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Recent Developments in the Application of Water Resource Dispatching Systems in China

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Abstract: This paper addresses recent developments in the application of water Resource dispatching systems (WRDSs) in China. Through a survey of watershed managers and a literature analysis, it was found that water diversion projects should be the top priority of water resource management by considering the recovery construction of water diversion projects. Case studies of WRDSs in the South-to-North Water Diversion (SNWD) and Pearl River Basin are discussed in this article. The results show that total water consumption management (WCM), water quality monitoring and management (WQMM), minimum discharge flow management (MDFM), and water dispatch management (WDM) modules should be considered in WRDSs. Finally, strategies and needs for resolving water resource management problems are discussed, along with other applications of WRDSs in China.

Keywords: water resources; dispatching; South-to-North Water Diversion; Pearl River basin

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1. Introduction

Water availability and water demand are not evenly distributed in time and space. With social progress and economic development, demand for water is growing. The contradiction between supply and demand of water resources is becoming increasingly prominent [1]. A scientific and robust management of water resources is of great importance for the alleviation of water resource shortages, the sustainable utilization of water resources, and the maximization of regional ecological and economic benefits. Reasonable design of water resources scheduling scheme is becoming more and more important [2–4].

A number of inter-basin water diversion projects have been launched in Australia, Canada, and the United States of America (the U.S.). These include the Snowy Mountains Scheme [5], the Great Lakes Water Diversion [6], and the Central Valley Project [7]. Inspired by such developments around the world, China has advocated for the reallocation of water resources from basins perceived as being water rich to ones where water scarcity is a constraint on the growth of urban population and industrial economy [8]. The reasonable scheduling of water resources for water diversion projects or inter-basin allocation is important for improving the efficiency of the utilization of water resources and ensuring food security.

The necessity for river basin planning has been widespread around the world since the 1940s, and many scholars have therefore studied the development strategies of water resource systems to determine the optimal scheduling of several proposed projects. The water resource dispatching problem centered on reservoirs was first proposed by Masse

in the 1940s [9,10]. Over the past few decades, thanks to the hard work of researchers, the study of water resource dispatching has gradually matured, and engineering practice has seen a greater number of achievements in this area. Rockstrom [11] introduced water resource dispatching on farms. Arunkumar et al. [12] devised chaotic evolutionary algorithms for multi-reservoir optimization. Comair et al. [13] proposed a GIS-based system to guide water resource management. Mortazavi-Naeini et al. [14] established a multi-objective optimization model to schedule urban water resources. Nouiri et al. [15] optimized water resource management by using a genetic algorithm. In China, electric power scheduling models of reservoirs were established based on Markov theory and the dynamic programming method and were successfully used in the optimization scheduling of hydropower stations. Sun et al. [16] set up a soil and water assessment tool (SWAT) model to assess crop yields and crop water productivity for irrigation. All these works feed into the development of related studies.

However, in terms of complex systems of water resource allocation and scheduling, traditional models and methods have many defects [17], which introduce difficulties in the application of water resource dispatching systems (WRDSs) in China. First, traditional theories and methods of water resource allocation and scheduling often pay more attention to supply and demand issues. They usually consider intermediate links from the viewpoint of technical feasibility only, such as the size of a pipeline and amount and type of facilities. The demands of users, the cost-to-efficiency ratio, and the quality of service are rarely considered. The timing and scale of developing proposed projects affect project scheduling [2]. Second, incomplete information is one of the bottlenecks in complex systems of water resource allocation and scheduling. Uncertainty will result in bad decisions, yet traditional methods usually ignore information balance [17]. Therefore, there is still a long way to go in devising scientific and reasonable water resource allocation and scheduling strategies and algorithms [18,19].

Unlike analyses conducted of small-scale water resource studies and construction projects [20], there is a lack of comprehensive analyses of water resource dispatching on a basin scale or from a national perspective [21]. This study conducted an analysis of the rapid construction of water diversion projects and recent developments in WRDSs in China.

2. Linkages between Water Resource Management and WRDSs in China

2.1. State of Water Diversion Projects in China

The construction of water engineering projects is highly valued in China [22]. The construction of Anfeng Tang, which created a still-existing reservoir 100 km in circumference that can irrigate an area of 24,000 square kilometers, has a long history, one that is almost as old as the nation itself.

Because the world is facing increasing insecurity concerning its water supplies, with both droughts and floods on the increase, the global water crisis is frequently in the news. The planet urgently needs to face the dilemma of how to secure access to adequate water resources for expanding populations and economies while maintaining healthy freshwater ecosystems and the vital services they provide. Water diversions—massive engineering projects that divert water from rivers with perceived surpluses to those with shortages—have been promoted as a solution. Water diversion schemes attempt to make up for water shortages by constructing elaborate systems of canals and pipes and dredging over long distances to convey water from one river basin (the donor basin) to another (the recipient basin).

Inter-basin water diversion schemes are not a new phenomenon. Like the outbreak of dam building that marked the second half of the 1900s, inter-basin water diversions are now widely praised as a quick fix, designed to meet escalating demands for water, to encourage economic development, and to feed rapidly growing human populations.

China is being increasingly forced to face the challenge of how to ensure access to adequate water resources for its expanding population and economy while maintaining

its freshwater ecosystems [23,24]. The ongoing water shortage in northern China is very severe. There are many planning projects and projects under construction (as shown in Figure 1), and many ambitious projects are currently under consideration. These include a number of schemes to transfer water over thousands of kilometers, as well as many others that are less grand in scale. To solve the problem of the shortage of water resources, a number of inter-basin water diversion projects are being conducted. By 2015, the total amount of diverted water in China reached 100 billion m^3 (including projects built, being built, and planned), and water diversion distances had exceeded 16,000 km. Nearly a quarter of diverted water schemes involve distances over 350 km, and water diversion projects cover more than 17 provinces, including 60 cities [25].



Figure 1. Layout plan for water diversion projects in China (red: planning project; blue: project under construction).

As shown in Figure 1, backbone projects for river and lake water systems have been constructed. Engineering precepts such as reasonable guidance, good communication, adequate drainage, and so on are taken into account, establishing or improving relationships between water bodies of rivers or lake reservoirs. Through these measures, the level of water resource regulation and control has improved, enhancing the ability to resist floods and droughts and improving the water ecological environment.

2.2. Current State of Water Resource Management in Dispatching

Work on China's water resource dispatching management started relatively late but developed quite rapidly. In the early 1960s, China conducted research on bulk water distribution with reservoir operations as a starting point. This later evolved into research on flood control dispatching in the 1980s. In the 1990s, with the development of water conservation projects in China, water resource dispatching was focused on engineering, with a limited focus on utilization and a general disregard for ecological water requirements.

