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Optimization of Pump Start-Up Depth in Drainage Pumping Station Based on SWMM and PSO

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Abstract: The pumps in multistage drainage pumping stations are often subject to frequent start-up and shutoffs during operation because of unreasonable start-up depths of the pumps; this will reduce the service lives of the pumps. To solve this problem, an optimization method for minimizing pump start-up and shutoff times is proposed. In this method, the operation of pumps in pumping station was optimized by constructing a mathematical optimization model. The storm water management model (SWMM) and particle swarm optimization (PSO) method were used to solve the problem and the optimal start-up depth of each pump is obtained. Nine pumping stations in Beijing were selected as a case study and this method was applied for multistage pumping station optimization and single pumping station optimization in the case study. Results from the case study demonstrate that the multistage pumping station optimization acquired a small number of pump start-up/shutoff times, which were from 8 to 114 in different rainfall scenarios. Compared with the multistage pumping station optimization, the single pumping station optimization had a bigger number of pump start-up/shutoff times, which were from 1 to 133 times, and the pump operating time was also longer, from 72 min to 7542 min. Therefore, the multistage pumping station optimization method was more suitable to reduce the frequency of pump start-up/shutoffs.

Keywords: multistage drainage pumping stations; optimization of pumping station operation; SWMM; PSO

1. Introduction

Urban rainwater pipe networks are an important part of urban drainage systems. These networks are mainly used to collect runoff rainwater that forms after precipitation. After rainwater collection, the runoff flows through the pipe network and eventually discharges out of the system [1]. However, under circumstances of heavy precipitation, some locations in the rainwater pipe network will have insufficient capacity. This leads to an overflow in the pipe network and flooding can occur, resulting in waterlogging disasters [2,3]. To solve this problem, rainwater storage tanks and pumping stations need to be installed at locations in the rainwater pipe network where the drainage capacity is insufficient. Peak flooding can be reduced with the use of storage tanks, and the drainage pressure within the pipe network can be relieved [4].

Pumping stations play an important role in flood mitigation in metropolitan areas. The urban drainage system is facing a great challenge of fast-rising peak flow resulting from urbanization and climate change. Therefore, many scholars are committed to flood control by optimizing the operation of pumps. A new technique was created to operate multiple pump stations for reducing urban flood is proposed [5]. A forecasting model was used to predict trends in precipitation and the operation of rainwater pump stations was predicted [6]. A novel robust approach was proposed to obtain an optimal operation policy on reducing flood damage [7]. A new cooperative operation scheme was proposed for urban drainage systems to maximize the flood mitigation efficiency [8]. Proactive pump operation and capacity expansion in an urban drainage system were conducted to improve system resilience [9]. A real-time optimization approach was developed to find optimal policies for the collaborative operation of drainage facilities [10]. A two-stage intelligence-based pumping control (TWOPC) was proposed for pumping operations, where a multilayer perceptron (MLP) was used to forecast the desired pump flow and tree-derived rules obtained from relevant classifiers were used to forecast the optimal pump combination [11]. Two real-time pumping station operation models, namely ANFIS-His (adaptive network-based fuzzy inference system using historical operation records) and ANFIS-Opt (adaptive network-based fuzzy inference system using the best operation series), were developed for flood mitigation in urban areas, and it has been shown that the ANFIS-Opt is better than the ANFIS-His based on the operation simulations using the two operation models [12]. Graber [13,14] presented a generalized solution for the hydrologic and hydraulic design of small to medium-sized storm-water pumping stations in order to improve the pump operation. A rainfall-storage-pump-discharge model was developed to determine the reduced peak flow and increased design return period for a combination of tank volume and pumping rate [15]. Uchida [16] investigated impacts of discharge from drainage pump stations on the flood flow in the Rokkaku River and the Ushizu River at the 2009 flood using the unsteady 2D numerical model. A pumping operation model has been developed to predict pumping discharge, which used the storm and operating records to train and verify the model's performance [17]. Tamoto [18] used a forecasting model to predict trends in precipitation and simulated the flow rate in storm sewer pipes in order to lay down rules governing coordinated pump operation. Bu [19] optimized a low-specific speed centrifugal pump across a flow rate ratio to improve the overall efficiency at the multioperation point. Fecarotta [20] built a mixed-integer optimization model able to find the scheduling solution that minimizes required pumping energy.

The above researchers have carried out in-depth studies of pump operation on flood control. Multistage drainage pumping stations consist of multiple pumping stations in a series. During a storm, if the start-up depth of the pump is unreasonable, excess start-up/shutoff times may be imposed. The phenomenon of frequent start-up and shutoff times will reduce the service life of the pumps. Therefore, when formulating the operation rules of pumps, the protection of pumps should be considered in addition to flood control.

An optimization algorithm has been widely used and applied to pump operation optimization. CFNN and ANFIS were proposed for extracting flood control knowledge and applied to the operation of a pumping station [21,22]. An online accurate model was constructed to forecast inundation levels during flood periods and used to optimize the operation of the pumping station [23]. Fuzzy logic control and genetic algorithms were applied to improve pump operations in a combined sewer pumping station [24]. Multi-period and single-period simulation-optimization were used to derive real-time control policies for operating urban drainage systems [25]. Based on the current literature, optimization of pump operation in water supply and distribution systems has also been successful [26–31].

