water

*Article*

# Study on Water Quantity Allocation Optimization for Single Main Canal in Large-Scale Irrigation Area Based on DP Method

**Yi Gong [1,*], Wenhao Zou [1], Xiuwei Yuan [2], Xiaoling Yang [3] and Yongfeng Chen [4]**

1 College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China
2 Hongze District Water Conservancy Bureau, Hongze 223100, China
3 Chongqing Academy of Agricultural Sciences, Chongqing 401329, China
4 Liyang Water Conservancy Bureau, Liyang 213300, China
* Correspondence: gongyi@yzu.edu.cn

**Abstract:** The mathematical model of optimal water quantity allocation for a single main canal in a large-scale irrigation area was constructed that took the minimal sum of the squared deviation of water shortage for water receiving areas controlled by the single main canal in one given irrigation period as the study target, and the total irrigation quantity of the single main canal as a constraint condition. Taking the optimal allocation of water quantity of each branch canal as decision variables, and several branch canals under the irrigation sequence of the main canal as a state variable, this model was solved by the one-dimensional dynamic programming (DP) method, by which the minimal water shortage and corresponding optimal water quantity allocation of each branch canal was calculated. The proposed method could provide a decision-making reference for optimal water resources allocation of single main canal irrigation areas, and also provide the theoretical basis for optimal water quantity allocation of a main canal with rotation irrigation by strips or with segmented rotation irrigation mode in China's large-scale irrigation areas. Taking Hengliu Main Canal of Zhouqiao Irrigation Area in Jiangsu Province as a study case, optimization results showed that in a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%), minimal water shortage for water receiving areas controlled by Hengliu Main Canal was respectively $2.57 \times 10^4$ m$^3$ and $23.31 \times 10^4$ m$^3$ during the ponding period of rice. The corresponding water quantity allocation for each branch canal has reflected a compellent model solution precision and efficiency.

**Keywords:** canal; optimization; water quantity allocation; dynamic programming; irrigation area



**Citation:** Gong, Y.; Zou, W.; Yuan, X.; Yang, X.; Chen, Y. Study on Water Quantity Allocation Optimization for Single Main Canal in Large-Scale Irrigation Area Based on DP Method. *Water* **2022**, *14*, 3917. https://doi.org/10.3390/w14233917

Academic Editor: Enrico Creaco

Received: 9 November 2022
Accepted: 28 November 2022
Published: 1 December 2022



## 1. Introduction

As an important kind of infrastructure in agricultural water conservancy project, canals are also indispensable components of water transfer modes in large-scale irrigation areas. China's single large-scale irrigation areas usually cover over $30 \times 10^4$ acres of irrigation area, which leads to the characteristics that water conveyance canals usually include multi-stage and long-distance water conveyance with multiple hydraulic structures along canals at all levels. Affected by water rights control policy enforced by the Chinese government that focuses on agricultural water consumption saving in recent years, and combined with still relatively extensive water distribution management, it is necessary to improve agricultural water resources efficiency in irrigation areas by means of scientific water resources allocation methods. According to the current agricultural farming structures of irrigation areas, a system optimization model could be applied to optimize water quantity allocation for each branch canal of a single main canal to improve full utilization of water resources in irrigation areas, which will also promote increased agricultural production and increasing farmers' income in irrigation areas, and serve China's rural revitalization strategy.