After 2000, with increasingly unequal water access and mounting serious water pollution, China began to focus on the eco-civilization of water, paying attention to ecological water requirements in rivers and lakes. Water resource dispatching management entered a comprehensive utilization stage, with the integrated water quantity dispatching of the Yellow River Basin and the Heihe and Tarim river basins, the water replenishment of the Zhalong wetlands, the ecological dispatching of the Nansi Lake, the diversion of water from the Yangtze River to Taihu Lake, and the gradual completion of many other inter-basin and long-distance water dispatching projects. Thus, a comprehensive dispatching system to counteract droughts and deal with emergencies, mid-term supply and demand balance, and long-term ecological maintenance gradually formed.

At present, the pattern of unified management and dispatching of water resources in China is in its infancy, as shown by the following:

(a) Dispatching organization

With respect to a dispatching management system, a joint dispatching management system involving river basin institutions and regional government departments has emerged.

(b) Dispatching rules

With respect to dispatching rules, a strict water resource management system has been formed, meaning that the state distributes bulk water in an integrated way. The province (the autonomous region and municipality directly under the central government) takes charge of water distribution and planning and important water intake, and key reservoirs are dispatched in an integrated way. Meanwhile, principles of sustainable utilization and human–water harmony are followed.

(c) Dispatching methods

With respect to dispatching methods, water quantity dispatching has been conducted comprehensively by its administration in accordance with the law and engineering principles and in line with economic development needs.

(d) Dispatching scheme

The schedules required for the dispatching schemes were on an annual, monthly, ten-day, and daily basis among the different basins in China. Methods called long–short combinations, rolling adjustments, and real-time dispatching schemes have been devised during the application of WRDSs in China.

3. Recent Developments of WRDSs in China

3.1. Application of Dispatching Algorithms

When referring to water resource dispatching management, multi-stage reservoir and inter-basin regulation are always involved. Thus, in addition to the basic task of water quantity distribution, flood control, power generation, and ecological benefits must be considered in a comprehensive way. Therefore, water resource dispatching is a complex, nonlinear optimization problem, featuring multiple stages, variables, objectives, and constraints, the key to which lies in solving the problems of water resource dispatching.

At present, the methods of solving the problem of water resource dispatching can be divided into two major categories as follows: the classes of the conventional dispatching method and the classes of the optimized dispatching method. The former, a simple method that combines practical experience, mainly comprises chronological [26] and statistical methods [27] and is used more in the flood control group dispatching of small- and medium-sized group reservoirs. However, it has some limitations owing to the absence of forecasting. The latter method focuses on optimization and plays a diverse role in terms of solving methods, which include two main categories. The first is a mathematical programming analysis method, comprising linear programming [28,29], nonlinear programming [30,31], dynamic programming [32,33], and the coordinated decomposition of large-scale systems [34,35]. The other is an intelligent optimization algorithm, including fuzzy mathematics [36,37], genetic algorithm [38,39], neural network algorithm [40,41],

and chaos theory [42]. See Table 1 for details on the advantages and disadvantages of the different algorithms.

Table 1. Dispatching algorithms used by water Resource dispatching systems (WRDSs) in China.

Basis	Classification	Method	Advantages and Disadvantages
Conventional dispatching	Conventional method	Chronological and statistical methods	Simple and widely applied but does not consider forecasting; fit for small and medium-sized reservoirs
Optimized dispatching	Mathematical programming analysis method	Linear programming	Fit for simple linear problems; has limitations when solving problems
		Nonlinear programming	Complex modelling and slow convergence rate
		Dynamic programming	Easy to simplify but can easily result in dimensionality issues owing to segmentation
		Coordinated decomposition of large-scale systems	Fast calculation and effectively avoids dimensionality issues
	Intelligent optimization algorithm	Fuzzy mathematics	Quantifies fuzzy factors and more efficient for solving practical problems
		Genetic algorithm	Effectively solving issues dimensionality; very robust and stable
		Neural network algorithm	High-speed parallel, anti-noise data interference
		Chaos theory	Fast convergence rate and reduces issues caused by dimensionality

A total of 326 articles were selected on water resource scheduling from 1986 to 2018 in the China Knowledge Resource Integrated Database (CNKI) (www.cnki.net) and the articles on the dynamic planning algorithm and genetic algorithm were counted in these articles. The research database search of WRDSs and different dispatching algorithms in the CNKI Database (www.cnki.net) is shown in Figure 2.

As shown in Figure 2, since 1986, literature on water resource dispatching has been emerging in China, and for a time it was increasing. The trend has finally stabilized, with a maximum of 29 articles produced in 2013. In 2002, literature on the use of dynamic programming in water resource management emerged in China (Figure 2b), and almost every year since then, articles associated with the subject have appeared. Meanwhile, since 2008, literature on the use of genetic algorithms in water resource management has been developing in China (Figure 2c). Likewise, almost every year since then, one or two articles related to this subject have appeared.

There are nine different basins in China as follows: Southeast Basin, Northwest River Basin, Songhua and Liaohe River Basin (SLRB), Hai River Basin (HRB), Huai River Basin (HuRB), Pearl River Basin (PRB), Southwest Basin, Yangtze River Basin (CJB), and Yellow River Basin (YRB). Figure 3 shows that the dynamic programming method was mainly applied to the northern region, whereas the genetic algorithm method was mainly applied to the southern region. The dynamic programming method was used once in the Continental Basin, four times in the YRB, and twice in the HRB. The genetic algorithm method was used three times in the PRB and once in the HRB.

3.2. Different WRDS Modules in China

Based on the demand of water scheduling information, we created a survey sample table, as shown in Table 2 below. We then invited relevant leaders of the Haihe River Water Conservancy Commission, Huaihe River Water Conservancy Commission, Yellow River Water Conservancy Commission, Songhua River and Liaohe River Water Conservancy Commission, Yangtze River Water Conservancy Commission, and Pearl River Water

Conservancy Commission to fill in the data. The sample table includes a survey of the formulation of the water distribution plan, the implementation of the distribution plan, existing problems, and information on the next plan of each water conservancy commission.

