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Leakage control of multi-source water distribution system by network partition and optimal pump schedule in China

Jinliang Gao, Shihua Qi, Jun Nan and Chen Chen

ABSTRACT

The main aim of an optimal schedule of conventional multi-source water distribution system is to reduce the energy consumption rather than minimizing the network leakage. This research is on the premise of meeting water demand, pressure and water quality considering the states of valve opening and closing, the states of pump opening and closing, and the pump speed as solution space. The optimization objectives are to minimize the network leakage and power consumption and to find the optimal valve closing scheme for network partitioning and the optimal pump scheduling scheme. NSGA-II algorithm is employed for solving the optimization problem. The obtained network partitioning and pumping scheduling solutions are applied to a real water network in Changping town, and the results prove that this method can simultaneously reduce the power consumption and network leakage.

Key words | leakage control, multi-source water distribution system, network partition, NSGA-II, optimal pump schedule

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INTRODUCTION

Due to the rapid urbanization in China, water demand has significantly increased. As a result, the water supply system has developed gradually from a single water source to multiple water sources, which causes the problems of mismatched water supply capacity, unbalanced water supply pressure and unreasonable pump schedules among water sources. These not only lead to wastage of water and energy resources but also pollute the surrounding areas when pipe leakage occurs. This paper presents an economical method to reduce the water leakage and save energy through water network partitioning, by using optimal states of valves' opening and closing, and reconstructing several connecting pipes and network partition.

Empirical methods are commonly used for partitioning the water supply network by adjusting the valve opening and closing status in the area, factitiously designating the water supply boundary and testing the partition using a hydraulic model. This partitioning method is time-consuming and suffers from a lack of theoretical basis, therefore, it is rarely used in practical projects (Giugni *et al.* 2008). The UK Water Industry Research (UKWIR) (1999) and Farley (2001) have successively published the principal guidance for district metering area (DMA) design. Morrison (2004) and Thornton (2004) summarized the essential role of using pressure metering area and DMA to control leakage. Izquierdo *et al.* (2009) proposed an agent-based division partition method for DMA design, and Herrera *et al.* (2011) improved Izquierdo's method through a semi-supervised learning method of using all existing information. However, all the research that has been conducted so far was based on small-scale water distribution networks. The partition methods for multi-source water supply networks cannot be applied to practical projects in the current state because there is still the unsolved problem of determining the boundary of water supply caused by constantly changing water consumption.

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The ongoing research proved that the leakage in water distribution systems can be minimized through optimal valve actions (Vairavamoorthy & Lumbers 1998; Creaco & Pezzinga 2014). Di Nardo *et al.* (2015) developed a genetic algorithm for demand pattern and leakage estimation in a water distribution network. Ali (2014) presented a knowledge-based optimization model for leakage minimization in a water supply network by finding an effective location to set the control valves. Islam *et al.* (2012) evaluated leakage in water distribution systems using a fuzzy-based method. Burrows (2011) proposed an intelligent technology for continuous optimal adjustment of pressure at the outlet of the water pump and pressure reducing valve (PRV) to reduce the network leakage, decrease pipe bursting, and power consumption. Giustolisi *et al.* (2008) described a new hydraulic simulation model which is capable of quantifying the pressure-driven demand and leakage simultaneously. Real-time control of valves for minimizing the leakage in water distribution networks was reported, and head-driven simulation of a water network was considered under successive steady conditions in their work (Campisano *et al.* 2012; Creaco & Franchini 2013). A fast and efficient way to calculate the optimal time schedules and flow modulation curves for the boundary and internal PRVs to reduce the leakage in water supply networks was presented (Ulanicki *et al.* 2009). An optimal pump scheduling model, taking into account pressure control aspects in complex and large-scale water distribution networks, was studied by Skworcow *et al.* (2009, 2014).

In China, the generic water supply systems have pump stations. Each pump station has its own control for pump speed, no water tanks that are necessary to regulate water amount due to a large amount of water supply and centralized water users.

METHODS

This research addresses two issues simultaneously: (i) saving energy by scheduling the pump optimally and (ii) reducing leakage by partitioning the water network. Water supply network partition and water pump schedule after partitioning are interdependent; it is difficult to achieve optimization by only considering one aspect. In this paper, it is assumed that the existing water supply boundary of a multi-water source system is acceptable but not optimal and the boundary is fluctuated with time to form a water supply boundary zone. The valves within the zone are taken as a feasible solution set of partitioning the network. The method of closing valves within a water supply boundary zone to secure the water supply boundary does not make a significant change to the original water supply conditions, which can be readily accepted by water enterprises and users.

From the point of scheduling and deployment of multi-source water, the minimization of network leakage and power consumption as the optimization goal is taken to be a measurement standard of the water supply network partition (Li *et al.* 2015), that is, to guide the network partition through an optimal schedule objective function of the water supply network and use the partition scheme to determine the optimal schedule for pump set. These two aspects complement each other.

In China, the water supply network is complex, including branches and loops. The total capacity of water supply is greater than the users' demand. Thus, according to various water source locations, this complex water network is divided into a distributed system and a single side system. The multi-source water distribution system has only one key point, and energy waste would occur as the outlet pressure of each water source has to meet the requirements of the key point. In the partitions of the multi-source water distribution network, the positions of most minimum service head control points for each water source are different. The minimum service head of the most important locations will be significantly reduced in comparison to the non-partitioned situation when water is delivered in the same direction from multiple water sources. This is called a single side water supply system and is shown in Figure 1. Therefore, the required pressure at the outlet and average pressure inside the water network of many water plants will have to be greatly reduced to reduce the power consumption and leakage. If the water is delivered from various directions, called a distributed water supply system as shown in Figure 2, the energy consumption and leakage can be reduced by dividing the water supply boundary of each water source and optimizing the corresponding outlet pressures.