Aiming at efficient utilization of water resources in irrigation areas, conventional research has mainly covered optimization design for vertical and cross sections of canals [1,2], optimal layout of a canal system [3], water allocation optimization of a canal system [4], and optimal allocation of water resources for irrigation areas including canals and field crops [5,6]. Also there is some relevant research focused on heat preservation for lining canals in alpine areas [7,8]. In recent years, studies have paid more attention to multi-objective optimization, including optimization design for canal sections with considerations of water conveyance efficiency and construction cost demands [1], optimal water delivery with multi-objectives of minimal water loss, maximal net benefit of irrigation and drainage [9], multi-water resources optimal allocation with increasing water net benefit and decreasing water-use amount [10], and optimal allocation of water resources considering minimal water loss of the main canal combined with maximal economic benefit of crops in irrigation areas [11,12]. Considering the uncertainties of agricultural irrigation based on agricultural sustainability, stochastic and multi-objective programming [13], multi-scale multi-objective programming [14], inexact interval programming [15], and interval two-stage stochastic programming [16] were developed to optimize agricultural water resources. Wu et al. [17] optimized the cross-section parameters with Matlab, which has the advantages of calculation stability and simplicity on the optimization design of the cross-sections of canals. Xu et al. [18] studied the optimal scheduling of water distribution in irrigation areas, and the optimal scheduling model of water distribution in dry and branch channels was established with the optimization objective of minimum water loss in the irrigation area, and even with changes of the water level in the main channel, using the NSGA-II algorithm. Wang et al. [19] took the minimum leakage loss in the water allocation process as the goal to establish the water allocation model for a channel system with an improved particle swarm optimization algorithm. Singh [20] presented the formulation and application of a management model for the optimal allocation of available good quality water and land resources to maximize the farm revenue of a canal command area.

Considering the researches carried out at home and abroad, it is clear that the optimal water resources allocation of branch canals for a single main canal with a total given water quantity is an important basis for further research on multi-objective optimization, which requires constructing complex mathematical models and applying modern intelligent algorithms. Taking a single main canal with its controlling branch canals as the research object, a mathematical model of optimal water quantity allocation for a single main canal has been put forward in this paper. Optimization theory of complex systems was applied to solve the constructed model, which is used to obtain the optimal water quantity allocation of each one of the branch canals corresponding to the minimal water shortage for water receiving areas. The study results could provide the theoretical basis for optimal water quantity allocation for main canals with rotation irrigation (either by strips or with segmented rotation irrigation) in large-scale irrigation areas, and also provide a highly informative decision-making reference for managers of relevant irrigation areas.

## 2. Model Construction of Optimal Water Quantity Allocation for Single Main Canal

Taking the minimal sum of the squared deviation of the water shortage for the water receiving areas controlled by all of the branch canals of a single main canal in one given irrigation period as the study target, a mathematical model of water quantity allocation optimization for a single main canal in a large-scale irrigation area was constructed that took the optimal allocation of water quantity of each one of the branch canals as decision variables, and the total irrigation quantity of a single main canal as the constraint condition.

$$\text{Objective function}: \ F = \min f = \min \sum_{j=1}^{m} \left( X_j - YS_j \right)^2 \tag{1}$$

$$\text{Constraint condition}: \ \sum_{j=1}^{m} X_j \le W_0 \tag{2}$$

where $F$ = minimal sum of the squared deviation of the water shortage for the water receiving areas controlled by all of the branch canals of a single main canal in one given irrigation period; $f$ = sum of the squared deviation of the water shortage for the water receiving areas controlled by all of the branch canals for a single main canal in one given irrigation period; $m$ = quantity of branch canals for a single main canal; $j$ = branch canal number ($j$ = 1, 2, . . . , $m$); $X_j$ = water quantity allocation of the $j$-th branch canal (m$^3$); $YS_j$ = water requirement of the water receiving area controlled by the $j$-th branch canal (m$^3$); $W_0$ = water right of single water diversion of the main canal (m$^3$).

## 3. Model Solution Method

The above constructed model (1)~(2) is a non-linear mathematical model that takes the position number of each one of the branch canals as stage variables, and the optimal allocation of water quantity of each one of the branch canals as decision variables. Considering the total water quantity allocation of former branch canals as state variable $\lambda_j$, this constructed model could be solved by one-dimensional dynamic programming.

(1) Considering the position number of each one of the branch canals as stage variable $j$, and the total water quantity allocation of former branch canals as state variable $\lambda_j$, the state transition equation could be constructed as follows:

$$\lambda_j = X_j + \lambda_{j-1} \tag{3}$$

(2) According to objective function (1) and state transition Equation (3), the merit function of each optimization stage could be obtained as follows:

① Stage $j$ = 1

$$g_1(\lambda_1) = \min(X_1 - YS_1)^2 \tag{4}$$

The state variable of the first stage $\lambda_1$ is discretized into 0, $W_1$, $W_2$, . . . , $W_0$. For each one of $\lambda_1$, the decision variable $X_1$ is discretized into 0, $X_{11}$, $X_{12}$, . . . , $X_{1\max}$, where $X_{1\max}$ is the maximal water quantity allocation corresponding to the state variable of the first stage $\lambda_1$. The inequality of $X_1 \geq \lambda_1$ should be met according to Formula (2).