This study aimed to minimize pump start-up/shutoff times during operation of pumps in multistage drainage pumping stations. This was achieved by constructing an optimization model and optimizing the start-up depths of pumps. The results provide reasonable start-up depths for each pump in multistage drainage pumping stations to ensure that the number of pump start-up/shutoff times is minimized during operation, and the service life of the pumps will be prolonged.

This paper is organized as follows: The "Materials and Methods" section presents the design parameters of a drainage pumping station, establishment of an optimization model, and a solution based on SWMM and PSO to the optimization model. The materials of the case study located in Beijing are also presented. In the "Results and Discussion" section, for the nine drainage pumping stations in the case study, the pump start-up and shutoff times of two applications of the proposed optimization method were obtained and compared with each other. Brief conclusions are given in the "Conclusions" section.

2. Methodology

2.1. Operational Optimization of Start-Up and Shutoff of Pumps

A typical urban drainage pumping station is usually installed in a rainwater pipe network system. The upstream and downstream of the drainage system are connected to the rainwater pipe network system, as shown in Figure 1. The pumping station contains a storage tank and a pump unit. In the construction of urban drainage pumping stations, the effective volume, bottom area, maximum design water depth, minimum design water depth, and the number, flow, start-up depth, and shutoff depth of the pump need to be designed, as shown in Figure 1. The design parameters are as follows [32]:

(1) The effective volume of the storage tank was calculated according to the upstream and the downstream flow within the pipe network of the pumping station.
(2) The bottom area of the storage tank depended on the actual land use condition.
(3) The total flow of the pump depended on the design flow of the downstream pipe network.
(4) The number of pumps generally ranged from two to eight.
(5) The minimum design water depth of the storage tank depended on the requirements of the suction head of the pumps.
(6) The maximum design water depth of the storage tank was generally equal to the top of the inlet pipe or was set to ensure that the storage tank will not overflow during the operation of the pumping station.
(7) During the operation of the pump, the number of start-up/shutoff times should not exceed six times per hour.

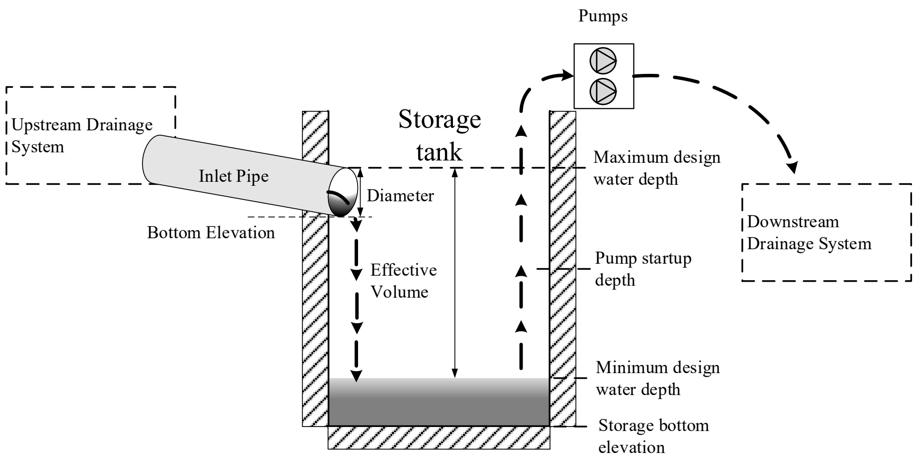


Figure 1. Design parameters of a drainage pumping station.

After the above parameters were designed, the pumping station was constructed according to each parameter. During the operation of the pumping station, the start-up and shutoff of the pumps were controlled by the start-up depth and shutoff depth of pumps. It should be noted that pumps in a drainage pumping station were typically single-frequency and worked in parallel, so the optimization study in this research mainly investigated pumping stations of this operation type. Therefore, the pump start-up depth and shutoff depth needed to be determined to control pump operation. However, the pump shutoff depth was generally set to the same as the minimum design water depth of the storage tank. Therefore, for the start-up/shutoff operation control of pumps, only the pump start-up depth needed to be set.

Two rules were followed when setting up the start-up depth of each pump:

(1) The pump start-up depth was set to ensure that the water depth in the storage tank did not exceed the maximum design water depth during the operation of the pumping station.
(2) The pump start-up depth was set to ensure that the start-up/shutoff times of each pump were not too numerous during the operation of the pumping station, and the phenomenon of frequent start-ups and shutoffs was avoided.

A drainage pumping station does not exist independently from a rainwater pipe network system. Several pumping stations usually constitute a system in series and form multistage drainage pumping stations. It was necessary to consider the flow relationship between each pumping station to set the start-up depth of each pump. It was difficult to find the optimal start-up depth and it was easy to end up with frequent start-up and shutoff times for the pumps. To resolve the problem, a pump start-up/shutoff optimization method for multistage drainage pumping stations was proposed, and the optimal start-up depth of each pump was obtained using this method. However, for some specific conditions, the operation of pumps in only one pumping station can be optimized in multistage drainage pumping stations. For example, only one pumping station was in the manager's responsibility and he did not care about other pumping stations. Under these conditions, the operation of pumps in a single pumping station was optimized independently, and its operation should consider the inflow boundary conditions in the model to obtain more reasonable optimization results. This research investigated two aspects, multistage drainage pumping stations optimization, single pumping station optimization, to optimize the pump start-up depth and minimize the number of start-up/shutoff times.

