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Optimal water intake and supply pump scheduling considering water quality safety in multiple water intake system

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ABSTRACT

As of 2016, a large portion (84.7%) of the annual energy consumption for operating water supply business in Korea was for power [1]. As of 2014, about 70%–80% of the power costs for water purification plants in S city were used as water intake and supply pumping costs. Accordingly, the current waterworks business is required to save power costs for efficient management. So, this research utilized a genetic algorithm, a representative optimization technique, to develop an optimal pump operation method that enables the supply of stable water quantity and safe water quality. To propose the optimal pump operation method, the objective of minimizing the costs incurred from water intake to supply was considered, and the pump switching, the water level range of distribution reservoirs and clearwell, which should be considered in actual pump operation, were set as constraints. In addition, the concept of CT values was used to consider water safety. From the results of this research, it is judged that reasonable pump operation would enable not only the saving of power cost and raw water purchase cost but also the supply of tap water to consumers with stable water quantity and safe water quality.

Keywords: CT value; Genetic algorithm; Pump scheduling; Water intake; Water supply

1. Introduction

With energy resource depletion has become an issue, international society is endeavoring to increase energy efficiency and decrease energy consumption. In line with such a global issue of energy resource depletion, every year South Korea worries about probable power risk in summer and winter. Power risk is due to the high power peaks occurring during some time zones of the seasons when intensive energy consumption is demanded and can cause problems that can cause economic loss, such as blackout. For this reason, to decentralize power demand, South Korea has introduced the price discrimination policy, which applies different rates according to different usages, seasons and times. The price discrimination policy applies a high rate during a period that usually shows high power demand and a low rate during a period that usually shows low power demand. In such a situation, energy optimization is drawing high attention, especially for social infrastructure operation, and the water supply system also needs optimal energy operation as a representative social infrastructure.

As of 2016, a large portion (84.7%) of the annual energy consumption for operating water supply business in Korea was for power [1]. That is, a large portion of the energy used in waterworks is for the operation of power units such as a pump. Particularly in the case of a water purification plant, 70%–80% of power cost is incurred by water supply pump operation. Therefore, it is expected that the preparation of a proper operation schedule for dynamic power units can achieve a power cost-saving effect for the water supply business.

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There has been steady research on pump scheduling for power cost saving. Preceding researches on pump scheduling involved a variety of methods according to optimization purposes, constraints and optimization technique types. Preceding researches are shown in Table 1.

However, as preceding researches on pump scheduling focused mostly on water quantity, it is judged that further research that considers water quality together is necessary to meet the level demanded by water supply consumers who desire to be supplied with stable water quantity and safe water quality.

This research utilized a genetic algorithm (GA), a representative optimization technique, to develop an optimal pump operation method that enables the supply of stable water quantity and safe water quality at minimum power cost and raw water purchase cost. Accurate water quantity was pursued by using the pump efficiency and discharge amount calculated by thermodynamic pump efficient measurement method, whereas safe water quality was pursued by setting CT value-based water level as constraint for clearwell, which is located prior to water supply pump room.

2. Material and methods

2.1. Target area

As the target area, this research selected the water intake and supply system of G water purification plant in S city, since the operation data of its water intake pumps and water supply pumps could be secured. G water purification plant has a facility capacity of 500,000 m^3/d, supplying water to 432,000 households in 70 buildings as of 2016. G water purification plant receives raw water from the G intake facility through 6 pumps and also from J intake facility through 4 pumps, and supplies tap water to 3 reservoirs through 12 pumps, and Fig. 1 shows a diagram of water intake and supply system in target area.

G intake facility operates 4 main pumps and 2 auxiliary pumps, while J intake facility operates 3 types of 4 pumps. Unlike the J intake facility, which does not involve raw water purchase, the G intake facility incurs a raw water purchase cost of 0.054 USD/m^3.

On the other hand, a water supply pump system consists of 2 main pumps and 2 auxiliary pumps. The water supply system operates a total of 8 pumps of A and W systems to supply water to A and Y reservoirs, and a total of 4 pumps of Y system to supply water to D reservoir. In the case of D and A distribution reservoirs of the target area, they receive an extra amount of tap water from other water purification plants. Table 2 presents the specifications of the water intake facilities, G water purification plant and distribution reservoirs, and Table 3 presents the installation specifications of the water intake and supply pumps.

2.2. Thermodynamic measurement of pump efficiency

Pump efficiency has traditionally been measured by a hydraulic method based on the measurement of flow rate, pressure increase, and the axial torque and revolutions per minute of the pump; or by thermodynamic method utilizing pump energy loss assessment based on the measurement of fluid temperature increase. Efficiency calculation by hydraulic method requires a measuring device such as flow meter. However, with many pumps in the field, it would be difficult and uneconomical to install a flow meter for every one of them. Accordingly, this research used the thermodynamic method, which has relatively less spatial and financial limitations in installing the measuring device, to measure the efficiency of the target water supply pumps.

The thermodynamic measurement of pump efficiency is conducted according to ISO 5198 Precision class (Testing Class A).

First of all, the pump is simplified to a normal adiabatic open system with an entrance and an exit. Then energy loss is directly assessed based on the measured enthalpy change of the fluid passing through the pump, by applying the first law of thermodynamics using Eqs. (1)–(3).

$$W_{\text{in}} = W_{\text{out}} + \text{Losses} \quad (1)$$

$$W_{\text{out}} = \rho g H Q \quad (2)$$

$$\text{Losses} = \rho Q C_p \Delta T \quad (3)$$

Table 1
Preceding researches for pump schedule optimization

Preceding researches	Description
Puleo et al. [2]	Puleo et al. [2] proposed a pump scheduling technique for achieving minimum cost by using linear programming and the constraints of water level and pump discharge amount.
Kougias and Theodossiou [3]	Kougias and Theodossiou [3] utilized the harmony search algorithm (HSA) for pump scheduling, to minimize energy cost by applying penalty for the energy wasted by exceeding proper reservoir water level and daily demand.
Wang et al. [4]	Wang et al. [4] utilized a multipurpose genetic algorithm (GA) to prepare an operation schedule for the pumps that drew water directly from underground water resources to supply water to various reservoirs.
Van Zyl et al. [5]	Van Zyl et al. [5] carried out GA-based pump scheduling by setting energy cost minimization as objective function and reservoir water level as constraint while applying to objective function the relation between penalty for improper final distribution tank water level and trade-off about pump On/Off. By utilizing dynamic programming, simulated annealing (SA) and GA.