② Stage $j$ = 2, 3, . . . , $m-1$

$$g_j(\lambda_j) = \min\left[(X_j - YS_j)^2 + g_{j-1}(\lambda_{j-1})\right] \tag{5}$$

The state variable of the first stage $\lambda_j$ is also discretized into 0, $W_1$, $W_2$, . . . , $W_0$. For each one of $\lambda_j$, the decision variable $X_j$ is also discretized into 0, $X_{j1}$, $X_{j2}$, . . . , $X_{j\max}$, where $X_{j\max}$ is the maximal water quantity allocation corresponding to the state variable of the $j$-th stage $\lambda_j$. The inequality of $\sum\limits_{j=1}^{j} X_j \geq \lambda_j$ should be met, where $j$ = 2, 3, . . . , $m-1$.

According to the state transition Equation (3), the merit function of Formula (5) could be transformed into the following form:

$$g_j(\lambda_j) = \min\left[(X_j - YS_j)^2 + g_{j-1}(\lambda_j - X_i)\right] \tag{6}$$

③ Stage $j$ = $m$

The merit function is as follows:

$$g_m(\lambda_m) = \min\left[(X_m - YS_m)^2 + g_{m-1}(\lambda_{m-1})\right] \tag{7}$$

The state variable of the $m$-th stage $\lambda_m$ is set as $W_0$. According to $\lambda_{m-1} = \lambda_m - X_m$, Formula (7) could be transformed into the following form:

$$g_m(W_0) = \min\left[(X_m - YS_m)^2 + g_{m-1}(W_0 - X_m)\right] \tag{8}$$

The decision variable $X_m$ is also discretized in its feasible region, by which to obtain the minimal sum of the squared deviation of the water shortage for the water receiving areas $F$ and the corresponding optimal water quantity allocation of the $m$-th branch canal $X_m{}^*$.

Finally, searching of the reverse order is carried out by means of a state transition equation of each stage, which would help determine the minimal sum of the squared deviation of the water shortage for the water receiving areas $F$ and the corresponding optimal water quantity allocation of the each one of the branch canal $X_j{}^*$ ($j = 1, 2, 3, \ldots, m$).

## 4. Model Application of Study Case

### *4.1. Basic Information of Hengliu Main Cain System in Zhouqiao Irrigation Area*

Zhouqiao Irrigation Area, located in Hongze District of Jiangsu Province, is a large-scale irrigation area with a designed irrigation area of 0.32 million mu and effective irrigation area of 0.3195 million mu. As the water diversion project, Zhouqiao Sluice has a water diversion capacity of 28 m$^3$/s. There are 8 main canals (sub-trunk canals) with a combined total length of 84.1 km, and 101 branch canals with a combined total length of 267.38 km.

Zhouqiao Irrigation Area has a main canal with a segmented rotation irrigation mode as its operating regime. The Hengliu Main Canal system is chosen from within Zhouqiao Irrigation Area as a study case, which has a length of 4.96 km covering an irrigation area of 11,635 mu. The water receiving area controlled by the Hengliu Main Canal is usually used for rice-wheat crop rotation, whose system generalization and basic information are shown in Figure 1 and Table 1, respectively. The basic information of each one of the branch canals in the Hengliu Main Canal system is shown in Table 2.

