previous studies have provided a limited exploration of the principles governing coordination and collaboration among various water sources (local reservoirs, rivers, imported water, etc.). Moreover, it is essential to prioritize the development of inter-district water supply infrastructure and establish standardized regulations to improve the overall efficiency of water supply systems. Moreover, current research primarily emphasizes the optimization of typical annual water supply schemes, making it challenging to simultaneously consider the requirements of a guaranteed rate. Hence, performing simulation scheduling analysis using long time series data to evaluate the stability and effectiveness of the solution is highly significant.

Therefore, this paper presents novel ideas and methods for optimizing the scheduling of urban raw water based on previous studies. This paper preliminarily discusses issues, including identifying urban water supply problems and establishing water supply regulations across different districts. This study focuses on the city of Lanzhou in Zhejiang Province, China, as the research object and establishes a multi-source and multi-objective joint optimization scheduling model. The study utilizes long time series data for simulation and scheduling research to analyze the impact of joint optimization scheduling measures on the benefits of water supply. The paper is structured as follows: Section 2 introduces the general process of optimizing the dispatching of urban raw water. Taking Lanzhou City as a case study, we establish a mathematical model for the joint optimization scheduling of multiple sources. In Section 3, the rationality of the optimal scheme is analyzed from two perspectives: the optimized scheduling diagram of the main water supply reservoir and the long-term simulation of the water supply process in each water supply zone. Next, the optimal plan is compared with the existing schemes. Section 4 is the conclusion.

2. Materials and Methods
2.1. General Process of Optimal Dispatching of Urban Raw Water

Urban raw water refers to water resources sourced from reservoirs, rivers, lakes, and ponds and supplied to the economic and social systems. These water resources must be purified through facilities such as water plants and transported to users through pipeline networks to meet specific water quality requirements. The urban raw water supply system encompasses a multitude of water sources with complex spatial distribution and intricate hydraulic connections. The study of optimal urban raw water scheduling often involves using abstract models of water plants and pipe networks. These systems’ water production and transportation capacities are constraint conditions, considering the potential water loss during transmission. The goal is to optimize raw water’s spatial and temporal scheduling, ensuring an adequate supply to meet the users’ demand. This paper proposes general ideas and methods for optimal scheduling of urban raw water systems from four aspects: problem identification, system generalization, rule formulation, and model construction and solution.

(1) Problem identification. Identifying the issues with the existing raw water scheduling system is the fundamental work for optimization scheduling. From this perspective, we can analyze multiple factors, including the spatial distribution of the water source and its alignment with water demand, the compatibility of incoming water conditions with reservoir storage capacity, the severity of water shortage in key areas, and the status of water supply assurance. If the aforementioned problems exist, measures such as scheduling multiple water sources and implementing cross-area water replenishment and regulation can be considered.
(2) System generalization. By conducting investigations to understand the spatial distribution and connections between the raw water source, water treatment plants, distribution networks, and users, we can merge smaller water supply zones into several larger zones based on the characteristics of the service scope of the treatment plants and distribution networks and establish a one-to-many connection relationship between the raw water source and the supply zones. This study aims to analyze the feasibility of providing water supply to other districts by integrating the variations in urban topography and the connectivity of the pipeline network to construct a water supply topology network consisting of raw water sources and water supply zones.

(3) Rule formulation. Considering the issues in the current water supply system and the water supply topological network diagram, it is feasible to effectively improve the localized or overall water supply regulations, primarily including the water supply sequence and scheduling diagram, etc. If only a few regions are experiencing water shortage issues, the emphasis should be on optimizing water supply regulations tailored to those regions. If the issue remains unresolved, introducing cross-zone water supply regulations could be considered. When faced with a significant water shortage in the infrastructure, where the capacity of the water sources is inadequate, it becomes imperative to explore additional resources from other territories and establish a comprehensive joint scheduling mechanism. Additionally, it is crucial to systematically optimize the regulations governing multiple water sources.

(4) Model construction and solution formulation. The objective function should comprehensively consider the minimum water shortage of the entire city, the maximum partition guarantee rate, and the minimum reservoir wastewater discharges to balance the supply level, guarantee, and waste of resources. When considering the capacity constraints of water treatment plants and distribution networks, it is necessary to consider them. If cross-regional water supply regulations are implemented, it is necessary to carefully consider the constraints on the water balance. Accurately defining the specific content of decision variables is imperative for solving the problem. When considering the scheduling scheme for a specific year as the central component, the decision variables consist of the monthly water supply for each water source. When considering the scheduling rules as the foundation, it encompasses the sequencing of water supply and the scheduling chart for reservoirs and other water sources. The widely used multi-objective intelligent solution method that can be used includes NSGA-II [21], NSGA-III [22], MOEA/D (Multi-Objective Particle Swarm Optimization) [23], LMPSO (large-scale many-objective particle swarm optimizer) [24], etc. When choosing a method, it is necessary to consider the number of objective functions and decision variables while striking a balance between efficiency and accuracy.

2.2. Study Area and Data

2.2.1. Study Area

Lanxi City is located in the central-western part of Zhejiang Province, China, in the middle reach of the Qiantang River (Figure 1). The geographical range of the region is approximately from 29°5′20″ N to 29°27′30″ N and from 119°13′30″ E to 119°53′50″ E, with a total area of about 1312 km². The topography and geomorphology of the city are as follows: the Qu River flows in an east–west direction, while the Jinhua (JH) River flows in a north–south direction. These two rivers converge in the city’s southwest region to form the Lan River. Lan River divides the city into three parts: east, south, and northwest. Mountains surround the northeastern part, the southwestern part consists of continuous low hills, and the central part is a flat plain. Lanxi City is in the East Asian subtropical monsoon region, characterized by specific climate and hydrological conditions. The city experiences an average annual precipitation of 1470.4 mm and has an average annual surface water resource of 1.057 billion m³. The region is susceptible to floods and droughts, during the rainy and dry seasons, respectively. Lanxi City has 13 townships under its jurisdiction.
Based on the Statistical Bulletin on the National Economic and Social Development of Lanxi City in 2020 (http://www.lanxi.gov.cn/art/2022/5/26/art_1229637868_59255100.html, accessed on 5 July 2023), the resident population reached 574,800, the urbanization rate reached 55.4%, and the annual GDP was 40.016 billion yuan.

