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# A hydraulic simulation-optimization model of the joint operation of multiple devices in long-distance water diversion systems under the pumps shutdown process using a parallel NSGA-II approach

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## ABSTRACT

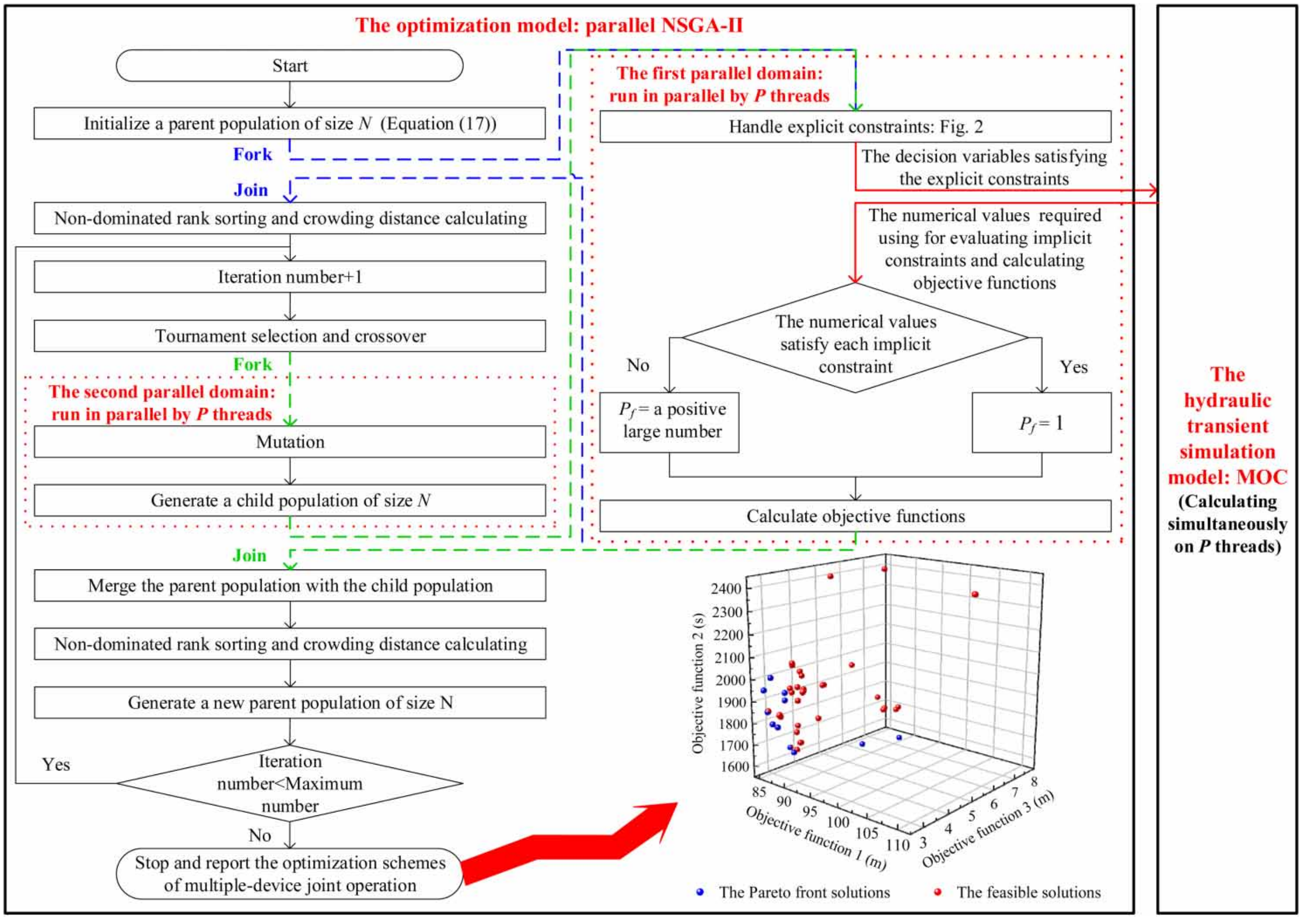
The operation of a long-distance water diversion system in the transient process is a rather complicated problem requiring the joint operation of multiple devices. In this study, the joint operation of multiple hydraulic devices in the pumps shutdown process is expressed as a multi-objective optimization problem, and the hydraulic simulation-optimization model is proposed. The model is a bi-level framework, where the optimization model comprehensively considering various safety risks and efficiency through three objective functions is coupled with the MOC-based hydraulic transient simulation model. The parallel NSGA-II approach is proposed to solve the model. Besides, a process for effectively handling the constraints of the joint optimal operation of multiple hydraulic devices is proposed. Finally, the proposed model and approach are applied to a real long-distance water diversion project. The results show that the proposed model can find a set of feasible Pareto front solutions. The parallel approach greatly improves the computational efficiency. For the Pareto front schemes, the hydraulic devices are adjusted less frequently and the total regulation time is only 1/8.92–1/11.49 of that of the current operation scheme. Thus, this study provides an effective approach to formulate the joint operation scheme of multiple devices of long-distance water diversion systems.

**Key words:** hydraulic simulation-optimization model, long-distance water diversion systems, multiple devices, parallel NSGA-II, transient operation

## HIGHLIGHTS

- A hydraulic simulation-optimization model of the joint operation of multiple devices in long-distance water diversion systems under the pumps shutdown process is proposed.
- The parallel NSGA-II for solving the hydraulic simulation-optimization model is proposed.
- The effectiveness and efficiency of the proposed model and approach are verified with a real long-distance water diversion project.

## GRAPHICAL ABSTRACT




## 1. INTRODUCTION

The water diversion project is intended to divert water from water-rich areas to where it is needed, which contributes significantly to optimizing the spatial distribution of water resources, alleviating water shortage in water-scarce areas, and eventually promoting the coordinated development of society, economy and ecology. Such a project can be regarded as a nonlinear system involving many hydraulic devices and structures. Among them, active hydraulic devices and structures such as pumps and valves are adjustable, while passive ones such as pipes and tanks should be kept to a desired level (Skulovich *et al.* 2016). In the operation of a water diversion project, the transient processes induced by abrupt velocity change of fluid flow is inevitable because of the sudden opening and closing of valves, the pump startup, the pump shutdown, etc. However, the unreasonable design and improper operation may cause harmful transient processes, which may lead to severe vibration, pipe rupture, pipe collapse, tank overtopping, etc (Schmitt *et al.* 2006; Afshar *et al.* 2010; Chen *et al.* 2015; Ye *et al.* 2020). Therefore, the transient processes should be taken into account in the optimal design and operation of any water diversion project.

First, the research on the optimal design considering transient processes has been relatively comprehensive. Jung & Karney (2004) investigated the optimal selection of pipe diameters considering transient analysis by genetic algorithms (GA) and particle swarm optimization (PSO). Liu *et al.* (2011) used the method of characteristics (MOC) to determine the appropriate orifice diameter of air-inlet valves in the pumps shutdown process in a long pipeline pumping system. Lingireddy *et al.* (2000) proposed a surge tank design model that gave an optimal set of surge tank sizes while satisfying a specified set of pressure head constraints. Wang *et al.* (2013) used MOC to investigate the effects of installation mode and position of air vessel on water hammer processes in pumping systems with high working pressure head. Second, in the operation of the water diversion project, the research focuses on effectively controlling the transient processes by optimizing the operation of active hydraulic devices (Zhang *et al.* 2008; Guo *et al.* 2017). Skulovich *et al.* (2016) adopted GA and quasi-Newton to investigate the optimal closure law of the downstream valve by taking the minimization of the maximum pressure head as the objective. Vakil & Firoozabadi (2009) investigated the effects of different valve closure laws on the maximum pressure head rise at the end of the pressure shaft and other components. Bazargan-Lari *et al.* (2013) used a multi-objective optimization model and Bayesian networks to develop an optimal valve closure curve for controlling the water pressure head. However, previous studies of the optimal operation have focused mainly on a single hydraulic device. Due to the limited control range of a single hydraulic device, it is difficult to take into account overall safe and efficient operation requirements of water diversion projects at the same time, especially long-distance water diversion projects. Therefore, it is necessary to study the joint operation of multiple devices in long-distance water diversion projects (Feng & Zheng 2003).