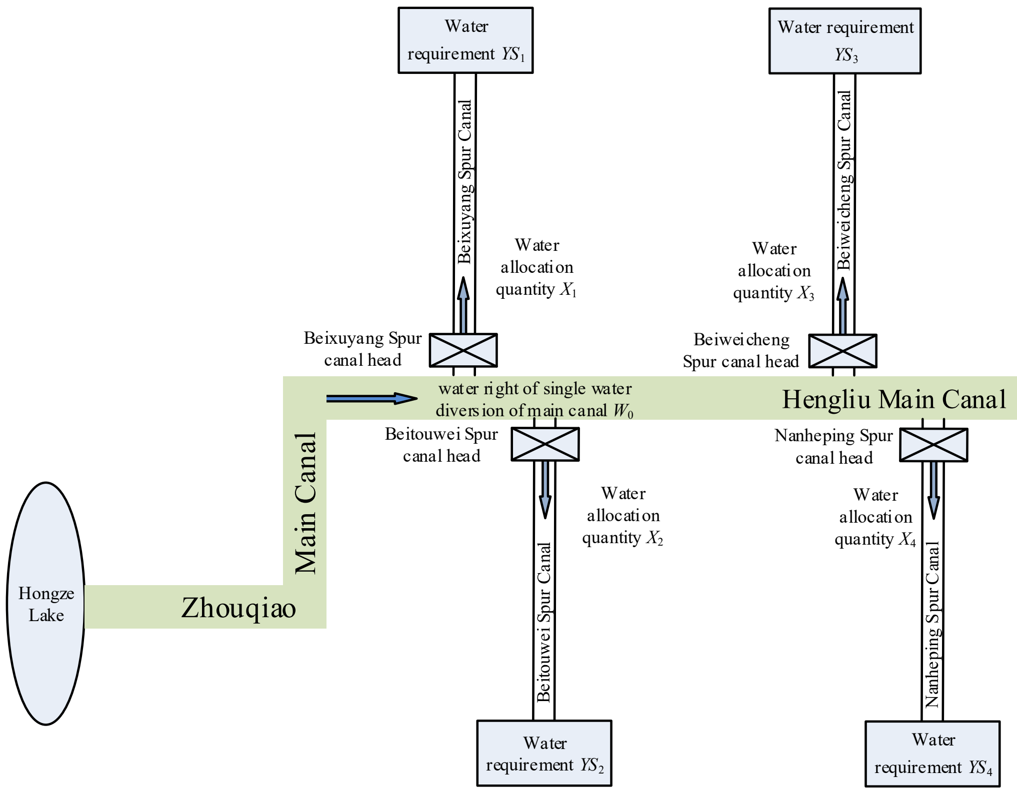


**Figure 1.** System generalization of the water receiving area controlled by the Hengliu Main Canal.

**Table 1.** Basin information of the Hengliu Main Canal.

| Main Canal | Stake Number | Bottom Width $b$ (m) | Slope Ratio $m$ (m) | Water Depth $h$ (m) | Longitudinal Slope $i$ | Roughness $n$ | Design Flow $Q$ ($m^3$/s) |
|---|---|---|---|---|---|---|---|
| Hengliu Main Canal | 0 + 000~2 + 800 | 4.00 | 1.50 | 2.00 | 0.000125 | 0.0225 | 4.14 |
| | 2 + 800~4 + 960 | 4.20 | 1.50 | 1.40 | 0.000125 | 0.0225 | 1.86 |

**Table 2.** Basic information of each of the branch canals in the Hengliu Main Canal system.

| Main Canal | Branch Canal | Length of Branch Canal (km) | Covered Irrigation Area (mu) | Canal Head Structure |
|---|---|---|---|---|
| Hengliu Main Canal | Beixuyang Branch Canal | 2.50 | 2700 | Beixuyang Branch canal head |
| | Beitouwei Branch Canal | 2.52 | 2750 | Beitouwei Branch canal head |
| | Beiweicheng Branch Canal | 2.70 | 3000 | Beiweicheng Branch canal head |
| | Nanheping Branch Canal | 3.99 | 3185 | Nanheping Branch canal head |

### 4.2. Optimal Water Quantity Allocation for Each Branch Canal along Hengliu Main Canal

#### 4.2.1. Analysis of Water Requirement during the Ponding Period of Rice Controlled by the Hengliu Main Canal

Taking the ponding period of rice as an example, and considering 110 $m^3$/mu as the irrigation quota, and respectively considering 0.9, 0.91, and 0.95 as the water utilization coefficient of branch canals, field canals, and fields, respectively, the irrigation water demand of each piece of the water receiving area corresponding to each branch canal was calculated, and is shown in Table 3.