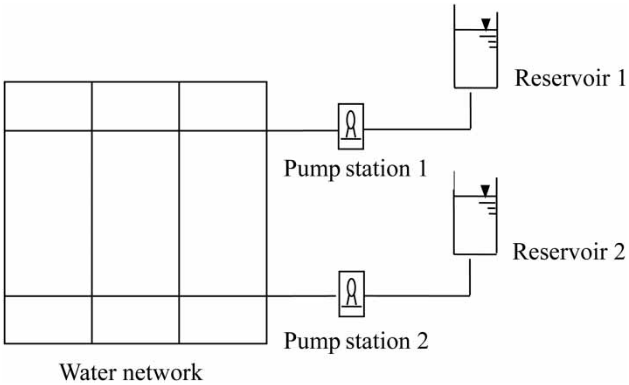

Figure 1 | Single side water supply system.

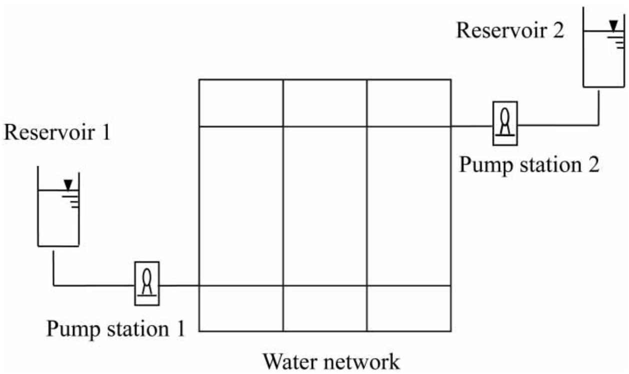

Figure 2 | Distributed water supply system.

Partitioning of water networks is essential for a multi-source water network optimal schedule. By modifying a small length of pipeline and partitioning the network appropriately, the reduced pressure during normal operation and flexibility to switch the water source of the main pipeline during accidents can be ensured. Primary partitions can be formed simply by closing certain valves in the partition zone. On the basis of the primary partitions, each primary partition can be subdivided into multiple secondary partitions; smart PRVs are installed at the entrance of secondary partitions. There are many ways to close the valves in the primary partition, however, in the practical water distribution network, there are only a handful of schemes that are feasible. According to different locations of water sources, terrain elevation of secondary partitions and bulk line distribution, the feasible alternative solution set for closing the valve is established to reduce the search space of closing valve solutions, thereby increasing the search speed to perform the next optimal schedule.

The ultimate goal of optimal scheduling of a traditional water supply system is to minimize the power consumption, which does not guarantee the minimum amount of leakage in a water supply system. The leakage in the pipe network is a non-linear function of pressure in the pipe network. To ensure the minimum amount of leakage in the water supply network, the pressure at all nodes of the network should be kept at a minimum value under the premise that the head of the minimum water supply services could be met (Thornton 2004; Nicolini *et al.* 2011). This ideal pressure state cannot be achieved through optimal scheduling of the pump. Different pump set scheduling schemes will produce different water supply area boundaries, and the pressure at each node will vary with different water supply area boundaries and scheduling schemes.

To meet the requirements of water demand from users, pressure and quality, a reasonable optimal schedule of pump set can balance the pressure in the partitioned water pipe network during day and night. Moreover, it can reduce the leakage, save water and fundamentally improve the efficiency of water supply. After identifying the valves that need to be closed, assuming no significant changes to the pipes in the water supply system (such as laying new bulk pipes, building a new pump station), each pump station serves their partition independently, i.e. water networks among pump stations are no longer connected. Therefore, water network partitioning and pump scheduling based on partition need to be considered simultaneously.

The optimal leakage control model is to design a feasible set of valve closing in a multi-source water supply network. A multi-source water supply partition model is actually the optimization process of the water supply boundaries at different times with a combination of urban water demand forecast model and the leakage hydraulic model of water supply network to calculate the node demand and pipe flow (Giustolisi *et al.* 2008).

The method of obtaining a feasible set of valves is as follows.

1. The first step is to calculate the main water supply route. Each node that belongs to a particular water source can be identified by calculating the main water supply route to each node, and the process is shown in Figure 3.

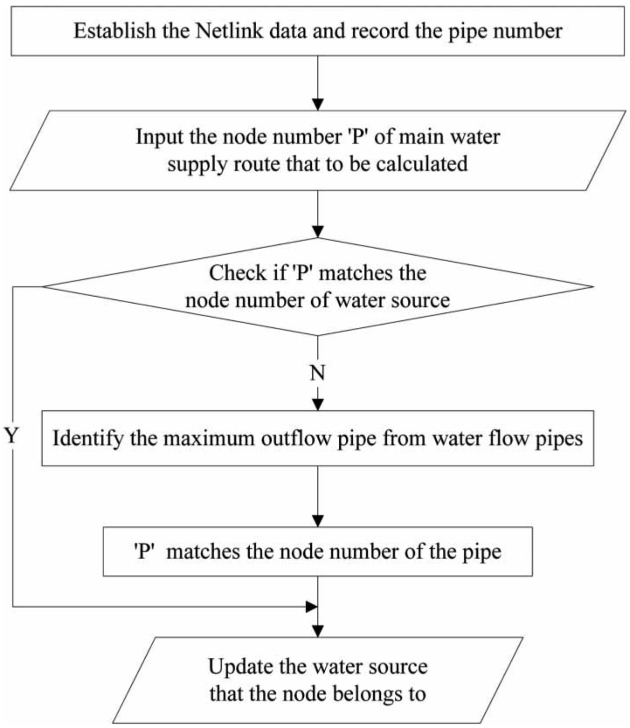

Figure 3 | Calculation of main water supply route.

2. The second step is to calculate the boundary of water supplies. In this paper, the water supply boundary is calculated based on the pressure transfer energy analysis. It is different from an EPANET water tracer as the application is different. The water supply condition of a standard day is calculated on an hourly basis to identify the water supply boundary of the multi-source water supply network. These boundary lines form a water supply crossing area. The valves within the water supply crossing area can be closed to form network partitions; the scheduled valve sets are developed as shown in Figure 4. Therefore, the search space for optimization will be reduced significantly. In the optimization algorithm, if no independent partitions are formed through connecting judgment after closing several valves, then penalties need to be imposed to the objective function.