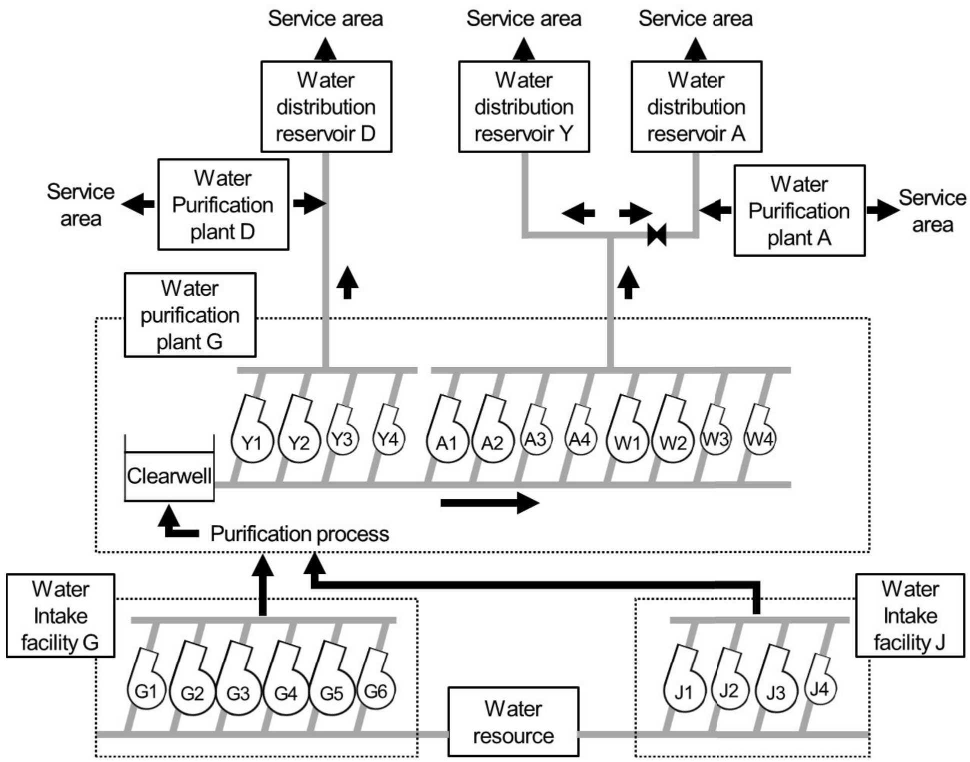

Fig. 1. Diagram of water intake and supply system in the target area.

Table 2
Specifications of the water intake facilities, water purification plant, and distribution reservoirs

Facilities	Volume (m^3)	Water level		Number of pumps
		H.W.L. (m)	L.W.L. (m)	
Water intake facility G	–	–	–	Main pumps 4, auxiliary pumps 2
Water intake facility J	–	–	–	Main pumps 2, auxiliary pumps 2
Water purification plant G	500,000	–	–	(Water-supply pumps) main pumps 6, auxiliary pumps 6
Clearwell in water purification plant G	52,000	30.0	25.0	–
Distribution reservoir A	100,000	73.0	67.0	–
Distribution reservoir Y	80,000	75.1	69.1	–
Distribution reservoir D	200,000	75.8	70.0	–

The energy loss calculated in this way can be used, along with measured head value, to calculate pump efficiency, as shown in Eq. (4).

$$\eta_p = \frac{W_{\text{out}}}{W_{\text{in}}} = \frac{1}{1 + \frac{C_p \Delta T}{gH}} \quad (4)$$

Finally, the pump discharge amount can be calculated using calculated pump efficiency by using Eq. (4), motor efficiency and motor power consumption, as shown in Eq. (6).

$$W_{\text{out}} = \rho g H Q = P_M \eta_M \eta_p \quad (5)$$

$$Q = \frac{P_M \eta_M \eta_p}{\rho g \Delta H} \quad (6)$$

Calculation of pump efficiency needs the installation of temperature sensors with a 1/1,000°C error and pressure sensors at the suction and discharge parts of the pump to measure temperature and pressure, and also motor power meters to collect additional data. Pump performance and efficiency can be estimated by substituting measured data into the above equations.

Table 3
Installation specifications of the water intake and supply pumps

Pump	Location	Discharge (m^3/h)	Total head (m)	Pump efficiency (%)	Motor efficiency (%)	Power consumption (kW)	Installation year
G1		3,246				650	
G6							
G2	Water intake facility G		54	84	95		2010
G3		6,486				1,300	
G4							
G5							
J1		4,800		87		740	
J3	Water intake facility J		42		95		2016
J2		3,000		86		450	
J4		1,800				300	
Y1		4,086		86	94.5	870	
Y2			54				
Y3		2,046		83	93.5	450	2011
Y4							
A1	Water purification plant G	3,168		86		640	
A2					94.0		
A3		1,584		81		315	2012
A4			49				
W1		3,168		86	95.0	640	
W2							2013
W3		1,584		81	95.0	315	
W4							

This research measured water temperature, as well as pressure at the suction and discharge ports of the pump, at 5 min intervals to collect data for the thermodynamic calculation of pump efficiency, total head and discharge amount. The average values of individual pumps' efficiencies obtained during the measurement period were utilized as an input factor to deduce the optimal water supply pump operation method. In addition, curve fitting was carried out for total head and discharge amount to deduce a formula for pump performance curve. It is possible to obtain more precise values for deducing the pump performance curve by increasing the degree of formula. However, as too high a degree makes calculation very complex, a formula of quadratic equation was applied [6].