**Table 3.** Analysis of water supply and demand during the ponding period of rice for each piece of the water receiving area corresponding to each branch canal in the Hengliu Main Canal system in different year types.

| Branch Canal | Control Area (mu) | Planting Proportion $\alpha$ | Planting Area (mu) | Crop Water Requirement ($10^4$ $m^3$) | | Available Water Supply ($10^4$ $m^3$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Water Requirement | Water Requirement Converted to Branch Head | Gross Water Supply | | Water Supply Converted to Branch Head | |
| | | | | | | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% |
| Beixuyang Branch Canal | 2700 | 0.68 | 1836 | 20.20 | 23.36 | 25.31 | 20.12 | 22.78 | 18.11 |
| Beitouwei Branch Canal | 2750 | 0.70 | 1925 | 21.18 | 24.49 | 26.54 | 21.09 | 23.88 | 18.99 |
| Beiweicheng Branch Canal | 3000 | 0.72 | 2160 | 23.76 | 27.48 | 29.78 | 23.67 | 26.80 | 21.30 |
| Nanheping Branch Canal | 3185 | 0.70 | 2230 | 24.53 | 28.37 | 30.74 | 24.44 | 27.67 | 21.99 |
| Total | 11,635 | | 8151 | 89.67 | 103.7 | 112.37 | 89.32 | 101.13 | 80.39 |

#### 4.2.2. Analysis of Available Water Supply during the Ponding Period of Rice Controlled by the Hengliu Main Canal

The agricultural water permits of 2019 for Zhouqiao Irrigation Area was 160 million $m^3$ with an effective irrigation area of 0.3195 million mu. For the 11,635 mu covered by the Hengliu Main Canal and the corresponding planting proportion controlled by each branch canal, considering a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%), water demand quantity is respectively 27.53% and 21.88% of the irrigation quota with the corresponding available water supply of 1.604 million $m^3$ and 1.275 million $m^3$, respectively. According to crop planting area of each water receiving area controlled by each branch canal, available water supply for each branch canal under two different year types is obtained which is shown in Table 3.

### *4.3. Results and Analysis of Optimal Water Quantity Allocation for the Hengliu Main Canal System*

Table 3 shows that the total water supply of all the branch canals controlled by Hengliu Main Canal during the ponding period of rice is 1.0113 million $m^3$ and 0.8039 million $m^3$ in a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%), respectively. These two water supply quantities are both less than the total water requirement of 103.7 million $m^3$ for all of the branch canals controlled by Hengliu Main Canal, which makes it necessary to carry out optimal water quantity allocation for all branch canals under the certain water rights.

Taking 1.0113 million $m^3$ and 0.8039 million $m^3$ as the total water supply of Hengliu Main Canal for a ponding period of 6.5 days in a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%), respectively, a one-dimensional dynamic programming can be applied to solve mathematical model (1)~(2) for the total water requirement of 103.7 million $m^3$. From this, the optimal water quantity allocation of each branch canal can be obtained for a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%). The optimization results are shown in Table 4. On the other hand, water quantity allocation results by equal proportion for each water receiving area controlled by its branch canal calculated from the total water quantity of Hengliu Main Canal are shown in Table 5, with the same consideration of a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%). For convenience of discussion, DP-mode was defined as the optimal water quantity allocation with dynamic programming, while EP-mode was defined as water quantity allocation by equal proportion for each water receiving area controlled by its branch canal. The comparison of the water quantity allocation for each branch canal for two above modes is shown in Figure 2.

