A Multi-Timescale Integrated Operation Model for Balancing Power Generation, Ecology, and Water Supply of Reservoir Operation

Wenlin Yuan 1, Xueyan Yu 1, Chengguo Su 1,*, Denghua Yan 1,2 and Zening Wu 1

1 School of Hydraulic Science and Engineering, Zhengzhou University, Zhengzhou 450001, China; ywl2009@zzu.edu.cn (W.Y.); yxy2020@gs.zzu.edu.cn (X.Y.); yandh@iwhr.com (D.Y.); zeningwu@zzu.edu.cn (Z.W.)
2 Water Resources Department, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
* Correspondence: suchguo@163.com

Abstract: In traditional ecological scheduling, a single monthly or daily model will lead to the incomplete transmission of ecological information or increase the complexity of solving problems. Therefore, a multi-timescale nested model (MTNM) is proposed. Although the MTNM can express the daily flow process of environmental flow, the quadratic nested calculation method cannot obtain the optimal solution for the daily scheduling scheme. Targeting the problem that long and short-term objectives cannot obtain the optimal solution at the same time, this paper proposes a multi-timescale integrated model (MTIM) which considers the monthly, 10-day, and daily scale. The model is applied to the Luijiaxia reservoir. The scheduling results show that, compared with the MTNM, the MTIM can better meet the multi-objective demand. In a wet year, when both models can guarantee water supply and ecological demand, the MTIM increases electricity generation by 0.91%. In a dry year, electricity generation can still be increased by 4.35% without sacrificing the ecological and water supply benefits of the lower reaches. In different typical years, the MTIM can improve the contradictory relationship between multi-objective by improving the utilization efficiency of water. The results can improve the decision support for the operation process of other reservoirs with ecological needs.

Keywords: multi-objective scheduling; multi-timescale integrated operation model; energy production; environmental flow; water supply

1. Introduction

The reservoirs change the natural runoff of rivers [1], which can supply water to industries and agriculture, prevent the occurrence of flooding as much as possible, and use hydropower to generate electricity to promote economic and social development. The conventional practice of reservoir operation is predominantly to reconcile the benefits of flood control with power generation, with the goals of maximizing the utilization of water resources and economic benefits. However, there are insufficiencies regarding the environmental protection requirements of downstream rivers in the related operation schemes and, as a result, large changes in downstream river discharge severely alter natural flow regimes and impose serious damage on the structure and function of river ecosystems [2–5]. Therefore, it is of great necessity to study the multi-objective reservoir operation based on an ecological operation by integrating ecological objectives into the operation process, with an aim to realize the balance between economic benefits development, such as power generation [6], irrigation [7], flood control [8], and ecological environment protection. With the fulfillment of economic benefits, the negative influence on ecology can be reduced through the regulation of the reservoir scheduling method [9,10]. Therefore, it is very necessary to study the reservoir operation of multi-objective water use problems.
is no single global optimal solution for multi-objective scheduling problems, but there is a group of solutions, which is called Pareto optimal solution or non-dominant solution. Limited by solving techniques in the early stage, the solution of multi-objective optimization problems has been centered on optimization methods [11–13]. However, there are some limitations in applying classical methods to solve multi-objective problems. Although Genetic algorithms (GAs) and Multi-objective evolutionary algorithms (MOEAs) can solve these shortcomings of classical methods, their convergence performance is not good. Deb et al. [14] proved that Nondominated Sorted Genetic Algorithm II (NSGA-II) based on the evolutionary algorithm is superior to Pareto Archived Evolutionary Strategy (PAES) and Strength Pareto Evolutionary Algorithm (SPEA) in finding different solution sets and in finding a truly Pareto optimal solution set. NSGA-II reduces the complexity of the genetic algorithm and has the advantages of fast running speed and good convergence of the solution set. As an effective search algorithm for solving multi-objective problems, the NSGA-II has been widely used in the multi-objective optimization operation of reservoirs and is welcomed by people [15,16]. Bai et al. [17] and Chen et al. [18] used NSGA-II to solve the multi-objective scheduling model. By comparing the benefit changes between multi-objective and single-objective scheduling, the mechanism of action between objectives was analyzed. Xu et al. [19] put forward an analytical framework to guide the rational allocation of water resources and solved it with NSGA-II, which provided technical support for the formulation of local water-saving policies. Although these studies have obtained the scheme set through efficient solving algorithms, most of these schemes still focus on improving the transformation relationship between the benefits of power generation and other dispatching objectives and paid little attention to ecology. It is still necessary to study multi-objective scheduling which focuses on the ecological direction.

In recent years, scholars have carried out a series of experiments and studies in order to explore multi-objective ecological problems. Chen et al. [20] sought the balance of water-energy-ecosystem in the operation of cascade reservoirs through a system modeling approach and proved that the increase of ecological benefits can make up for a loss of benefits of hydropower under certain ecological conditions. Ding et al. [21] determined the environmental flow based on the physical habitat simulation model (PHABSIM), improved the reservoir dispatching map, and guided the multi-objective operation of the reservoir so as to realize the joint improvement of power generation benefit and ecological benefit. Huang et al. [8] and Hirsch et al. [22] formulated reservoir operation rules that could meet ecological requirements through quantitative analysis of the combination of weight coefficients of multiple targets. In the process of calculation, the improved algorithm could solve the Pareto optimal solution, which was closer to the real solution set [23,24]. However, the environmental flow calculation in the ecological operation model merely considers the simple monthly environmental flow. For some aquatic organisms, such as fish, the monthly mean environmental flow cannot convey information such as the timing and duration of hydrological events like pulse flow [25,26]. The sensitivity of hydrological parameters to different timescales should also be considered in mathematical models [27,28]. Changing daily flow process lines can meet the needs of fish at different stages [29,30]. When formulating the ecological operation plan of the reservoir, consideration should be given to increasing the environmental flow process line at daily intervals [31].