However, the joint operation of multiple hydraulic devices currently relies heavily on personal experience and requires repeated adjustment, resulting in low decision-making efficiency and high manpower cost. Moreover, it is difficult for decision-makers to reduce the complex interrelationships between various operational risks and efficiency into a single-objective problem (Jung *et al.* 2011). Therefore, in this study, the joint operation of multiple hydraulic devices in long-distance water diversion systems is expressed as a multi-objective optimization problem, and a hydraulic simulation-optimization model for the joint operation of multiple devices is proposed. In the hydraulic simulation-optimization model, the optimization model is coupled with the hydraulic transient simulation model. The hydraulic transient simulation model is developed using MOC (Izquierdo & Iglesias 2002; Wang & Yang 2015; Wan & Zhang 2018), which is the most commonly used method (Tian *et al.* 2008; Chalghoum *et al.* 2016). The reason is that the MOC has evident advantages in terms of feasibility, simplicity and efficiency in comparison with other methods (Afshar *et al.* 2010), such as wave characteristics method (WCM) (Wood 2005), finite volume method (FVM) (Zhao & Ghidaoui 2004), finite element method (FEM) (Kochupillai *et al.* 2005) and finite difference method (FDM) (Chaudhry & Hussaini 1985). The pumps shutdown process is selected as the operation process for the study because it is inevitably one of the most common operation conditions. Considering the complex interrelationships of multiple hydraulic devices, and taking various safety risks and efficiency as the objective functions, the optimization model is established. The widely used non-dominated sorting genetic algorithm II (NSGA-II) is adopted to estimate non-dominated solutions.

However, the computational expense of NSGA-II would increase exponentially with increasing number of objectives (Li & Mallick 2015). Thus, the computation is cumbersome for the hydraulic simulation-optimization model that involves a large number of decision variables and objective functions. This problem can be solved by parallel computation (Feng *et al.* 2018). Some simple but powerful parallel frameworks, such as Fork/Join and Message Passing Interface, have also been successfully developed (Dias *et al.* 2013; Pinto *et al.* 2013). In this study, based on the parallel programming OpenMP, the parallel NSGA-II approach is proposed to solve the proposed hydraulic simulation-optimization model. OpenMP is used due to the following advantages: (1) OpenMP provides good single-source portability for shared-memory parallelism, which can consolidate different models into a single syntax and semantics; (2) OpenMP specifically addresses the needs of scientific programming, such as support for Fortran, C/C++ and data parallelism, and our previous NSGA-II algorithms are encoded in C++; (3) OpenMP facilitates an incremental approach to the parallelization of sequential programs, allowing programmers to add a parallelization directive to one loop or subroutine of the program at a time (Hu *et al.* 2000; Rabenseifner *et al.* 2009).

The rest of this paper is organized as follows. Section 2 describes the proposed hydraulic simulation-optimization model; Section 3 describes the parallel NSGA-II approach for solving the model; in Section 4, the effectiveness and efficiency of the proposed hydraulic simulation-optimization model based on a parallel NSGA-II approach is demonstrated by a case study; and conclusions are drawn in Section 5.

## 2. THE HYDRAULIC SIMULATION-OPTIMIZATION MODEL OF THE JOINT OPERATION OF MULTIPLE DEVICES FOR THE PUMPS SHUTDOWN PROCESS OF LONG-DISTANCE WATER DIVERSION SYSTEMS

In practical engineering, limited by economic and geographical conditions, the layout of a long-distance water diversion system is usually one long main pipe with multiple hydraulic devices and structures arranged in series. Its hydraulic devices and structures mainly include pipes, pumping stations, high-level water tanks, regulating tanks, surge tanks, valves, air valves, branch pipes, etc. The pumping station usually contains multiple pump-valve units, which are connected with the main pipe through several branch pipes. Each unit consists of a pump and a valve in series. Besides, the modes of water delivery always involves pressurized water delivery, gravity water delivery and so on. Thus, due to the limited control range of a single hydraulic device, it is difficult to take into account overall safe and efficient operation requirements of long-distance water diversion systems at the same time. The joint operation of multiple hydraulic devices is very necessary but it currently relies heavily on personal experience, and repeated adjustments are often required because of the complex hydraulic coupling relationship of multiple hydraulic devices, resulting in low decision-making efficiency and high manpower cost. Therefore, taking the pumps shutdown process as the research operation condition, a hydraulic simulation-optimization model of the joint operation of multiple devices of long-distance water diversion systems is proposed. The hydraulic simulation-optimization model is composed of the optimization model and the hydraulic transient simulation model, which is a bi-level framework. The coupling idea of the two models is to use an optimization algorithm to generate decision variables in the optimization model that are then passed to a lower level hydraulic transient simulation model to obtain numerical values for use in evaluating all implicit constraints and calculating the objective functions.

## 2.1. The optimization model

The purpose of the optimization model is to optimize the joint operation of multiple hydraulic devices in order to control the transient responses of the pumps shutdown process, so as to realize the overall safe and efficient operation.

### 2.1.1. Decision variables

For the pumps shutdown process, the hydraulic devices that can be actively regulated mainly include multiple pump-valve units in the pumping station and multiple series valves along the pipes. For multiple pump-valve units, a suitable operational time interval between pumps can prevent backflow and overpressure. The one-phase valve closure law and two-phase valve closure law are the main operational rules in the engineering. The valve in the pump-valve unit adopts two-phase closure law to effectively limit the reverse flow rate and the reverse speed of the pump, reducing the pressure pulsation amplitude. The valves along the pipes adopt one-phase closure law, which also can effectively prevent overpressure and water level overlimit by adjusting appropriate corresponding openings when pumps are started to close. Therefore, select the shutdown time intervals between pumps, the total closure time and the inflection openings of the valves in pump-valve units, the time required to reach the inflection openings, and the corresponding opening of each valve along the pipeline when each pump is closed as decision variables.

### 2.1.2. Objective functions

The main indexes to evaluate the safety of the pumps shutdown process are the maximum pressure head of the system, the minimum pressure head of the system, the highest water level of control structures, and the lowest water level of control structures. The control structures refer to the structures with free water surface, such as high-level water tanks, regulating tanks and surge tanks. Therefore, in order to ensure the overall safety and efficiency of the pumps shutdown process and to keep the water level at the design ideal value as much as possible, the proposed optimization model is a three-objective problem. The objective functions include: (1) minimizing the difference between the maximum and minimum pressure head of the system; (2) minimizing the total regulation time; and (3) minimizing the sum of the difference between the highest and design water level and that between the lowest and design water level of control structures:

$$\min P_f(H_{\max} - H_{\min}) \tag{1}$$

$$\min\left(\sum_{p=1}^{l} \varepsilon_p t_{2p} - t_{2m} + \sum_{o=1}^{m-1} t_{go} + t_{\beta m\_\max}\right) \tag{2}$$

$$\min P_f\left[\sum_{r=1}^{y} \left(|Z_{r\max} - Z_{rs}| + |Z_{r\min} - Z_{rs}|\right)\right] \tag{3}$$

where $H_{max}$ and $H_{min}$ are the maximum and minimum pressure head of the system, respectively; $P_f$ is a penalty factor; $m = \sum_{p=1}^{l} \varepsilon_p$, $\varepsilon_p$ is the number of the $p$th type pump, $l$ is the number of pump types; $m$ is the number of pump-valve units connected with the main pipe; $t_{2p}$ is the total closure time of the valve in the $p$th type pump-valve unit; $t_{2m}$ is the total closure time of the valve in the $m$th pump-valve unit; $t_{\beta m\_max} = \max[\beta_{1(m-1)} - \beta_{1m})/100, \ldots, T_{Zu}(\beta_{u(m-1)} - \beta_{um})/100, \ldots, T_{Zc}(\beta_{c(m-1)} - \beta_{cm})/100]$, $\beta_{um}$ is the corresponding opening of the $u$th valve on the main pipe when the $m$th pump is closed; $u = 1,2,\ldots,c$; $c$ is the number of valves along the main pipe; $T_{Zu}$ *is* the time required from fully open (100%) to fully closed (0%) for the $u$th valve on the main pipe; $t_{go}$ is the shutdown interval between the $o$th and $(o+1)$-*th* pumps; $Z_{rmax}$ and

$Z_{rmin}$ are the highest and lowest water level of the $r$th control structure, respectively; $Z_{rs}$ is the design water level of the $r$th control structure; $y$ is the number of control structures.

### 2.1.3. Constraints

1. The constraints of the closure law of the valves in pump-valve units:

$$t_{pc\_\min} \leq t_{1p} \leq t_{1p\_\max} \tag{4}$$

$$t_{2p\_\min} \leq t_{2p} \leq t_{pc\_\max} \tag{5}$$

$$\theta_{p\min} \leq \theta_p \leq \theta_{p\max} \tag{6}$$

In practice, a fast-then-slow valve closure law is preferable to avoid sharp changes in pressure head and to reduce water hammer damage. Thus:

$$t_{1p} < t_{2p} - t_{1p} \tag{7}$$

$$\theta_p < \frac{100(t_{2p} - t_{1p})}{t_{2p}} \tag{8}$$

where $t_{pc\_min}$ and $t_{pc\_max}$ are the minimum and maximum allowable control time of the valve in the $p$th type pump-valve unit, respectively; $\theta_p$, $t_{1p}$ are the inflection openings of the valve in the $p$th type pump-valve unit and the time required to reach that, respectively; $t_{1p\_max}$ *is* the maximum allowable time required to reach the inflection openings of the valve in the $p$th type pump-valve unit; $t_{2p\_min}$ *is* the minimum allowable total closure time of the valve in the $p$th type pump-valve unit; $\theta_{pmin}$ *and* $\theta_{pmax}$ *are* the minimum and maximum inflection openings of the valve in the $p$th type pump-valve unit, respectively.