The method of obtaining a main water supply route and water supply crossing area mentioned above verified the feasibility and effectiveness of engineering rather than theory. If all the water valves in the network are put into the search scope, the resultant search space is too large.

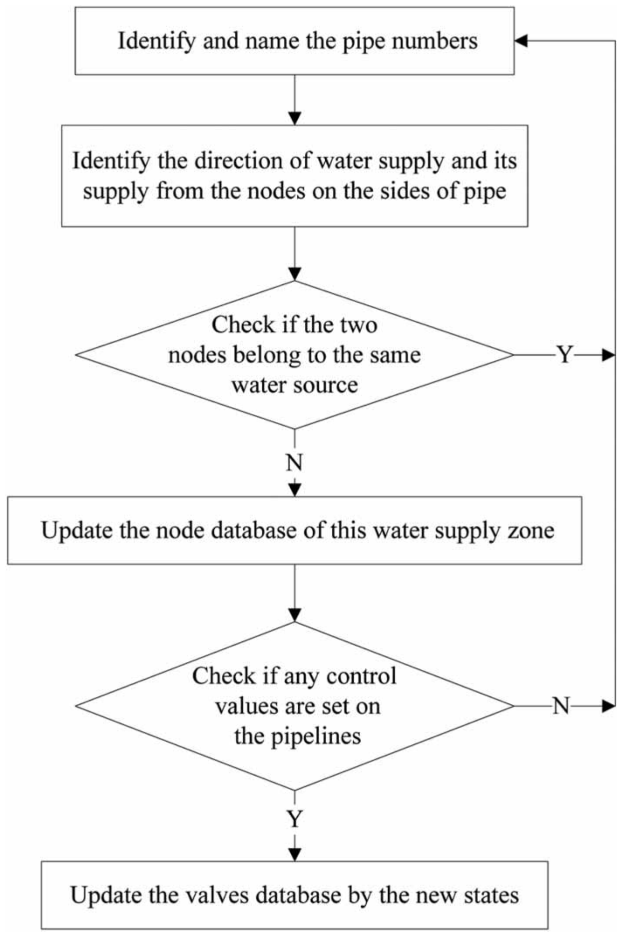

Figure 4 | Procedure to obtain the states of the valves.

By integrating the partition model of the water supply network with a pump optimal scheduling model of a water distribution system, a pump optimal leakage control model of the multi-source water distribution system can be obtained. By further solving this multi-objective problem, optimal partitioning can be found. Based on the obtained results, the separated valves will be closed and pump optimal scheduling can be worked out. The process is shown in Figure 5. This research of network partitioning and optimal pump scheduling is based on the hydraulic microscopic model and with the historical 24 hours' data of node flow changes from a standard day. This optimal scheduling is performed for an extended period, on an offline simulation rather than a real time online simulation. Therefore, network partitioning in this paper refers to the stable partition in the given period. Partitioning and optimal

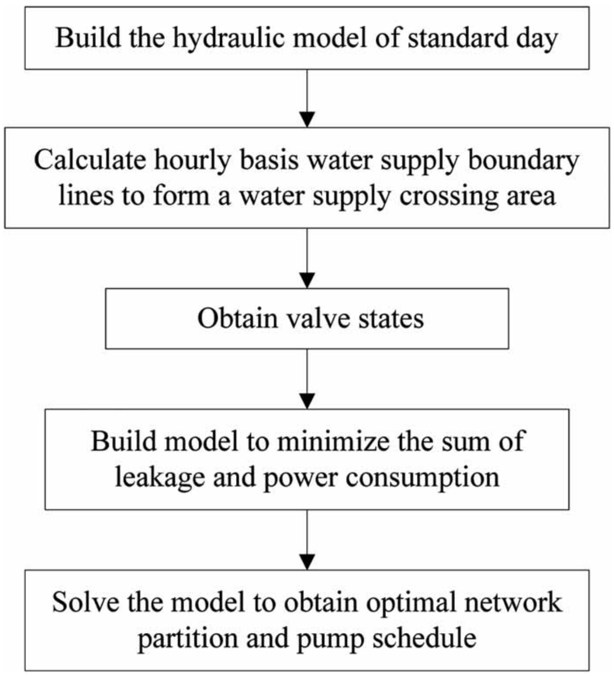

Figure 5 | Leakage control of multi-source water distribution system by optimal pump scheduling.

scheduling are required to be recalculated when a significant change occurs in the water network.

Model building

The goal of an optimal leakage control model in a multi-source water distribution system is to minimize the sum of power consumption and leakage. That is to say, water supply enterprises can gain economic benefits only by adjusting the opening or closing of valves and pumps (Tucciarelli *et al.* 1999).

The objective function used to minimize the sum of power consumption and leakage is as follows:

$$F_1 = \sum_{t=1}^{T} \sum_{i=1}^{I} C\alpha_{i,t} H_{i,t}^{1.18} \quad (1)$$

$$F_2 = \sum_{m=1}^{M} SP_{m,t} \sum_{k=1}^{K_m} \frac{np_{m,k,t} \cdot QP_{m,k,t}(ns_{m,k,t}) \cdot HP_{m,k,t}(ns_{m,k,t})}{\eta_{m,k,t}(ns_{m,k,t})} \quad (2)$$

where C is the per unit cost of water supply (CNY/m^3); $\alpha_{i,t}$ is the leakage coefficient of node i at stage t; $H_{i,t}$ is the pressure of node i at stage t (m); $SP_{m,t}$ is electricity cost of per unit power consumption of mth pumping station at stage t, (CNY/kWh); K_m is the total number of pumps in mth pumping station at stage t; $np_{m,k,t}$ is opening or closing state of the pump within mth pumping station at stage t (when pump is working: $np_{m,k,t} = 1$; when pump is not working: $np_{m,k\ t} = 0$); $QP_{m,k,t}$ is the amount of water supplied by pump k in mth pumping station at stage t (m^3/h); $ns_{m,k,t}$ is the speed ratio of pump k in mth pumping station at stage t (the speed ratio of constant speed pump is one); $HP_{m,k,t}$ is the head of pump k in mth pumping station at stage t (m); $\eta_{m,k,t}$ is the efficiency of pump k in mth pumping station at stage t (%).