Therefore, the daily model is often used in ecological scheduling. He et al. [32] and Li et al. [33] used the Range of Variability Approach (RVA) and the Indicators of Hydrologic Alteration (IHA) to calculate the more detailed environmental flow, including the daily maximum and minimum flow, and incorporated these parameters into the reservoir operation model. Chen et al. [34] took into account the daily demand for native river fish when formulating the environmental flow so as to ensure that the expected ecological benefits would remain unchanged in extremely dry years. By adding detailed ecological constraints during the modeling process or in the selection of schemes, an ecological scheduling scheme satisfying multiple objectives could be formulated. Dhaubanjar et al. [35] established a visual multi-objective scheme decision system to identify multiple scenario comparisons.
Wang et al. [36] introduced a subjective trade-off rate (STOR) and ecological risk analysis to work out a decision-making method for selecting multi-objective schemes. When using the diurnal model, the precision and ecological requirements of the calculation could be satisfied. However, this would involve a large number of decision variable calculations, which would prolong the solving time and increase the complexity of the problem. As a result, the complexity of solving the problem increases. Therefore, a method is needed to deal with a large number of decision variables and daily environmental flow in the optimization model, so as to effectively deduce the daily operation scheme of the reservoir.

Guo et al. [37] proposed the multi-timescale nested reservoir operation model (MTNM), which took into account the monthly model and the daily model. The principle of nested computing ensures that a feasible and high-precision ecological scheduling scheme can be obtained under the macro scheduling law, taking into account both ecological and economic benefits. However, this nested calculation method also has its shortcomings. When the MTNM is used for calculation, the monthly model is used as the boundary condition input of the daily model. Thus, the scheduling scheme solved by the daily model is not closely related to the scheduling scheme of other periods, and the final scheduling effect cannot be fed back to the setting of boundary conditions. The traditional nesting approach uses the output from a long-term operating model to guide short-term operation and gives the long-term objective a higher priority than the short-term objective. The short-term objective could be improved if the constraints imposed by the long-term model are relaxed.

This paper focuses on the optimization of the operation of hydropower stations, which gives consideration to both the power generation benefits and the ecological needs, as well as water supply benefits so as to provide potential technical references for the management and operation of reservoirs. Hence, we propose a methodology that is different from the traditional nesting approach. The multi-timescale integrated model (MTIM) is established by taking the Liujiaxia reservoir in the upper reaches of the Yellow River as an example. Compared with the MTNM, the comprehensive benefit of the reservoir is changed after improving the combination mode of different time scales. Specifically, the MTIM gives long-term scheduling and short-term scheduling the same priority, and the benefits of long-term goals and short-term goals are coordinated and do not interfere with each other. The coordination function of this benefit is reflected in the scheduling scheme, which means that the daily flow process of the month does not need to be constrained by the average daily flow within the month, and the two models will receive feedback from each other’s model and optimize and adjust. Consequently, the contents of this study are (1) use the NSGA-II algorithm to solve the scheduling scheme of the MTIM in three typical representative years: a wet year, a normal year, and a dry year. First of all, it is necessary to establish a mathematical model according to the reservoir task. Then, the whole scheduling period should be divided into different stages according to the characteristics of upstream water and downstream water demand, and the time scale used for calculation should be selected in different stages; (2) compare the calculated results with those of the MTNM. The remainder of the paper is organized as below. Section 2 introduces the Liujiaxia reservoir and divides the dispatching period. Section 3 introduces the MTIM. Section 4 gives the NSGA algorithm for the MTIM and introduces the method for calculating environmental flow. Section 5 compares the MTIM with the MTNM and gives the advantages of the MTIM, and Section 6 summarizes the conclusions.

2. Overview of the Liujiaxia Reservoir on the Yellow River

The Liujiaxia reservoir is located in the upper reaches of the Yellow River in China. It is characterized by year regulating storage and is a very important reservoir on the mainstream of the Yellow River. As shown in Figure 1, the Liujiaxia reservoir is responsible for flood control, power generation, water supply, and other tasks. The discharge of the Liujiaxia reservoir consists of two parts. The first part is the water that passes through the turbine to generate electricity. Since the plant is running at full capacity, the rest of the water can only flow downstream through the spillway. This part of the water is not
used for hydroelectric power. In the lower reaches of the reservoir, the domestic, industrial, and agricultural sectors take the planned amount of water through the drainage channel, and the remaining water is used to maintain the environmental flow of the control section of the river. The normal water level and dead water level of the Liujiaxia reservoir are 1735 m and 1694 m, respectively. The flood control limit water level is 1726 m. The output coefficient of the power station is 8.3, and the installed capacity is 1225 MW.

Figure 1. Watershed map of the Liujiaxia reservoir.

According to the location of the Liujiaxia reservoir, the inflow characteristics of the upstream, and the water demand characteristics of the downstream, the main dispatching target is selected. The primary scheduling target is grouped into category (1), and the remaining scheduling targets are grouped into category (2). Category (1) needs to be given priority when selecting the timescale for calculation, but during the calculation, all scheduling targets are calculated at the same priority. The reasons for assigning scheduling periods and choosing time scales are as follows.