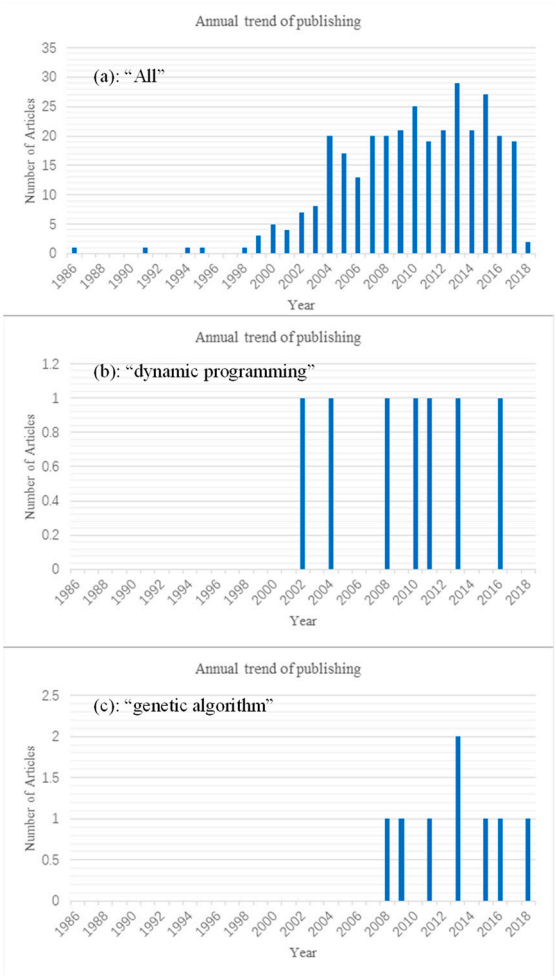


Figure 2. Yearly publications on WRDSs in the field of water sciences and the contribution rate of these common algorithm methods based on the China Knowledge Resource Integrated Database (CNKI) (www.cnki.net). (**a**) "All" is based on the search terms "Water resource dispatching" + "algorithm" in the CNKI. (**b**) "Dynamic programming" is based on the search terms "Water resource dispatching" + "dynamic programming" in the CNKI. (**c**) The "genetic algorithm" is based on the search terms "Water resource dispatching" + "genetic algorithm" in the CNKI.

The following factors should be considered when developing a scheduling strategy [2]: (i) every project should pass an environmental impact assessment and social impact assessment, (ii) the required construction time for each project should be kept in mind, (iii) the storage or transmission capacity of each project must be took into account, (iv) the water demand process during the scheduling horizon needs to be considered, and (v) the increased system yield of a combination of projects should be calculated. Following the operating rules of each reservoir and other water allocation principles, four modules of WRDSs in China based on the requirements of government regulation were determined as follows: total water consumption management (WCM module); water quality monitoring and management (WQMM module) for the boundary section; minimum discharge flow management (MDFM module) for the main control section; and water dispatch management (WDM module). As shown in Figure 4, the application of different modules on a basin scale occurs at different stages of development.

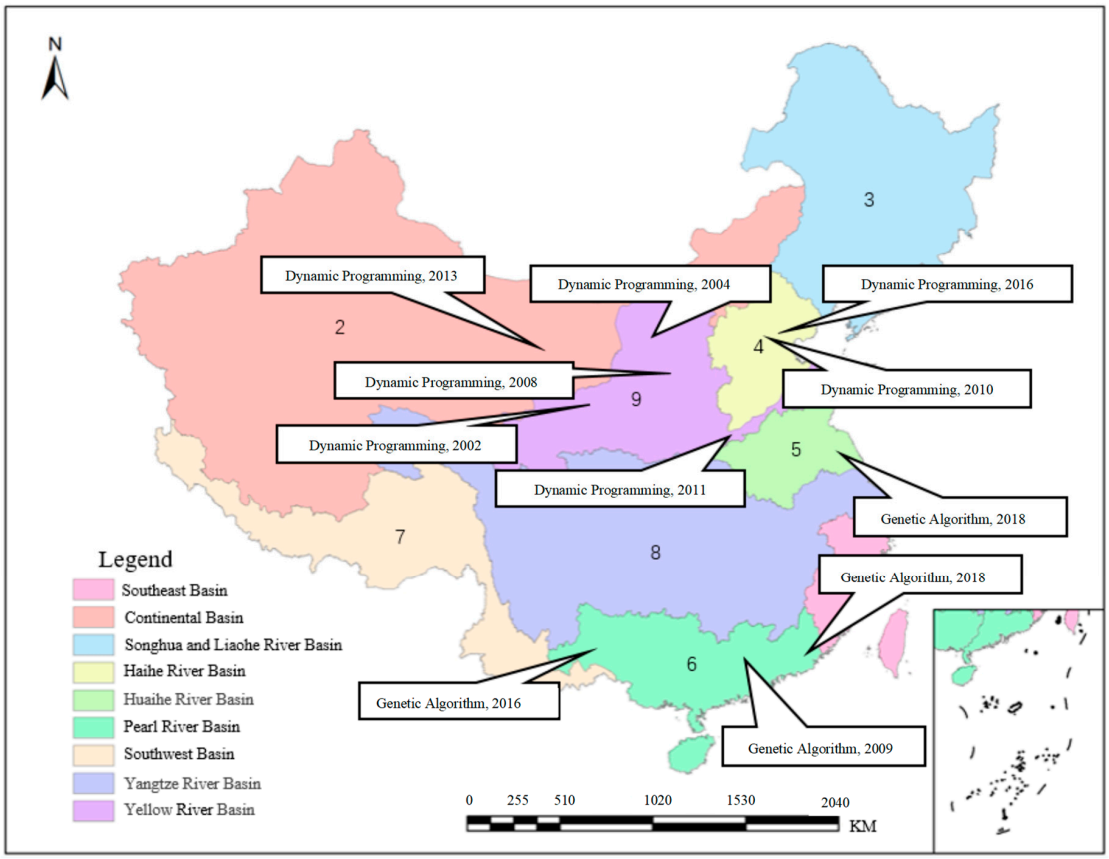


Figure 3. The situation with respect to the application of water resource dispatching.

Table 2. Questionnaire for Basin Managers (Sample table).

Serial Number	Content	Remark
1	Formulation of distribution plan	To expound on the formulation of water allocation schemes in each basin.
2	Implementation of the distribution plan	To expound on the implementation of water allocation schemes in each basin.
2.1	Water resources monitoring module	To expound on the construction of water resources monitoring station networks and on-line monitoring of section water quality and quantity through the implementation of national water resources monitoring capacity building,
2.2	Water resources demonstration and license management module	Technical review of water resources demonstration and approval of water intake permit
2.3	Ecological flow dispatching module	According to the relevant requirements of the Ministry of Water Resources, to expounds on the pilot work of ecological flow (water level) in each basin, etc.
3	Main problems in water dispatching management	To expounds on the main problems in the water dispatching management of each basin.
4	Next steps	To expounds on the next plan of each basin for water quantity dispatching work.