![Figure 1. Distribution of ground observation stations and reservoirs in Lanxi City.](https://dwtkns.com/strm30m/) (accessed on 5 July 2023). The boundary of China and Lanxi City is obtained from http://bzdt.ch.mnr.gov.cn/).

Lanxi City is located in a water-abundant region in southern China. However, it has consistently encountered the challenge of managing structural imbalances between water supply and demand. From the supply side, although the transboundary water resources are abundant, they are mainly in the form of floods and cannot be effectively utilized. The availability of high-quality water resources in the local area is limited, and their distribution is uneven throughout the year. Reservoirs, such as Zhiyan (ZY), Qiantanglong (QTL), and Chengtou (CT) reservoirs, are important engineering measures to redistribute the temporal distribution of high-quality water. However, spatial variations in the regulation performance of different reservoirs do not align with the actual water inflow. For instance, reservoirs are encountering a significant challenge of excessive water discharge caused by their insufficient regulation capacity. Lanxi City has established a multi-source water supply system consisting of reservoirs, Lan River, and water diversion from the JH City. The major reservoirs comprise ZY reservoir, Shangwang (SW) reservoir, QTL reservoir, and CT reservoir. The urban waterworks include ZY, QTL, and CT waterworks. Although the exchange of river water between the Lan River and the introduction of high-quality water from outside the region have increased the supply capacity of high-quality water, it remains challenging to effectively address the issue of water resource supply and demand imbalance. In this context, addressing the uneven temporal distribution of high-quality water and the spatial differences in reservoir regulation capacity, implementing joint scheduling of water supply reservoir groups, and strengthening the collaborative regulation of local reservoirs with JH water diversion and Lan River have emerged as key challenges in the current raw water allocation.

### 2.2.2. Data

The basic data utilized in this paper comprise three categories of parameters: social and economic, meteorological and hydrological, and characteristics of water supply engineering.
(1) Socio-economic data. Based on statistical yearbooks and bulletins (http://www.lanxi.gov.cn/col/col1229637865/, accessed on 5 July 2023), we have collected significant data points, including permanent population, urbanization rate, GDP, and proportions of industrial structures across different towns and streets. We have also collected data from the seventh national population census of Lanxi City.

(2) Meteorological and hydrological data. Precipitation, evaporation, and runoff data were collected from meteorological stations, rainfall stations, and hydrological stations in and around Lanxi City. The data were obtained from hydrological almanacs and the China Meteorological Data Network (http://data.cma.cn/) (Figure 1). The reservoir management department obtained the incoming runoff data of the ZY, QTL, and CT reservoirs. The data’s basic information is shown in Table 1. The remaining three reservoirs have strong regulating capacity except for the SW reservoir. The dispatch cycle starts at the beginning of the flood season and ends at the end of the dry season. Given that the flood season in Lanxi City is from 15 April to 15 October, this study restruc- tures the runoff sequence by organizing the monthly runoff data spanning from 1960 to 2020 (a total of 61 years), covering the period from April to March of the following year. Figure 2 presents the three reservoirs’ average annual runoff volumes and intra-annual distribution processes. The charts show that the inflow distribution patterns of different reservoirs exhibit a similar pattern, which can be described as a temporal sequence of increasing, decreasing, and then increasing again. Specifically, the highest consecutive four months are concentrated between March and June, with the cumulative inflow accounting for 56.9% to 64.1% and the peak occurring in June. There are variations in the distribution of the lowest four consecutive months among different reservoirs, primarily between August and January of the following year. The cumulative inflow percentage ranges from 10.3% to 16.6%.

(3) Water supply project. We collected the characteristic parameters and the water level–area–capacity curves of the ZY, SW, QTL, and CT reservoirs. We obtained the water supply capacity data for ZY, QTL, and CT waterworks, as well as the JH district.

Table 1. Basic information of precipitation, evaporation, and runoff data in Lanxi City.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Gauge Name</th>
<th>Type</th>
<th>Length of Series</th>
<th>Temporal Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>Shangbao; Zhuge; Yanggang; Lanxi; Majian; Baijiu; Xinzhai; Yangzheng; Sanhe Jiandel; Longyou; Jinhua; Pujiang</td>
<td>Rain gauge</td>
<td>1960–2021</td>
<td>Month</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weather station</td>
<td>1960–2021</td>
<td>Month</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Lanxi</td>
<td>Weather station</td>
<td>1960–2021</td>
<td>Month</td>
</tr>
<tr>
<td>Runoff</td>
<td>Zhiyan (ZY); Shangwang (SW); Qiantanglong (QTL); Chengtou (CT)</td>
<td>Reservoir</td>
<td>1960–2021</td>
<td>Month</td>
</tr>
</tbody>
</table>

Figure 2. Average annual runoff and intra-annual distribution of ZY, SW, and CT reservoirs.
2.3. Model Construction and Solution Method of Lanxi City

2.3.1. Generalization of Water Supply System

This paper aims to conduct a comprehensive study on the joint operation of the water supply system in Lanxi City, aiming to meet the projected water demand by 2025. Based on the current water supply system, the construction of the DS waterworks is planned to be completed and operationalized by 2025. The waterworks will extract water from the Lan River, which is expected to have slightly inferior water quality compared to the reservoir. The water supply capacity will reach 80,000 m\(^3\)/d. Considering the waterworks and pipeline service scope, we have classified the thirteen townships in Lanxi City into four water supply districts: ZY, QTL, JH, and CT. The water supply system primarily serves as a comprehensive domestic and industrial sectors. The total integrated domestic water usage encompasses residential water consumption, water usage in the construction industry, tertiary industry, and ecological environment. Industrial water demand can be classified into two categories based on the difference in water sources: industrial water supplied by pipeline networks and general industrial water (excluding circulating water used by thermal power enterprises). The term “pipe network industry” refers to the industrial sector supplied with water from the municipal pipe network, while “general industry” refers to the industrial sector supplied with water from DS waterworks, which do not have high requirements for water quality.