2.2. Optimization Model of the Start-Up Depths of Pumps

The establishment of pump start-up depth needs to consider each pump and the flow boundary relationship between different pumping stations in order to optimize the combination of pump start-up depths. In addition, it should be ensured that the number of pump start-up/shutoff times during the operation of the pump is minimized. Therefore, this issue of how to establish the optimal pump start-up depth was a problem for the optimization, and it was solved by developing a mathematical optimization model. Using the number of pump start-up/shutoff times as the optimization target and using the start-up depth of each pump as the optimization variable, the objective function of the optimization model was constructed as follows:

$$\begin{cases} N_{Total} = \min(N_1 + N_2 + \dots N_n) \\ [N_1, N_2, \dots, N_n] = F(h_1, h_2, \dots h_n, q_1, q_2, \dots, q_n, A, H) \\ H_{\min} < h_1, h_2, \cdots, h_n \leq H_{\max} \end{cases} \quad (1)$$

where N_{Total} is the total number of start-up/shutoff times of the pumps; N_1, N_2, … ,N_n is the number of start-up/shutoff times of each pump; h_1, h_2, … , h_n is the start-up depth of each pump.; q_1, q_2, … , q_n is the pumping flow of each pump; A is the area of the storage in pumping station; H is the height of the storage in pumping station; For a pumping station which has been built, the q, A, and H have been determined. The function F means simulation of a hydrodynamic model (the SWMM was selected in this paper). Therefore, the N_1, N_2, … ,N_n was obtained through simulation after h_1, h_2, … , h_n were set in the model. $H_{\min}$ and $H_{\max}$ are the minimum value and maximum value of constraints of the variables (h_1, h_2, … and h_n). $H_{\min}$ is equal to the pump shutoff depth. Since the pump shutoff depth was equal to the minimum design water depth, the value of $H_{\min}$ was set to the minimum design water depth. In addition, $H_{\max}$ is equal to or less than the maximum design water depth [33]. The learning factors c_1 and c_2 were both 2.0 [34].

2.3. Solution to the Optimization Model of Start-Up Depths of Pumps

In this study, particle swarm optimization (PSO) was used to solve the optimization model [35,36]. PSO is a swarm iterative optimization algorithm that has been widely used [37,38]. The iterative calculation takes the pumping stations as particles and uses the start-up depths of the pumps as optimization variables to obtain the optimal solution.

The storm water management model (SWMM) is an urban drainage model developed by the United States Environmental Protection Agency (USEPA) and has been widely used for simulation analyses of urban drainage systems [39–41]. In the iterative calculation process, the SWMM was used to simulate the operation process of the pumps and to solve the objective function. Before the optimization calculation, an SWMM model of the study area should be built, and then the optimization algorithm can be combined with the simulation of the SWMM model for iterative calculation. The steps of the optimization were as follows:

Step1: Establish the SWMM model. Based on rainfall data, pipe network data, and pumping station data, the SWMM model of the study area was established and this was used to solve the objective function in the iterative calculation process.

Step 2: Initialize the particle swarm. The initialization of the parameters of the particle swarm include the times of iterative calculation, the particle number of the swarm, and the initial position and the velocity of each particle.

Step 3: Fitness calculation of particles. The SWMM model was run to solve the objective function. Then, the number of pump start-up/shutoff times of each particle was obtained.

Step 4: Comparison of the fitness of particles with each other. The optimal historical position of each particle and the optimal global position of the swarm were obtained.

Step 5: Update the position and velocity of each particle according to the optimal historical position and the optimal global position.

Step 6: Determine whether the terminating condition of the iterative calculation is satisfied. If not, return to step 3. Otherwise, the optimal global position and the optimal start-up depth of each pump were obtained.

The optimization calculation process is shown as follows Figure 2. Using the above optimization process, the optimal start-up depth of each pump can be acquired for different rainfall scenarios, and the number of pump start-up/shutoff times will be minimized.

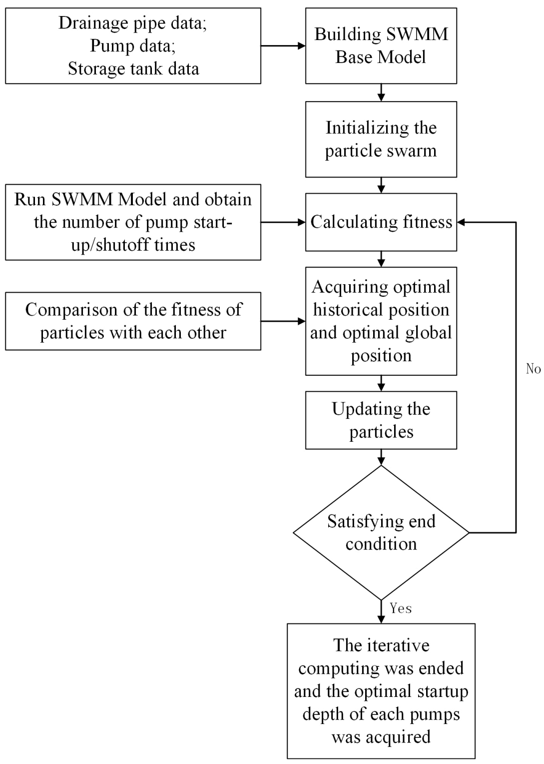


Figure 2. The optimization process for the start-up depths of the pumps.