2.3. Clearwell water level considering CT value

Clearwell is the facility of the last stage of the water purification process. It is a tank that stores purified water to control and reduce the imbalance between water filtration amount and water supply amount that occurs during water treatment operation and maintenance. It also serves to cope with water quality change caused by accident or breakdown, as well as to be prepared for abnormal conditions of tap water source or water quality, and for such as facility inspection and safety work. This means that a clearwell must secure a capacity that can cope with peak demand and can allow proper CT. Water treatment standard for clearwell operation, which focuses on water quality, is based on Article 28 of Water Supply and Waterworks Installation Act; Article 18, Clause 2 of Enforcement Regulations of Water Supply and Waterworks Installation Act; and Regulations on Inactivation Rate Calculation Method and Water Treatment Certification.

The aim of the law is to secure the safety of the drinking water supplied by multi-regional and local water suppliers against pathogenic microorganism, by removing or inactivating 99.99% of virus, 99.9% of Giardia Cysts and 99% of *Cryptosporidium oocyst* that are present between water intake location and clearwell discharge location.

The aim mentioned above refers to the total removal rates of individual kinds of microorganisms, whereas the microorganism removal rates that have to be achieved by an actual water treatment process vary according to the types of facility and process. A water treatment process is generally subdivided into a filtration process and a disinfection process, and removal rate depends on the filtration method and disinfectant type [7].

Particularly, the criteria of pathogenic microorganism removal or inactivation in the disinfection process differ according to the operation methods of the filtration process, which is followed by the disinfection process. Table 4 shows the criteria of pathogenic microorganism removal or inactivation for the disinfection process that follows the rapid filtration process specified in Regulations on Inactivation Rate Calculation Method and Water Treatment Certification (Table 1).

The concept of CT value, which was publicized in 1989 through the Surface Water Treatment Rule in the USA, was

Table 4
Criteria of pathogenic microorganism removal or inactivation in Korea (rapid filtration)

Criteria	Virus	Giardia cyst
Minimal removal efficiency (inactivation criteria)	99.99% (4.0 log)	99.9% (3.0 log)
Removal efficiency in filtration prose	99% (2.0 log)	99.68% (2.5 log)
Removal efficiency in disinfection prose	99% (2.0 log)	68.38% (0.5 log)

introduced for microorganism inactivation during the disinfection process. And refers to the relation between disinfectant concentration and CT that is required to inactivate microorganism. CT value is an empirical expression that defines the extent of microorganism inactivation by a particular disinfection method, as assessed based on the microorganism disinfection effect. In general, CT value increases as water temperature and/or residual disinfectant concentration decrease(s), and as pH increases. An increase in CT value accordingly demands an increase in the required CT value for the disinfection process. The standard for required CT values by temperatures and pHs are presented in Regulations on Inactivation Rate Calculation Method and Water Treatment Certification (Table 1), which has been proclaimed by the Ministry of Environment and includes the following Eqs. (7) and (8) as the CT calculation method.

$$\mathrm{CT}_{\mathrm{calculation}} = C \times T_{10} \tag{7}$$

$$T_{10} = R \times T \tag{8}$$

According to Eqs. (9) and (10), it is reasonable to say that clear well water level, which is related to retention time, should be affected by disinfectant concentration, and also by CT value according to CT. Therefore water level must be controlled to allow sufficient CT.

$$T_c = \frac{A \times H_{w,\min}}{q_{\max}} \tag{9}$$

$$H_{c,\min} = \frac{q_{\max} \times \mathrm{CT}_{\mathrm{requirement}}}{C \times R \times A} \tag{10}$$

CT value is calculated by multiplying disinfectant concentration and hydraulic retention time together. Hydraulic retention time can be deduced based on the flow rate inside clearwell and the treated water storage amount of clearwell. Treated water storage amount is determined by floor area and clearwell water level, and so a decision can be made on proper water levels that can satisfy required CT values for different pHs and water temperatures. That is, it is possible to set a minimum clearwell water level in such a way that the inactivation rate is at least 1.

Hydraulic retention time that satisfies the required CT value can be expressed as Eq. (9), by properly manipulating Eq. (9) in combination with Eqs. (7) and (8), the minimum clearwell water depth that satisfies the required CT value can be expressed as Eq. (10). Thus proper minimum clearwell water depth can be determined by Eq. (10).

Required CT value for Eq. (10) was calculated using the empirical formula presented by [7], which calculates the log removal rate of virus and Giardia Cysts based on calculated CT value.

2.4. Optimal pump scheduling method

An optimal pump operation schedule is demanded efficient power energy use and power cost saving. This research attempted to deduce a GA-based optimal pump operation schedule for the water intake pump and water supply pump.

To deduce an optimal pump operation schedule, the sum of minimum power cost and raw water purchase cost was set as the objective function, while the water level ranges of individual reservoirs and water purification plants were set as a constraint. Preceding researches considered a water supply pump first by setting a constraint on the reservoir water level. In contrast, the present research considered optimal water supply pump operation along with the securing of sufficient CT at clearwell and, in addition, established a water balance equation for both reservoir and clearwell to deduce an optimal operation that considers water intake pump as well.

Further, the discharge amount and efficiency of each pump was determined based on total head according to reservoir water level change, and the determined values were applied to deducing pump operation schedule to obtain a realistic pump operation schedule. For this purpose, the relation between the total head, discharge amount, efficiency of the pump was deduced based on the measurement of pump efficiency by the thermodynamic method, and the deduced result was used to estimate the current efficiency and pump performance curve of the pump.

Fig. 2 shows the flow diagram of the GA-based optimal pump scheduling method.