The amount of water in the upper reaches of the Yellow River varies greatly with the seasons, and the boundary between flood season and non-flood season is obvious. The flood season is from July to October. In this stage, the amount of water is abundant and the probability of floodplain floods is relatively high. The floodplain floods can provide habitat and adequate food for juvenile fish, as shown in Table 1. Therefore, it is necessary to set the artificial flood process of the control section of Liujiaxia according to the flood situation of the upstream reservoir. The ice flood season is from late November to late March. The geographical location of the upper reaches of the Yellow River leads to a lower temperature. When the temperature drops below the freezing point, the main channel of the Ningmeng Reach will freeze. To maintain the safety of the Ningmeng Reach, the flow during ice flood season must be reduced to the safety level prescribed by the Yellow River Conservancy Commission (YRCC). Because the Liujiaxia reservoir is the nearest reservoir in the upper reaches of Ningxia and Inner Mongolia, the Liujiaxia reservoir is required to control the flow of the control section of Liujiaxia during the ice flood season. According to the regulations of the YRCC, the discharge of the reservoir should be considered for a 10-day time interval. From April to June, according to the investigation and statistics of the local agricultural department, the main cash crops in the agricultural irrigation area responsible for agricultural water supply in the Liujiaxia reservoir are corn and spring wheat, so there is a large amount of water needed for agricultural irrigation. Irrigation water schemes are usually made on a monthly basis. In addition, domestic and industrial water use does not change much from month to month. The monthly time interval can meet the water supply requirements. Spring is also the season for spawning of carp in the Yellow River. The water temperature above 18 °C is a necessary condition for the spawning of parent fish. The pulse flow of small floods will accelerate the spawning process of parent fish [38]. It is comprehensively considered that Liujiaxia Reservoir undertakes an important task of agricultural water supply, so only setting an appropriate ecological flow in spring will not have a negative impact on the spawning behavior of carp, and the main dispatching objective is still the water supply.
Table 1. Life stages of carp in the Yellow River.

| Life Stages                          | Month | Water Temperature | Main Influencing Factors                         |
|--------------------------------------|-------|-------------------|--------------------------------------------------|
| The gonads mature                    | 2–4   | 17–18 °C          | Water temperature, small pulse floods            |
| Breeding season (spawning and hatching) | 4–6   | 18–25 °C          |                                                  |
| Growing season (juvenile fish growing) | 7–10  | 19–24 °C          | Large floods                                     |
| Overwintering season                 | 11–3  | —                 | —                                                |

Therefore, it is necessary for the reservoir operation model to include multiple time intervals to meet the demand for characteristic reservoir discharge in different periods. As depicted in Table 2, the three operation periods of the Liujiaxia reservoir have been divided, and the time scale of the period needs to be selected. In this study, the MTIM includes the monthly, 10-day, and daily time scales.

Table 2. Scheduling period divided by scheduling cycle.

| Period                          | Spring Irrigation Period (April to June) | Flood Control Period (July to October) | Ice Control Period (November to March of the Following Year) |
|---------------------------------|----------------------------------------|--------------------------------------|-------------------------------------------------------------|
| Key scheduling objectives and priorities | ① Water supply                         | ① Ecology                           | ① Power generation                                           |
| Timescale                       | ② Ecology                              | ② Power generation                   | ② Ecology                                                  |
|                                 | ③ Power generation                     | ③ Water supply                       | ③ Water supply                                              |
|                                 | Monthly                                | Daily                                | 10-Day                                                      |

3. Mathematical Modeling

3.1. Object Functions

With limited water resources, the goal of the multi-objective problem in this research is to seek the maximum comprehensive benefits for power generation, water supply, and ecology in the scheduling horizon. In this paper, three objective functions are selected—maximizing the total power generation, minimizing water supply, and minimization of ecological water shortage. To facilitate comparison, the sequence of the reservoir downstream follows certain principles. In the irrigation period and the transit flood season, the priority of water intake is as follows: (1). Adequate water for domestic and industrial use; (2). Adequate water for agriculture; (3). Sufficient ecological water (the downstream discharge of the reservoir reaches the appropriate ecological discharge); (4). Basic agricultural water (70% of agricultural water); (5). Basic ecological water (the discharge from the reservoir reaches the basic environmental flow). In the flood season: (1). Adequate water for domestic and industrial use; (2). Sufficent ecological water (the downstream discharge of the reservoir reaches the appropriate ecological discharge); (3). Adequate water for agriculture; (4). Basic ecological water (the downstream discharge of the reservoir reaches the basic ecological discharge); (5). Basic agricultural water (70% of agricultural water). Particularly, the water supply objective and ecology objective are indicated with minimizing the shortage of water supply demand and environmental flow. The objectives of flood control and ice flood control are considered as hard operation constraints.

(1) Objective 1: Maximizing the total power generation

The first objective is to maximize the power generation of the reservoir during the scheduling horizon, which is expressed as follows:

\[ \text{max} E = \sum_{j=1}^{N} P_j t_j, \]  \hspace{1cm} (1)

\[ P_j = k q_j^{\text{el}} h_j, \] \hspace{1cm} (2)

where \( E \) represents the total power generation of the hydropower plant during the whole scheduling horizon (in MW·h); \( P_j \) represents the power output in the \( j \)th time interval (in MW); \( N \) is the number of time intervals; \( q_j^{\text{el}} \) denotes the generating
water flow of the hydropower in the $j$th time interval (in m$^3$/s); $h_j$ is the net head of the hydropower in the $j$th time interval (in m); $k$ is the power coefficient of the hydropower; $t_j$ is the duration of the $j$th time interval.

2) Objective 2: Minimizing the total water supply shortage

$$\text{min} W_S = \sum_{j=1}^{N} \left( q_j^{wd} - q_j^{ws} \right) \cdot t_j.$$  (3)

where $W_S$ represents the total water supply shortage during the whole scheduling horizon (in m$^3$), $q_j^{wd}$ denotes the water supply flow in the $j$th time interval (in m$^3$/s), and $q_j^{ws}$ is the corresponding water supply flow demand (in m$^3$/s).

3) Objective 3: Minimizing ecological flow shortage

$$\text{min} W_E = \sum_{j=1}^{N} \left( q_j^e - q_j^{ed} \right) \cdot t_j.$$  (4)

where $W_E$ represents the total ecological water shortage during the whole scheduling horizon (in m$^3$), $q_j^e$ is the environmental flow in the $j$th time interval (in m$^3$/s), and $q_j^{ed}$ is the ecological flow demand in the $j$th time interval (in m$^3$/s).