Constraints of pipe network hydraulic balance include the node demand continuity equation and the energy conservation equation as follows:

$$G(\vec{H}, \vec{Q}, \vec{a}) = 0 \quad (3)$$

where H is pressure at the node; Q is demand at the node; a is the specific resistance of pipe.

The constraint on the water supply capacity of each pumping station is as follows:

$$Q_{\min\ N,t} \leq Q_{N,t} \leq Q_{\max\ N,t} \quad (4)$$

where $Q_{min\ N,t}$ is the minimum allowable quantity of water supplied by pumping station N at time t (m^3/h); $Q_{N,t}$ is the quantity of water supplied by pumping station N at time t (m^3/h); $Q_{max\ N,t}$ is the maximum allowable quantity of water supplied by pumping station N at time t (m^3/h).

The constraint on the pressure of monitoring point is as follows:

$$H_{\min,t} \leq H_t \leq H_{\max,t} \quad (5)$$

where $H_{min,t}$ is the minimum allowable pressure of node i (m); H_t is the pressure of node i (m); $H_{max,t}$ is the maximum allowable pressure of node i (m).

The constraint on the speed ratio of the pump is as follows:

$$n_{\min\ N,k} \leq n_{N,k} \leq n_{\max\ N,k} \quad (6)$$

where $n_{min\ N,k}$ is the minimum allowable speed ratio of the kth pump in pumping station N when the pump is running;

$n_{N,k}$ is the speed ratio of the kth pump in pumping station N when the pump is running; $n_{max\,N,k}$ is the maximum allowable speed ratio of kth pump in pumping station N when the pump is running.

The constraint on pump efficiency is as follows:

$$\eta_{\min\ N,k} \leq \eta_{N,k} \tag{7}$$

where $\eta_{min\,N,k}$ is the minimum required pump efficiency of kth pump at pumping station N when the pump is running; $\eta_{N,k}$ is the pump efficiency of kth pump at Nth pumping station when the pump is running.

The solution of optimal leakage control model in multi-source water distribution system is a solution of water supply network partition model and pump optimal schedule model. This model is a multi-dimensional and multi-objective optimization problem, which contains both non-linear and linear constraints. It is difficult to work it out by any simple mathematical methods. Hence, NSGA-II algorithm is adopted for choosing the state of all valves and pumps in the network–opening or closing to be the solution domain. Further, the partition scheme is determined for solving the optimal off valve and the optimal pump scheduling programs (Giugni *et al.* 2014).

CASE STUDY: LEAKAGE CONTROL PROJECT OF WATER SUPPLY SYSTEM IN CP TOWN

CP town is adjacent to Hong Kong, with a total area of 108 km^2 and population of approximately 500,000. The water distribution system of CP town is mainly composed of two water treatment plants (No. 1 and No. 2 water treatment plant), 300 km water pipeline, 1,022 valves and other structures. The terrain of CP town is flat, with a maximum of 20 m elevation. Two water treatment plants are located in the east of the town. As a result, the length of water pipeline is long, and the pressures at the west CP town are low. The water distribution network topology of CP town is shown in Figure 6. The total design scale of water treatment plant No. 1 is 130,000 m^3 per day with 12 water pumps and water treatment plant No. 2 is 300,000 m^3 per day with four water pumps. The current schedule of pump set is shown in Tables 1 and 2.

Figure 6 | Water distribution network topology of CP town.

Table 1 | The current schedule of pumps at water treatment plant No. 1

Time	Pump no. 1	2	3	4	5	6	7	8	9	10	11	12
00:00	0	0	0	0	0	0	0	1	0	1	0	0
01:00	0	0	0	0	0	0	0	1	0	1	0	0
02:00	0	0	0	0	0	0	0	1	0	1	0	0
03:00	0	0	0	0	0	0	0	1	0	1	0	0
04:00	0	0	0	0	0	0	0	1	0	1	0	0
05:00	0	0	0	0	0	0	0	1	0	1	0	0
06:00	0	0	0	0	0	0	0	1	0	1	1	0
07:00	0	0	0	0	0	0	0	1	0	1	1	0
08:00	0	0	0	0	0	0	0	1	0	1	1	0
09:00	0	0	0	0	0	0	0	1	0	1	1	0
10:00	0	0	0	0	0	0	0	1	0	1	1	0
11:00	0	0	0	0	0	0	0	1	0	1	1	0
12:00	0	0	0	0	0	0	0	1	0	1	1	0
13:00	0	0	0	0	0	0	0	1	0	1	1	0
14:00	0	0	0	0	0	0	1	1	0	0	0	0
15:00	0	0	0	0	0	0	1	1	0	0	0	0
16:00	0	0	0	0	0	0	1	1	0	0	0	0
17:00	0	0	0	0	0	0	1	1	0	0	0	0
18:00	0	0	0	0	0	0	1	1	0	0	0	0
19:00	0	0	0	0	0	0	1	1	0	0	0	0
20:00	0	0	0	0	0	0	1	1	0	0	0	0
21:00	0	0	0	0	0	0	1	1	0	0	0	0
22:00	0	0	0	0	0	0	0	1	0	1	0	0
23:00	0	0	0	0	0	0	0	1	0	1	0	0

Note: Pumps 1, 2, 6, 7 and 9 are large pumps; pumps 3, 4, 5, 8, 10, 11 and 12 are small pumps.

Table 2 | The current schedule of pumps at water treatment plant No. 2

Time	Pump no. 1	2	3	4
00:00	0	1	0	1
01:00	0	1	0	1
02:00	0	1	0	1
03:00	0	1	0	1
04:00	0	1	0	1
05:00	0	1	0	1
06:00	1	0.96	0	0
07:00	1	0.96	0	0
08:00	1	0.96	0	0
09:00	1	0.96	0	0
10:00	1	0.96	0	0
11:00	1	0.96	0	0
12:00	1	0.96	0	0
13:00	1	0.96	0	0
14:00	1	0	1	0
15:00	1	0	1	0
16:00	1	0	1	0
17:00	1	0	1	0
18:00	1	0	1	0
19:00	1	0	1	0
20:00	1	0	1	0
21:00	1	0	1	0
22:00	0	1	0	1
23:00	0	1	0	1

Note: Pumps 1 and 3 are large pumps; pumps 2 and 4 are small pumps.