This research set a constraint on the operation water level of clearwell and reservoir, which plays a buffering role, to secure stability and safety in water quantity and quality; and also on the continuous operation time of pump to prevent excessive pump switching. The objective function shown in Eq. (11) aimed at the power cost minimization for water supply pump in consideration of the power rates applied discriminately for different time zones, seasons and days of the week, according to the levels of power consumption; and was used for adequacy assessment.

$$\mathrm{Min}\ C = M\,\mathrm{in}\sum_{j=0}^{k-1}\left(\sum_{i=1}^{l}\left(R_{i,j} \times \mathrm{EC}_j \times X_{i,j}\right) + \mathrm{WC} \times I_{j+1}\right) \tag{11}$$

$$R_{i,j} = \frac{9.8 \times h_{i,j} \times Q_{i,j}}{\eta_{P_{i,j}} \times \eta_{M_{i,j}}} \tag{12}$$

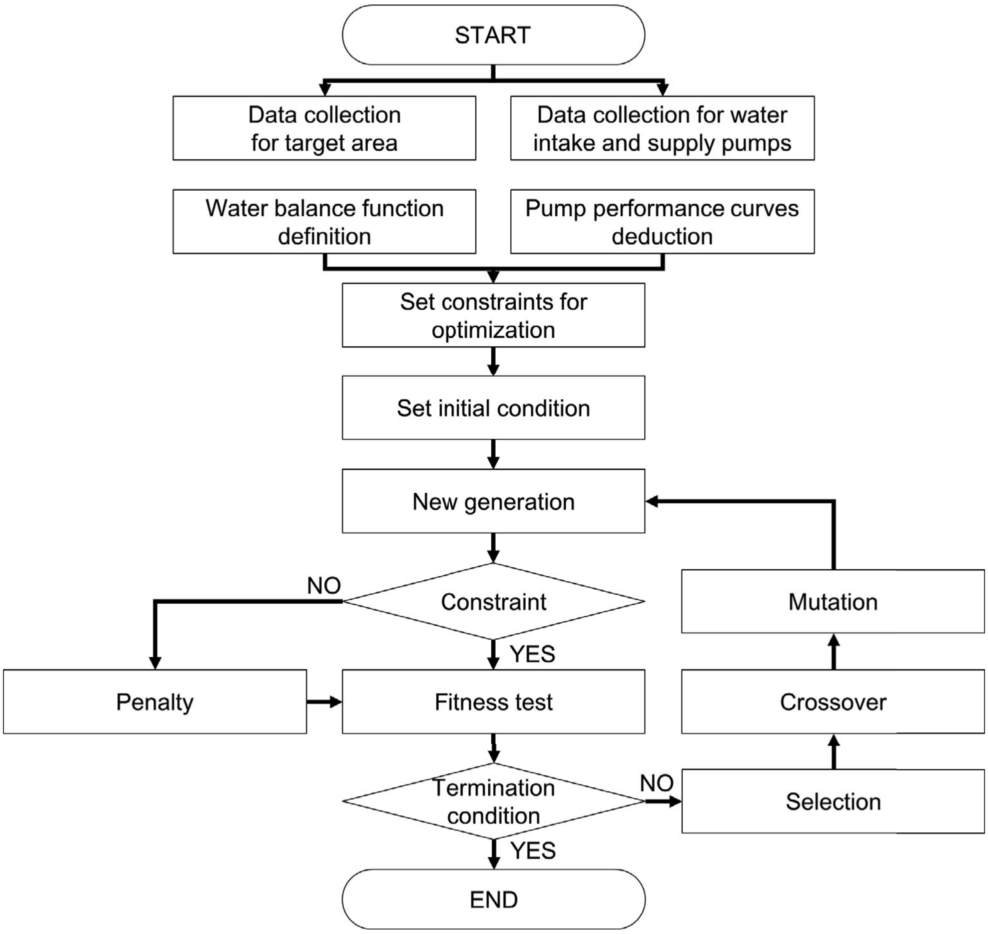

Fig. 2. Flow diagram of the GA-based optimal pump scheduling method.

Pump efficiency calculated by the thermodynamic method may vary according to the total head changes caused by discrepancies in water level between clearwell and reservoir and accordingly deduced pump discharge amount and efficiency may vary from moment to moment. Eq. (12) considers such a situation and was used to calculate the power consumption of *i* pump.

To use the water levels of clearwell and reservoir as constraint, Eqs. (13) and (14) were established as water balance equations for clearwell and reservoir.

$$\mathrm{CW}_j = \mathrm{CW}_{j-1} + \mathrm{WP}_j - \sum_{i=1}^{l} Q_{i,j} X_{i,j} \tag{13}$$

$$\mathrm{DR}_{r,j} = \mathrm{DR}_{r,j-1} + \mathrm{WS}_{r,j} + \alpha_r \sum_{i=1}^{m} Q_{i,j} X_{i,j} - \mathrm{WD}_{r,j} \tag{14}$$

Here, according to the characteristic of the target area, the distribution coefficient for water supply amount was defined in consideration of the condition that treated water is divided to be supplied to A and Y reservoirs by 8 pumps, and to D reservoir by 4 pumps.

In addition, the target area has the condition that one of the 2 intake facilities being operated incurs raw water purchase cost. An optimal pump operation schedule deduced under such a condition may heavily depend on the pump operation of the one facility that does not incur raw water purchase cost. However, as a water supplier would plan to operate both intake facilities, Eq. (15) was set as a constraint.

$$N \geq M \tag{15}$$

Eq. (15) refers to a constraint on the number of operated pumps per day for the G intake facility, which incurs raw water purchase cost. The number of G intake facility's operated pump per day was calculated by counting each main pump as 1 unit of the pump, and each auxiliary pump as 0.5 unit of the pump.

The water level was determined by calculation using the water balance equations for reservoir and clearwell, while operation condition was satisfied by setting water level operation range as constraint. In the case of a reservoir, a water level range from 3 m up to 5.5 m was set as water level constraint based on actual water level operation data. As for clearwell, a water level from the minimum required water level calculated in consideration of required CT value up to the maximum water level of 6.5 m was set as a constraint. However, in case the clearwell water level calculated in consideration of required CT value is lower than 3 m, the constraint on the lowest water level was set at 3 m, which is the lowest water level generally used for water purification plant operation.