3. Materials and Methods

Nine pumping stations in Beijing were selected for a case study, and the optimization of pump start-up depth method was applied to them for multistage pumping station optimization and single pumping station optimization. The pumps of each pumping station were single-frequency pumps and the drainage pipe network data, pump data, and storage tank data of these nine pumping stations are shown in Figure 3, Tables 1 and 2.

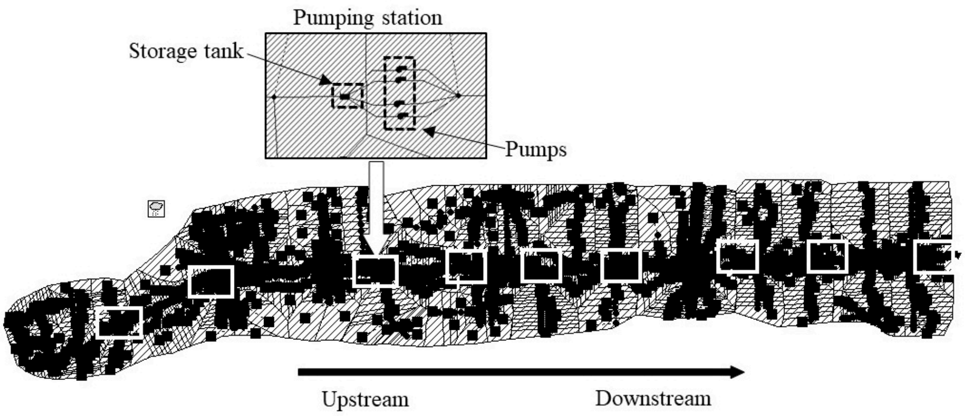


Figure 3. The SWMM (Storm Water Management Model) model for the study area. The white square in the figure is the locations of nine pump stations.

Table 1. Design parameters of the nine pumping stations.

Design Parameters		Design Parameter Values of Nine Pumping Station								
		1	2	3	4	5	6	7	8	9
Storage	Effective volume (m^3)	134.4	315	553.5	592	748	860	769.5	874	986.7
	Bottom area (m^2)	38.4	70	135	160	187	200	202.5	218.5	253
	Bottom elevation (m)	42.3	44	44	42.6	41.7	40.5	39.5	40	40
	Bottom elevation of inlet pipe (m)	45.1	47.8	47.4	45.6	45	44.1	42.6	43.3	43.1
	Diameter of inlet pipe (m)	2	2	2	2	2	2	2	2	2
	Maximum design depth (m)	4.8	5.8	5.4	5	5.3	5.6	5.1	5.3	5.2
	Minimum design depth (m)	1	1	1	1	1	1	1	1	1
Pumps	Total flow of pumps (m^3/s)	0.4	0.8	1.4	1.8	2	2.4	2.6	3.2	3.6
	Number of pumps	4	4	4	4	4	4	4	4	4

Table 2. The main properties of the drainage system in the SWMM model.

Properties of Drainage System	Value of Properties
Pipe diameters	From 0.3 m to 2.5 m
Number of pipes	1136
Total length of pipes in the drainage system	51 km
Elevation of the pipes	From 41.8 m to 54.2 m

The SWMM model was established based on the above data and was applied to the optimization.

3.1. Optimization of the Start-Up Depths of Pumps for Multistage Drainage Pumping Stations

Rainfall amounts during different recurrence periods were used as the different scenarios for the simulation. In this research, the 24-h design rainfall patterns of different recurrence periods, provided by the Beijing Meteorological Bureau, were applied in the model. It has been noted that because the design recurrence period of these nine pumping stations was twenty years, a design recurrence period of one year to twenty years was selected for this case study. The twenty-year rainfall pattern is shown in Figure 4.

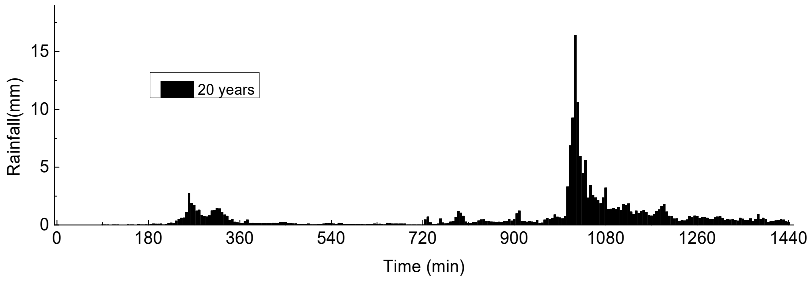


Figure 4. Design rainfall pattern for the twenty-year recurrence period.

An extremely heavy rainfall event occurred in Beijing on 21 July 2012, and caused a serious urban flooding disaster. Similarly, on 24 June and 30 July 2012, there were rainfall events that had large volumes of rainfall and lasted a long period of time. The process of three rainfall events is shown in Figure 5. The total rainfall during these three events was 160.2 mm, 64 mm, and 49 mm. The process distribution, rainfall intensity, and rainfall duration of the three rainfall events were different. Therefore, in addition to the pattern of different recurrence periods, these three rainfalls events were also selected for the optimization study of the nine pumping stations.