The hydraulic model of a standard day was established in a multi-source water supply network in CP town to simulate 24 hours water supply boundary (the peak hours are shown in Figure 7) and free head (the peak hours are shown in Figure 8.). The set of valves that can be closed were obtained, and the positions of closed valves are shown in Figure 9. The locations of closed valves for each solution are shown in Table 3. The leakage control model of optimal pump scheduling is established for CP town. The sum of power consumption of pumps and network leakage loss was taken as the objective function, and genetic algorithms are used to optimize. The water supply boundary of the first six feasible partition solutions at peak hours are shown in Figures 10–15, and the

Figure 7 | Water supply boundary at peak hour.

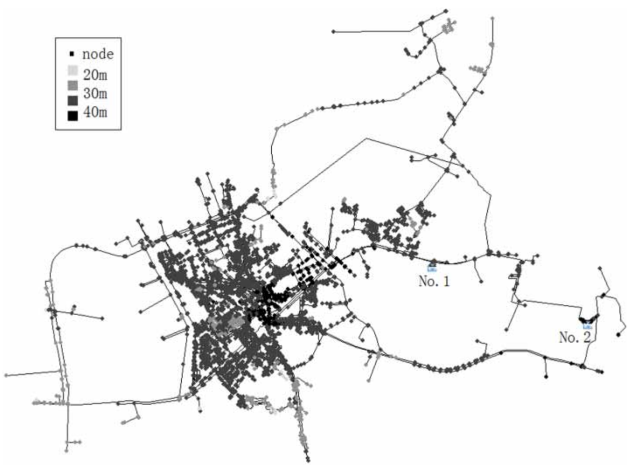

Figure 8 | Free head at peak hour.

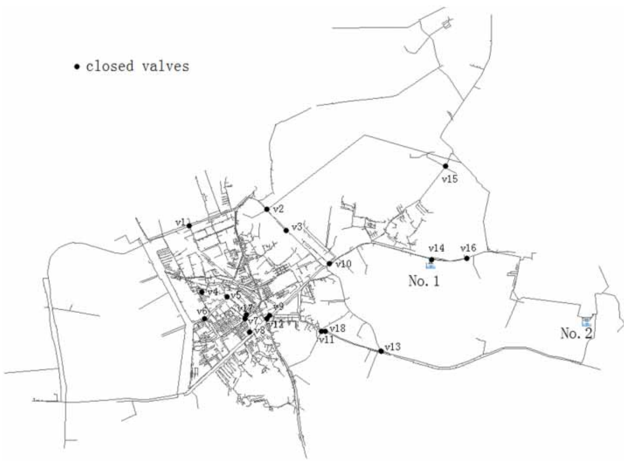

Figure 9 | Locations of closed valves.

Table 3 | The positions of closed valves for each solution

Solution	Closed pipe no.	Pipe diameter	Valve no.	Summary
Solution 1	42,148	1,000	V14	10 valves closed
	27,009	300	V13	
	17,904	800	V10	
	42,166	600	V11	
	17,761	800	V3	
	12,370	1,000	V9	
	42,160	600	V8	
	11,628	200	V5	
	2,330	50	V4	
	42,116	400	V1	
Solution 2	42,148	1,000	V14	9 valves closed
	27,009	300	V13	
	17,904	800	V10	
	42,166	600	V11	
	12,371	800	V12	
	42,168	1,200	V2	
	11,536	400	V17	
	11,524	400	V7	
	41,570	300	V6	
Solution 3	42,148	1,000	V14	7 valves closed
	27,009	300	V13	
	17,904	800	V10	
	42,166	600	V11	
	42,168	1,200	V2	
	12,370	1,000	V9	
	42,160	600	V8	
Solution 4	42,148	1,000	V14	10 valves closed
	42,160	1,600	V8	
	41,337	200	V15	
	27,009	300	V13	
	17,904	800	V10	
	42,166	600	V11	
	12,371	800	V12	
	11,536	400	V17	
	11,524	400	V7	
	41,570	300	V6	
Solution 5	42,148	1,000	V14	8 valves closed
	42,168	1,200	V2	
	41,337	200	V15	
	27,009	300	V13	
	17,904	800	V10	
	42,166	600	V11	
	12,370	1,000	V9	
	42,160	1,600	V8	
Solution 6	18,106	1,200	V16	8 valves closed
	41,337	200	V15	
	27,009	300	V13	
	42,150	800	V18	
	17,761	800	V3	
	11,628	200	V5	
	2,330	50	V4	
	42,116	400	V1	

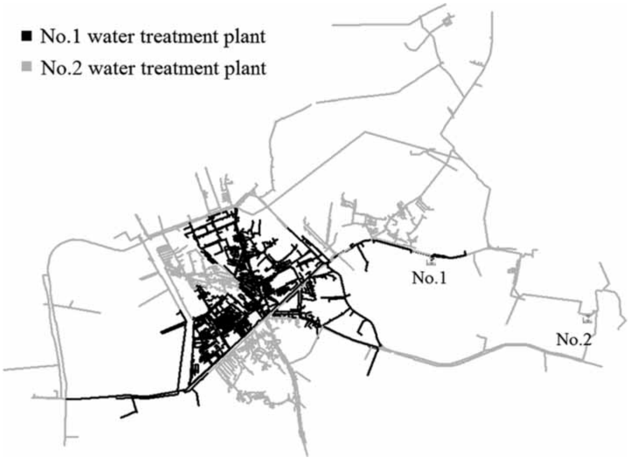

Figure 10 | Feasible partition solution 1.