In addition, in order to prevent frequent pump switching, which exert adverse effect causing such as pump performance deterioration, the continuous operation time of pump was restricted so that each pump operation can continue for at least 2 h.

The genetic parameters of population, generation, crossover rate, and mutation were set at 100; 40,000; 0.5; and 0.01, respectively, and computation was set to end upon the completion of calculation for the set generation.

3. Results and discussions

3.1. Results of pump performance assessment by the thermodynamic measurement method

The characteristics of the currently operated pumps were analyzed based on the data collected through the temperature sensors and pressure sensors installed on the suction/discharge ports of the 8 water supply pumps of A and W systems. The data was collected from September 1 to December 31, 2016. pump performance curves were deduced by utilizing the efficiency, total head and discharge amount calculated based on the data measured at 5 min intervals for individual pumps. However, some observed values were judged to be outlying values caused by such as sensor error. Therefore the preparation of pump performance curve and the deduction of pump efficiency excluded, as outlying values, the observed values that caused discharge amount to fall outside the $\pm 3\sigma$ interval. However, there were limitations in collecting data for the water supply pumps and water intake pumps of the Y system. For this reason, the efficiencies of the Y system's pumps whose efficiencies could not be measured were estimated based on their performance deterioration rates in terms of performance efficiency, by comparing their specifications at the time of installation with their current specifications based on the efficiencies obtained for the pumps of A and W systems. In addition, pump characteristic curves were deduced by the single-point method presented in [8]. Table 5 presents the specifications of the water supply pumps of A and W systems at the time of installation, along with the current specifications deduced by the thermodynamic pump efficiency measurement method. Also, this table presents the equations for the pump characteristic curves deduced by the thermodynamic pump efficiency measurement method and the single-point method by [8].

In the case of the deduced pump characteristic curves, it was shown that the coefficient of determination was 0.85 or higher and root mean square error (RMSE) was 50 m^3/h or lower. From such a result, it is judged that an expression of the relation between total head and pump discharge amount that can represent well the performance of the currently operated pumps has been deduced.

3.2. Results of proper clearwell water level operation range considering CT value

This research analyzed minimum clearwell operation water level based on the data about the water temperature, pH and residual chlorine concentration of clearwell influx collected from January 1, 2016 to January 31, 2017; and then determined the period that requires optimal clearwell pump operation, as well as the minimum clearwell operation water level that considers CT value.

Fig. 3 shows the minimum daily clearwell operation water level, as well as the minimum clearwell operation water level that considers CT value, calculated in this way.

As shown in Fig. 3, the minimum clearwell operation water level used during January of 2016 and January of 2017, when water temperature was low, could not satisfy CT value. Accordingly, this research selected January 9–15, 2017 as the target period, as constraint on minimum clearwell water level for the optimal pump operation method is high in winter.

Table 5
Comparison of the specifications for the water supply pumps between installation year and present

Pumps	Installation year			Present			Current performance curve by thermodynamic method or EPANET manual	R^2	RMSE (m^3/h)
	Discharge (m^3/h)	Total head	Efficiency (%)	Discharge (m^3/h)	Total head	Efficiency (%)			
Y1	4,086	54 m	86	4,163	55.63	81.62	$H = 73.99 - 9.673e^{-7}Q^{2.011}$	EPANET manual	
Y2	4,086	54 m	86	4,114	55.69	81.79	$H = 74.07 - 9.920e^{-7}Q^{2.011}$		
Y3	2,046	54 m	83	1,990	55.51	81.00	$H = 73.83 - 4.259e^{-6}Q^{2.011}$		
Y4	2,046	54 m	83	2,010	55.66	83.04	$H = 74.02 - 4.183e^{-6}Q^{2.011}$		
A1	3,168	49 m	86	3,215	50.26	81.55	$Q = -6.78H^2 + 560.9H - 7826$	0.8663	48.53
A2	3,168	49 m	86	3,137	50.41	81.48	$Q = -13.33H^2 + 1205H - 23720$	0.9079	42.99
A3	1,584	49 m	81	1,589	50.17	80.07	$Q = -2.46H^2 + 189.1H - 1704$	0.9374	14.96
A4	1,584	49 m	81	1,576	50.47	81.16	$Q = -1.38H^2 + 82.49H - 915.2$	0.9803	7.37
W1	3,168	49 m	86	3,241	50.69	81.69	$Q = -14.91H^2 + 1382H - 28490$	0.9289	34.48
W2	3,168	49 m	86	3,242	50.66	82.10	$Q = -14.47H^2 + 1334H - 27180$	0.9034	46.69
W3	1,584	49 m	81	1,492	50.57	78.02	$Q = -3.82H^2 + 332.6H - 5563$	0.9829	6.73
W4	1,584	49 m	81	1,537	50.54	80.91	$Q = -2.917H^2 + 237H - 2984$	0.9804	7.97