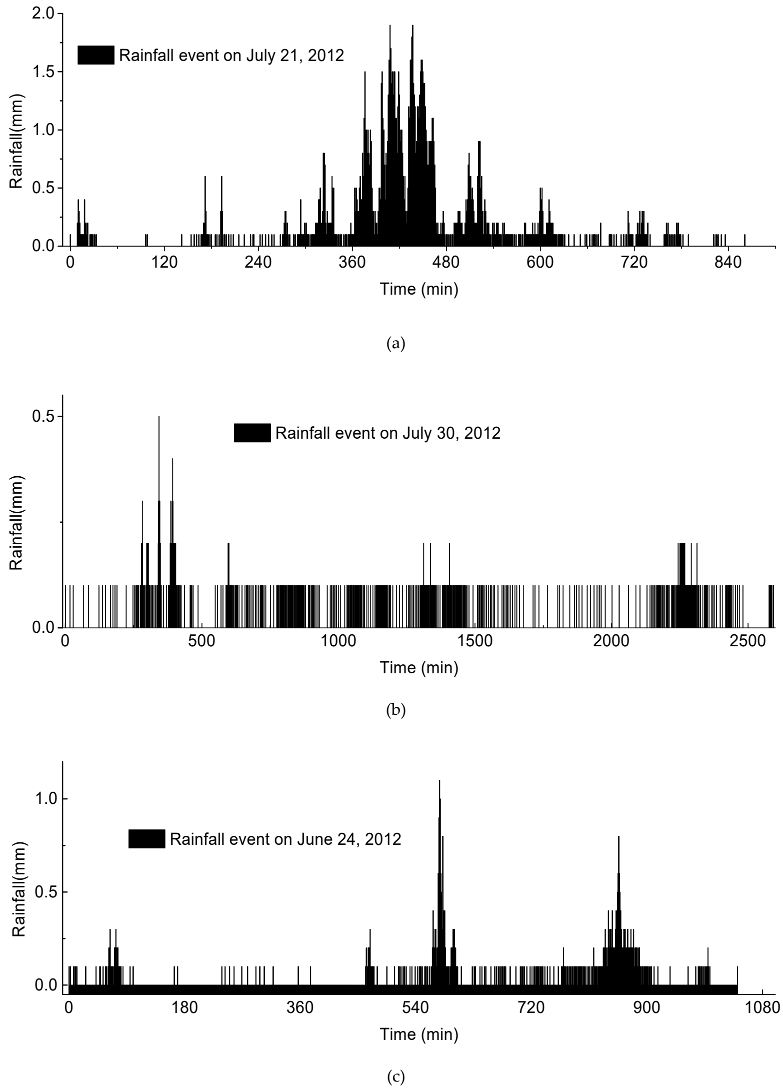


Figure 5. The data of the three rainfall processes: (**a**) rainfall event on 21 July 2012, (**b**) rainfall event on 30 July 2012, and (**c**) rainfall event on 24 June 2012.

For the different rainfall scenarios above, the optimization method developed in this research was applied to the nine pumping stations to optimize the pump startup depths in multistage drainage pumping stations. Rainfall data of different scenarios were input into the SWMM model, and the optimization method was used to calculate the optimal start-up depth of each pump.

Before the calculation, the parameters for PSO were initialized as follows: times of iterative calculation was 100, the particle number of the swarm was 100, the initial position of each particle was a random value in ($H_{\min}$, $H_{\max}$), and the initial velocity of each particle was a random value in ($-(H_{\max} - H_{\min})$, $(H_{\max} - H_{\min})$).

3.2. Optimization of the Start-Up Depths of Pumps for Each Single Pumping Station

For the optimization of a single pumping station, an SWMM model was built separately depending on the data from each pumping station and the pipe network of its catchment area. When building the SWMM model for each pumping station, the inflow boundary condition of upstream was used as input. Therefore, the SWMM models of the nine pumping stations were built independently, and the outflow of the upstream pumping station was used as the inflow boundary of the downstream pumping station during the optimization calculation process. Then, the optimization method developed in this study was used to calculate the optimal pump start-up depth for each pump in the pumping station.

4. Results and Discussion

4.1. Verification of the Two Methods

The verification should be made for the results of the two methods that the water depth in the storage tank does not exceed the maximum design water depth during the operation of the pumping station. All the results satisfy this and taking the twenty-year rainfall scenario as an example, the water depth process of the two methods is shown in Figures 6 and 7. These figures show that the water depthwas lower than the maximum design water depth in each storage tank. Therefore, the optimal start-up depths of the two methods satisfy the rule. It also can be seen that the multistage pumping station optimization method was better because its water level fluctuation was smaller than that of the single pumping station optimization method.

4.2. Comparison of Number of Pump Start-Up/Shutoff Times

The total number of start-up/shutoff times of two methods is shown in Table 3 and Figure 8. The results of the multistage pumping station optimization method for twenty-year recurrence period are shown in Table 4. From Table 4, it can be seen that the value of n of each pump is small, and the maximum value is 18 and the minimum value is 0. Therefore, through the multistage pumping station optimization method, the small number of pump start-up/shut off times can be obtained. It also can be seen from Table 3 that the values of N in other recurrence periods are smaller than that of twenty-year recurrence periods, and the minimum value was 8. Therefore, the multistage pumping station optimization method can also obtain good optimization results in other rainfall scenarios.