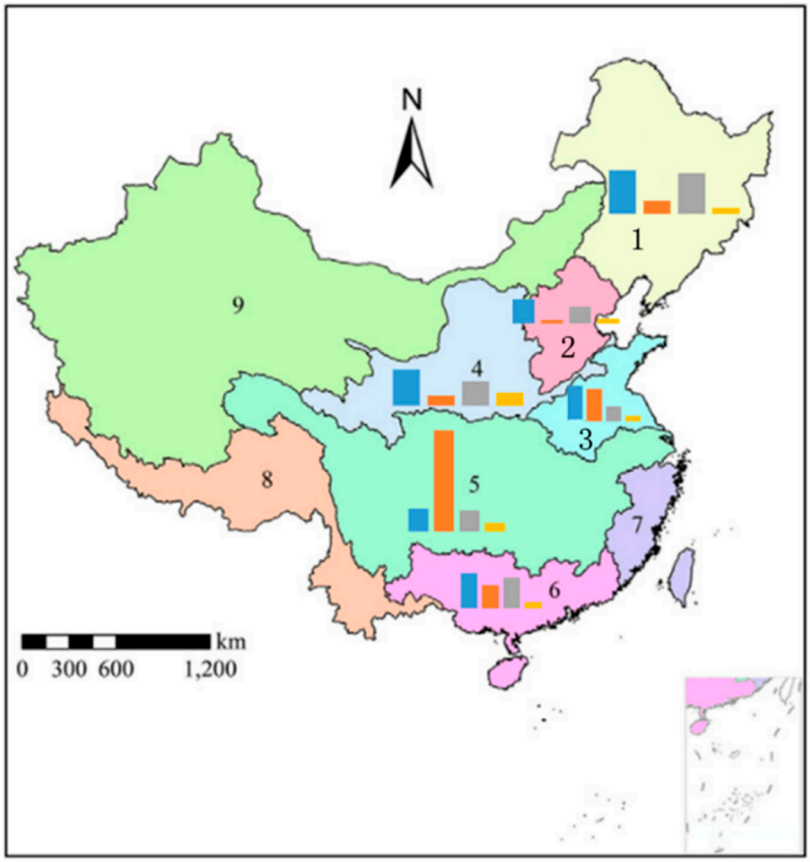


Figure 4. Nine major water basins in China. 1 = Songhua and Liao River Basin; 2 = Hai River Basin; 3 = Huai River Basin; 4 = Yellow River Basin; 5 = Yangtze River Basin; 6 = Pearl River Basin; 7 = Southeast River Basin; 8 = Southeast River Basin; 9 = Northwest River Basin. The completion percentages of different modules are shown as a histogram (blue: water consumption management (WCM module); red: water quality monitoring and management (WQMM module); grey: minimum discharge flow management (MDFM module); yellow: water dispatch management (WDM module)).

Figure 4 illustrates the four parts from left to right as bar graphs. It can be seen from the figure that the overall level of the southern basin is better than that of the northern basin. For example, for the WQMM module, there has been 26% completion in the PRB, 95% completion in the CJB, and 41% completion in the HuRB. In the northern basin, there was only 9% completion in the SLRB, 7% completion in the YRB, and 3% completion in the HRB. See Table 3 for details on completion percentages for the four modules in the different basins.

Table 3. Completion percentages for the four modules in the different basins (unit: %). WCM, total water consumption management; WQMM, water quality monitoring and management; MDFM, minimum discharge flow management; WDM, water dispatch management.

Different Modules	Pearl River Basin (PRB)	Yangtze River Basin (CJB)	Songhua and Liao River Basin (SLRB)	Yellow River Basin (YRB)	Huai River Basin (HuRB)	Hai River Basin (HRB)
WCM module	40	22	30	25	45	20
WQMM module	26	95	9	7	41	3
MDFM module	35	20	28	17	19	14
WDM module	7	8	4	9	7	4

4. Case Study

4.1. Case Study A: Application of WRDSs in the South-to-North Water Diversion (SNWD)

4.1.1. Study Area

The SNWD is a mega water diversion project encompassing a large scale, large investment, wide coverage, and profound and lasting influence. Its overall layout is divided into three water dispatching lines, namely the west line project, the middle line project, and the east line project. Water is dispatched from the upper reaches, the middle reaches, and downstream of the Yangtze River to meet the demands of development throughout northwest and northern China. Figure 5 shows the location and different dispatching lines of the SNWD.

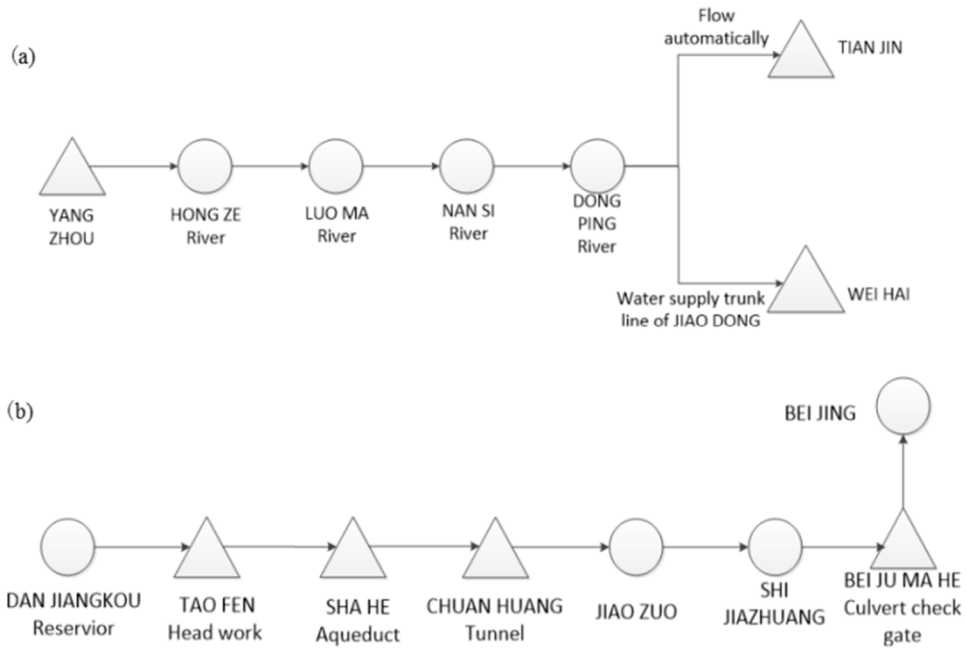


Figure 5. Location and different dispatching lines of the South-to-North Water Diversion (SNWD): (**a**) eastern module; (**b**) middle module.

4.1.2. WRDS Framework for the SNWD

As for the SNWD, one key to successful dispatching is ensuring that agricultural and ecological water consumed by cities can be returned at the required volume, on time. The other issue is whether groundwater that has been seriously depleted can be effectively controlled and gradually restored in order to have a strategic reserve of water resources. The key point for the unified management of water resources lies in the unified management of basin and urban water consumption. Figure 6 shows the framework of dispatching management systems for the SNWD.

4.1.3. WRDS Operation for the SNWD

The general idea of dispatching a management system for the SNWD involves the establishment of a limited liability company or water supply company under state macro control, by means of shareholding system operations, enterprise management, and water user participation. It comes under the guidance of the various government departments in charge of the industry according to the circumstances that apply and is mainly based on the specific conditions of the water source and water receiving areas. A reasonable scientific water supply plan (annual or monthly) is implemented, and a dispatching plan for the turn-out gate, pumping station, and check gate in operation dispatching is devised to provide support for the operation and dispatching of water resources.