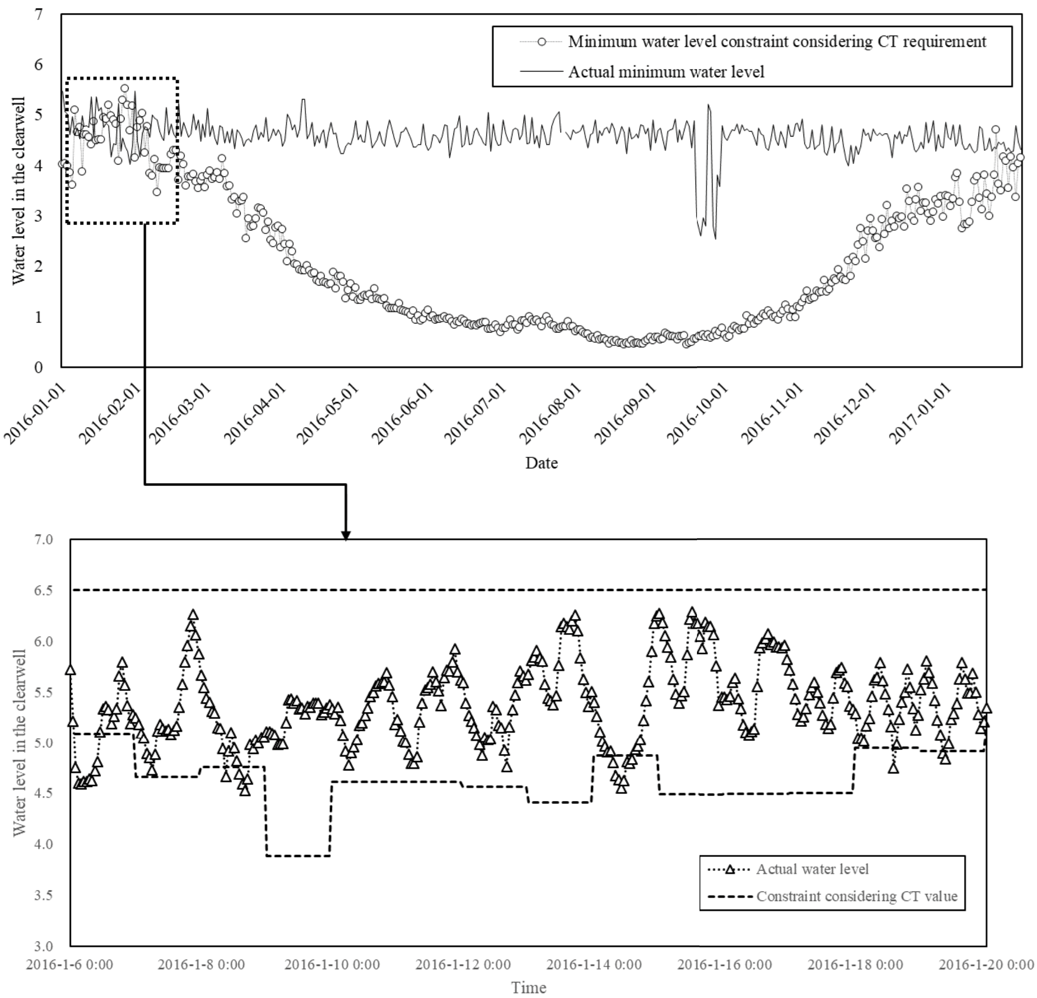

Fig. 3. Actual minimum daily clearwell operation water level that do not meet CT value.

Table 6
Water intake pumps schedule in actual operation and optimization scenarios (2017/01/09)

Scenario	Pump	Number of water intake pumps operated (hourly)																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Actual operation	G1, G6	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	G2, G3, G4, G6	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	J1, J3	1	1	1	2	2	2	2	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	J2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	J4	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Optimization 1	G1, G6	0	1	1	1	1	2	1	0	1	1	0	0	0	0	0	0	1	0	1	0	2	1	0	0
	G2, G3, G4, G6	1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	1
	J1, J3	2	1	2	2	2	2	2	2	1	2	2	1	1	2	1	1	0	1	1	1	2	1	1	0
	J2	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	J4	1	1	0	0	1	1	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Optimization 2	G1, G6	1	0	1	1	1	0	0	0	2	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
	G2, G3, G4, G6	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1
	J1, J3	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	0	2	1	2	2	0	0
	J2	0	0	0	1	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1
	J4	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3.3. Results of pump schedule optimization

To achieve optimal pump operation, optimization scenarios were established according to the numbers of G intake facility's pumps that can be operated per day. Optimization scenarios 1 and 2 involve the operation of 12 and 10 pumps per day, respectively, at the G intake facility. Here, the number of operated pumps per day was calculated by counting each main pump as 1 unit of the pump, and each auxiliary pump as 0.5 unit of the pump.

Tables 6 and 7 show the result of a comparison between actual water intake and supply pump operation schedule and the optimal pump operation schedule for the day of the 7 d research period deduced in this research.

For the detailed analysis on the effect of the optimal pump operation method, a comparison was made using the water levels of clearwell and reservoir, as well as power cost and raw water purchase cost, involved in actual pump operation during a 7-d period in January 9~15, 2017, when pump operation is disadvantageous in terms of CT value.

Table 8 presents raw water purchase cost, water intake pump power cost, water supply pump power cost, saving and saving rate.

Table 7
Water supply pumps schedule in actual operation and optimization scenarios (2017/01/09)

Scenario	Pump	Pump schedule (On: gray, Off: white)																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Actual operation	Y1																								
	Y2																								
	Y3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Y4																								
	A1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	A2	■	■	■	■	■	■	■	■	■	■								■	■	■	■	■	■	■
	A3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	A4																								
	W1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	W2																								
	W3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	W4	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Optimization 1	Y1																								
	Y2																								
	Y3	■	■			■	■								■	■		■	■				■	■	
	Y4																								
	A1	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
	A2	■	■	■	■	■	■	■	■	■	■	■									■	■	■	■	■
	A3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	A4					■	■																		
	W1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■
	W2																								
	W3	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	
	W4		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■	■
Optimization 2	Y1																								
	Y2																								
	Y3	■	■			■	■								■	■		■	■						
	Y4																								
	A1	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■
	A2	■	■	■	■	■	■	■	■	■	■	■									■	■	■	■	■
	A3	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	A4			■	■	■	■																		
	W1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■
	W2																								
	W3	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■	■			■	■	■	
	W4	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■	■

Table 8
Comparison of the optimization operation scenarios and the raw water purchase cost, water intake pump operation cost, and water supply pump operation cost