The water supply source, water supply waterworks, and water supply districts are as follows, and the spatial relationship is shown in Figure 3. ZY waterworks and DS waterworks supply the ZY district. QTL waterworks mainly supply the QTL district; the JH district is supplied by JH water diversion; and waterworks supply the CT district. A complementary relationship exists between the ZY, QTL, and JH districts. Furthermore, the CT reservoir alone plays a minor role in agricultural irrigation, as irrigation in other areas primarily depends on ponds and rivers, which is outside the scope of this study. To fulfill the ecological water requirements in the river channel, the ZY reservoir releases 10,000 m\(^3\) of water into the downstream river channel daily. However, the inflow from the QTL reservoir and the CT reservoir’s tributaries are sufficient to meet the ecological base flow requirements, eliminating the need for separate consideration of supplying ecological water to the river channel.

Figure 3. Distribution of water sources, waterworks, and water supply districts in the Lanxi City of 2025.

2.3.2. Joint Dispatching Rules of Water Supply System

(1) Sequence of water supply for different users

This article examines the pipe network’s combined residential and industrial water demand in the context of urban water supply. Both are supplied through the municipal
pipe network, as it is difficult to distinguish between them. Meeting the water needs of cities in this region is essential. Subsequently, the water demand across different areas should be considered sequentially for water supply. Lastly, the ZY reservoir also plays a crucial role in meeting the ecological water demand of the downstream river, while the CT reservoir also serves as an important source of agricultural irrigation water supply.

(2) Multi-source water supply regulations and cross-district water supply regulations

Based on the general urban raw water joint dispatching analysis process, Lanxi City mainly solves the problem of the coexistence of water abandonment and water shortage in QTL reservoir. The mismatch between the regulation capacity of reservoirs and the variability of water inflow mainly causes water abandonment. Based on this, concerning the water supply system in 2025, the ZY, QTL, and JH districts will fully utilize the JH diversion. Simultaneously, they will also consider the coordinated regulation between the ZY reservoir and SW reservoir as well as between the ZY reservoir and QTL reservoir. The objective is to maximize storage capacity utilization in various reservoirs by implementing a joint water supply schedule among three partitions, which will effectively address the issue of excessive abandoned water volume in the QTL reservoir. Considering the limited regulation capacity of the SW reservoir, we have chosen to employ a combination of qualitative and joint dispatching rules. Stages I and II prioritize supplying water to the SW reservoir, followed by the ZY reservoir. In Stage III, we supply water in the reverse order. This scheduling method optimizes the utilization of surplus water in the reservoir during the flood season, bolstering the region’s capacity to withstand droughts. The joint operation of the ZY and QTL reservoirs is based on the operation chart. Based on the long-term average annual hydrograph distribution patterns of ZY and QTL reservoirs, these reservoirs can be categorized into three stages: March to July, August to October, and November to February of the subsequent year.

Stage I: From March to July

Regarding the QTL district, the QTL reservoir will provide water supply at its maximum capacity. Excess water resources in this area will be allocated to the ZY district. Regarding the ZY district, the first step should be to fully utilize the remaining water capacity of the JH and QTL districts. Therefore, it is important to consider supplementing the water supply from the SW reservoir. The water supply from the ZY reservoir should only be considered after exploring all of these options. It is worth noting that the DS waterworks supplies the general industrial water in this area. Meeting the water demands of the JH district will be our top priority. We will supply water to the ZY waterworks if there are excess water resources. If an unforeseen circumstance leads to the suspension of water diversion in JH, the QTL waterworks and ZY waterworks will provide our water supply. The water supply for the CT area primarily depends on the CT reservoir.

Stage II: From August to October

QTL waterworks will supply water to the QTL district according to its demand. If there is a water shortage in this area, it will be supplemented by a cross-district water supply from ZY waterworks. Given the ZY waterworks, we should first prioritize using the surplus water from the JH district. Secondly, we should rely on the SW reservoir for replenishment and only then consider the water supply from the ZY reservoir. The JH and CT district regulations are the same as Stage I.

Stage III: From November to February of the following year

The rules for the QTL district are the same as Stage II. In the ZY district, priority will be given to utilizing excess water from the JH district, followed by the water supply from the ZY reservoir. If there is a shortage of water supply, it will be supplemented by the SW reservoir. The JH and CT districts’ regulations are identical to those of Stage I.

(3) Establishing the reservoir scheduling diagram. The reservoir scheduling diagram is an important basis for water supply in various regions. Currently, ZY, QTL, and
CT reservoirs have their scheduling diagrams, but joint scheduling with the neighboring SW reservoir has yet to be considered. Furthermore, considering the substantial shifts in water demand across economic and social sectors, it becomes imperative to redesign a reservoir operation schedule that caters to coordinated scheduling needs. Based on the priority order of water supply tasks and water use objects [25,26], we can determine the relative order of the lines in the dispatch graph as follows: the upper limit of operating water level (including normal water storage level and flood control water level), agricultural restricted or ecological restricted water supply line, urban restricted water supply line, and dead water level. Furthermore, we suggest implementing a two-tier urban restricted water supply system to enhance the effectiveness of urban water supply scheduling. The first level corresponds to a relatively mild drought situation, whereas the second level corresponds to a more severe drought situation, with varying reduction ratios for water supply. The water supply for the ZY, QTL, and CT reservoirs will be regulated based on the following scheduling guidelines (Figure 4).