In the SNWD middle line project, for example, the dispatching scheme was devised mainly from the perspectives of the time scale and corresponding engineering areas. The time scale primarily refers to the non-flood and flood seasons. The flood season extends from May to October. The non-flood season runs from November to April of the following year. The corresponding engineering areas include the water source area and the water receiving area. Preconditions for water diversion in the water source area and the water requirement plan for the water receiving area are analyzed from the perspective of the time scale of the flood and non-flood seasons. In the corresponding time scale, the execution plan is formulated according to the dispatching plan. A corresponding dispatching scheme is formulated on a monthly and ten-day time scale, which enriches the real-time dispatching scheme of the dispatching engineering. By combining the different dispatching requirements of different regions in different time scales, rolling corrections are made in the summary of the year-end dispatching plan to serve as the preconditions for the following year's dispatching scheme, balancing the rights and interests of each water receiving area.

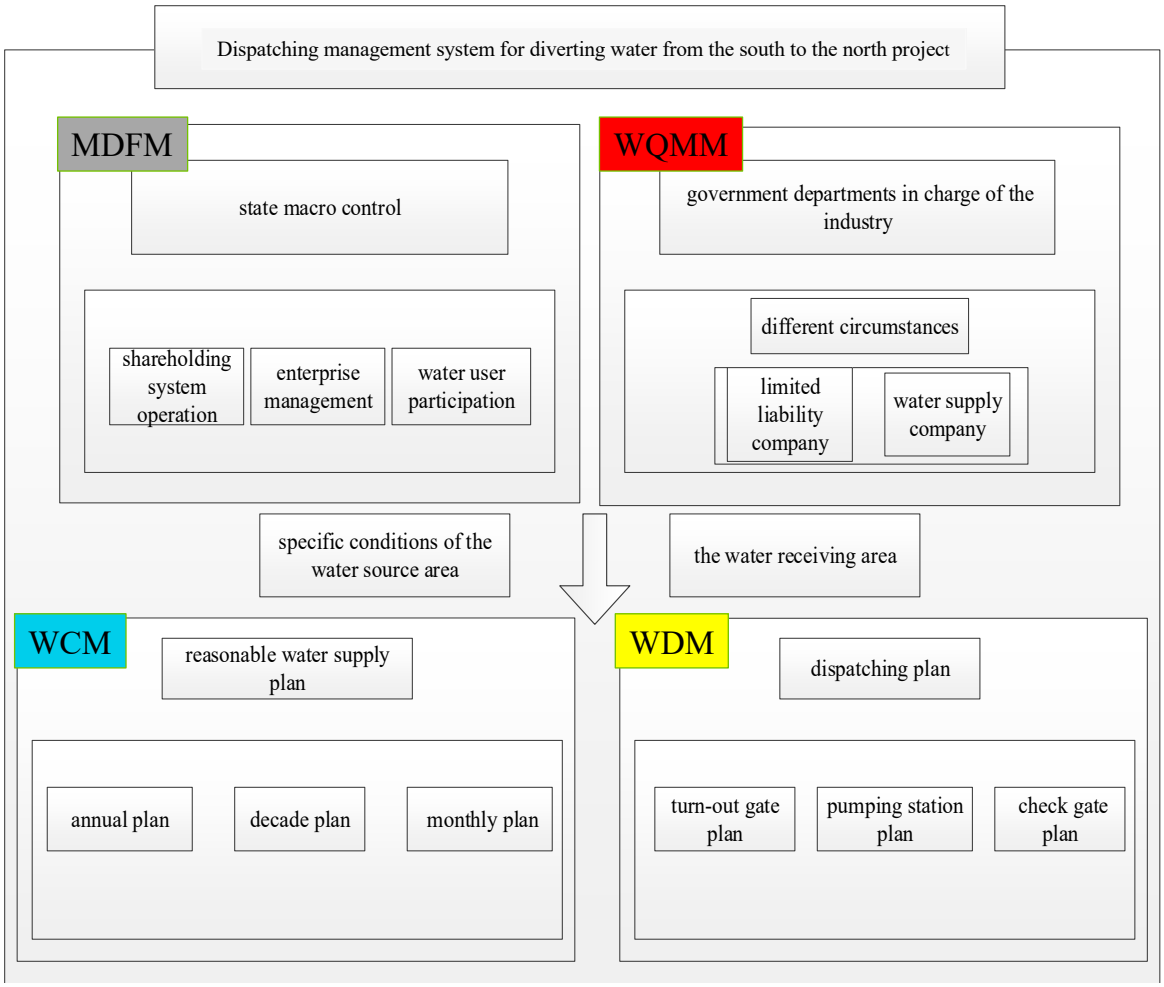


Figure 6. Framework of dispatching management systems for the SNWD. The four modules are shown in different colors (blue: WCM module; red: WQMM module; grey: MDFM module; yellow: WDM module).

4.2. Case Study B: Application of WRDSs in the Pearl River Basin (PRB)

4.2.1. Study Area

The PRB, composed of the Xijiang, Beijiang, and Dongjiang river basins and the Pearl River Delta, extends across the six provinces (regions) of Yunnan, Guizhou, Guangxi,

Guangdong, Hunan, and Jiangxi and into part of Vietnam, covering an area of 455,000 km^2, of which 422,000 km^2 is in China. With a main river total length of 2214 km, the Xijiang River is the main tributary of the PRB and composed of five sections, including the Nanpan River, Hongshui River, Qianjiang River, Xunjiang River, and Xijiang River. Water resource dispatching in the PRB is of great significance to the whole Pearl River Delta and to the economic reserve of cities in southeastern China. Figure 7 shows the linkage of key reservoirs in the PRB.

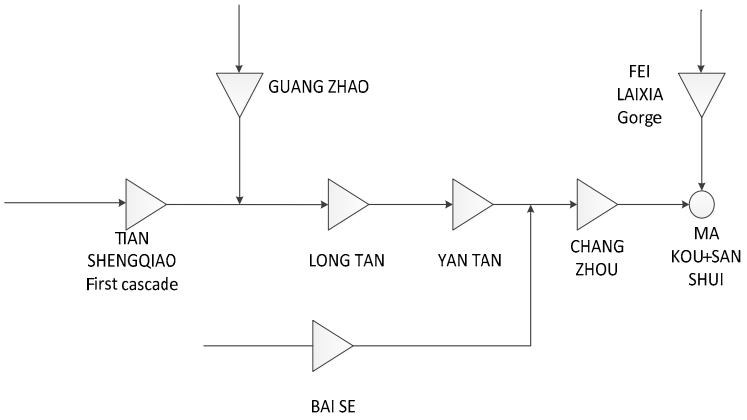


Figure 7. Linkage of key reservoirs in the Pearl River Basin.

4.2.2. WRDS Framework for Key Reservoirs in the PRB

A dispatching management system of water resources in the PRB refers to a system combining basin dispatching management and administrative region management, in which regional dispatching management is deemed to be essential. Basin dispatching management is a supplementary activity managed by water-related management departments such as environmental protection and electricity.

As the direct basin management agency for the PRB, the Pearl River Water Resources Commission undertakes the dispatching management of water resources in the whole basin; can formulate long-term water supply and demand plans and water allocation schemes for inter-provincial and autonomous regions in the basin; and is responsible for supervision and management. The local administrative departments at all levels respond to the Pearl River Water Resources Commission's water resource dispatching management and undertake dispatching management in their own regions. Figure 8 shows the framework of the dispatching management system for the PRB.