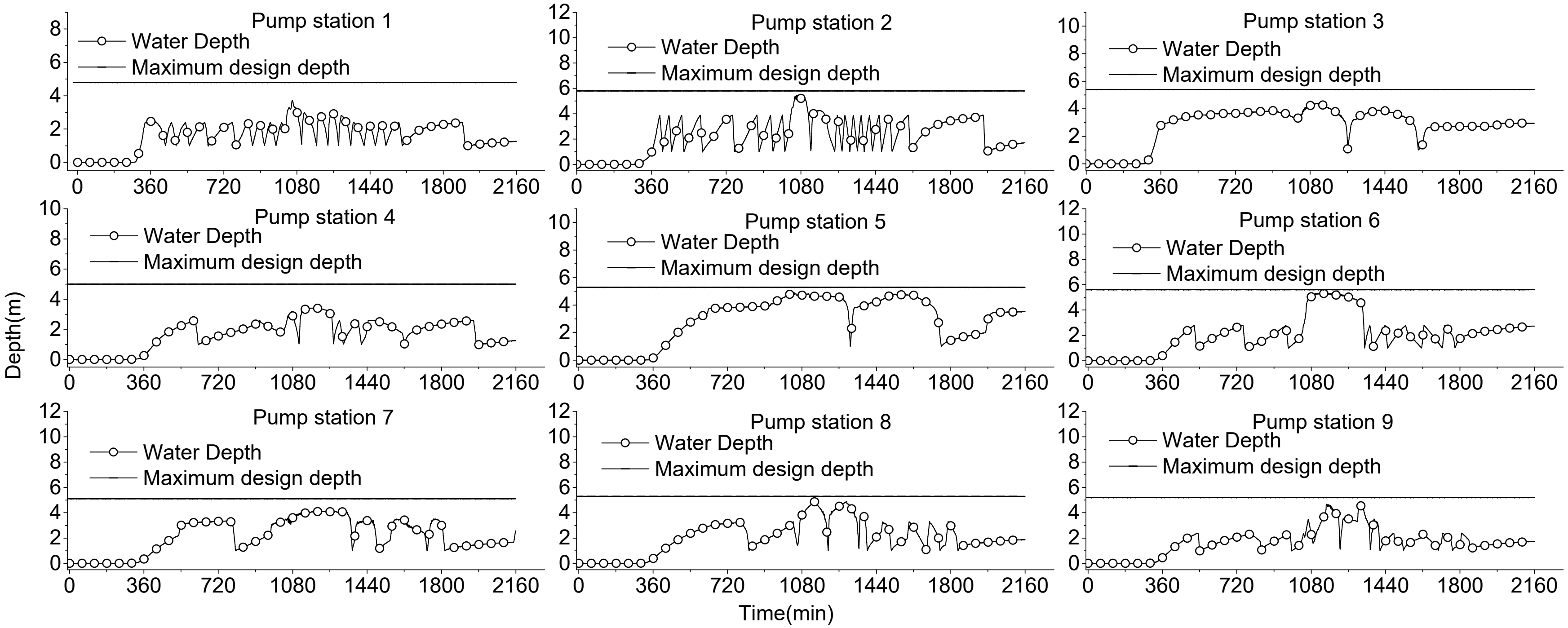


Figure 6. Water depth changing process in the storage tanks for the multistage pumping station optimization in the twenty-year scenario.