**Figure 4.** The predefined schematic diagrams of reservoir operation rules.

The hourly water supply regulations for ZY reservoir are as follows: During each period $t$, if the water level at the beginning of the period $Z_i$ is higher than the ecological restriction water supply line, both ecological and urban water demand will be fully supplied; if there is a gap in QTL district, the smaller value between the shortfall and the remaining available water in the reservoir (i.e., the water volume above the dead storage level) will be used for supplementation. If the water level at the beginning of the period $Z_i$ is lower than the ecological water supply limit but higher than the urban first-level water supply limit, the urban water demand will be supplied on demand, while the ecological water demand will be supplied after adjustment according to the limiting factor $\alpha$. If there is a water supply gap in the QTL district, the smaller value between the gap and the remaining available water supply in the reservoir will be supplemented. If the water level at the beginning of the period $Z_i$ is lower than the water supply line of the first urban level, urban water demand will be supplied following the restriction coefficient $\beta_1$, and at the same time, ecological water supply and inter-area water supply will be stopped. If the water level at the beginning of the period $Z_i$ is below the secondary limit supply line for the city, the urban water demand will be adjusted and supplied based on the restriction factor $\beta_2$.

The hourly water supply rules of the QTL reservoir are divided into three stages: In Stage I, if the initial water level $Z_i$ is higher than the urban first-level restricted water supply
line, the water supply will be provided at total capacity based on the water supply capacity of QTL waterworks, and ZY waterworks will supply the excess water demand of the area. During Stage II and Stage III, if the initial water level $Z_t$ is higher than the urban first-level restricted water supply line, then the water will be supplied according to the demand of the area; if the initial water level $Z_t$ is lower than the first urban water supply limit line, then the urban water demand will be supplied according to the restriction coefficient $\beta_1$ after narrowing down, and the inter-area water supply will be stopped; if the initial water level $Z_t$ is lower than the second urban water supply limit line, then the urban water demand will be supplied according to the restriction coefficient $\beta_2$ after narrowing down, and the inter-area water supply will be stopped.

The hourly water supply rules for CT reservoir are as follows: During time period $t$, if the initial water level $Z_t$ is higher than the agricultural restriction water supply line, both agricultural and urban water demands will be met as needed. Suppose the initial water level $Z_t$ is lower than the agricultural restriction water supply line but higher than the urban primary restriction water supply line. In that case, the urban water demand will be met as needed, and the agricultural water supply will be based on the restriction coefficient $\gamma_1$. If the initial water level $Z_t$ is lower than the urban primary restriction water supply line, the urban water demand will be reduced based on the restriction coefficient $\beta_1$, and the agricultural water supply will be reduced based on the restriction coefficient $\gamma_2$. If the initial water level $Z_t$ is lower than the urban secondary restriction water supply line, the urban water demand will be reduced based on the restriction coefficient $\beta_2$, and the agricultural water supply will be stopped.

### 2.3.3. Objective Function and Constraints

The objective of this study is to develop a mathematical model using the “simulation-optimization” technique to optimize the scheduling of multiple water sources in Lanxi City. In this context, “simulation” refers to the long-term simulation scheduling of a multi-source joint water supply system, while “optimization” refers to optimizing each constrained water supply line in the reservoir scheduling diagram.

#### (1) Objective function

Three objective functions have been defined to encompass the entire city and individual districts based on water shortage, guarantee rate, and reservoir water abandonment considerations. We set the total water shortage of all periods in the city as the first objective function $F_1$, the minimum guarantee rate of urban water supply in each partition as the second objective function $F_2$, and the total amount of water wasted from the main water reservoirs as the third objective function $F_3$.

(i) The total water deficit of the city is minimized. Considering $M$ scheduling periods, $N$ zoning districts, and the water deficit matrix being denoted as $L$, there are

$$ F_1 = \min(\sum_{j=1}^{M} \sum_{i=1}^{N} L_{ij}) \quad (1) $$

(ii) The minimum value of the guaranteed rate of urban water supply in each sub-district is maximized. Remember that the guaranteed rate of urban water supply in each sub-district is denoted as $P_1, P_2, \ldots, P_N$, then there are

$$ F_2 = \max(\min(P_1, \cdots, P_N)) \quad (2) $$

(iii) Reservoirs with the smallest amount of abandoned water. Statistics on the sum of water discarded from Chiyan reservoir ($A_1$), Chiantang Ridge reservoir ($A_2$), and Chengtou reservoir ($A_3$).

$$ F_3 = \min(\sum_{i=1}^{M} A_i) \quad (3) $$
(2) Decision variables

The decision variables consist of the water level values on each ZY, QTL, and CT reservoir scheduling diagram control line. To optimize the transition of each schedule line over two consecutive months, it is important to consider that increasing the scale of the decision variables will make the model more challenging to solve. Therefore, due to the consistent water demand process in the cities in the three reservoir zones, decision variables can be simplified in stages by considering the distribution pattern of inflow. The study is divided into three stages: March to July, August to October, and November to February of next year. In total, 24 decision variables are being considered. The coefficients of urban water supply limitation $\beta_1$ and $\beta_2$ are 0.9 and 0.5, the coefficient of ecological water supply limitation $\alpha$ is 0.5, and the coefficients of agricultural water supply limitation $\gamma_1$ and $\gamma_2$ are 0.7 and 0.5.