3.2. Constraints

1) Water balance constraints

$$v_j = v_{j-1} + (q_j^{in} - q_j^{out}) \cdot t_j.$$  (5)

where $v_j$ is the storage volume of the reservoir in the $j$th time interval (in m$^3$); $q_j^{in}$ and $q_j^{out}$ are the inflow and the discharge of the reservoir in the $j$th time interval, respectively (in m$^3$/s).

2) Water level constraints

$$z_{j,\text{min}} \leq z_j \leq z_{j,\text{max}},$$  (6)

$$z_0 = z^{\text{beg}},$$  (7)

$$z_N = z^{\text{end}}.$$  (8)

where $z_{j,\text{max}}$ and $z_{j,\text{min}}$ are the maximum and minimum water level of the reservoir in the $j$th time interval, respectively (in m); $z^{\text{beg}}$ is the initial final water level; and $z^{\text{end}}$ is the target water level at the end of the scheduling horizon (in m).

3) Generating water flow constraints

$$q_{j,\text{min}}^{\text{ele}} \leq q_j^{\text{ele}} \leq q_{j,\text{max}}^{\text{ele}}.$$  (9)

where $q_{j,\text{max}}^{\text{ele}}$ and $q_{j,\text{min}}^{\text{ele}}$ are the maximum and minimum generating water flow of the hydropower plant in the $j$th time interval, respectively (in m$^3$/s).

4) Water discharge balance constraints

$$q_j^{out} = q_j^{\text{ele}} + q_j^{\text{chan}} = q_j^{ws} + q_j^{f}.$$  (10)

where $q_j^{\text{chan}}$ is the flow that flows directly to the downstream reservoir area through the spillway, not involved in power generation in the $j$th time interval (in m$^3$/s); $q_j^{f}$ is the total spillage of the reservoir in the $j$th time interval (in m$^3$/s).
Total water discharge constraints

\[ \frac{q_{j,\text{min}}^{\text{out}}}{\frac{\text{m}^3}{\text{s}}} \leq q_{j}^{\text{out}} \leq \frac{q_{j,\text{max}}^{\text{out}}}{\frac{\text{m}^3}{\text{s}}} \quad (11) \]

where \( q_{j,\text{max}}^{\text{out}} \) and \( q_{j,\text{min}}^{\text{out}} \) are the maximum and minimum water discharge in the \( j \)th interval, respectively (in m\(^3\)/s).

Power output constraints

\[ P_{j,\text{min}} \leq P_{j} \leq P_{j,\text{max}} \quad (12) \]

where \( P_{j,\text{max}} \) and \( P_{j,\text{min}} \) are the maximum and minimum power output in the \( j \)th time interval, respectively (in MW).

### 4. Model Solution Method

#### 4.1. Analysis of the Contradictory Relationship between the Objectives

The conflict of interests among the three objectives mentioned above is a challenge for the optimal operation of the reservoir and the efficient utilization of water resources. Specifically, measures to ensure downstream environmental flow (Obj.3) will cause electricity abandonment that reduces the ability of power generation (Obj.1) and reduces the reservoirs’ storage, which may cause insufficient water supply (Obj.2) during irrigation periods. Besides, during the ice control period, the safe discharge of the Lanzhou Reach is too little to meet the demands of water supply (Obj.2, Obj.3) and power generation (Obj.1) of the Liujiaxia reservoir. To generate more hydroelectric power, the Liujiaxia reservoir tends to reduce the discharge and keeps the reservoir water at a high level to operate at high-efficiency zones in some cases. This may violate the environmental flow demand of the downstream river channel and the water supply demand of downstream cities.

#### 4.2. The NSGA-II Algorithm

As discussed above, the optimal operation of the Liujiaxia reservoir is a multi-object problem, and there is a competitive relationship among the three objective functions. In the NSGA-II approach adopted in this study, the water storage of the reservoir is set as the gene (i.e., decision variable). The chromosomes are made up of genes. Each chromosome (individual) represents a feasible solution, and these individuals form a population.

\[ C_{r_{m}} = \{ v_{1}, ..., v_{j}, ..., v_{n} \}_{m}, m \in [1, P]. \]  

(13)

where \( C_{r_{m}} \) denotes the \( m \)th chromosome in the entire population, \( n \) is the number of individuals in a \( m \)th generation population, and \( P \) is the population size.

#### 4.3. The Shrinkage of Feasible Search Space

In order to take into account the constraints of each period, it is necessary to reduce the search range of the feasible region to improve the speed of calculation. Constraints are divided into three categories: water level constraints, flow constraints, and output constraints. First of all, the water level constraint can determine the search space of the initial feasible region and reduce the search space of the feasible region. Then, the model generates the initial individual according to the flow constraint, judge whether the output constraint is satisfied or not, and regenerate the new individual if it does not meet the requirement. The search scope of the narrowed feasible domain is shown in Figure 2.
4.3. The Shrinkage of Feasible Search Space

In order to take into account the constraints of each period, it is necessary to reduce the search range of the feasible region to improve the speed of calculation. Constraints are divided into three categories: water level constraints, flow constraints, and output constraints. First of all, the water level constraint can determine the search space of the initial feasible region and reduce the search space of the feasible region. Then, the model generates the initial individual according to the flow constraint, judges whether the output constraint is satisfied or not, and regenerates the new individual if it does not meet the requirement. The search scope of the narrowed feasible domain is shown in Figure 2.

Figure 2. Flow chart of shrinking the feasible search space.

The initial population is randomly generated in a certain search feasible region. After the operation of selection, crossover, and mutation, a new generation with a better fitness index is obtained. The evolution process is stopped when a predefined generation time is met. The algorithm is stopped when the number of iterations reaches the predefined generation G. Utilizing iterative optimization, the near-optimal or optimal Pareto solutions can be gradually obtained. The complete solution process for the NSGA-II is shown in Figure 3.