2. The constraints of the shutdown interval between two pumps:

$$t_{go\_\min} \leq t_{go} \leq t_{go\_\max} \tag{9}$$

   where $t_{go\_min}$ and $t_{go\_max}$ are the minimum and maximum shutdown interval between the $o$th and $(o+1)$-*th* pumps, respectively.

3. The constraints of the closure law of valves along the main pipe:

$$\beta_{ue\_\min} \leq \beta_{ue} \leq \beta_{ue\_\max} \tag{10}$$

In the study, in order to avoid repeated regulation, in the pumps shutdown process, the openings of the valves on the main pipe gradually decrease, which should satisfy Equation (11). What is more, in order to reduce the mutual interference between the control of various devices, the relationship between the openings of the valves on the main pipe and shutdown intervals between pumps should satisfy Equation (12):

$$\beta_{ue} < \beta_{u(e-1)} \tag{11}$$

$$\frac{\beta_{\mathrm{u(e-1)}} - \beta_{\mathrm{ue}}}{100} T_{Zu} \leq t_{ge} + t_{2e} \tag{12}$$

where $\beta_{ue}$ is the corresponding opening of the $u$th valve on the main pipe when the $e$th pump is closed; $e = 1,2,\ldots,m$; $u = 1,2,\ldots,c$; $\beta_{ue\_min}$ *and* $\beta_{ue\_max}$ are the minimum and maximum allowable opening of the $u$th valve on the main pipe when the $e$th pump is closed, respectively; $t_{ge}$ is the shutdown interval between the $e$th and $(e+1)$-*th* pumps; $t_{2e}$ is the total closure time of the valve in the $e$th pump-valve unit.

4. The constraints of the maximum and minimum pressure head of system:

$$H_{\max} \leq H_{s\_\max} = \mathrm{b}H_{w\_\max} \tag{13}$$

$$H_{\min} \geq H_{s\_\min} \tag{14}$$

where $H_{s\_max}$ and $H_{s\_min}$ are the maximum and minimum allowable pressure head of system, respectively; $H_{w\_max}$ is the maximum initial steady-state pressure head of the system; $b$ is a coefficient, which is generally 1.3; $H_{s\_min}$ should not be less than −7.5 m water column height.

5. The constraints of highest and lowest water level of control structures:

$$Z_{rs\min} < Z_{r\min} \tag{15}$$

$$Z_{r\max} < Z_{rs\max} \tag{16}$$

where $Z_{rsmax}$ and $Z_{rsmin}$ are the highest and lowest allowable water level of control structures, respectively.

### 2.2. The hydraulic transient simulation model

A one-dimensional hydraulic transient simulation model is constructed by the MOC method. The MOC method transforms the governing equations (including the momentum and continuity equations) with partial differential form into that with ordinary differential form. The hydraulic devices and structures, such as valves, air valves and pumps, are often treated as boundary conditions, which provide the corresponding supplementary equations (Wylie & Streeter 1978; Tian *et al.* 2008; Chaudhry 2014).

## 3. PARALLEL NSGA-II FOR THE HYDRAULIC SIMULATION-OPTIMIZATION MODEL

Given the computational complexity inherent in solving the hydraulic simulation-optimization model, an parallel NSGA-II approach is proposed in this study to improve the computational efficiency.

### 3.1. Parallel NSGA-II

NSGA-II is an elitist multi-objective evolutionary algorithm (MOEA) with a fast non-dominated sorting and diversity preservation mechanism. NSGA-II has been shown to be capable to find a set of solutions as close as possible to the true Pareto front while maintaining diversity in the obtained solutions (Deb *et al.* 2002). Elitism, where both parent and child populations are considered in selecting members for the consecutive generation, improves the convergence properties of evolutionary algorithms (Stoffa & Sen 1991; Sen & Stoffa 1992; Rudolph 1996). The main challenge with any stochastic optimization algorithm is its computational complexity. The NSGA-II for example has a computational complexity of O ($MN^2$), where $M$ is the number of objectives and $N$ is the population size (Deb *et al.* 2002). This makes NSGA-II computationally expensive. In this work, parallel NSGA-II is implemented to improve the computational efficiency. NSGA-II in detail has been outlined in the literature of King & Rughooputh (2003), Padhi & Mallick (2013a, 2013b), etc. Here we only outline its parallel implementation. The OpenMP based on a fork-join framework is used for parallel execution. OpenMP starts from a single thread called the master thread, which runs continuously in a serial manner until the first parallel domain, and then the content in the parallel domain will be executed by $p$ threads. The internal structure of each sharing task in OpenMP is required to be dynamically encapsulated in the specified parallel region and executed in parallel with the parallelization directive. No new threads are generated when the sharing task is running, and no synchronization directives are set up before the sharing task. Thus, the execution of the task is not affected even if the thread starts at a different time. However, there will be a synchronization directive at the end of the sharing task to ensure OpenMP thread synchronization. That is, when a synchronization directive is encountered at the end of each parallel region and task sharing region, the thread must wait for all threads in the parallel region to finish executing and then proceed to execute the following code. The schematic flow diagram of our parallel NSGA-II is shown in Figure 1.

First, a random parent population of size $N$ is generated within the range of decision variables. This population is then distributed to $p$ threads in the first parallel domain, and the objective functions are calculated on each thread. After all threads in the first parallel domain finish executing, all objective functions of the parent population are sent back to the master thread to sort into different non-dominated ranks. After ranking, the crowding distances for the members belonging to each rank are then calculated. The parent population then undergoes the genetic algorithm (GA) processes of tournament selection, crossover and mutation to generate the child population of size $N$ and the objective functions of the child population are calculated. Among them, the second parallel domain includes the processes of mutation to generate the child population,

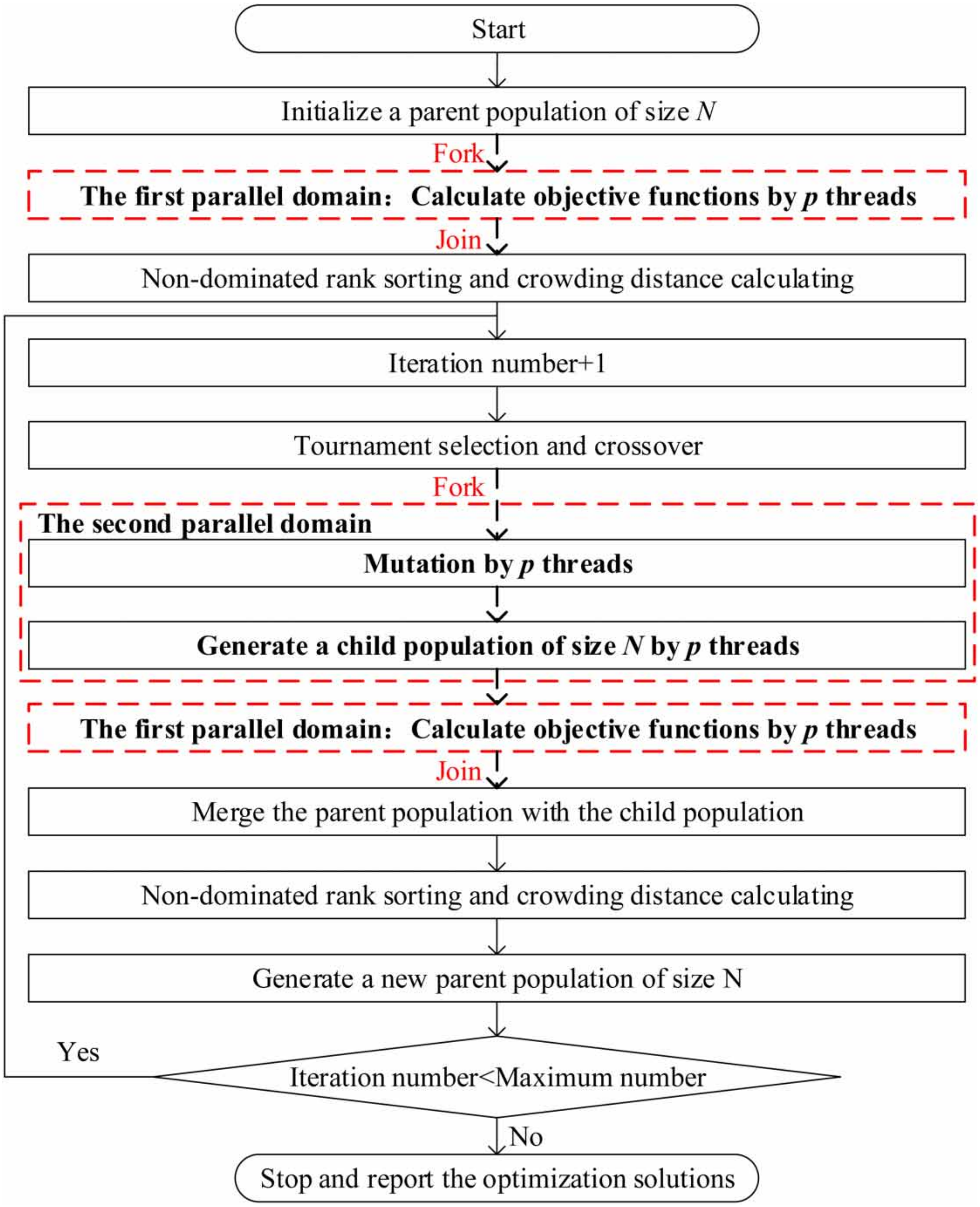



**Figure 1** | Parallel NSGA-II workflow.

which is executed by $p$ threads. After all threads in the second parallel domain finish executing, all objective functions of the child population are calculated by $p$ threads in the first parallel domain. Then, all objective functions of the child population are sent back to the master thread to merge the parent population with the child population and sort the $2N$ solutions into different non-dominated ranks. After ranking, the crowding distances for the members belonging to each rank are calculated and the $N$ new members are selected from the combined population as the new parent population to proceed until the stopping criterion (the maximum number of iterations).