4.2.3. WRDS Operation in the PRB

With respect to the flood control scheme, based on the policy of "'combination of levees and reservoirs, giving priority to discharge, concurrent discharging and storing" and the principle of "ensuring emphasis and giving consideration to ordinary", the flood control scheme in the PRB is intended to make full use of the river course to discharge floods under the premise of guaranteeing the safety of the levee. If there is excessive flooding, emergency measures in terms of flood control and protection are taken in a timely manner to ensure the safety of important assets. Meanwhile, according to the distribution and hydrographic characteristics of the PRB, with flood control standards and flood control targets for different reaches comprehensively considered, reasonable flood control modes and control application indicators are determined, and operation measures are implemented according to the river system, river section, and mode.

With respect to the dry season scheduling scheme, during the drought period, a unified allocation scheme of "storage first and then supplement" is adopted for the allocation of water resources in the PRB. "Storage first" primarily refers to carrying out the work of flood resource utilization at the end of the flood season on the premise of ensuring flood control safety. It also appropriately reduces outflow and increases water storage in

upstream backbone reservoirs to reserve water for later dispatching when the water flow of the basin can meet the demands of the estuary pushing brackish water in September and October. The term "then supplement" refers to increasing the outflow of the upstream reservoir by generating power to increase water discharge in the river course when the water flow of the basin cannot meet the demands of downstream water pushing brackish water from November to the following February. Monitoring and rolling forecasts of the water regime and salinity are carried out based on the dispatching mode of "monthly plan, ten-day dispatching, weekly adjustment, and daily tracking", and the real-time scheduling scheme is continuously optimized.

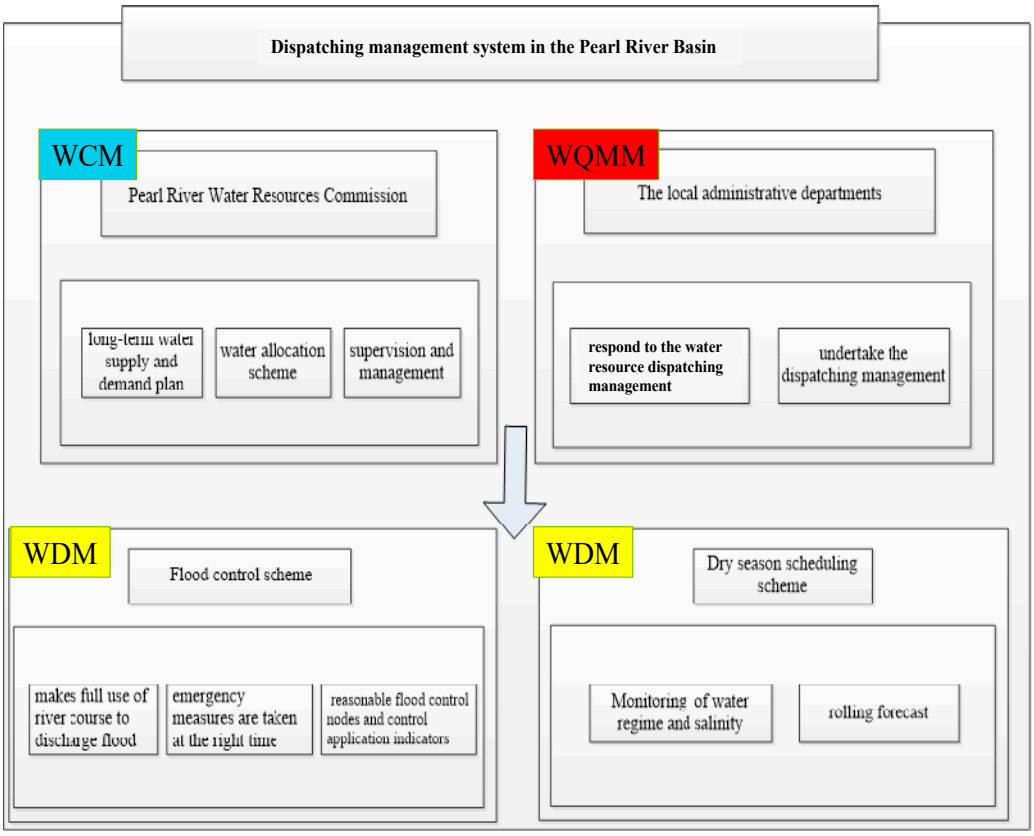


Figure 8. Framework of the dispatching management system for the Pearl River Basin (PRB). Different modules are shown in different colors (blue: WCM module; red: WQMM module; yellow: WDM module). There is no MDFM module owing to the abundance of water in the PRB.

5. Discussion

Water resource dispatching management is an extremely important strategy for managing the changes in hydrological processes that are occurring under current and future climatic and environmental changes and is also an important link within water resource management in China. Reasonable and standardized water resource dispatching management plans are relevant, not only to the future economic development of China but also to the sustainable and continual development of human society.

5.1. Some Challenges

However, some challenges in dispatching management and strategies that remain to be overcome are the following:

(a) Fragmented management system

Although the main body of China's water resource dispatching management is very organized, management fragmentation results from inter-basin dispatching across a num-

ber of regions and jurisdictions, hindering integrated management, as the numerous government departments and units involved struggle to communicate and coordinate effectively.

(b) Lack of legal documents regulating the management of inter-basin water diversion

Due to the uneven spatial distribution of water resources in China, management of water in a water-deficient area can involve a combination of the real-time management of water in a basin and the introduction of water through inter-basin water diversion. The economic and social benefits of inter-basin water diversion are self-evident. Current laws related to water resource management include the "Water Law of the People's Republic of China" and "Measures for the Implementation of the Water Intake Permit System in the People's Republic of China"; however, no laws, regulatory documents, or corresponding provisions specifically relating to inter-basin water diversion management yet exist, so there is an apparent disconnect between the law and the current situation of the regular regional implementation of an inter-basin water diversion management scheme.

(c) Immature water price mechanism

The problem of pricing water within a diversion project is one of the key factors restricting the benefits of water engineering. The sustainable provision of funds required for the normal maintenance of water diversion infrastructure is not guaranteed, because the water price standard is insufficient to cover operational costs, which can result in infrastructure degradation.

(d) Lack of consideration of environmental water requirements

Water resource dispatching depends mostly on water diversion; however, water diversion projects can have large effects on the ecological environment. For example, Panjiakou is an important link in the water diversion project from the Luanhe River to Tianjin. It became evident during the construction phase that the project seriously impacted the traditional cage fish culture, which previously comprised more than 60,000 fish cages. The upper reaches of the project contain many chemical plants, which discharge large volumes of effluent into the river, leading to serious water quality problems downstream.