4.4. Ecological Flow Acquisition

According to the annual runoff and fish breeding demand, the environmental flow of the control section of the Liujiaxia reservoir is determined. In order to obtain the basic environmental flow during the non-flood season, the Tennant method is applied to treat 10% and 20% of the average annual runoff as the basic and suitable environmental flow. In the flood season (months 7 to 10), which overlaps with the breeding season of fish in reservoirs and rivers, the basic environmental flow should be increased to 20% of the average annual runoff. The impact of pulse flow on fish should be considered in a suitable environmental flow. The fish-based index of biotic integrity (FIBI) was used to evaluate the river ecosystem in the Yellow River Basin, and the conclusion was that carp was the most abundant fish. Therefore, carp was taken as the representative population to set the necessary factors for the aquatic environment. Ecologists suggest that natural flow factors such as flow, duration, and frequency should be taken into account when managing water resources and that extreme flow events ensure the development and reproduction of indigenous species [39,40].

The pulse flow required for fish should be based on natural runoff data. Matthews et al. [41] improved the ability to calculate the environmental flow by adding five components of flow (Table 3) that are important to river ecosystem health—extreme low flows, low flows, high flow pulses, small floods, and large floods—to the IHA. In this study, the improved IHA are used to calculate the flow process lines needed for fish growth and reproduction.
4.4. Ecological Flow Acquisition

According to the annual runoff and fish breeding demand, the environmental flow of the control section of the Liujiaxia reservoir is determined. In order to obtain the basic environmental flow during the non-flood season, the Tennant method is applied to treat 10% and 20% of the average annual runoff as the basic and suitable environmental flow.

In the flood season (months 7 to 10), which overlaps with the breeding season of fish in reservoirs and rivers, the basic environmental flow should be increased to 20% of the average annual runoff. The impact of pulse flow on fish should be considered in a suitable environmental flow. The fish-based index of biotic integrity (FIBI) was used to evaluate the river ecosystem in the Yellow River Basin, and the conclusion was that carp was the most abundant fish. Therefore, carp was taken as the representative population to set the necessary factors for the aquatic environment. Ecologists suggest that natural flow factors such as flow, duration, and frequency should be taken into account when managing water resources and that extreme flow events ensure the development and reproduction of indigenous species [39,40].

The pulse flow required for fish should be based on natural runoff data. Mathews et al. [41] improved the ability to calculate the environmental flow by adding five components of flow (Table 3) that are important to river ecosystem health—extreme low flows, low flows, high flow pulse, small floods, and large floods.

**Table 3. Ecological flow grouping.**

| Environmental Flow Component | Definition |
|------------------------------|------------|
| Extreme low flows           | The minimum flow required by a river in a dry season, which reduces river connectivity and affects the activity of aquatic organisms. Maintain the continuous flow conditions of the river and maintain a certain water depth in the low-lying parts of the river, which is beneficial to fish and other fish to survive the winter. Provide necessary tips for the migration and spawning of fish; provide a place for the growth of juvenile fish; determine the distribution and abundance of floodplain plants; provide food for aquatic animals. Small floods are not floodplain floods, which are beneficial to expand the habitat area and food sources of aquatic organisms in rivers. Floodplain floods are conducive to river erosion, and high sediment-laden flows can provide a wider habitat and food sources. |
| Low flows                    |            |
| High flow pulse              |            |
| Small floods                 |            |
| Large floods                 |            |
5. Results and Discussion

5.1. Data Input

The data used in this study are from the historical measured data of the Xunhua Hydrological Station from 1965 to 2000. After reduction calculation, frequency analysis was carried out on the long series of runoff data. Three typical runoff types were selected, a wet year (1979–1980), a normal year (1993–1994), and a dry year (1995–1996). The inflow runoff process is shown in Figure 4, and water supply requirements are shown in Figure 5.

The historical daily flow data of the Xunhua hydrological station from July 20 to August 20 of each year from 1965 to 2000 were analyzed, and the hydrologic events were classified by the environmental flow group method. Since most hydrological events do not obey normal distribution, a nonparametric statistical method was used to classify hydrological events in a typical ecological year (1987). As shown in Figure 6, the artificial flood lasted for 17 days. The ratio of the peak discharge of each of the three typical years to peak discharge of this field flood was taken as the proportion of the process line of amplifying typical artificial flood. $k_{\text{wet}} = Q_{\text{m, wet}} / Q_m = 0.9$, $k_{\text{normal}} = Q_{\text{m, normal}} / Q_m = 0.54$, $k_{\text{dry}} = Q_{\text{m,dry}} / Q_m = 0.47$. According to the natural runoff data of the Xunhua hydrographic station from 1956 to 2000, the basic environmental flow is shown in Table 4.

![Figure 4](image-url)  
**Figure 4.** The inflow of the multi-timescale integrated model (MTIM) in a wet year, normal year, and dry year.

**Table 4.** Ecological basic flow in the lower reaches of the Liujiaxia Reservoir.

| Month | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 |
|-------|---|---|---|---|---|---|----|----|----|---|---|---|
| Environmental base flow (m$^3$/s) | 92 | 150 | 200 | 310 | 300 | 330 | 270 | 83 | 42 | 33 | 31 | 40 |
Figure 5. The downstream of the Liujiaxia Reservoir water supply for domestic, industry, and agricultural use in a wet year, normal year, and dry year.

Figure 6. Artificial flood process line representing the year 1987.