### 3.2. Parallel NSGA-II for the hydraulic simulation-optimization model

In this section, the procedure of the parallel NSGA-II for solving the hydraulic simulation-optimization model of the joint operation of multiple devices is described in detail. The main procedure includes initialization, constraint handling and the coupling of the optimization model and the hydraulic transient simulation model.

### 3.2.1. Structure of individuals and initialization

The array of the decision variable vector is described as follows:

$$[t_{11}, \theta_1, t_{21}, \ldots, t_{1p}, \theta_p, t_{2p}, \ldots, t_{1l}, \theta_l, t_{2l}, t_{g1}, \ldots, t_{go}, \ldots, t_{g(m-1)}, \beta_{11}, \ldots, \beta_{1e}, \ldots, \beta_{1(m-1)}, \ldots, \beta_{u1}, \ldots, \beta_{ue}, \ldots, \beta_{u(m-1)}, \beta_{c1}, \ldots, \beta_{ce}, \ldots, \beta_{c(m-1)}] \tag{17}$$

Individuals are initialed randomly while satisfying various constraints, which are randomly generated between the minimum and maximum values. For instance, $t_{2p}$ is randomly generated between $t_{2p\_min}$ and $t_{pc\_max}$. Generally, these newly generated individuals do not satisfy all the constraints and thus need to be modified by the constraint handling method, which will be described in the next section.

### 3.2.2. Constraint handling

The joint optimal operation problem of multiple devices for the pumps shutdown process of long-distance water diversion systems has a number of inequality constraints, and handling these constraints is critical to effectively solve the problem. The constraints 1–3 (Equations (4)–(12)) are explicit constraints, whose handling flowchart is shown in Figure 2. The constraints 4–5 (Equations (13)–(16)) are implicit constraints, which can only be evaluated by using the corresponding numerical values fed back from the hydraulic transient simulation model. In case any one of the implicit constraints is not satisfied, a penalty factor with a positive large number is added to the objective functions (1) or (3). Otherwise, the penalty factor equals to 1.

As shown in Figure 2, in the first step, if the decision variables do not satisfy Equations (4)–(6) and (9)–(10), those values out of the boundaries can be simply set to be equal to the boundaries. In the second step, if the decision variables do not satisfy Equation (7), $t_{2p}$ can be calculated by Equation (18), and the constraint handling process goes back to the first step:

$$t_{2p} = 2t_{1p} + \Delta t \tag{18}$$

In the third step, if the decision variables do not satisfy Equation (8), $\theta_p$ can be calculated by Equation (19), and the constraint handling process goes back to the first step:

$$\theta_p = \frac{100(t_{2p} - t_{1p})}{t_{2p}} - \Delta\theta \tag{19}$$

In the fourth step, if the decision variables do not satisfy Equation (11), $\beta_{ue}$ can be calculated by Equation (20), and the constraint handling process goes back to the first step:

$$\beta_{ue} = \beta_{u(e-1)} - \Delta\beta \tag{20}$$

In the fifth step, if the decision variables do not satisfy Equation (12), $t_{ge}$ can be calculated by Equation (21), and the constraint handling process goes back to the first step:

$$t_{ge} = \frac{\beta_{\mathrm{u(e-1)}} - \beta_{\mathrm{ue}}}{100} T_{Zu} - t_{2e} \tag{21}$$

### 3.2.3. Coupling of the optimization model and the hydraulic transient simulation model

The calling executive file in the programming language C ++ is used to couple the optimization model and the hydraulic transient simulation model. Specifically, the hydraulic transient simulation model is compiled as an external program into the executive file of the optimization model written in C++. It is also necessary to generate the codes for data transition between the two models. The codes mainly include: (1) writing the decision variables generated by the initialization or iteration of the optimization model into the corresponding position of the input files for the hydraulic transient simulation model; (2) reading and feeding back numerical values used for evaluating all implicit constraints and calculating objective functions in the optimization model from the output files of the hydraulic transient simulation model.

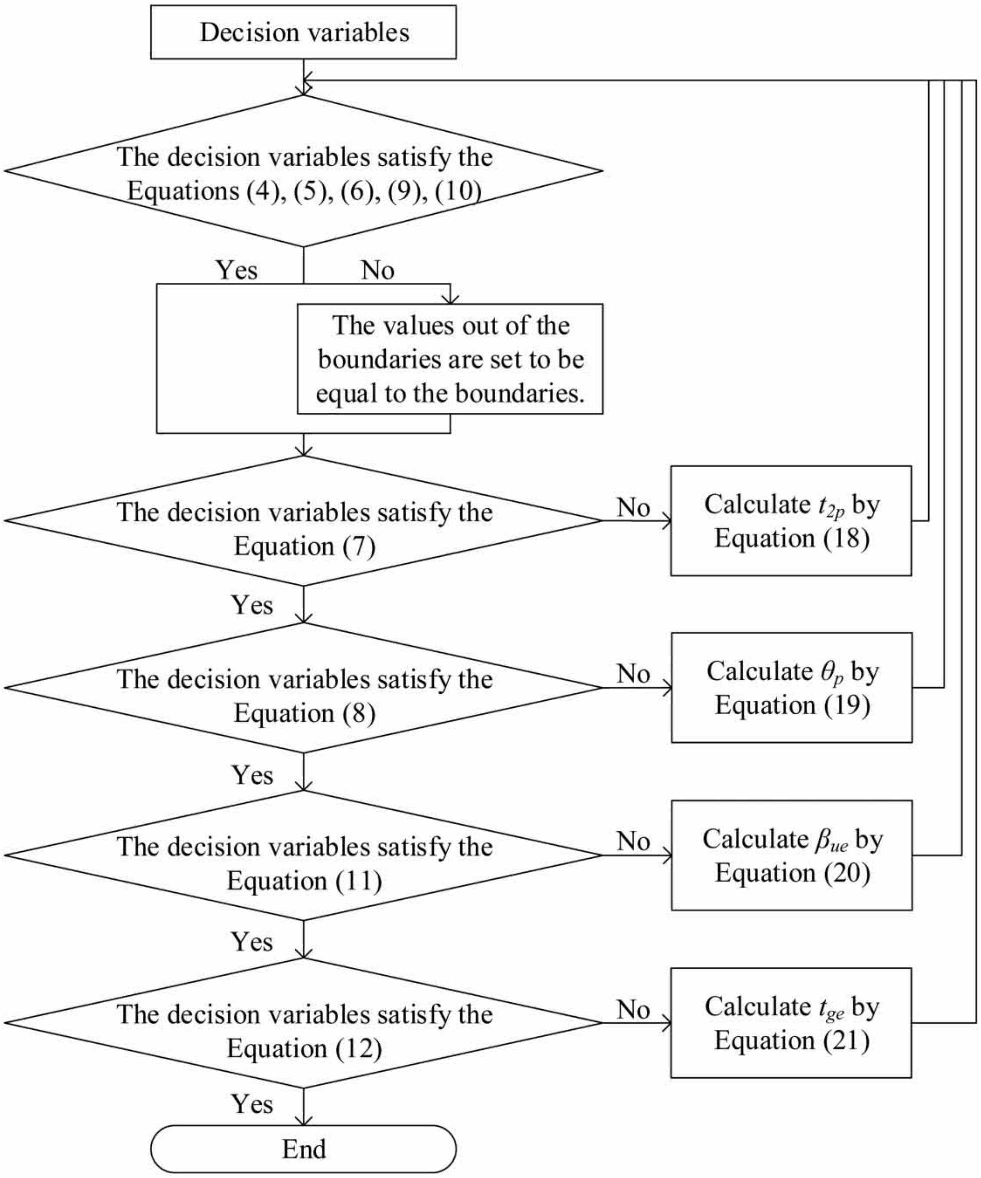



**Figure 2** | Handling flowchart of explicit constraints.

#### 3.2.4. Flow chart of parallel NSGA-II for the hydraulic simulation-optimization model

The flow chart of the proposed parallel NSGA-II for solving the hydraulic simulation-optimization model of the joint operation of multiple devices is illustrated in Figure 3.