5.2. Suggestions for Strategies

Based on the analysis above, some strategies to overcome these challenges are suggested, as follows:

(a) Strengthening the construction of WRDSs

Establishing an integrated management system for water resources through the unified management of main river reaches, reservoirs along the river, water inflows, and water receiving areas can increase the security of the water supply and maximize the benefits of a water diversion project. Meanwhile, a river-basin consultative decision-making and negotiation mechanism could be formed, including local government and the public to facilitate a scientific, efficient, and coordinated water resource allocation and management system for water diversion projects. What is more, according to the characteristics of major water diversion projects, unified institutional construction and operation management could be optimized to improve work efficiency, reduce unnecessary waste, and strengthen the coordination and management of projects. Some advanced algorithms could be used in water resource dispatching management systems [18,23,43].

(b) Perfecting the laws regulating WRDSs

To regulate water resource dispatching management in China, particularly inter-basin water resource dispatching management, it is recommended that appropriate water resource dispatching management norms be used. Once all regions devise management regulations and countermeasures based on their own needs, an integrated strategy for the rational and effective deployment of water resource dispatching management can be ensured.

(c) Water pricing and ecological compensation

Through market-based pricing of water and full integration of democratic consultation, water market development, and government functions, the efficiency and quality of water

resource dispatching management can be improved. The process of monitoring water quality and quantity should be left to a national-level agency. The calculation of a compensation fee should take the quality and quantity of water into account to ensure the integration of ecological compensation such as project compensation and capital compensation, thereby ultimately improving the value of the ecological compensation mechanism.

(d) Building a unified platform for WRDSs

Improvements in information technology will facilitate a trend of increasing access to information in the future. This will enable the construction of intelligent dispatching management systems for river basins, including the establishment of integrated monitoring, simulation, diagnosis, and early warning systems.

6. Conclusions

This study has provided a systematic summary of water resource allocating schemes in China, in terms of their current applications. The construction of water diversion projects and recent developments in water resource dispatching systems on the basin scale were examined, and then the application of different algorithms was reviewed. Finally, the application of WRDSs was addressed, and case studies were examined. The following conclusions can be drawn.

First, in this study, a systematic statement of the development and application of water resource management in China is presented for the first time, including management strategies and techniques. Second, water resource management in different basins has similar demands. The four modules for WRDSs in China are summarized.

Then, by considering the differences in water resource management between inter-basin and single basins, problems of management were highlighted, and techniques were proposed for the South-to-North Water Diversion (inter-basin water diversion) process and Pearl River Basin (water diversion within basins) project. Finally, strategies to resolve the problems of water resource management in China were proposed.

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References

1. Graaf, I.E.M.D.; Beek, L.P.H.V.; Wada, Y.; Bierkens, M.F.P. Dynamic Attribution of Global Water Demand to Surface Water and Groundwater Resources: Effects of Abstractions and Return Flows on River Discharges. *Adv. Water Resour.* **2014**, *64*, 21–33. [CrossRef]
2. Chou, F.N.F.; Lee, H.C.; Yeh, W.; Chou, W.G. Effectiveness and Efficiency of Scheduling Regional Water Resources Projects. *Water Resour. Manag.* **2012**, *27*, 665–693. [CrossRef]
3. Reca, J.; García-Manzano, A.; Martínez, J. Optimal Pumping Scheduling for Complex Irrigation Water Distribution Systems. *J. Water Res. Plan. Manag.* **2014**, *140*, 630–637. [CrossRef]
4. Hassanzadeh, E.; Elshorbagy, A.; Wheater, H.; Gober, P. Managing Water in Complex Systems: An Integrated Water Resources Model for Saskatchewan, Canada. *Environ. Modell. Softw.* **2014**, *58*, 12–16. [CrossRef]