The flow constraint of the control section of the Liujiaxia reservoir during the transit flood season is shown in Table 5.
Table 5. The control range of discharge established by the Yellow River Conservancy Commission (YRCC) in the ice flood season.

| Month          | Late November | December | January | February | Early and Mid-March | Late March |
|----------------|---------------|----------|---------|----------|---------------------|------------|
| Maximum value (m³/s) | 750           | 600      | 600     | 410      | 400                 | 450        |
| Minimum value (m³/s)  | 650           | 400      | 400     | 310      | 300                 | 350        |

5.2. The Pareto Solution Set

After many calculations, the main parameters of the NSGA-II algorithm of population size, number of generation, crossover ratio, and mutation ratio were 300, 5000, 0.4, and 0.2, respectively. The average times spent solving the MTIM for a wet year, normal year, and dry year were 228.41 s, 215.50 s, and 208.53 s. The solution set is as follows: The Pareto front contains 300 feasible design alternatives, as shown in Figure 7. The X-axis, Y-axis, and Z-axis represent water supply shortage, ecological water shortage, and electricity generation, respectively. On the whole, the solution set is evenly distributed over the surface. When the power generation is at a maximum, the water shortage of the other two targets is larger, which is caused by the allocation of water resources, and when the water shortage increases to a certain extent, the increasing trend of electricity generation slows down. The relationship between the downstream water supply and ecological water is also studied. When there is a large amount of incoming water, the projection of the scheme set on the X-Y scheme is relatively dispersed, with no obvious linear relationship. The discharged flow can meet the water demand, and the competition between the two is relatively weak. When the inflow is small, the projection of the scheme set on the X-Y scheme is relatively concentrated, and the linear relationship is obvious, indicating the existence of water competition.

![Figure 7. Cont.](image-url)
5.3. Acquisition of Typical Plans

To analyze in detail the influence of the MTIM on the reservoir operation process in terms of time scale combination, typical plans 1–4 and 5–8 were selected from the plan plan sets calculated by the MTIM and MTNM for a wet year, normal year, and dry year. The principles of the selection plan are to lead the plan with minimum ecological water shortage, minimum water shortage, maximum power generation, and compromise. The selection method adopts a weight weighting method.

\[ F = \alpha_1 f_1^* + \alpha_2 f_2^* + \alpha_3 f_3^*. \]  

(14)
where $f^*_1, f^*_2,$ and $f^*_3$ denote the normalized plan target values, respectively; $\alpha_1, \alpha_2,$ and $\alpha_3$ denote the target weights of the plan, respectively; and $\alpha_1 + \alpha_2 + \alpha_3 = 1$. When selecting the plans, the corresponding target weight coefficients were used: plans 1 and 5, $(0,0,1)$; plans 2 and 6, $(0,1,0)$; plans 3 and 7, $(1,0,0)$; plans 4 and 8, $(0.33,0.33,0.33)$.

5.4. Analysis of Plans in a Wet Year

This section mainly makes a comparative analysis of the differences between the two models in different typical years and explains the influence of multiple integrated time scales on the formulation of the scheduling plan.

5.4.1. Competitive Relationships between Multi-Objectives in a Wet Year

It can be seen from Table 6 that, compared with plans 5–7, the power generation of plans 1–3 increased by 0.91%, 0.91%, and 0.31%, respectively, and the downstream ecology and water supply shortage decreased. In particular, the ecology and water supply shortages in plan 3 decreased by 99% and 87%, respectively. However, compared with plan 8, the power generation of plan 4 is increased and the downstream ecological water shortage is reduced, but the downstream water supply shortage is increased. This is due to the mutual transformation of benefits among multiple targets. When selecting a plan, the value of weights will have a certain influence on the distribution of benefits among multiple targets. However, as the benefits of the three scheduling targets cannot be measured by unified standards, the transformation among targets in this study will not be analyzed in too much detail.

Table 6. The set of typical plans calculated by the MTIM and MTNM in a wet year.

| Plan   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Power generation (10^5 MW·h) | 47.85 | 47.85 | 47.89 | 47.86 | 47.42 | 47.42 | 47.74 | 47.48 |
| Water supply shortage (10^6 m³) | 0    | 0    | 2.00 | 1.61 | 0    | 0    | 15.76 | 0.12 |
| Ecological water shortage (10^6 m³) | 0    | 0    | 0.03 | 0.53 | 0    | 0    | 204.25 | 4.24 |

5.4.2. Influence of the MTIM on Power Generation

Plans 1 and 5 have been selected for analysis. When all downstream water demands were satisfied, the generation process of the MTIM and MTNM were compared for analysis.

As shown in Figure 8, the variation trend of the water level in plans 1 and 5 is basically the same. Besides, since the search space was generated in reverse order at the end of the scheduling in the calculation, the water level of plan 1 fell not far above the water level of plan 5 on October 31. Therefore, from November to March of the following year, the change process is similar due to the limitation of flow constraints. As shown in Figure 9, the power generation from April to October is affected by the gap in water level change, and the gap is also large. From April to June and from July to October, plan 1 generated $2.8 \times 10^4$ MW·h and $1.3 \times 10^4$ MW·h more electricity, respectively, compared to plan 5. From April to June, plan 1 released more water to generate electricity. From July to October, the reservoir is in the impoundment period. Although the water level of plan 1 was eventually higher than that of plan 5, and the adjustable water volume of the reservoir was less than that of plan 5, it can be seen from Figure 10 that the minimum value of downstream discharge of plan 1 was lower. During the construction of the artificial flood from August to September, the water head was still high, so the output was always large. In the flood season, the amount of water used for hydropower in plan 1 was 1.87% higher than that in plan 5.
Figure 8. Water level process lines in a wet year.

Figure 9. Diagram of electricity generation in a wet year.