## 4. CASE STUDY

The proposed hydraulic simulation-optimization model is applied to a real long-distance water diversion project. In this case study, the joint operation schemes of multiple hydraulic devices during the pumps shutdown process is obtained, the benefits and implications of the Pareto front solutions are discussed, and the efficiency of parallel computing is evaluated.

### 4.1. Case description

The water diversion project is schematically shown in Figure 4, and its longitudinal profile is shown in Figure 5. The project is about 62.6 km long, including 2192 km of tunnel and 60.425 km of pipe. The design cross-section of the tunnel is city gate-shaped, where the bottom width is 2.4 m, the high of the vertical wall is 1.9 m, and the top arch angle is 180°. The diameter of

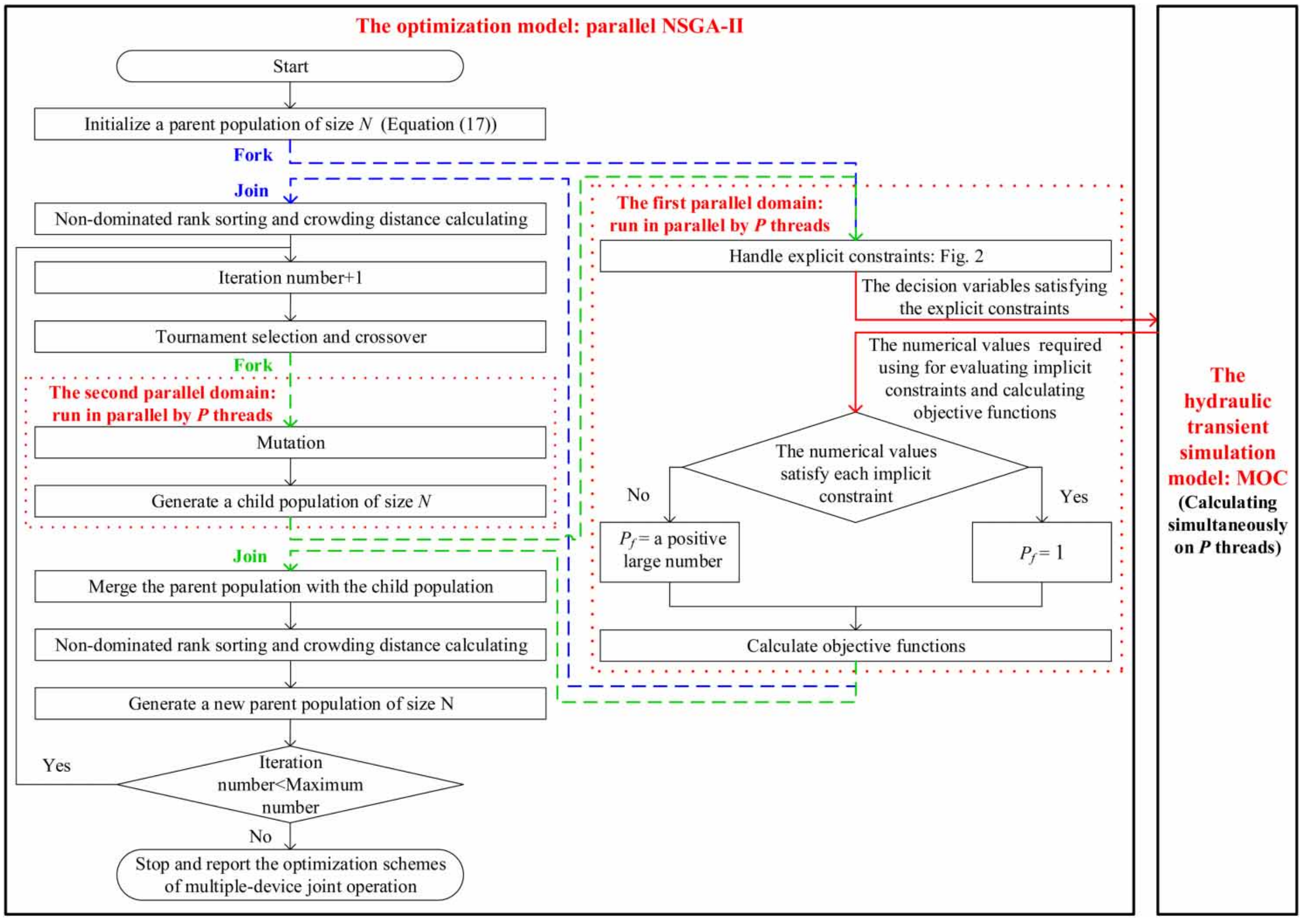



**Figure 3** | Flow chart of the proposed parallel NSGA-II for solving the hydraulic simulation-optimization model.

the steel pipe between 50.906 and 56.367 km and between 60.467 and 62.612 km is 2.0 m, and that of the rest of the pipe is 2.2 m. The design flow rate before the branch pipe is 5.5 $m^3$/s, and that after the branch pipe is 4.8 $m^3$/s. The pumping station consists of four pump-valve units of the same type, including a spare pump-valve unit and three frequently used pump-valve units. The characteristic curves of the pump are shown in Figure 6. The design water level of the forebay of the pumping station is 30.68 m. The high-level water tank is 20 m long and 10 m wide. The top elevation, highest allowable water level, design water level, and lowest allowable water level of the high-level water tank are 94.1, 93.5, 87.53 and 86.8 m, respectively. Both the length and width of the non-pressure regulating tank are 19.8 m. The overflow water level, highest allowable water level, design water level, and lowest allowable water level of the non-pressure regulating tank are 65.0, 65.0, 61.0 and 59.2 m,