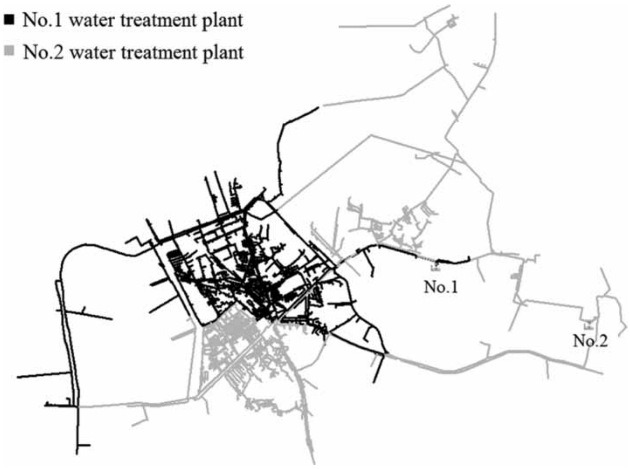

Figure 11 | Feasible partition solution 2.

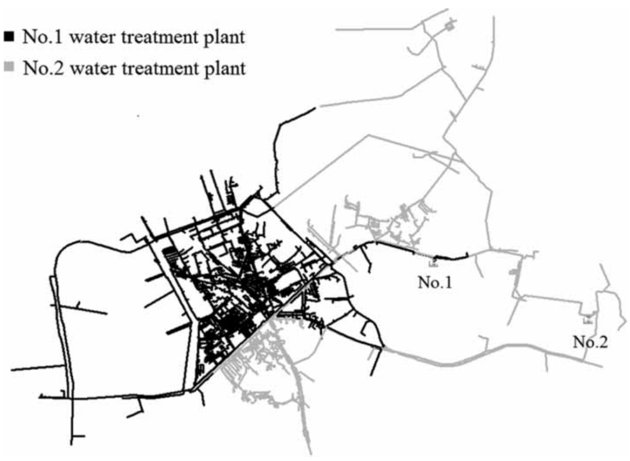

Figure 12 | Feasible partition solution 3.

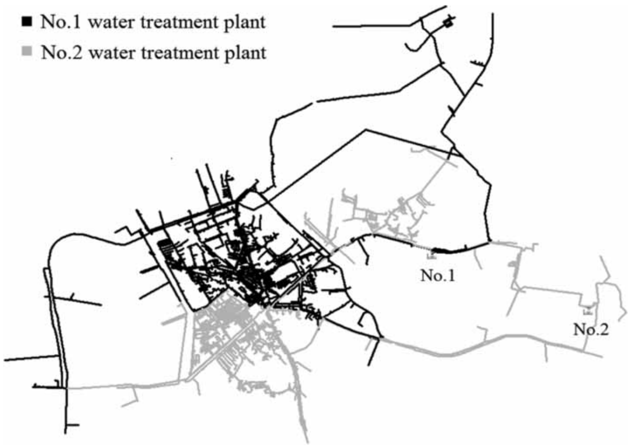

Figure 13 | Feasible partition solution 4.

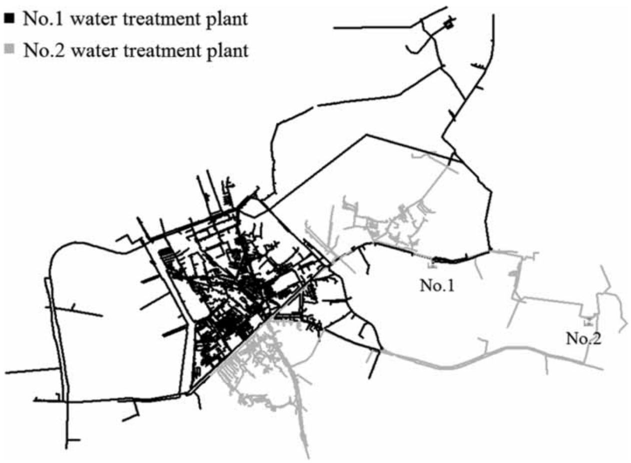

Figure 14 | Feasible partition solution 5.

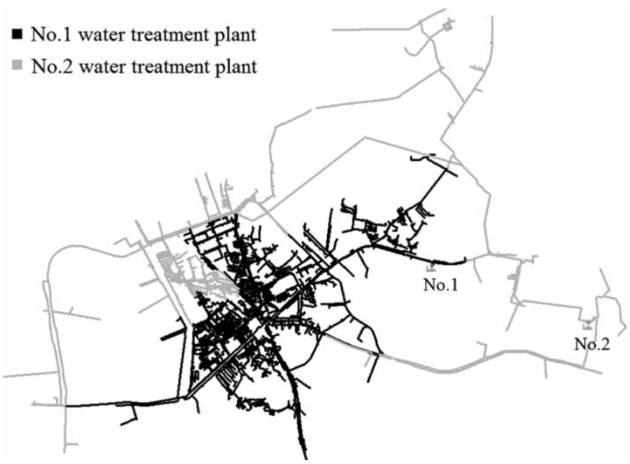

Figure 15 | Feasible partition solution 6.

corresponding free heads at peak hours are shown in Figures 16–21.

According to optimal pump scheduling at peak hours of the above six partition solutions, the total supply amount and outpressure of each water plant are compared with the current situation and the results are shown in Table 4.

RESULTS AND DISCUSSION

Saving electricity cost = electricity unit price × annual energy saved = electricity unit price × annual energy

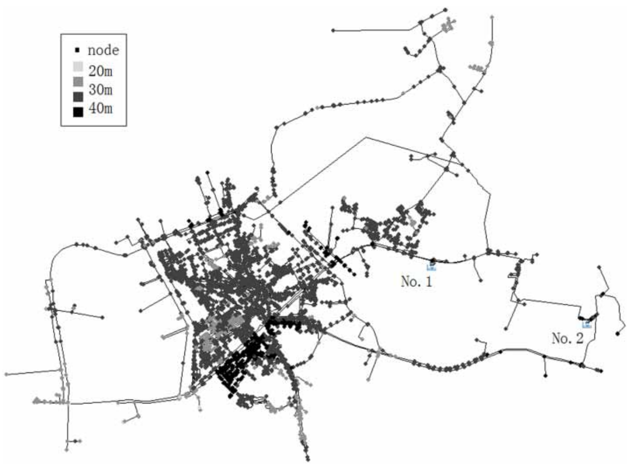

Figure 16 | Free head in solution 1.