Figure 10. Cont.
Therefore, the output of plan 5 is small. Specifically, the MTNM first uses the monthly model to calculate the boundary water level at the beginning and end of each month and then uses the daily model to calculate the daily dispatching process. When calculating the boundary conditions, the MTNM only considers the average monthly inflow flow and the downstream average monthly ecological water demand. When there is a maximum or minimum of the inflow flow on the same day, the discharge under the reservoir may decrease the output due to the excess of the maximum generation flow or the excessively small generation flow, leading to the decrease of the head or generation flow. However, the MTIM adopts an integrated multi-timescale, and the daily model takes into account all timescale runoff characteristics throughout the year, which enhances the regulating performance of the reservoir.
5.5. Analysis of Plans in a Dry Year

5.5.1. Competitive Relationships between Multi-Objectives in A Dry Year

When the inflow runoff of the Liujiaxia reservoir becomes dry, the water contradiction of the Liujiaxia reservoir becomes more prominent. As can be seen from Table 7, compared with plans 5–8, the power generation of plans 1–4 has increased by 4.24%, 4.09%, 5.97%, and 3.83%, respectively, and the water supply shortage and ecological shortage in the downstream of the reservoir have reduced.

| Plan | 1     | 2     | 3     | 4     | 5    | 6    | 7    | 8     |
|------|-------|-------|-------|-------|------|------|------|-------|
| Power generation (10^5 MW·h) | 47.42 | 47.31 | 47.56 | 47.48 | 45.49 | 45.45 | 44.88 | 45.73 |
| Water supply shortage (10^6 m³) | 0.24  | 0     | 4.66  | 0     | 0.79 | 0.71 | 10.79 | 0     |
| Ecological water shortage (10^6 m³) | 0     | 0     | 119.23 | 59.25 | 24.92 | 24.92 | 178.02 | 91.11 |

5.5.2. Influence of the MTIM on Ecology and Water Supply

Compared with plan 6, the water consumption of hydropower in plan 2 increased by 4.35% in flood season. Not only has the efficiency of power generation been improved, but the demand for downstream water supply and ecological water has also been met. On the whole, plans 1–4 better meet the water use process of the reservoir in a dry year. Although there is a certain water shortage, compared with plans 5–8, the water shortage of all departments is reduced.

A comparison between plans 2 and 6 shows the water allocation process when water inflow is low. As shown in Figure 11, there is a large gap between the water level of plan 2 and that of plan 6 during flood season. As shown in Figure 12, in plan 6, large downstream discharge occurred at the end of July, August, and September. The reason is that the daily scheduling process first needs to meet the constraints of the boundary conditions, and then the optimal scheduling process can be found by using the daily model. At the beginning of the month, the discharge flow under the reservoir in plan 6 is small, and the hydraulic head is lifted, which increases the output process. As shown in Figure 13, when the discharged water cannot meet the water demand, water shortage will occur downstream of the reservoir.

![Figure 11. Water level process lines in a dry year.](image-url)
Figure 12. Daily flow process lines in a dry year.

Figure 13. Water shortage downstream during flood season in a dry year: (a) Water supply shortage; and (b) Ecological water shortage.

There are two reasons for this situation. First, when the MTNM calculated the boundary conditions from July to October, it did not consider the daily maximum inflow in flood season, so the daily model could only raise the head instead of increasing the discharge flow to increase output. Second, after the MTNM uses the monthly model to calculate, it selects the optimal monthly scheduling plan, and then uses the daily model and the ten-day model to solve, which cannot verify that the final daily and ten-day scheduling results are the global optimal solution.

5.6. Analysis of Plans in a Normal Year

Competitive Relationships between Multi-Objectives in A Normal Year

As can be seen from Table 8, the power generation of plans 1–4 is 2.39%, 2.19%, 2.98%, and 4.17% more than that of plans 5–8, respectively. The downstream water supply and ecological water shortage are both reduced. Although it is found that there is still a competitive relationship among the benefits of the three objectives after comparing each other between plans 1–4. Compared with MTNM, MTIM can play a better role in water resource allocation and ensure downstream water consumption. To a certain extent, it alleviates the degree of competition among multi-objectives.
Table 8. The set of typical plans calculated by the MTIM.

| Plan | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------|---|---|---|---|---|---|---|---|
| Power generation ($10^5$ MW·h) | 47.52 | 47.52 | 47.69 | 47.68 | 46.41 | 46.50 | 46.31 | 45.77 |
| Water supply shortage ($10^6$ m$^3$) | 0 | 0 | 2.09 | 1.40 | 0 | 0 | 13.81 | 5.04 |
| Ecological water shortage ($10^6$ m$^3$) | 0 | 0 | 11.89 | 6.29 | 0 | 0.33 | 223.80 | 68.01 |

6. Conclusions

In this paper, on the basis of fully considering power generation, downstream water supply, and ecological benefits, the multi-timescale integrated model (MTIM) was established, and the multi-objective operation scheme of the Lijiaxia reservoir was studied. Aiming at the needs of ecology, the model improves the multi-timescale nested model (MTNM) and adopts the method of integrated calculation. The main content of this paper is the solution to the reservoir dispatching plan for different typical years and a comparison of the two models. Finally, the conclusions of the study are as follows.

The MTIM strengthens the capacity of the reservoir to regulate water, so the benefits of power generation, water supply, and ecology are improved. Specifically, the model reduces the discharge of unused hydroelectric power by reducing the maximum and minimum discharge in the flood discharge process of the reservoir during the impoundment period. According to the plan data, in a wet year, dry year, and normal year, compared with the MTNM, the power generation of the MTIM increased by 0.73%, 4.53%, and 2.93% on average, the ecological water shortage decreased by 93.74%, 67.00% and 95.15% on average, and the downstream water supply shortage decreased by 77.27%, 75.48%, and 78.54% on average, respectively. This is mainly due to the collaborative calculation of monthly, 10-day, and daily models in the MTIM, and the pairwise feedback of the three models to adjust the operation process of the reservoir to its optimal state. As a result, the total amount of water used for power generation in the flood season increased, making it no longer necessary to ensure the power generation benefit during the water storage period at the expense of water supply and ecological benefits.

In summary, the method of integrated computing in the MTIM improves the shortcomings of nested computing in the traditional MTNM and avoids the secondary calculation that leads to the neglect of the optimization of short-term scheduling benefits. The allocation of water by the MTIM improves the water use efficiency of the reservoir and can better meet the multi-objective water demand.