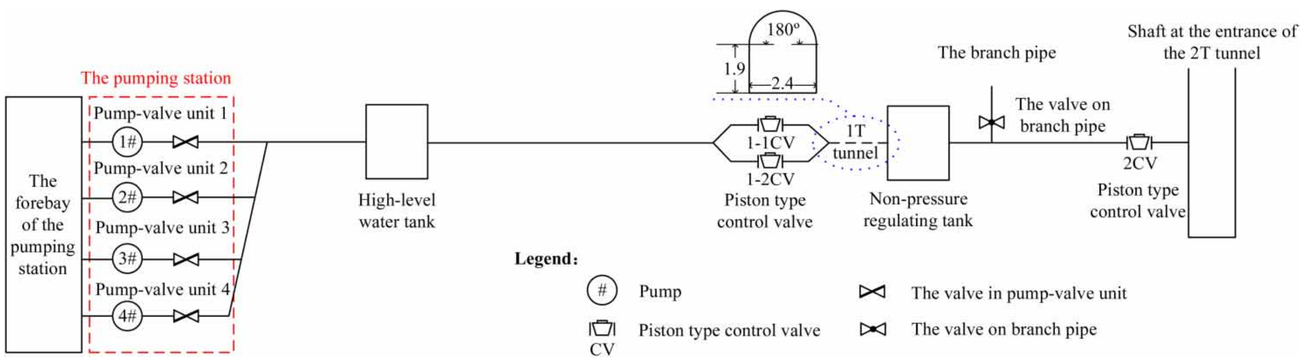



**Figure 4** | Schematic of the long-distance water diversion project.

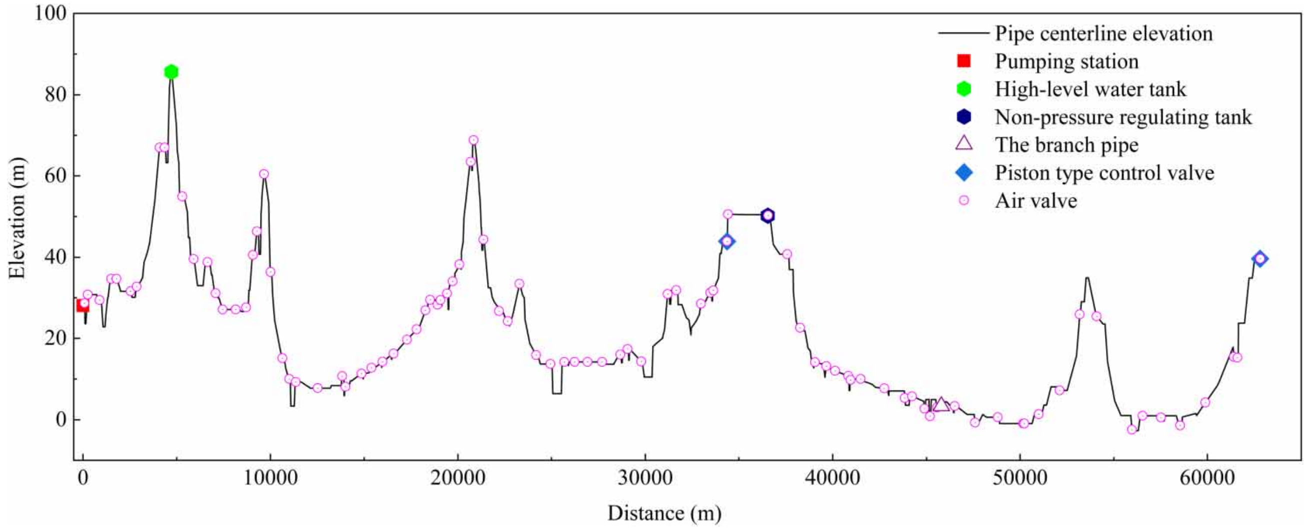



**Figure 5** | Longitudinal profile of the long-distance water diversion project.

respectively. There are 96 air valves along the pipeline. The inlet and outlet diameter of the air valve is 300 mm, and the diameter of the micro hole is 24.5 mm. The opening degree curves of the 1-1(or -2)CV and 2CV piston-type control valves are shown in Figure 7. The design water level of the shaft at the entrance of the 2-T non-pressure tunnel is 41.166 m. Under the design water level of the forebay of the pumping station and the shaft, the operating status of hydraulic devices and the water levels of hydraulic structures are shown in Table 1. The constraint parameters are shown in Table 2. The current pumps shutdown scheme of the project under the above stable state is as follows:

Step 1: Adjustment starts at 0 min. Adjust the opening degrees from 73.87 to 64.44% for 1-1CV and 1-2CV and from 67.36 to 46.11% for 2CV.

Step 2: At 43 min, close pump 1 within 60 s, and adjust the opening degrees from 64.44 to 61.67% for 1-1CV and 1-2CV and from 46.11 to 38.33% for 2CV.

Step 3: At 123 min, adjust the opening degrees from 61.67 to 56.67% for 1-1CV and 1-2CV and from 38.33 to 34.44% for 2CV.

Step 4: At 215 min, close pump 2 and the valve on the branch pipe within 60 s, and adjust the opening degrees from 56.67 to 46.67% for 1-1CV and 1-2CV and from 34.44 to 30 for 2CV.

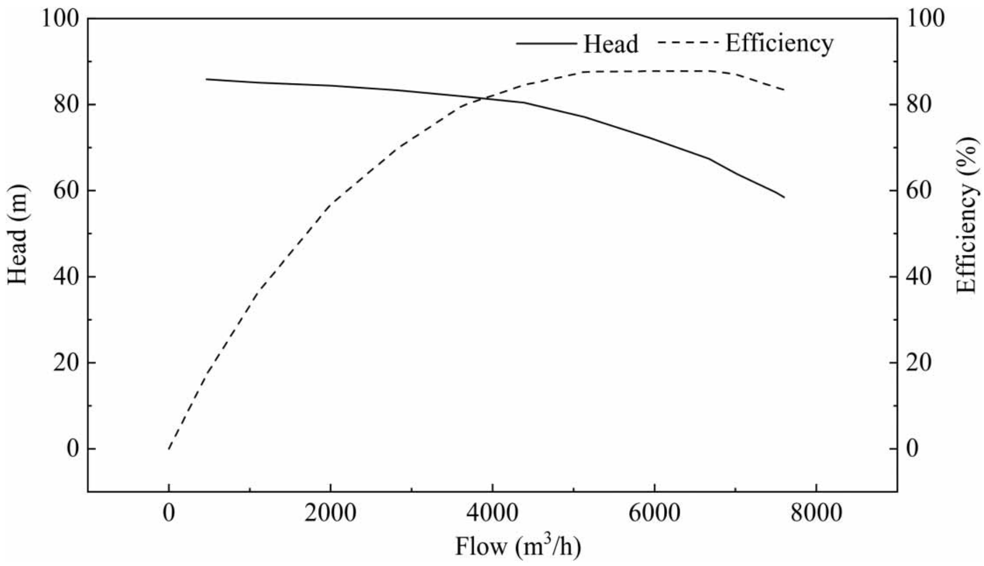



**Figure 6** | Characteristic curves of the pump.

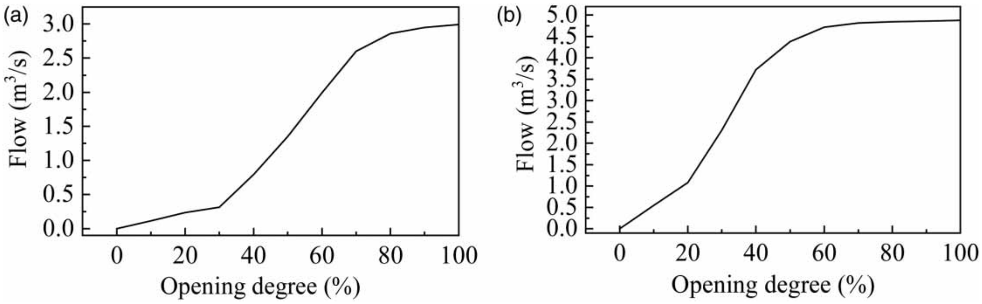



**Figure 7** | Opening degree curves of (A) 1-CV and (B) 2-CV piston-type control valves. (a) Design static pressure head difference: 26.5m. (b) Design static pressure head difference: 19.43m.

**Table 1** | Operating status of hydraulic devices and water levels of hydraulic structures

| | |
|---|---|
| Ratio of the running speed of pump 1 to the rated speed | 1 |
| Ratio of the running speed of pump 2 and 3 to the rated speed | 0.99 |
| Opening degree of the 1-1(or -2)CV piston-type control valve (%) | 73.87% |
| Opening degree of the 2CV piston-type control valve (%) | 67.36% |
| Water level of the high-level water tank (m) | 87.53 |
| Water level of the non-pressure regulating tank (m) | 61.00 |

**Table 2** | Constraint parameters of the joint operation of multiple hydraulic devices

| Constraint parameters | Values | Constraint parameters | Values |
|---|---|---|---|
| $t_{1c\_min}$ (s) | 10 | $\beta_{11\_min}$ or $\beta_{12\_min}$ (%) | 0 |
| $t_{1c\_max}$ (s) | 100 | $\beta_{11\_max}$ or $\beta_{12\_max}$ (%) | 73.87 |
| $t_{11\_max}$ (s) | 20 | $\beta_{21\_min}$ or $\beta_{22\_min}$ (%) | 0 |
| $t_{21\_min}$ (s) | 50 | $\beta_{21\_max}$ or $\beta_{22\_max}$ (%) | 67.36 |
| $\theta_{1\ min}$ (%) | 10 | $T_{Z1}$ (min) | 27 |
| $\theta_{\ 1max}$ (%) | 90 | $T_{Z2}$ (min) | 32 |
| $t_{g1\_min}$ (s) | 390 | $\Delta t$ (s) | 1 |
| $t_{g1\_max}$ (s) | 900 | $\Delta\theta$ (%) | 0.01 |
| $t_{g2\_min}$ (s) | 390 | $\Delta\beta$ (%) | 0.01 |
| $t_{g2\_max}$ (s) | 900 | – | – |

Step 5: At 284 min, close pump 3 within 60 s, and adjust the opening degrees from 46.67 to 0% for 1-1CV and 1-2CV and from 30 to 0% for 2CV.

Under the current pumps shutdown scheme, the total regulation time ($T_{total}$), the maximum, minimum pressure head of the system ($H_{max}$, $H_{min}$), the highest, lowest water level of the high-level water tank ($Z_{1max}$, $Z_{1\ min}$), the highest, lowest water level of the non-pressure regulating tank ($Z_{2max}$, $Z_{2\ min}$) are 296 min, 90.227 m, −0.372 m, 90.51 m, 85.40 m, 61.31 m, 60.49 m, respectively. The values of three objective functions are 90.599 m, 296 min, 5.93 m, respectively.

## 5. RESULTS AND DISCUSSION

### 5.1. Pareto front schemes obtained by the hydraulic simulation-optimization model

There are nine decision variables of this case, $t_{11}$, $\theta_1$, $t_{21}$, $t_{g1}$, $t_{g2}$, $\beta_{11}$, $\beta_{12}$, $\beta_{21}$, $\beta_{22}$, respectively. In order to avoid the problem that the system may be directed toward local optimum rather than the obvious global optimum, and that the calculation time is too much because of many evaluations of objective functions, Haupt & Haupt (2004) considers this population size choice between 20 and 100 as appropriate. The population size as 32 is used in the case study. Mutation probability is 0.04, crossover probability is 0.90, and the number of iterations is 70. The optimization results obtained by the hydraulic simulation-optimization model are shown in Figures 8 and 9, where blue points represent the multi-objective Pareto front solutions, and red points represent the feasible solutions that can be dominated by any member of the multi-objective Pareto front solutions. The detailed information of the multi-objective Pareto front solutions is shown in Table 3.