Property		Actual	Optimization 1	Optimization 2
Total cost		97,410 USD	87,871 USD	85,841 USD
Total saving cost		–	9,539 USD	11,570 USD
Total saving ratio		–	9.79%	11.88%
Raw water purchase cost	Cost	32,541 USD	30,230 USD	27,212 USD
	Saving cost	–	2,311 USD	5,330 USD
	Saving ratio	–	7.10%	16.38%
Water intake pump power cost	Cost	29,544 USD	25,487 USD	25,809 USD
	Saving cost	–	4,057 USD	3,734 USD
	Saving ratio	–	13.73%	12.64%
Water supply power cost	Cost	35,325 USD	32,154 USD	32,820 USD
	Saving cost	–	3,171 USD	2,505 USD
	Saving ratio	–	8.98%	7.09%

In Table 8, raw water purchase cost saving ratios in optimization 1 and 2 scenarios are 7.10% and 16.38%, respectively. And water intake pump operation cost saving ratios in each optimization scenarios are 13.73% and 12.64%. In addition, in these optimization scenarios, the water supply pump operation also achieved cost savings of 8.98% and 7.09%. Therefore, in all the optimization scenarios, the cost-saving effect is shown to be higher than that of the actual operation, and the result of optimization 2 showed the best cost-saving effect.

Fig. 4 presents intake amounts by actual intake pump operation and optimal intake pump operation.

It was shown that optimal operation reduces the ratio of the intake amount of the G intake facility, which incurs raw water purchase cost while increasing the ratio of the intake amount of J intake facility, which does not incur raw water purchase cost.

Fig. 5 shows the water levels of clearwell and reservoirs by actual pump operation and the optimal pump operation deduced in this research.

Based on the result of the actual clearwell water level operation shown in Fig. 5, it is considered that the operator was not utilizing the sufficient capacity of clearwell. Whereas the result of optimal vs. actual pump operation showed that optimal pump operation can achieve even pump operation for constraints on the water levels of reservoir and clearwell. Also, it is judged that satisfying the water level constrains optimal pump operation enables the supply of sufficient water quantity to consumers and the securing of sufficient CT.

4. Conclusions

This research was proposed an optimal pump scheduling method from water intake to water supply by using GA based on water quantity and quality data as well as pump performance deduced by the thermodynamic pump efficiency measurement method.

As proper retention time is required to allow sufficient CT at clearwell, minimum clearwell operation water level

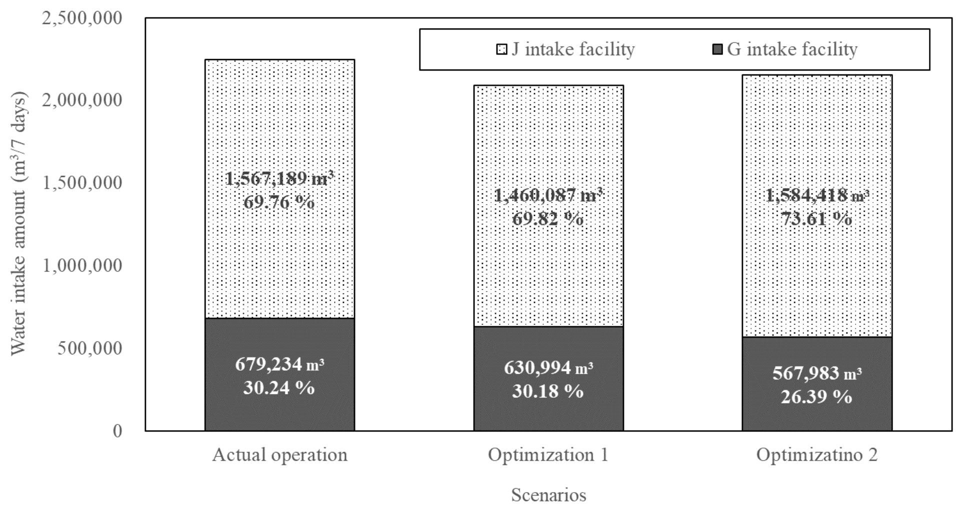

Fig. 4. Comparison of water intake amounts by actual intake pump operation and optimal intake pump operation.