(3) Constraints

1. Water balance constraints.

$$V_{t+1} = V_t + I_t - L_t - (O_{1t} + O_{2t} + O_{3t}) - ZQ_t - A_t$$

where $V_t$ is the amount of water stored in the reservoir at the beginning and end of month $t$, respectively. It is the amount of water entering the reservoir. $L_t$ is the amount of water lost through evaporation and seepage from the reservoir. The amount of water supply (WS) for urban, ecological, and agricultural irrigation, respectively. ZY reservoir is related to ecological WS, and CT reservoir is related to agricultural irrigation WS. $ZQ_t$ is the amount of WS across the area; for ZY reservoir, it is the amount of WS to QTL waterworks; for QTL reservoir, it is the amount of WS to ZY reservoir. This is the amount of water discarded from the reservoir.

2. Reservoir capacity constraints.

$$V_{t,\text{min}} \leq V_t \leq V_{t,\text{max}}$$

where $V_{t,\text{min}}$ indicates the lower limit of reservoir capacity in month $t$, i.e., dead storage capacity. $V_{t,\text{max}}$ indicates the upper limit of reservoir capacity in month $t$. The flood limit levels of ZY, QTL, and CT reservoirs are the same as the normal storage levels.

3. Water supply capacity constraints.

$$M_{i,t} \leq M_{i,\text{max}}$$

where $i = 1, 2, 3, 4$, denotes ZY waterworks, QTL waterworks, CT waterworks, and JH water diversion, respectively. $M_{i,t}$ denotes the water supply quantity of the $i$th water plant or JH district in the $t$th time period. $M_{i,\text{max}}$ denotes the water supply capacity. The water supply capacities of the three water plants are 100,000 m$^3$/d, 40,000 m$^3$/d, and 18,700 m$^3$/d. The capacity of JH water diversion is related to JH City and the storage status of the ZY reservoir. If the monthly precipitation of JH City is higher than 40% of the multi-year average, and if the water level of the ZY reservoir does not reach the normal storage level, water will be diverted from JH water diversions according to 27,400 m$^3$/d, and if the ZY reservoir reaches the normal storage level, water will be diverted from JH according to 20,000 m$^3$/d. If the monthly precipitation of JH City is 60–80% less than the average of many years, a yellow warning will be activated, and water will be diverted from JH water diversion under 20,000 m$^3$/d. If the monthly precipitation is more than 80% less than the average of many years, the orange warning will be activated, and water diversion from JH will be stopped.

4. Decision variable constraints. In a given month, the water level value of each dispatch line should meet the requirements of the agricultural or ecological restricted water supply line > urban primary restricted water supply line > urban secondary restricted water supply line. Additionally, the decision variables must satisfy non-negativity constraints.
2.3.4. Multi-Objective Optimization Solution

The model construction involves dividing the simulation scheduling periods and collecting the inflow and water demand data, as illustrated below:

(1) Simulation of scheduling hours

The long-term simulation is conducted monthly, wherein each scheduling period spans from April to March of the subsequent year. The simulation period extends from April 1960 to March 2021, totaling 732 months.

(2) Runoff into reservoirs and water demand data

The input data for our model consist of the inflow discharge data obtained from various reservoirs, spanning from April 1960 to March 2021. No inflow data were recorded for the SW reservoir; therefore, it is necessary to reconstruct it using hydrological simulation methods. The study employs long-term collected precipitation, evaporation, and inflow runoff data from the ZY reservoir to construct a dual-parameter water balance model (WBM-DP) [27]. Additionally, a post-processing model based on quantile mapping (QM) [28] is utilized to enhance the accuracy of simulated runoff. The research results indicate that the correlation coefficient of the simulated runoff sequence reaches 0.918, and the relative error of the total runoff volume decreases to 1.4%. The parameters of the constructed WBM-DP and QM models were transferred to the SW reservoir and driven by ground-observed precipitation and evaporation data. This approach successfully generated inflow runoff data consistent with other reservoirs in the series. The average annual runoff of the SW reservoir is 2.17 million m$^3$, and its yearly allocation closely resembles that of other reservoirs.

Based on the Long-Term Water Resources Planning of Lanxi City, we extracted the water demand data for the urban area in 2025. The district water demand data were obtained by accumulating the township scale, as shown in Figure 5. It is worth noting that the required amount refers to the net water demand, whereas the local reservoir and JH water diversions provide untreated raw water, considering water leakage in the pipeline network. We assume a leakage rate of 5% to calculate the demand for raw water. The monthly ecological water demand of the downstream channel of the ZY reservoir is calculated by multiplying the daily water usage of 10,000 m$^3$/d by the number of days in a month. The CT reservoir is not only used for irrigating a small amount of farmland but also the irrigation demand of farmland is calculated based on the average actual water supply in each month from 2010 to 2018. The irrigation period is from June to October, with water requirements of 50,000 m$^3$, 440,000 m$^3$, 1,080,000 m$^3$, 750,000 m$^3$, and 80,000 m$^3$, respectively. The total annual water demand for agricultural irrigation is 2,300,000 m$^3$.

![Figure 5. Water demand for four districts of the Lanxi City in 2025.](image-url)
This study utilizes the NSGA-III algorithm [29] to solve the joint optimization scheduling model. NSGA-III (Non-dominated Sorting Genetic Algorithm III) has improved compared to NSGA-II, mainly in the selection mechanism. NSGA-II selects individuals on the same non-dominant level by calculating their crowding distances and crowding degrees (larger crowding distance is better), while NSGA-III maintains population diversity in high-dimensional objectives using distribution reference points and exhibits excellent convergence. We utilize the TOPSIS [30] to select the optimal scheduling from Pareto solution set with three objective functions as multiple attribute indicators.