**Table 4.** Optimal water quantity allocation of each branch canal in the Hengliu Main Canal system during the ponding period of rice in different year types using DP-mode.

| Branch Canal | Water Requirement Converted to Branch Head ($10^4$ $m^3$) | Optimal Water Quantity Allocation for Each Branch Canal ($10^4$ $m^3$) | | Minimal Water Shortage ($10^4$ $m^3$) | | Satisfaction Degree (%) | | Objective Value | |
|---|---|---|---|---|---|---|---|---|---|
| | | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% |
| Beixuyang Branch Canal | 23.36 | 22.72 | 17.54 | 0.64 | 5.82 | 97.26 | 75.09 | 0.41 | 33.87 |
| Beitouwei Branch Canal | 24.49 | 23.85 | 18.66 | 0.64 | 5.83 | 97.39 | 76.19 | 0.41 | 33.99 |
| Beiweicheng Branch Canal | 27.48 | 26.84 | 21.65 | 0.64 | 5.83 | 97.67 | 78.78 | 0.41 | 33.99 |
| Nanheping Branch Canal | 28.37 | 27.72 | 22.54 | 0.65 | 5.83 | 97.71 | 79.45 | 0.42 | 33.99 |
| Total | 103.7 | 101.13 | 80.39 | 2.57 | 23.31 | 97.52 | 77.52 | 1.65 | 135.84 |

**Table 5.** Water quantity allocation of each branch canal in the Hengliu Main Canal system during the ponding period of rice in different year types using EP-mode.

| Branch Canal | Water Requirement Converted to Branch Head ($10^4$ $m^3$) | Optimal Water Quantity Allocation for Each Branch Canal ($10^4$ $m^3$) | | Minimal Water Shortage ($10^4$ $m^3$) | | Satisfaction Degree (%) | | Objective Value | |
|---|---|---|---|---|---|---|---|---|---|
| | | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% | $p$ = 75% | $p$ = 95% |
| Beixuyang Branch Canal | 23.36 | 22.78 | 18.11 | 0.58 | 5.25 | 97.52 | 77.52 | 0.34 | 27.58 |
| Beitouwei Branch Canal | 24.49 | 23.88 | 18.98 | 0.61 | 5.51 | 97.52 | 77.52 | 0.37 | 30.31 |
| Beiweicheng Branch Canal | 27.48 | 26.80 | 21.30 | 0.68 | 6.18 | 97.52 | 77.52 | 0.46 | 38.16 |
| Nanheping Branch Canal | 28.37 | 27.67 | 21.99 | 0.70 | 6.38 | 97.52 | 77.52 | 0.50 | 40.67 |
| Total | 103.7 | 101.13 | 80.39 | 2.57 | 23.31 | 97.52 | 77.52 | 1.66 | 136.72 |