5. Domicelj, S. The Australian Snowy Mountains Scheme: National Growth and Regional Development. *Habitat. Int.* **2010**, *5*, 601–616. [CrossRef]
6. Becker, N.; Easter, K.W. Water Diversions in The Great Lakes Basin Analyzed in A Game Theory Framework. *Water Resour. Manag.* **1995**, *9*, 221–242. [CrossRef]
7. Fischhendler, I.; Zilberman, D. Packaging Policies to Reform the Water Sector: The Case of The Central Valley Project Improvement Act. *Water. Resour. Res.* **2005**, *41*, 41. [CrossRef]
8. Yu, M.; Wang, C.; Liu, Y.; Olsson, G.; Wang, C. Sustainability of Mega Water Diversion Projects: Experience and Lessons from China. *Sci. Total. Environ.* **2018**, *619*, 721–731. [CrossRef]
9. Maier, H.R.; Kapelan, Z.; Kasprzyk, J.; Kollat, J.; Matott, L.S.; Cunha, M.C.; Reed, P.M. Evolutionary Algorithms and Other Metaheuristics in Water Resources: Current Status, Research Challenges and Future Directions. *Environ. Modell. Softw.* **2014**, *62*, 271–299. [CrossRef]
10. Chen, X.; Shi, C.; Wang, Y.; Zhang, H.; Wang, D. Sustainable Water Dispatching for the Lower Reaches of the Yellow River in Non-flood Seasons. *Water. Int.* **2004**, *29*, 492–498. [CrossRef]
11. Rockstrom, J. Water resources management in smallholder farms in Eastern and Southern Africa: An overview. *Phys. Chem. Earth B* **2000**, *25*, 275–283. [CrossRef]
12. Arunkumar, R.; Jothiprakash, V. Chaotic Evolutionary Algorithms for Multi-Reservoir Optimization. *Water Resour. Manag.* **2013**, *27*, 5207–5222. [CrossRef]
13. Comair, G.F.; McKinney, D.C.; Maidment, D.R.; Espinoza, G.; Sangiredy, H.; Fayad, A.; Salas, F.R. Hydrology of the Jordan River Basin: A GIS-Based System to Better Guide Water Resources Management and Decision-Making. *Water Resour. Manag.* **2014**, *28*, 933–946. [CrossRef]
14. Mortazavi-Naeini, M.; Kuczera, G.; Cui, L. Application of Multi Objective Optimization to Scheduling Capacity Expansion of Urban Water Resource Systems. *Water. Resour. Res.* **2014**, *50*, 4624–4642. [CrossRef]
15. Nouiri, I. Multi-Objective Tool to Optimize the Water Resources Management Using Genetic Algorithm and the Pareto Optimality Concept. *Water Resour. Manag.* **2014**, *28*, 2885–2901. [CrossRef]
16. Sun, C.; Ren, L. Assessing Crop Yield and Crop Water Productivity and Optimizing Irrigation Scheduling of Winter Wheat and Summer Maize on The Haihe Plain Using the SWAT Model. *Hydrol. Process.* **2014**, *28*, 2478–2498. [CrossRef]
17. He, L.X.; He, S.H. Solving Water Resource Scheduling Problems Through an Improved Artificial Fish Swarm Algorithm. *Int. J. Simul. Model.* **2015**, *14*, 170–181. [CrossRef]
18. Lei, X.; Tan, Q.; Wang, X.; Wang, H.; Wen, X.; Wang, C.; Zhang, J. Stochastic Optimal Operation of Reservoirs Based on Copula Functions. *J. Hydrol.* **2017**, *557*, 265–275. [CrossRef]
19. Wen, X.; Liu, Z.; Lei, X. Future Changes in Yuan River Ecohydrology: Individual and Cumulative Impacts of Climates Change and Cascade Hydropower Development on Runoff and Aquatic Habitat Quality. *Sci. Total Environ.* **2018**, *633*, 1403–1417. [CrossRef]
20. Leroux, E.F.; Jorgensen, D.G. A System for Planning and Scheduling Water Resources Studies and Construction Projects. *Groundwater* **2010**, *7*, 16–18. [CrossRef]
21. Zhang, Y.R.; Sun, A.; Sun, H.W.; Gui, D.W.; Xue, J.; Liao, W.H.; Yan, D.; Zhao, N.; Zeng, X.F. Error Adjustment of TMPA Satellite Precipitation Estimates and Assessment of Their Hydrological Utility in The Middle and Upper Yangtze River Basin, China. *Atmos. Res.* **2018**, *216*, 52–64. [CrossRef]
22. Barnett, J.; Rogers, S.; Webber, M.; Finlayson, B.; Wang, M. Sustainability: Transfer Project Cannot Meet China's Water Needs. *Nature* **2015**, *527*, 295. [CrossRef] [PubMed]
23. Tan, Q.; Lei, X.; Wang, X.; Wang, H.; Wen, X.; Ji, Y.; Kang, A. An Adaptive Middle and Long-Term Runoff Forecast Model Using the EEMD-ANN Hybrid Approach. *J. Hydrol.* **2018**, *567*, 767–780. [CrossRef]
24. Lei, X.H.; Sugiura, N.; Feng, C.; Maekawa, T. Pretreatment of Anaerobic Digestion Effluent with Ammonia Stripping and Biogas Purification. *J. Hazard. Mater.* **2007**, *145*, 391–397. [CrossRef] [PubMed]
25. Kong, L.Z.; Quan, J.; Yang, Q.; Song, P.; Zhu, J. Automatic Control of The Middle Route Project for South-to-North Water Transfer Based on Linear Model Predictive Control Algorithm. *Water* **2019**, *11*, 1873. [CrossRef]
26. Afshar, A.; Skardi, M.J.E.; Masoumi, F. Optimizing Water Supply and Hydropower Reservoir Operation Rule Curves: An Imperialist Competitive Algorithm Approach. *Eng. Comput.* **2015**, *47*, 1208–1225. [CrossRef]
27. Chen, J. Regulation of Water Resources and Operation of Reservoir Group in The Yangtze River Basin. *J. Hydraul. Eng.* **2018**, *49*, 2–8. (In Chinese) [CrossRef]
28. Li, Y.; Li, W.; Wang, B.; Lui, X.W.; Xie, Y.L.; Liu, L. An Inexact Multi-Objective Programming Model for Water Resources Management in Industrial Parks of Binhai New Area, China. *Water Sci. Technol.* **2015**, *72*, 1879–1888. [CrossRef]
29. Gutman, P.O. A Linear Programming Regulator Applied to Hydroelectric Reservoir Level Control. *Automatica* **1986**, *22*, 533–541. [CrossRef]
30. Birhanu, K.; Alamirew, T.; Dinka, M.O.; Ayalew, S.; Aklog, D. Optimizing Reservoir Operation Policy Using Chance Constraint Nonlinear Programming for Koga Irrigation Dam, Ethiopia. *Water Resour. Manag.* **2014**, *28*, 4957–4970. [CrossRef]
31. Li, Y.P.; Huang, G.H. Interval-parameter Two-stage Stochastic Nonlinear Programming for Water Resources Management under Uncertainty. *Water Resour. Manag.* **2008**, *22*, 681–698. [CrossRef]
32. Anvari, S.; Mousavi, S.J.; Morid, S. Sampling/Stochastic Dynamic Programming for Optimal Operation of Multi-Purpose Reservoirs Using Artificial Neural Network-Based Ensemble Streamflow Predictions. *J. Hydroinform.* **2014**, *16*, 907. [CrossRef]

33. Tilmant, A.; Faouzi, E.H.; Vanclooster, M. Optimal Operation of Multipurpose Reservoirs Using Flexible Stochastic Dynamic Programming. *Appl. Soft Comput.* **2003**, *2*, 61–74. [CrossRef]
34. Ailing, L. A Study on the Large-scale System Decomposition—Coordination Method Used in Optimal Operation of a Hydroelectric System. *Water Int.* **2004**, *29*, 228–231. [CrossRef]
35. Moreira, R.M.M. Simulation–Optimization Modeling: A Survey and Potential Application in Reservoir Systems Operation. *Water Resour. Manag.* **2010**, *24*, 1107–1138. [CrossRef]
36. Yu, Y.B.; Wang, B.D.; Wang, G.L.; Li, W. Multi-Person Multi-Objective Fuzzy Decision-Making Model for Reservoir Flood Control Operation. *Water Resour. Manag.* **2004**, *18*, 111–124. [CrossRef]
37. Chang, J.; Guo, A.; Du, H.; Wang, Y. Floodwater Utilization for Cascade Reservoirs Based on Dynamic Control of Seasonal Flood Control Limit Levels. *Environ. Earth Sci.* **2017**, *76*, 260. [CrossRef]
38. Chen, L.; Chang, F.J. Applying a Real-Coded Multi-Population Genetic Algorithm to Multi-Reservoir Operation. *Hydrol. Process.* **2010**, *21*, 688–698. [CrossRef]
39. Chen, D.; Chen, Q.; Leon, A.S.; Li, R. A Genetic Algorithm Parallel Strategy for Optimizing the Operation of Reservoir with Multiple Eco-environmental Objectives. *Water Resour. Manag.* **2016**, *30*, 2127–2142. [CrossRef]
40. Liu, H.; Dong, J. Dispatching Rule Selection Using Artificial Neural Networks for Dynamic Planning and Scheduling. *J. Intell. Manuf.* **1996**, *7*, 243–250. [CrossRef]
41. Zheng, J.; Yang, K.; Ni, F.Q.; Liu, G.S. Research on Overall Improved Genetic Algorithm Applied in Optimal Generation Dispatching of Multi-Reservoir System. *J. Hydraul. Eng.* **2013**, *44*, 205–211. (In Chinese) [CrossRef]
42. Huang, X.F.; Dongguo, S.; Wenquan, G. Multi-objective chaotic optimization algorithm and its application in optimal water resources deployment. *Kybernetes* **2008**, *37*, 1374–1382. [CrossRef]
43. Sun, H.; Gui, D.; Yan, B.; Liu, Y.; Liao, W.; Zhu, Y.; Zhao, N. Assessing the Potential of the Random Forest Method for Estimating Solar Radiation Using an Air Pollution Index. *Energy Convers. Manag.* **2016**, *119*, 121–129. [CrossRef]