3. Results

3.1. Optimal Reservoir Scheduling Diagram and Its Rationality

The dispatching diagram of the ZY, QTL, and CT reservoirs under the scenario of joint scheduling is illustrated in Figure 6. Regarding the ZY reservoir, urban water supply is prioritized in terms of guarantee rate and priority over ecological water supply in the river. Therefore, the urban primary and secondary water supply lines are below the ecological water supply line. The ecological water demand in rivers and urban water demand fluctuate consistently throughout the year, and the shape of the supply line is primarily determined by the seasonal variation in inflow runoff into reservoirs. The ZY reservoir is divided into three stages: March to July, August to October, and November to February of the following year. These three stages’ average monthly runoff volumes are 6 million m$^3$, 1.47 million m$^3$, and 1.58 million m$^3$. From March to July, the reservoir has a relatively high inflow. Therefore, it is necessary to set the restricted supply line at a higher level. From August to October, the inflow into the reservoir decreases significantly, requiring the appropriate raising of the restricted supply line to ensure sufficient water supply during the dry season. From November to January of the following year, the inflow into the reservoir decreased, so the restricted supply line needs to be further raised. Overall, there is a consistent water supply line restrictions trend in primary and secondary cities. Hence, the dispatching diagram of the ZY reservoir aligns with the temporal variations in both water inflow and demand. The shape of the urban level one and level two restricted water supply lines in the QTL reservoir dispatch chart is similar to that of the ZY reservoir. However, the urban level one restricted water supply line is positioned at a higher elevation due to the proximity of the QTL district’s water demand to the reservoir’s water supply capacity.

Figure 6. Scheduling diagrams of ZY, QTL, and CT reservoirs under joint dispatching scenario.

For the CT reservoir, the guaranteed rate and priority of urban water supply are higher than that of agriculture. Therefore, the established water supply restriction line is relatively lower than agriculture. Regarding the agricultural water resources restriction line, there is a higher overall demand for agricultural water from August to October. However, the
storage capacity of reservoirs significantly decreases. To ensure the subsequent urban water supply, it is necessary to impose timely restrictions on agricultural water supply. Therefore, the agricultural water supply restriction line is relatively high from August to October. Regarding the primary and secondary urban water limited line, the water demand is significantly lower than the reservoir’s capacity for water supply. To ensure the safety and stability of the reservoir dam structure, it is necessary to maintain a water volume of 3 million m$^3$ (corresponding to a reservoir water level of 200.43 m) based on the current reservoir operation and scheduling. Therefore, the urban water limited line for the city’s primary and secondary water supply is slightly higher than 200.43 m, but these restrictions vary slightly during different stages.

3.2. Simulation Results for Water Supply Districts

The water supply sources and sequences are complicated regarding coordinated scheduling for the three water supply districts: ZY, QTL, and JH. To verify the reasonableness of the simulation results for water supply schedules, this study analyzes the annual variation patterns of the water supply structure during the 61-year simulation period (Table 2). The following section will analyze the simulation results of each partition one by one.

Table 2. Multi-year average water supply structure of water supply districts based on simulation results from joint dispatching.

<table>
<thead>
<tr>
<th>District</th>
<th>Month</th>
<th>Water Supply Project</th>
<th>Water Supply Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZY</td>
<td>April</td>
<td>Water diversion from JH</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>76.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>Water diversion from JH</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>76.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>Water diversion from JH</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>70.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>Water diversion from JH</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>82.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>Water diversion from JH</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>85.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>Water diversion from JH</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZY Reservoir</td>
<td>85.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW Reservoir</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QTL Waterworks</td>
<td>4.4</td>
</tr>
</tbody>
</table>

(1) ZY District

The water supply of the ZY district mainly comes from JH water diversion, ZY reservoir, SW reservoir, and QTL waterworks. Figure 7 shows the monthly simulated water supply process of ZY waterworks from 1960 to 2020. The annual water supply volume of JH water diversion is between 2.81 and 4.24 million m$^3$, accounting for 8.2% to 15.5%. The monthly average share of water supply ranges from 8.9% to 17.4%, with slight monthly variations. However, in certain years during January and February, there is a reduction in the total water supply due to inadequate reservoir capacity, increasing the proportion.
of JH water diversion. Regarding the water supply, the ZY reservoir and SW reservoir are the main water sources for this area. The former has an annual water supply of 18.94 to 29.99 million m³, accounting for between 76.7% and 87.5%; the latter has an annual water supply of 1.04 to 3.27 million m³, accounting for between 3.3% and 9.6%. The annual water supply from QTL to ZY waterworks ranges from 0 to 690,000 m³, accounting for a proportion between 0 and 2.1%. Regarding schedule, the monthly average water supply proportion of the ZY reservoir and SW reservoir ranges from 69.9% to 89.8% and from 0.4% to 16.0%, respectively, indicating that the water supply volume of the ZY reservoir is significantly higher than that of the SW reservoir. The water supply from the ZY reservoir is relatively low from March to July, while the water supply from August to December is above 85%. This is mainly because the SW reservoir and QTL waterworks contribute more water supply to the ZY reservoir from March to July. From March to July, the water level in the SW reservoir is relatively abundant, accounting for 5.1% to 15.3% of the total water supply. During the same period, the water supply from QTL waterworks to the ZY district ranged from 2.2% to 3.4% of the total water supply.