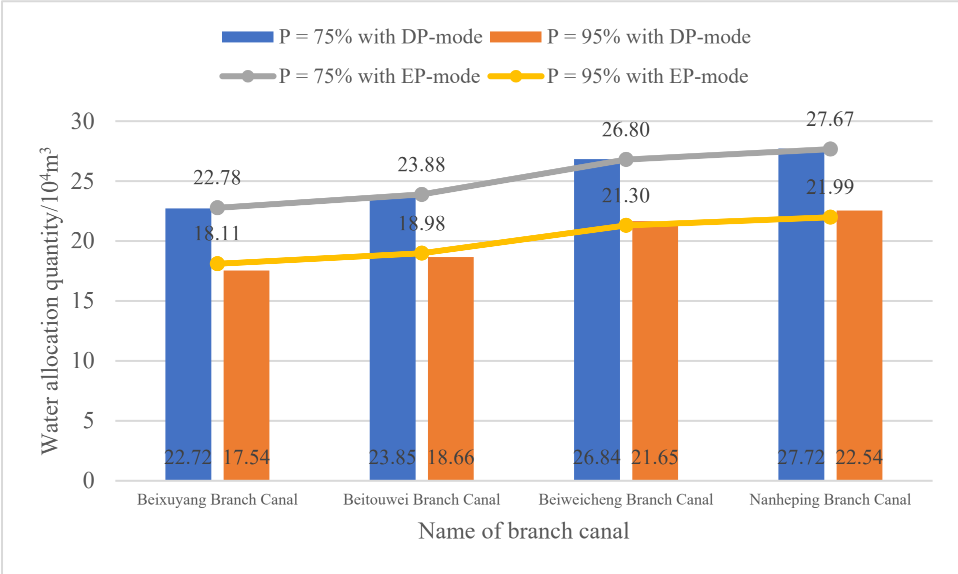


**Figure 2.** Comparison of the water quantity allocation for each branch canal for the two modes.

Combined with Tables 4 and 5, Figure 2 indicates that the minimal water shortage of the Hengliu Main Canal system are $2.57 \times 10^4$ m$^3$ and $23.31 \times 10^4$ m$^3$ in the medium and special drought years, respectively, calculated by the two above water quantity allocation modes. Compared with EP-mode, the real water shortage for each branch canal is better-distributed in a medium drought year ($p$ = 75%, 0.64~0.65 $\times 10^4$ m$^3$) and a special drought year ($p$ = 95%, 5.82~5.83 $\times 10^4$ m$^3$) when calculated using DP-mode, which contributes to alleviate water utilization contradictions of water consumers. By means of optimal water quantity allocation using DP-mode, the decreasing range of the minimal sum of the squared deviation of the water shortage for the water receiving areas is 0.76% and 0.64% corresponding to a medium drought year ($p$ = 75%) and a special drought year ($p$ = 95%), respectively, compared with water quantity allocation calculated using EP-mode.

## 5. Conclusions

Aiming at water supply uniformity for water receiving areas controlled by their respective branch canals in single main canal system, the mathematical model for optimal water quantity allocation of a single main canal was constructed, and a one-dimensional dynamic programming model solution was proposed, by which the optimal water quantity allocation of each branch canal controlled by a single main canal with a single total water supply right was obtained.

According to the optimization and analysis of the case study in different year types, the proposed model and its solution has been proved feasible (with high solution efficiency) for the management of water resources in single main canal systems in an irrigation area. On the basis of the optimization result above, it would be effective to carry out studies on optimal operation of sluice groups along a main canal, which can effectively improve optimal water resources allocation by long-distance automatic controlling of sluice groups. More importantly, the research achievements in this paper provides an important theoretical basis for further studies on the optimization of water resources allocation for main canals with rotation irrigation modes (strips or segmented rotation irrigation) in China's large-scale irrigation areas. For multiple canal systems with complicated operation regimes, large-scale decomposition-dynamic programming aggregation could be effectively applied to realize optimal water resources allocation by taking a single main canal as a subsystem.

A limitation of this study is that short-time rainfall forecasting has not been considered, and this may reduce the optimization benefit of this constructed model, which is something that should be focused on in future studies.

**Author Contributions:** Conceptualization, Y.G.; methodology, Y.G. and W.Z.; software, W.Z.; validation, Y.G.; formal analysis, Y.G.; investigation, Y.C. and X.Y. (Xiaoling Yang); resources, X.Y. (Xiuwei Yuan); data curation, X.Y. (Xiaoling Yang) and X.Y. (Xiuwei Yuan); writing—original draft preparation, Y.G. and X.Y. (Xiaoling Yang); writing—review and editing, Y.G. and X.Y. (Xiuwei Yuan); funding acquisition, Y.G. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by National Key R&D Program of China (2017YFC0403205); Natural Science Foundation of China (52079119); Yangzhou University Science and Technology Innovation Fund in 2019 (2019CXJ071).

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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