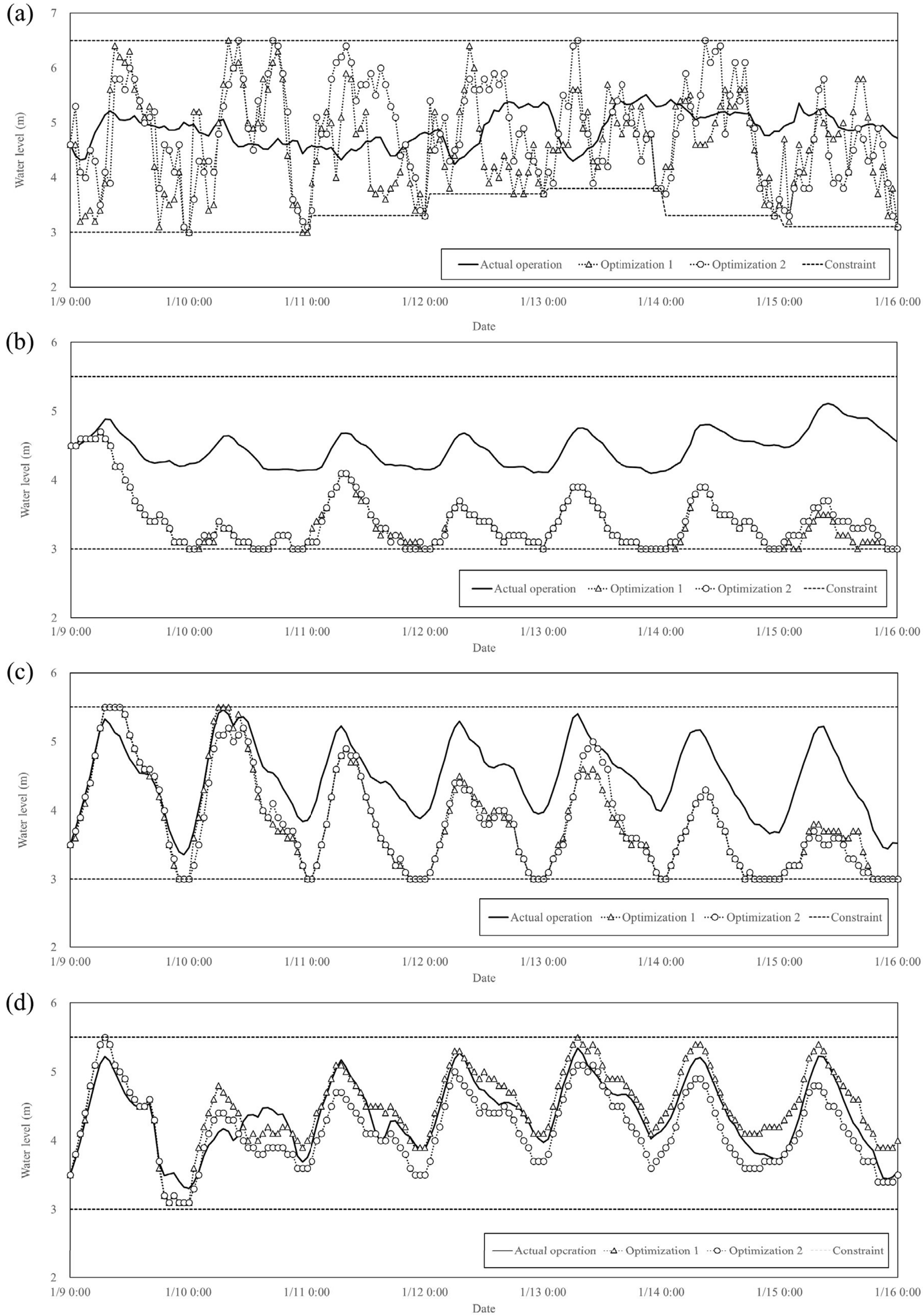

Fig. 5. Water levels of clearwell and reservoirs by actual pump operation and the operation of the optimal pump ((a) Clearwell, (b) Reservoir D, (c) Reservoir Y, and (d) Reservoir A).

that can satisfy such a condition was deduced. In addition, to consider the condition of the pumps whose current performance is much different from the performance at the time of installation according to time elapse after installation, pump performance curve was deduced by utilizing the efficiency, total head and discharge amount deduced by the thermodynamic method. Based on the result, this research established an optimal pump operation schedule and presented a cost-saving effect by optimal operation method.

Cost-saving by a 7 d of GA-based optimal pump operation was shown to vary according to the scenarios of constraint on the number of the G intake facility's operated pumps per day: (1) if the number is 12, a total of 9,539 USD can be saved (a raw water purchase cost of 2,311 USD, a water intake pump power cost of 4,057 USD, and a water supply pump power cost of 3,171 USD) and (2) if the number is 11,570 USD can be saved (a raw water purchase cost of 5,330 USD, a water intake pump power cost of 3,734 USD, and a water supply pump power cost of 2,505 USD). Cost-saving rates for the 2 scenarios were shown to be 9.79% and 11.88%, respectively.

Compared to actual operation, the optimal pump operations by the 2 scenarios achieved a cost-saving effect through the reduction of power consumption during maximum load time zone, by increasing power consumption during light and intermediate load time zones. Meanwhile, the optimization 2 scenario which constrains the use of the intake pump in the G intake facility more than the optimization 1 the pump operation cost savings was less than the optimization 1, but the cost savings of that are more than twice that of optimization 1. Accordingly, in addition to the achievement of cost-saving effect, optimal pump operation resulted in the utilization of a wider range of clearwell water level operation and the securing of sufficient CT at clearwell.

From the results of this research, it is judged that reasonable pump operation would enable not only the saving of power cost and raw water purchase cost but also the supply of tap water to consumers with stable water quantity and safe water quality. It is expected that follow-up research that involves the estimation of individual reservoirs' water demands, as well as the consideration of changes in pump characteristics (such as pump efficiency) according to parallel pump operation combinations, would lead to the development of a more advanced optimal water supply pump operation method.

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Subscripts

W_{in} — Power input to pump, W
W_{out} — Output power available, W
Losses — Loss power, W
Q — Discharge, m^3/s
H — Total pump head, m
C_p — Specific heat at constant pressure, J/kg/K
ΔT — Temperature difference between suction and discharge part, K
ρ — Density of passing fluid, kg/m^3
g — Acceleration of gravity, m/s^2
P_M — Power input to motor, W
η_M — Motor efficiency
η_P — Pump efficiency
CT — CT value, mg min/L
C — Residual disinfectant concentration, mg/L
T_{10} — Retention time for 90% of purified water in clearwell, min
R — Conversion factor of length-width ratio
T — Hydraulic retention time, min
T_C — Hydraulic retention time to meet required CT value in clearwell, min
A — Floor area of clearwell, m^2
$H_{c,\min}$ — Minimum water level to meet required CT value in clearwell, m
$q_{\max}$ — Maximum hourly flow rate, m^3/min
C — Total cost from water intake to water supply, USD
j — Time, h
i — Pump
$R_{i,j}$ — Power consumption of pump i at time j, kW
EC_j — Unit cost for power consumption at time j, USD/kWh
$X_{i,j}$ — Operation status of pump i at time j, On:1, Off:0
WC — Unit cost for raw water purchase in G water intake facility, USD/m^3
I_{j+1} — Water intake quantity between time j and time $j+1$ in G water intake facility, m^3
CW_j — Storage of clearwell at time j, m^3
WP_j — Water production at time j, m^3
$DR_{r,j}$ — Storage of reservoir r at time j, m^3
$WS_{r,j}$ — Water supplement from water purification plant A or D at time j, m^3
α_r — Distribution coefficient
$WD_{r,j}$ — Water demand for reservoir r at time j, m^3
N — Number of pumps operated per day in G water intake facility, Pump G1 and G6 = 0.5, Pump G2, G3, G4, G5, and G6 = 1

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