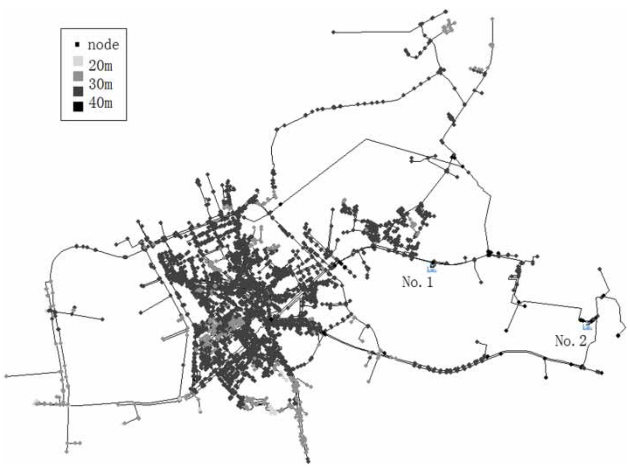

Figure 17 | Free head in solution 2.

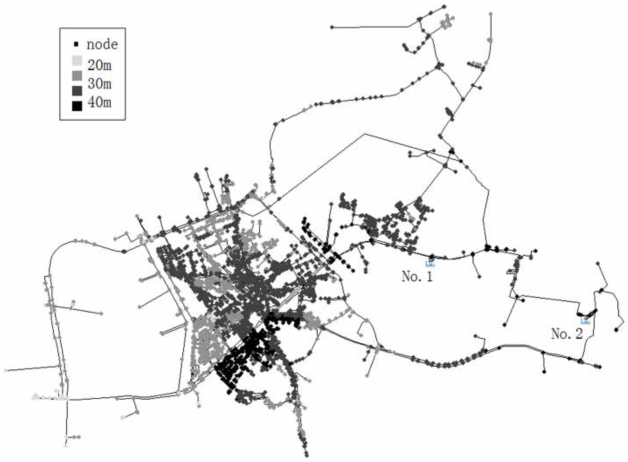

Figure 18 | Free head in solution 3.

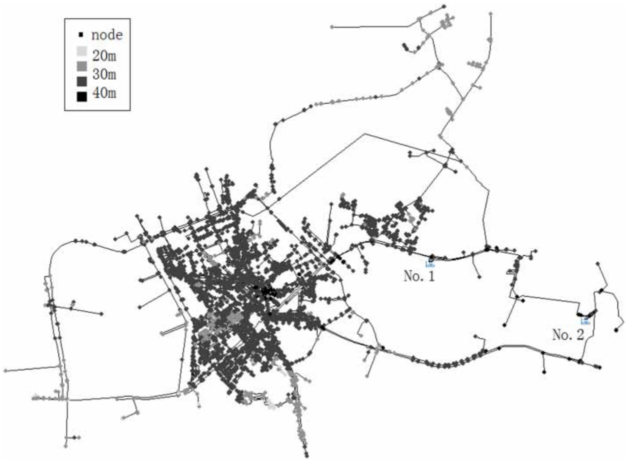

Figure 19 | Free head in solution 4.

consumption × percentage of energy saved. Where the electricity unit price is 0.8 CNY/KW h, the results are shown in Table 5, column 4.

Saving water purification cost = water purification unit price × annual leakage reduced amount = water purification unit price × current leakage amount × percentage of leakage reduced × 365 days. Where the water purification unit price is 0.23 CNY/m^3, the results are shown in Table 5, column 7.

Saving water resource cost = water resource unit price × annual leakage reduced amount = water resource unit price × current leakage amount × percentage of leakage reduced ×

Figure 20 | Free head in solution 5.

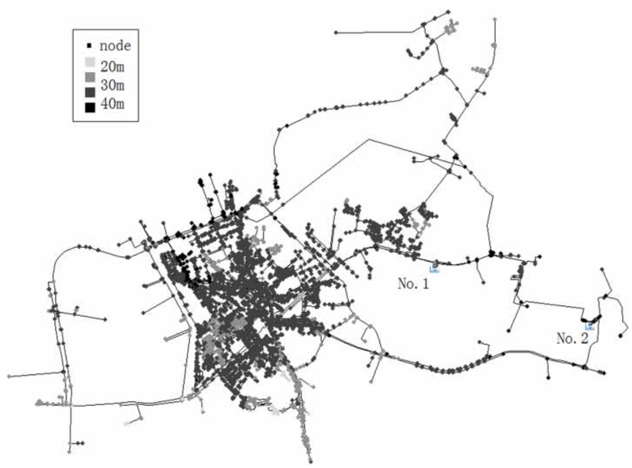

Figure 21 | Free head in solution 6.

Table 4 | The results of optimal schedule solution

	No. 1 water plant		**No. 2 water plant**		
Solution no.	**Amount (m^3/h)**	**Outlet pressure (m)**	**Amount (m^3/h)**	**Outlet pressure (m)**	**Quantity of closed valves**
1	3,788	41	7,154	42	10
2	4,186	42	6,756	42	9
3	6,253	45	4,689	37	7
4	4,818	39	6,124	42	10
5	6,885	43	4,057	36	8
6	6,263	39	4,679	41	8
Current situation	2,430	38	8,512	42	0

Table 5 | Energy saved and leakage reduced in the standard day

Solution No.	Energy consumption (KW h/10^3m³)	Energy saved (%)	Saving electricity cost (CNY/year)	Leakage amount (m³/d)	Leakage reduced (%)	Saving water purification cost (CNY/year)	Saving water resource cost (CNY/year)	Saving total cost (CNY/year)
1	485.19	–1.32	–196,194	52,957.8	6.60	314,157.69	450,747.99	568,711.68
2	489.21	–2.16	–321,045	54,261.9	4.30	204,678.5	293,669.15	177,302.64
3	484.23	–1.12	–166,468	51,540.3	9.10	433,156.82	621,485.87	888,174.68
4	473.84	1.05	156,063.5	53,751.6	5.20	247,518.18	355,134.78	758,716.46
5	470.63	1.72	255,646.8	50,973.3	10.10	480,756.47	689,781.02	1,426,184.28
6	464.22	3.06	454,813.6	51,483.6	9.20	437,916.78	628,315.38	1,521,045.76

Note: The sum of current energy consumption of two water plant is 478.87(KW h/10^3m³) and the sum of currently leakage amount is 56,700 m³/d.