## References

1. Liu, D.; Hu, Y.X.; Fu, Q.; Li, T.X. Optimization and parameter analysis for channel cross section with concrete lining in northern irrigation district. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 107–114.
2. Shang, G.L.; Liu, D.; Hu, Y.X. Optimization of irrigation channel section based on cat swarm algorithm and analysis on design parameters. *J. Drain. Irrig. Mach. Eng.* **2016**, *34*, 128–132.
3. Xu, Z.C. Optimal model of channel layout based on minimum spanning trees. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 124–130.
4. Akram, A.A.; Mendelsohn, R. Agricultural water allocation efficiency in a developing country canal irrigation system. *Environ. Dev. Econ.* **2017**, *22*, 571–593. [CrossRef]
5. Kanooni, A.; Monem, M.J. Integrated stepwise approach for optimal water allocation in irrigation canals. *Irrig. Drain.* **2014**, *63*, 12–21. [CrossRef]
6. Khandelwal, S.S.; Dhiman, S.D. Optimal allocation of land and water resources in a canal command area in the deterministic and stochastic regimes. *Water Resour. Manag.* **2018**, *32*, 1569–1584. [CrossRef]
7. Hao, J.C.; Lou, Z.K.; Gao, F. Numerical simulation and slope coefficient optimization of frost heave of trapezoidal channel. *J. Irrig. Drain.* **2017**, *36*, 81–86.
8. Wang, Y.; Liu, J.C.; Liu, Q.H.; Wang, Z.Z. Shape optimization of a trapezoidal canal structure for coupled temperature-water-soil conditions in cold regions. *J. Tsinghua Univ.* **2019**, *59*, 645–654. [CrossRef]
9. Xu, S.Q.; Wang, Y.J.; Qiao, H.Q.; Guo, X.T.; Li, Z.Y.; Xu, E.D. Optimal operation of irrigation and drainage channels based on multiobjective genetic algorithm. *J. Northeast. Agric. Univ.* **2020**, *51*, 80–86.
10. Fu, Q.; Xiao, Y.Y.; Cui, S.; Liu, D.; Li, T.X. Multi-water resources optimal allocation of irrigation district based on fuzzy multi-objective programming. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 222–227.
11. Li, R.H.; Chang, Y.L.; Wang, Z.C. Study of optimal allocation of water resources in Dujiangyan irrigation district of China based on an improved genetic algorithm. *Water Sci. Technol.* **2021**, *21*, 2989–2999. [CrossRef]
12. Pan, Q.; Guo, P.; Zhang, F.; Luo, B.; Zhang, X.X. Study on multi-objective optimal allocation of agricultural water resources in Huangyang Irrigated Area considering canal leakage. *J. Water Resour. Water Eng.* **2020**, *31*, 166–173.
13. Xu, Y.W.; Wang, Y.H.; Liang, D.L.; Fu, Q.; Zhou, Y.; Chen, X.H. Irrigation water resources allocation in Jinxi irrigation district based on agricultural sustainability. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 299–309.
14. Li, M.; Sun, H.; Liu, D.; Singh, V.P.; Fu, Q. Multi-scale modeling for irrigation water and cropland resources allocation considering uncertainties in water supply and demand. *Agric. Water Manag.* **2021**, *246*, 106687. [CrossRef]
15. Gong, X.H.; Zhang, H.B.; Ren, C.F.; Sun, D.Y.; Yang, J.T. Optimization allocation of irrigation water resources based on crop water requirement under considering effective precipitation and uncertainty. *Agric. Water Manag.* **2020**, *239*, 106264. [CrossRef]
16. Cheng, K.; Wei, S.; Ren, Y.T.; Fu, Q. Optimal allocation of agricultural water resources under the background of China's agricultural water price reform-a case study of Heilongjiang province. *Appl. Math. Model.* **2021**, *97*, 636–649. [CrossRef]
17. Wu, F.; Ma, D.; Zai, S.M.; Wu, Y.B.; Feng, X.F. Optimization design of channel cross section based on MATLAB. *J. North. China Univ. Water Resour. Electr. Power* **2018**, *39*, 86–90.
18. Xu, S.Q.; Gao, K.R.; Yue, J.; Wang, Y.C.; Qiao, H.Q.; Wang, Y.J. Based on the NSGA-II irrigation channels of two-stage water delivery and distribution optimization scheduling. *J. Northeast. Agric. Univ.* **2020**, *51*, 71–78.
19. Wang, Q.J.; Yue, C.F.; Li, Y.Z.; Liu, X.F. Optimal allocation of water resources with two-level channel based on improved particle swarm optimization algorithm. *Agric. Res. Arid. Areas* **2019**, *37*, 26–33.
20. Singh, A. Optimal allocation of water and land resources for maximizing the farm income and minimizing the irrigation-induced environmental problems. *Stoch. Environ. Res. Risk Assess.* **2017**, *31*, 1147–1154. [CrossRef]