Since the numerical values fed back from the hydraulic transient simulation model corresponding to the decision variables that satisfy the explicit constraints may not satisfy the implicit constraints, many schemes are not feasible. Figure 9 shows that there are 44 feasible solutions and 11 multi-objective Pareto front solutions for the pumps shutdown process of the project. The number of feasible solutions accounts for only 1.96% of the total simulated solutions and the Pareto front solutions are dispersedly distributed. The main reason is that the adjustment of multiple hydraulic devices can affect and restrict each other and their joint regulation is very sensitive. Thus, it is difficult to find a feasible solution, especially relying on the experience of decision-makers. However, the proposed hydraulic simulation-optimization model can find a set of feasible Pareto front solutions, which makes it possible to avoid the problems of the current joint operation scheme of multiple hydraulic devices that relies heavily on the experience of decision-makers. Compared with the current scheme, there is no need to adjust 1-1CV, 1-2CV and 2CV piston-type control valves before closing pumps 1 and 2 for the feasible schemes, needing less adjustment. The total regulation time required by the Pareto front schemes is only 1/8.92–1/11.49 of the current scheme. Besides, after the pumps shutdown, the steady-state water level of the control structure in the feasible schemes is between the highest and the lowest allowable water level, while that of the high-level water tank in the current scheme is slightly lower than its lowest allowable water level. This indicates that the feasible schemes calculated by the hydraulic simulation-optimization model is safer and more efficient, and can avoid repeated regulation, improve decision-making efficiency and reduce manpower cost and mechanical loss.

It can be known from Figure 9(b)–9(d) and 9(g) that the difference between the maximum and minimum pressure head in the feasible solutions is less than 89 m except for one feasible solution (111.58 m). The reason is that the opening degree at the

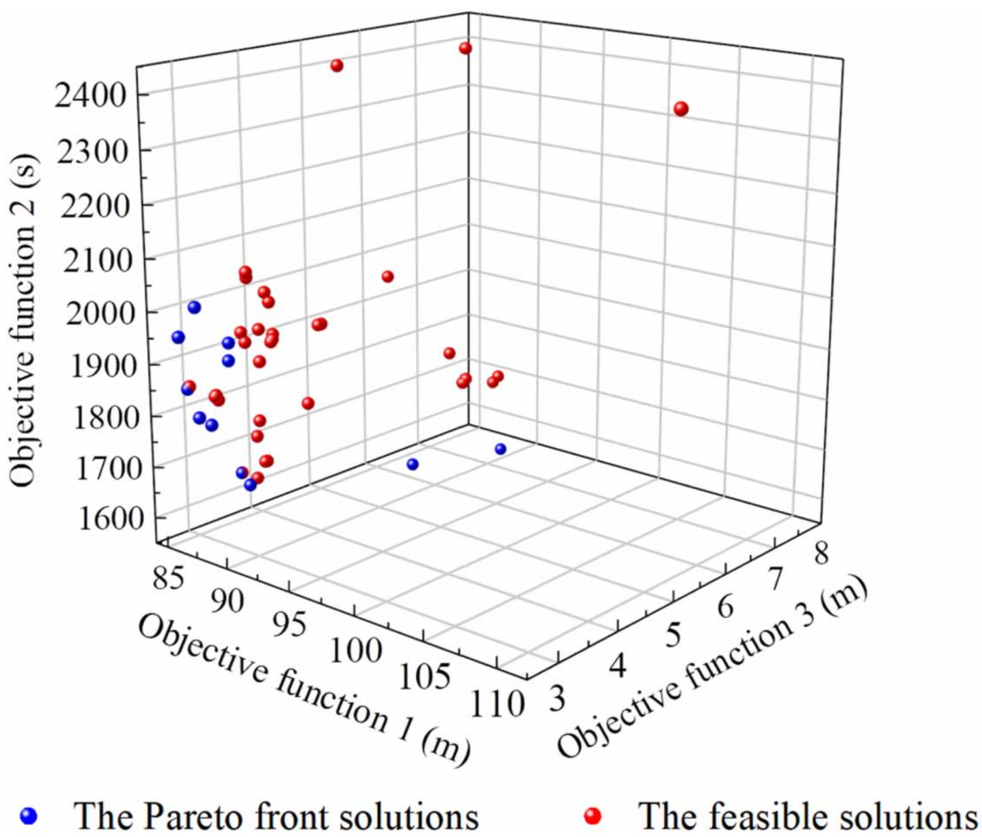



**Figure 8** | 3D representation of the optimization results.

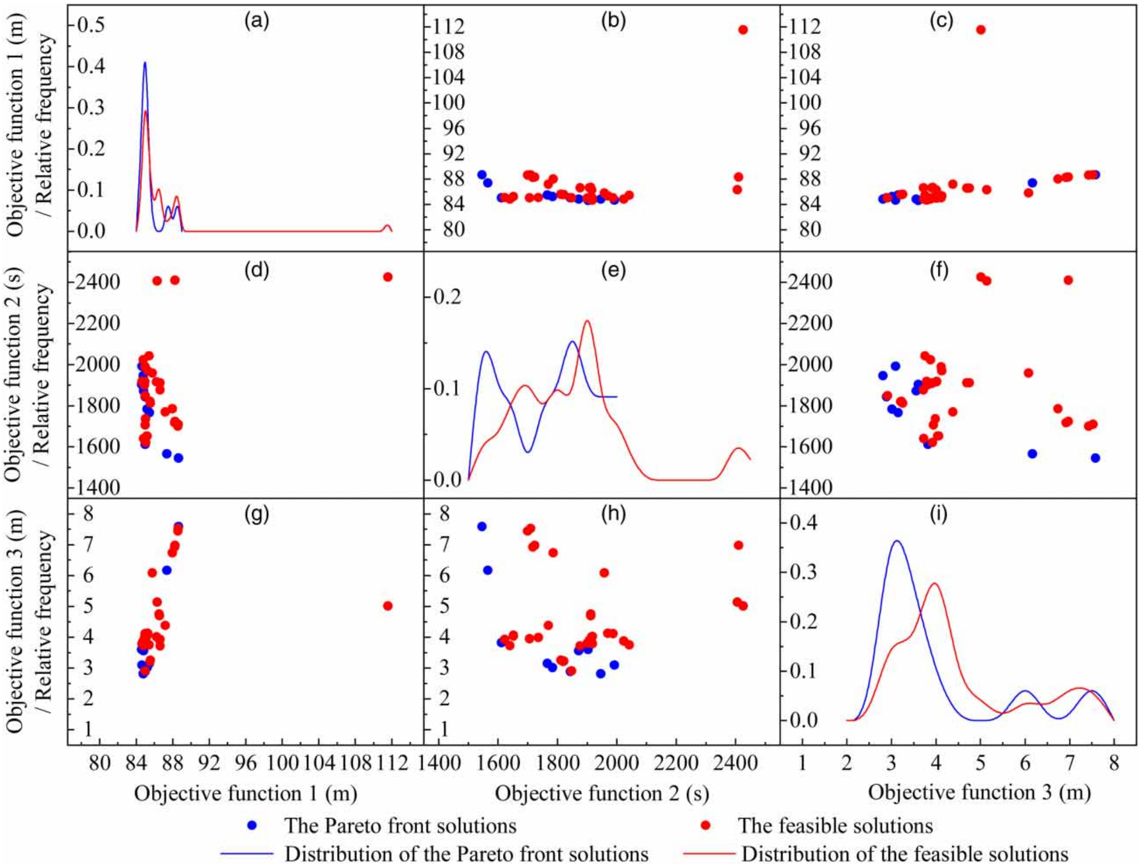



**Figure 9** | 2D representation of the optimization results.

end of fast closure of the valve in pump-valve unit of this feasible solution is larger, indicating that the fast closure is slower and the slow closure is faster. For this feasible solution, when other decision variables are kept unchanged and the opening degree at the end of fast closure of the valve in the pump-valve unit is adjusted from 40 to 22.22%, the pressure head fluctuation of the system can be reduced to 87.36 m. However, there are no significant changes in the water levels of the high-level water tank and the non-pressure regulating tank, except a slight decrease in the highest and lowest water levels. The highest water level of the high-level water tank has the greatest impact, but it is decreased by only 0.08 m. These results indicate that the closure law of the valve in the pump-valve unit has a greater impact on the water hammer pressure head of the pipes than on the water levels of the high-level water tank and the non-pressure regulating tank. The reason is that the water hammer process is relatively short relative to the change of the water levels of the high-level water tank and the non-pressure regulating tank. In addition, this solution will be dominated by the multi-objective Pareto front solutions in the optimization process. Comparison of Figure 9(a), 9(e) and 9(i) suggests that the distribution of feasible solutions of objective function 1 are nearer to that of the multi-objective Pareto front solutions compared to those of objective functions 2 and 3. The reason is that although the closure law of the valve in the pump-valve unit has a great impact on the water hammer pressure head of the pipes, it is easy to make the maximum and minimum pressure heads of the system within the allowable range because the pump is closed in sequence during the pumps shutdown process and the closing speed of the piston-type control valve on the main pipe is relatively slow. Given the restriction between the closure law of piston-type control valves and the shutdown intervals between pumps, objective functions 2 and 3 converge slowly near the multi-objective Pareto front solutions.