Admittedly, there are still some deficiencies in our current research results that need to be improved. The mathematical model we established is based on deterministic runoff. Therefore, at present, the model is only suitable for deterministic water scenarios. However, in the process of actual operation and management of the reservoir, these dispatching schemes do not have real-time performance. The suggestion to improve this problem is to consider the impact of uncertain incoming water on MTIM and the adverse impact on the transformation process of multiple objectives in the process of multi-objective scheduling when considering the inflow runoff. There are a large number of comprehensive utilization reservoirs on the Yellow River. How to realize the multi-objective utilization of water resources and how to develop social and economic benefits under the prospect of ecologically sustainable development is the research direction in the future.

Author Contributions: Conceptualization, W.Y.; methodology, W.Y. and X.Y.; software, X.Y.; validation, C.S.; formal analysis, W.Y. and C.S.; investigation, D.Y.; resources, Z.W.; data curation, X.Y.; writing—original draft preparation, X.Y.; writing—review and editing, W.Y. and C.S.; visualization, D.Y.; supervision, W.Y.; project administration, D.Y.; funding acquisition, W.Y. All authors have read and agreed to the published version of the manuscript.
22. Hirsch, P.E.; Schillinger, M.; Appoloni, K.; Burkhardt-Holm, P.; Weigt, H. Integrating Economic and Ecological Benchmarking for a Sustainable Development of Hydropower. *Sustainability* 2016, 8, 875. [CrossRef]

23. Zhang, H.F.; Zhou, J.Z.; Fang, N.; Zhang, R.; Zhang, Y.C. An Efficient Multi-Objective Adaptive Differential Evolution with Chaotic Neuron Network and Its Application on Long-Term Hydropower Operation with Considering Ecological Environment Problem. *Int. J. Electr. Power* 2013, 45, 60–70. [CrossRef]

24. Feng, Z.K.; Niu, W.J.; Cheng, C.T. Multi-Objective Quantum-Behaved Particle Swarm Optimization for Economic Environmental Hydrothermal Energy System Scheduling. *Energy* 2017, 131, 165–178. [CrossRef]

25. Poff, N.L.; Richter, B.D.; Arthington, A.H.; Bunn, S.E.; Naiman, R.J.; Kendy, E.; Acreman, M.; Apse, C.; Bledsoe, B.P.; Freeman, M.C.; et al. The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards. *Freshw. Biol.* 2010, 55, 147–170. [CrossRef]

26. Lessard, J.; Hicks, D.M.; Snelder, T.H.; Arscott, D.B.; Larned, S.T.; Booker, D.; Suren, A.M. Dam design can impede adaptive management of environmental flows: A case study from the Opuha Dam, New Zealand. *Environ. Manag.* 2013, 51, 459–473. [CrossRef] [PubMed]

27. Xie, H.I.; Shen, Z.Y.; Chen, L.; Qiu, J.L.; Dong, J.W. Time-Varying Sensitivity Analysis of Hydrologic and Sediment Parameters at Multiple Timescales: Implications for Conservation Practices. *Sci. Total Environ.* 2017, 58, 353–364. [CrossRef] [PubMed]

28. Thompson, S.E.; Katul, G.G. Multiple Mechanisms Generate Lorentzian and 1/F(Alpha) Power Spectra in Daily Stream-Flow Time Series. *Adv. Water Resour.* 2012, 37, 94–103. [CrossRef]

30. Yang, Z.F.; Sun, T.; Cui, B.S.; Chen, B.; Chen, G.Q. Environmental flow requirements for integrated water resources allocation in the Yellow River Basin, China. *Commun. Nonlinear Sci.* 2009, 14, 2469–2481. [CrossRef]

31. Li, R.N.; Chen, Q.W.; Duan, C. Ecological hydrograph based on Schizothorax chongi habitat conservation in the dewatered river channel between Jinping cascaded dams. *Sci. China Technol. Sc.* 2011, 54, 54–63. [CrossRef]

32. He, S.; Yin, X.A.; Yu, C.X.; Xu, Z.H.; Yang, Z.F. Quantifying Parameter Uncertainty in Reservoir Operation Associated with Environmental Flow Management. *J. Clean. Prod.* 2018, 176, 1271–1282. [CrossRef]

33. Li, D.N.; Wang, W.H.; Zhao, J.S. Optimizing Environmental Flow Operations based on Explicit Quantification of IHA Parameters. *J. Hydrol.* 2018, 563, 510–522. [CrossRef]

34. Chen, W.; Olden, J.D. Designing flows to resolve human and environmental water needs in a dam-regulated river. *Nat. Commun.* 2017, 8, 2138. [CrossRef] [PubMed]

35. Dhaubanjar, S.; Davidsen, C.; Bauer-Gottwein, P. Multi-Objective Optimization for Analysis of Changing Trade-Offs in the Nepalese Water–Energy–Food Nexus with Hydropower Development. *Water* 2017, 9, 162. [CrossRef]

36. Wang, X.J.; Dong, Z.; Li, R.N.; Shen, H.B. Study of ecological flow based on the relationship between cyprinus carpio habitat hydrological and ecological response in the lower Yellow River. *J. Hydraul. Eng.* 2020, 51, 1175–1187. [CrossRef]

37. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Stromberg, J.C. The Natura Flow Regime: A Paradigm for River Conservation and Restoration. *BioScience* 1997, 47, 769–784. [CrossRef]

38. Franssen, N.R.; Gido, K.B.; Probst, D.L. Flow Regime Affects Availability of Native and Nonnative Prey of an Endangered Predator. *Biol. Conserv.* 2007, 138, 330–340. [CrossRef]

39. Mathews, R.; Richter, B.D. Application of the Indicators of Hydrologic Alteration Software in Environmental Flow Setting. *J. Am. Water Resour. Assoc.* 2007, 43, 1400–1413. [CrossRef]