![Figure 7](image-url)

**Figure 7.** Monthly water supply process of ZY district based on joint scheduling from 1960 to 2020.

(2) QTL District

The water supply sequence of the QTL district consists of the ZY waterworks and the QTL reservoir. Figure 8 shows the simulated monthly water supply dynamics of the QTL district from 1960 to 2020. The annual water supply of the QTL reservoir is 7.28–12.48 million m³, accounting for 79.6–99.2%. From the perspective of schedule changes, the proportion of water supply from the QTL reservoir from March to July is consistently over 90%. However, as the dry season approaches, the water inflow to the reservoir significantly decreases, leading to a gradual reduction in water storage. In some years, there may be a shortage of water supply, and the proportion of water supply from November to February of the following year slightly decreases. The annual water supply volume of ZY waterworks is from 11 to 22.7 million m³, accounting for a percentage between 0.8% and 20.4%. From August to February of the following year, the proportion of water supply gradually increases, especially from November to February of the fol-
lowing year, exceeding 10%, consistent with the supplementary water supply from the ZY waterworks during this period.

![Figure 8. Monthly water supply process of QTL district based on joint scheduling from 1960 to 2020.](image)

(3) JH District

The water supply sequence of the JH district is JH water diversion, QTL waterworks, and ZY waterworks. Figure 9 shows the JH district’s monthly simulated water supply process from 1960 to 2020. Under normal water supply and yellow warning conditions, the amount of water diverted from JH is greater than the urban water demand in the area, and the water can be supplied according to the demand. If the precipitation in the month is less than the average of many years by more than 80%, the orange warning will be activated, and the diversion of water from JH will be stopped and supplemented by QTL waterworks and ZY waterworks. The annual water supply of JH water diversion is 4.36–5.78 million m$^3$, accounting for 87.7–100%; the annual water supply of QTL waterworks is 0–510,000 m$^3$, accounting for 0–9.3%; and the annual water supply of ZY waterworks is 0–160,000 m$^3$, accounting for 0–3.0%. In terms of temporal changes, the proportion of average monthly water supply in JH water diversion remains relatively stable. Supplementary water supply at QTL and ZY waterworks occurs from July to January of the following year. The proportion of the average monthly water supply at QTL waterworks is generally higher than that at ZY waterworks, and it is relatively higher from September to December, reaching its peak in November at 6.3%.

![Figure 9. Monthly water supply process of JH district based on joint scheduling from 1960 to 2020.](image)

(4) CT district

The water supply for the CT district is exclusively sourced from the CT reservoir and does not involve any coordinated scheduling with other regions. Figure 10 illustrates the detailed monthly water supply process. Most of the time, the city’s water demand can be met, but during extremely dry years, there may be a shortage of water resources in certain months.
3.3. Comparison of Water Supply Benefits with Relevant Dispatching Schemes

This section quantitatively demonstrates the impact of the joint optimization dispatch of multiple water sources on the water supply benefits through a comparison with the current independent scheduling scheme (CIS), multi-water source joint routine dispatching scheme based on the current dispatch diagram (MWSJD-CDD). Based on the current scheduling plan, the ZY, QTL, and JH districts implement an independent water supply. The ZY, QTL, and CT reservoirs supply water according to their operation schedules. The SW and ZY reservoirs are supplied together according to empirical rules. Specifically, water supply is only provided when the reservoir reaches its maximum capacity and needs to release water. This paper proposes incorporating cross-regional water replenishment rules into the existing scheduling scheme, forming a comprehensive scheduling scheme that integrates multiple water sources. The only difference between this scheme and the multi-water source joint dispatching scheme based on the optimal dispatch diagram (MWSJD-ODD) proposed in this study lies in the reservoir dispatch diagram.

The comprehensive simulations of water supply scheduling were conducted based on the CIS and the MWSJD-CDD. Statistical results of water supply indicators are shown in Table 3. Compared to the CIS, the joint optimization scheduling scheme derived from this paper reduced the total water shortage in the simulation period by 68.04 million m$^3$. The reduction mainly occurs in the ZY district, mainly due to the surplus water supply from the JH and QTL districts. Although the QTL district supplies water to the ZY district from March to July, which results in a marginal increase in water shortage, the water shortage in the ZY district remains relatively consistent. The scheduling rules for the CT district have remained unchanged, and the water shortage has remained stable. Based on the joint regular scheduling scheme of multiple water sources, the scheduling diagrams of the ZY, QTL, and CT reservoirs were optimized, successfully reducing the city’s total water shortage by 29.72 million m$^3$. Specifically, the ZY district was reduced by 22.72 million m$^3$, the QTL district by 390,000 m$^3$, the JH district by 4.2 million m$^3$, and the CT district by 2.4 million m$^3$. In addition, the annual maximum water shortage of the city generally decreased.

From the perspective of the urban water supply guarantee rate, the multi-water source joint dispatching scheme based on the current dispatch diagram has a more significant impact on the guarantee rate of the ZY district compared to the current independent scheduling scheme, resulting in an increase of 11.2% in the guarantee rate. By optimizing the reservoir scheduling chart, the guaranteed rate of the ZY district has been further
increased by 23.5% to reach 90.6%; the guaranteed rates of the QTL and the CT districts exceeded 98%, while the guaranteed rate of the JH district remained relatively stable.