### 5.2. Computational efficiency of parallel NSGA-II

In order to verify the computational efficiency of parallel NSGA-II for solving the proposed simulation-optimization model, a multi-core DELL server (Intel(R) Xeon(R) CPU E5-2630 v4 @ 2.2 GHz(10cores), 32GB RAM) is used to analyze the execution time, acceleration ratio and parallel efficiency of the case with a population size of 32 and a generation number

**Table 3** | Detailed information of the multi-objective Pareto front solutions

| | Objective functions | | | Decision variables | | | | | | | | | Numerical values calculated by the hydraulic transient simulation model for use in evaluating all implicit constraints and calculating the objective functions | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solutions | Objective functions 1 (m) | Objective functions 2 (s) | Objective functions 3 (m) | $t_{11}$ (s) | $t_{21}$ (s) | $\theta_1$ (%) | $t_{g1}$ (s) | $t_{g2}$ (s) | $\beta_{11}$ (%) | $\beta_{12}$ (%) | $\beta_{21}$ (%) | $\beta_{22}$ (%) | $H_{max}$ (m) | $H_{min}$ (m) | $Z_{1max}$ (m) | $Z_{1\,min}$ (m) | $Z_{2max}$ (m) | $Z_{2\,min}$ (m) |
| 1 | 88.64 | 1,546 | 7.58 | 17 | 76 | 22.22 | 580 | 670 | 54.44 | 8.89 | 33.33 | 5.56 | 89.89 | 1.25 | 92.59 | 86.85 | 60.92 | 59.24 |
| 2 | 87.37 | 1,566 | 6.17 | 13 | 80 | 14.44 | 530 | 750 | 58.89 | 7.78 | 37.78 | 1.11 | 88.58 | 1.22 | 91.56 | 86.82 | 60.92 | 59.66 |
| 3 | 84.99 | 1,612 | 3.82 | 14 | 79 | 13.33 | 530 | 510 | 58.89 | 25.56 | 37.78 | 7.78 | 86.19 | 1.21 | 89.20 | 86.81 | 60.92 | 59.66 |
| 4 | 84.81 | 1,640 | 3.72 | 13 | 80 | 13.33 | 530 | 500 | 58.89 | 27.78 | 37.78 | 12.22 | 86.02 | 1.21 | 89.10 | 86.81 | 60.92 | 59.66 |
| 5 | 85.48 | 1,766 | 3.15 | 13 | 80 | 13.33 | 530 | 500 | 58.89 | 35.56 | 37.78 | 7.78 | 86.68 | 1.21 | 88.53 | 86.81 | 60.92 | 59.66 |
| 6 | 85.21 | 1,784 | 3.01 | 13 | 80 | 13.33 | 530 | 500 | 58.89 | 36.67 | 37.78 | 7.78 | 86.41 | 1.21 | 88.40 | 86.81 | 60.92 | 59.66 |
| 7 | 84.99 | 1,844 | 2.89 | 13 | 81 | 13.33 | 570 | 500 | 58.89 | 37.78 | 37.78 | 7.78 | 86.20 | 1.21 | 88.31 | 86.81 | 60.97 | 59.64 |
| 8 | 84.81 | 1,872 | 3.56 | 13 | 76 | 18.89 | 590 | 500 | 58.89 | 38.89 | 33.33 | 6.67 | 86.04 | 1.23 | 88.29 | 86.83 | 61.83 | 59.72 |
| 9 | 84.81 | 1,946 | 2.81 | 15 | 73 | 18.89 | 690 | 480 | 58.89 | 38.89 | 33.33 | 24.44 | 86.03 | 1.22 | 88.27 | 86.83 | 60.92 | 59.72 |
| 10 | 84.61 | 1,904 | 3.61 | 13 | 83 | 18.89 | 590 | 500 | 58.89 | 40 | 33.33 | 7.78 | 85.86 | 1.25 | 88.23 | 86.86 | 61.96 | 59.73 |
| 11 | 84.64 | 1,992 | 3.1 | 14 | 82 | 14.44 | 660 | 520 | 58.89 | 40 | 37.78 | 7.78 | 85.86 | 1.22 | 88.22 | 86.83 | 61.30 | 59.60 |

of 70 in single, two, four, six, eight and ten-core computing environments. The results are shown in Table 4 and Figure 10. The acceleration ratio ($S_p$) is the ratio of the execution time in single-core computing environments to that in $W$-core computing environments under the same amount of calculation. The parallel efficiency ($E_p$) is the ratio of the acceleration ratio to the number of cores.

Table 4 shows that as the number of parallel cores increases, the execution time is significantly reduced and the acceleration ratio increases, which demonstrates the high computational efficiency of the parallel approach. However, the parallel efficiency decreases with the the number of parallel cores increasing, as shown in Table 4 and Figure 10. This is because the process of using the proposed parallel NSGA-II to solve the hydraulic simulation-optimization model includes not only parallel computing but also serial computing. In addition, the parallel efficiency is also related to the population size. If the ratio of the population size to the number of parallel cores is non-integer, the parallel efficiency decreases more obviously, such as the six and ten-core parallel efficiency shown in Figure 10(b). Therefore, it is expected that with the advance of computer equipment and the reasonable selection of the number of parallel cores and the population size, the computational efficiency of the parallel approach will become more prominent.

## 6. CONCLUSIONS

In this study, a hydraulic simulation-optimization model of the joint operation of multiple devices for pumps shutdown process of long-distance water diversion systems is proposed. The hydraulic simulation-optimization model is composed of the optimization model and the hydraulic transient simulation model, which is a bi-level framework. In order to ensure the overall safety and efficiency of the pumps shutdown process and to keep the water level at the design ideal value as much as possible, the proposed optimization model is a three-objective problem. The hydraulic transient simulation model is constructed by MOC. The hydraulic simulation model is compiled as an external program into the executive file of the optimization model using the calling executive file in the programming language C++ to realize the coupling of the two models. In order to reduce the computational burden, the parallel NSGA-II approach is used to solve the proposed hydraulic simulation-optimization model. Besides, a process of effectively handling the constraints of the joint optimal operation of

**Table 4** | Results of parallel NSGA-II for solving the simulation-optimization model

| Number of cores | T(s) | $S_p$ | $E_p$ |
|---|---|---|---|
| 1 | 606,996 | 1 | 1 |
| 2 | 329,727 | 1.841 | 0.920 |
| 4 | 168,409 | 3.604 | 0.901 |
| 6 | 128,219 | 4.734 | 0.789 |
| 8 | 99,824 | 6.081 | 0.760 |
| 10 | 99,049 | 6.128 | 0.613 |

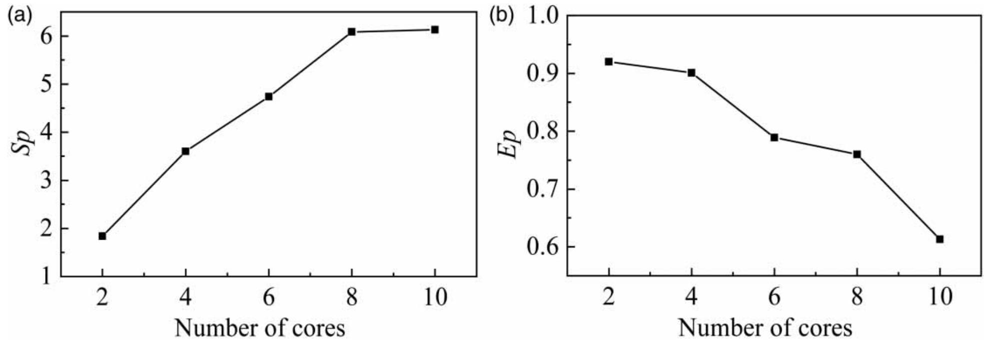



**Figure 10** | Acceleration ratio and parallel efficiency under the computing environments with different parallel cores.

multiple devices is proposed. Then, the proposed hydraulic simulation-optimization model and the parallel NSGA-II approach are applied to a real long-distance water diversion project consisting of a variety of hydraulic devices and structures. The results show that the proposed model can find a set of feasible Pareto front solutions, which improves the decision-making efficiency and avoids multiple trial calculations and repeated adjustment of hydraulic facilities in the actual operation. Importantly, mechanical loss and manpower cost are also reduced. In addition, the parallel approach greatly improves the computational efficiency in solving the hydraulic simulation-optimization model. Therefore, this study provides an effective approach to formulate the joint operation scheme of multiple devices of the long-distance water diversion system. However, it is necessary to further study higher-performance parallel computing for the hydraulic optimization model and the hydraulic transient simulation model to speed up the calculation, and further study the joint operation of multiple devices for other transient processes of long-distance water diversion systems.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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