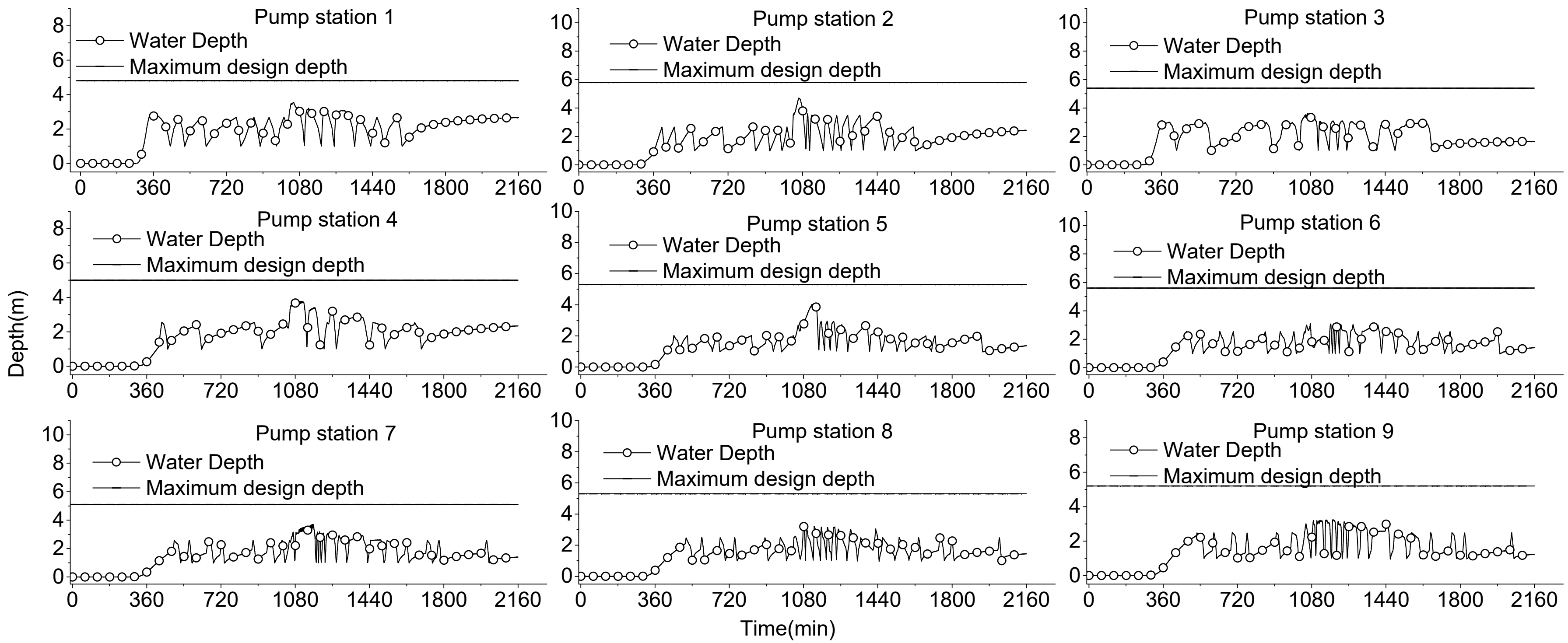
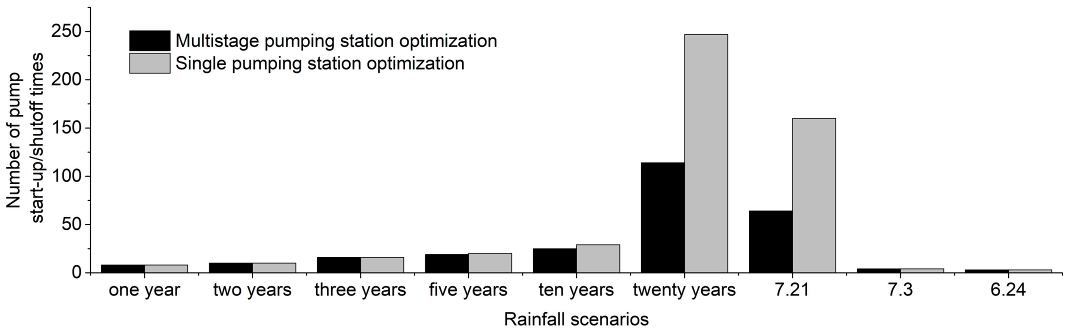


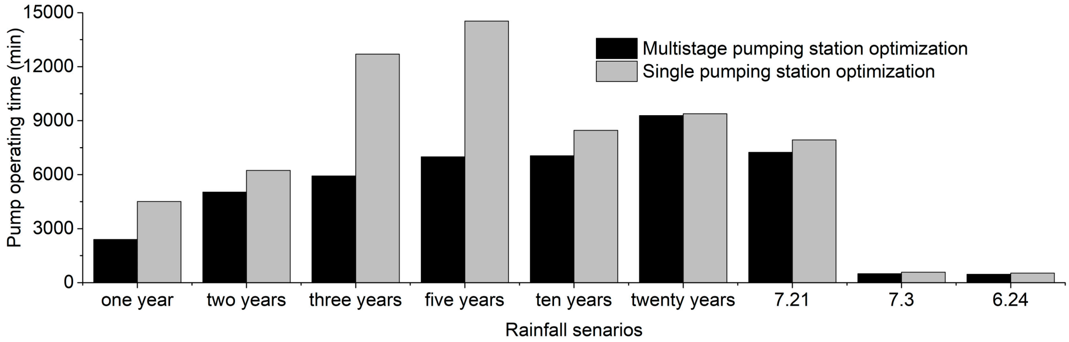
Figure 7. Water depth changing process in the storage tanks for the single pumping station optimization in the twenty-year scenario.

Table 3. Pump operation results using the three methods. *N* is the total number of pump start-up/shutoff times; *T* is the total pump operating time (unit: min); 7.21 means rainfall event on 21 July 2012; 7.30 means rainfall event on 30 July 2012; 6.24 means rainfall event on 24 June 2012.

Methods	One Year		Two Years		Three Years		Five Years		Ten Years		Twenty Years		7.21		7.30		6.24	
	N	*T*	*N*	*T*	*N*	*T*	*N*	*T*	*N*	*T*	*N*	*T*	*N*	*T*	*N*	*T*	*N*	*T*
Multistage pumping station optimization	8	2400	10	5030	16	5929	19	6991	25	7051	114	9286	64	7240	4	500	3	460
Single pumping station optimization	8	4509	10	6236	16	12,694	20	14,533	29	8462	247	9383	160	7933	4	582	3	532



(a)



(b)

Figure 8. Comparison of two optimization methods: (**a**) comparison of the number of pump start-up/shutoff times; (**b**) comparison of pump operating time. 7.21 means rainfall event on 21 July 2012; 7.30 means rainfall event on 30 July 2012; 6.24 means rainfall event on 24 June 2012.

Table 4. Results of multistage pumping station optimization method for twenty-year recurrence period. *h* is start-up depth (unit: m), *n* is the number of start-up/shut off times.