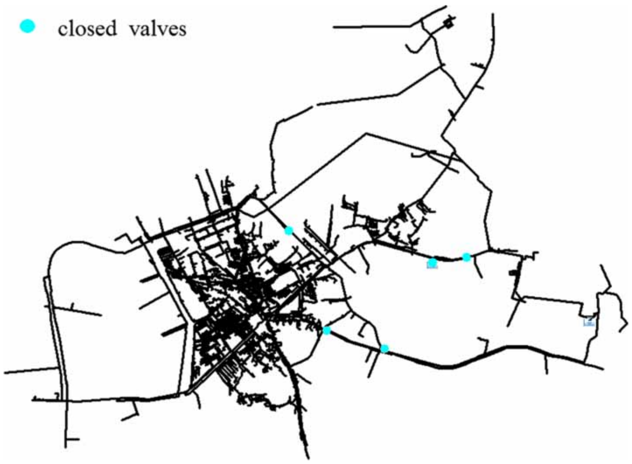

Figure 22 | The location of closed valves and rehabilitated pipelines.

365 days. Where the water resource unit price is 0.33 CNY/m^3, the results are shown in Table 5, column 8.

Saving total cost = saving electricity cost + saving water purification cost + saving water resource cost. The results are shown in Table 5, column 9.

It can be seen from Table 5 that the social and economic benefits were considered to evaluate the feasibility and effectiveness of energy savings, and reducing leakage through network partition and optimal pump schedule. An NSGA-II algorithm was used to solve multi-objective optimization problems. The calculated results indicate that the priority order of optimal solutions are as follows: solution 6, solution 5, solution 4, solution 3, solution 2, solution 1. Solution 6 had the best performance in terms of energy savings and reducing leakage, and is considered an optimal solution. The locations of closed valves of solution 6 are shown in Figure 22.

Table 6 | The optimized pump schedule of water treatment plant No. 1

	Pump no.											
Time	1	2	3	4	5	6	7	8	9	10	11	12
00:00	0	0	0	0	0	0	1	0	0	0	0	0
01:00	0	0	0	0	0	0	1	0	0	0	0	0
02:00	0	0	0	0	0	0	1	0	0	0	0	0
03:00	0	0	0	0	0	0	1	0	0	0	0	0
04:00	0	0	0	0	0	0	1	0	0	0	0	0
05:00	0	0	0	0	0	0	1	0	0	0	0	0
06:00	0	0	0	0	0	0	1	0	1	0	0	0
07:00	0	0	0	0	0	0	1	0	1	0	0	0
08:00	0	0	0	0	0	0	1	0	1	0	0	0
09:00	0	0	0	0	0	0	1	0	1	0	0	0
10:00	0	0	0	0	0	0	1	0	1	0	0	0
11:00	0	0	0	0	0	0	1	0	1	0	0	0
12:00	0	0	0	0	0	0	1	0	1	0	0	0
13:00	0	0	0	0	0	0	1	0	1	0	0	0
14:00	0	0	0	0	0	1	1	1	1	0	0	0
15:00	0	0	0	0	0	1	1	1	1	0	0	0
16:00	0	0	0	0	0	1	1	1	1	0	0	0
17:00	0	0	0	0	0	1	1	1	1	0	0	0
18:00	0	0	0	0	0	1	1	1	1	0	0	0
19:00	0	0	0	0	0	1	1	1	1	0	0	0
20:00	0	0	0	0	0	1	1	1	1	0	0	0
21:00	0	0	0	0	0	1	1	1	1	0	0	0
22:00	0	0	0	0	0	0	1	0	0	0	0	0
23:00	0	0	0	0	0	0	1	0	0	0	0	0

Considering the cost of pump start/stop and the stability of pump operation, the scheduled time is divided into three periods in this paper. The first period is 6:00–13:00 (average), the second period is 14:00–21:00 (peak), the third period is 22:00–5:00 (low), the optimal pump schedule solutions of each period of each water plant are shown in Tables 6 and 7.

CONCLUSIONS

This research simultaneously addressed two optimal aspects: saving energy by optimal pump scheduling and reducing leakage by water network partitioning. A leakage control model of a multi-source water distribution system is established by using optimal pump scheduling. The outcome of this research is to work out water supply network partitioning and pump set scheduling schemes. This method has been proved to be efficient for reducing energy consumption and network leakage simultaneously. Furthermore, it improves the water supply enterprises' services and economic profit. This part of the profit is net income, which can be gained by water supply enterprises only by switching valves, scheduling pumps and rehabilitating a few pipelines, and without the need of any extra capital investment.

Table 7 | The optimized pump schedule of water treatment plant No. 2

	Pump no.			
Time	**1**	**2**	**3**	**4**
00:00	0	1	0	0
01:00	0	1	0	0
02:00	0	1	0	0
03:00	0	1	0	0
04:00	0	1	0	0
05:00	0	1	0	0
06:00	1	0.86	0	0
07:00	1	0.86	0	0
08:00	1	0.86	0	0
09:00	1	0.86	0	0
10:00	1	0.86	0	0
11:00	1	0.86	0	0
12:00	1	0.86	0	0
13:00	1	0.86	0	0
14:00	1	1	0	0
15:00	1	1	0	0
16:00	1	1	0	0
17:00	1	1	0	0
18:00	1	1	0	0
19:00	1	1	0	0
20:00	1	1	0	0
21:00	1	1	0	0
22:00	0	1	0	0
23:00	0	1	0	0

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