### Table 3. Water supply benefit metrics of different scheduling schemes for water demand in 2025.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Spatial Scale</th>
<th>CIS</th>
<th>MWSJD-CDD</th>
<th>MWSJD-ODD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accumulated urban water shortage during the simulation period (10^4 m^3)</strong></td>
<td>Lanxi City</td>
<td>16,854</td>
<td>10,050</td>
<td>7078</td>
</tr>
<tr>
<td></td>
<td>ZY District</td>
<td>14,678</td>
<td>7624</td>
<td>5352</td>
</tr>
<tr>
<td></td>
<td>QTL District</td>
<td>30</td>
<td>367</td>
<td>327</td>
</tr>
<tr>
<td></td>
<td>JH District</td>
<td>1668</td>
<td>1581</td>
<td>1161</td>
</tr>
<tr>
<td></td>
<td>CT District</td>
<td>478</td>
<td>478</td>
<td>237</td>
</tr>
<tr>
<td><strong>Annual maximum urban water shortage during the simulation period (10^4 m^3)</strong></td>
<td>Lanxi City</td>
<td>1628</td>
<td>1396</td>
<td>1273</td>
</tr>
<tr>
<td></td>
<td>ZY District</td>
<td>1568</td>
<td>1064</td>
<td>1102</td>
</tr>
<tr>
<td></td>
<td>QTL District</td>
<td>4</td>
<td>157</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>JH District</td>
<td>129</td>
<td>148</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>CT District</td>
<td>131</td>
<td>131</td>
<td>112</td>
</tr>
<tr>
<td><strong>Guarantee rate of urban water supply during the simulation period (%)</strong></td>
<td>ZY District</td>
<td>55.9%</td>
<td>67.1%</td>
<td>90.6%</td>
</tr>
<tr>
<td></td>
<td>QTL District</td>
<td>98.1%</td>
<td>98.6%</td>
<td>98.4%</td>
</tr>
<tr>
<td></td>
<td>JH District</td>
<td>94.4%</td>
<td>94.5%</td>
<td>94.5%</td>
</tr>
<tr>
<td></td>
<td>CT District</td>
<td>89.5%</td>
<td>89.5%</td>
<td>98.4%</td>
</tr>
<tr>
<td><strong>Accumulated abandoned water of reservoirs (10^4 m^3)</strong></td>
<td>ZY Reservoir</td>
<td>18,729</td>
<td>30,688</td>
<td>31,321</td>
</tr>
<tr>
<td></td>
<td>QTL Reservoir</td>
<td>12,935</td>
<td>2705</td>
<td>2632</td>
</tr>
<tr>
<td></td>
<td>CT Reservoir</td>
<td>23,982</td>
<td>23,982</td>
<td>23,573</td>
</tr>
<tr>
<td></td>
<td>Summation</td>
<td>55,645</td>
<td>57,374</td>
<td>57,527</td>
</tr>
</tbody>
</table>

A multi-water source joint dispatching scheme based on the current dispatch diagram significantly reduces the amount of water discharged from the QTL reservoir, which is due to the QTL waterworks supplying water at full capacity and releasing part of the storage in advance from March to July, thus reserving water sources for future usage. After the implementation of joint scheduling across the area, the JH water diversion and QTL waterworks supply water to the ZY district to increase the storage capacity of the ZY reservoir. At the same time, considering the uncertainty of inflow runoff, the likelihood of water discharge increases when there is a significant amount of precipitation in the following months. The simulation results indicate that the accumulated amount of water released from the ZY reservoir has increased during the simulated period. Overall, the joint scheduling measures slightly increased the total amount of water released from the ZY, QTL, and CT reservoirs, resulting in a certain degree of spatial redistribution of the water releases. Further improvement measures could consider reducing the amount of water discharge by utilizing inflow runoff forecasting information.

### 4. Conclusions

1. This paper introduces a general approach and methodology for optimizing and scheduling urban raw water supply systems. The process consists of four steps: problem identification, system generalization, rule formulation, and model construction and solution. The problem identification and rule formulation differ from existing research. The former serves as the basis for the scientific formulation of rules for multiple water sources and cross-zoning water supply. Therefore, it cannot be overlooked in research.

2. We applied a general analytical process to study the coordinated scheduling of raw water in the urban water supply system in Lanxi City, Zhejiang Province. We formulated joint scheduling and cross-regional water supply rules for major water reservoirs' water discharge and urban water shortage problems and established a mathematical model for multi-source joint optimization scheduling to optimize the reservoir scheduling chart for water demand by 2025.
(3) Based on extensive long-term scheduling simulations, we determined that the total cumulative water shortage in the city is 70.78 million m³, and the annual maximum water shortage is 12.73 million m³. At the district scale, the annual maximum water shortage in the ZY district is higher than in other districts. The urban water supply guarantee rate of the QTL and CT districts exceed 95%, while those of the ZY and JH districts are 90.6% and 94.5%, respectively.

(4) Compared with the current independent scheduling scheme and the multi-water source joint dispatching scheme based on the current dispatch diagram, the joint optimization of multiple water sources and reservoir scheduling graph reduced the cumulative water shortage in the city by 68.04 million m³ and 29.72 million m³, respectively, during the simulation period. The guarantee rate in the ZY district increased by 11.2%, while the guarantee rates in the QTL and CT districts reached over 98%.

The general method proposed in this paper particularly emphasizes the identification of urban water supply issues. However, the mentioned problems do not cover all scenarios. Although the case of Lanxi City may provide some references, when urban water resource managers apply this method, they should pay more attention to specific problems and choose appropriate objective functions for optimizing water supply scheduling plans.

Author Contributions: L.L. and Y.W. conceived and designed the study; L.L. proposed the general process of optimal dispatching of urban raw water; L.W. and X.G. established a joint optimization scheduling model and solved the scheme; X.S. and R.G. drew related graphs and tables; L.L. and Y.W. advised on the work and performed the final checks. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (No. 2021YFC3000104), the National Science Foundation of China (No. 52009081), and the Consulting research project of Chinese Academy of Engineering (2022-FP-04).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References
3. Duan, K.; Caldwell, P.V.; Sun, G.; McNulty, S.G.; Qin, Y.; Chen, X.; Liu, N. Climate Change Challenges Efficiency of Inter-Basin Water Transfers in Alleviating Water Stress. Environ. Res. Lett. 2022, 17, 044050. [CrossRef]


Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.