Pumping Station 1			Pumping Station 2			Pumping Station 3			Pumping Station 4			Pumping Station 5		
Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*
P1-1	2.4	18	P2-1	3.9	15	P3-1	3.9	2	P4-1	2.6	7	P5-1	4.8	2
P1-2	2.8	5	P2-2	4	5	P3-2	4.1	1	P4-2	3.2	2	P5-2	4.9	1
P1-3	3.3	1	P2-3	4.3	1	P3-3	5	0	P4-3	2.9	2	P5-3	5.1	0
P1-4	3	4	P2-4	4.5	1	P3-4	4.4	1	P4-4	4.5	0	P5-4	5	1
Pumping Station 6			**Pumping Station 7**			**Pumping Station 8**			**Pumping Station 9**					
Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*	Pump Number	*h* (m)	*n*			
P6-1	4.8	2	P7-1	3.5	5	P8-1	4.9	1	P9-1	5	0			
P6-2	4.7	2	P7-2	3.7	1	P8-2	3.9	1	P9-2	4.8	1			
P6-3	2.8	10	P7-3	4.6	0	P8-3	5	0	P9-3	3.5	2			
P6-4	5.3	1	P7-4	3.6	1	P8-4	3.3	7	P9-4	2.4	11			

The number of pump start-up/shutoff times of the single pumping station optimization was almost equal to that of the multistage pumping station optimization in low recurrence period scenarios (≤ten years). While in heavy storms, the number was more than that of the multistage pumping station optimization, which was 133 times in the twenty-year rainfall scenario and 96 times in the rainfall event on 21 July 2012. Therefore, this method can obtain logical pump start-up depth in small storms, but not in heavy storms.

In the application of the two optimization methods, the results for the multistage pumping stations were better than that used for the single pumping station. This is because single pumping station optimization is a local optimization, and flow relationships between the pumping stations are not fully adequate. The multistage pumping station optimization method was a global optimization and considers all the pumping stations together to simulate the operation process. Therefore, the operation of pumps in all of the pumping stations with series relations should be optimized together so that the optimal pump start-up depth can be acquired.

4.3. Comparison of Pump Operating Time

The optimization method of this paper does not consider the pump efficiency. Pump efficiency is also important for the operation of the pumping station, and it usually focuses on optimizing the performance properties of the pumps to obtain the optimal pump efficiency, for example, improving the pump efficiency through optimizing the pump rotational speed [42]. How to combine the optimization of pump performance properties with the method of this paper, and minimize both the number of pump start-up/shutoff times and pump energy consumption needs further study. This is not involved in this paper. However, the method of this paper can save pump energy consumption to a certain extent (certainly not the most energy-saving) by reducing the pump operating time.

The optimization method not only reduced the number of pump startup/shutoff times but also reduced pump operating time. It can be seen from Table 3 that, compared with the single pumping station optimization method, the multistage pumping station optimization method reduced the operating time, which was 2109 min in one year, 1206 min in two year, 6765 min in three year, 7542 min in five year, 1411 min in ten years, 97 min in twenty years, 693 min in rainfall event on 21 July 2012, 82 min in rainfall event on 30 July 2012, 72 min in rainfall event on 24 June 2012. The shorter operating time is, the less energy pump costs. The multistage pumping station optimization method can also reduce the pump operating time by reducing the number of pump start-up/shut off times, and the energy cost was also reduced by this method.

For an operating time, the single pumping station optimization method was longer than that of the multistage pumping station optimization method in different rainfall scenarios. Therefore, the optimization effect of the single pumping station optimization method was worse than that of the multistage pumping station optimization method for not only the number of start-up/shutoff times but also for operating time.

5. Conclusions

During the operation of multistage drainage pumping stations, frequent start-up and shutoff times can be caused if the start-up depths of the pumps are set incorrectly. In this work, a new optimization method base on PSO was proposed to achieve a logical pump start-up depth for minimizing the number of start-up/shutoff times. The SWMM was used to simulation for solving the objective function and the optimal solution was obtained through the iterative computations of PSO.

The proposed method was applied in Beijing as a case study. It was found that the solution obtained by multistage pumping station optimization method can achieve a small number of start-up/shutoff times (from 8 to 114 in different rainfall scenarios). Therefore, a multistage pumping station optimization method can obtain the most logical solution to mitigate frequent start-ups and shutoffs, which will extend the service life of pumps. The single pumping station optimization method achieves higher numbers of start-up/shutoff times than that of multistage pumping station optimization method, which were 133 times in the twenty-year rainfall scenario and 96 times in the rainfall event on 21 July 2012.

It was also found that the multistage pumping station optimization method can reduce the pump operating time, and compared with single pumping station optimization method, the pump operating time was reduced from 72 min to 7542 min in different rainfall scenarios. Therefore, the multistage pumping station optimization method can also reduce the pump operating time through reducing the number of pump start-up/shut off times.

The optimization method developed in this research did not consider the optimization of pump efficiency. The pump efficiency was also an important parameter in the optimization of pumping station operation. Although this paper discusses energy saving in terms of pump operating time, it is not the most energy-saving method. Therefore, the question how to combine the optimization of pump performance properties with the method of this paper to minimize not only the number of pump start-up/shutoff times but also pump energy consumption, needs further study.

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