Research on minimizing electric power usage in water distribution system

Yasuhiro Arai, Toshiki Horie, Akira Koizumi, Toyono Inakazu, Atsushi Masuko, Satoshi Tamura and Takashi Yamamoto

ABSTRACT

The purpose of this study is to propose the optimal water supply control and management plan for minimizing power usage by water distribution pumps. The key topic of this study is to determine from which treatment plants water should be supplied, and through which supply stations it should be distributed. This study devised an optimal model of the 'route/flow decision problem' for minimizing power use in the water distribution system while meeting demand in the distributing areas, and formulated the model by means of mixed integer linear programming (MILP). Then to validate the MILP model we attempted a case study in an actual water distribution system. The research demonstrated the effectiveness of the proposed optimization when applied to minimizing power usage in water operation.

Key words | energy-saving, mixed integer linear programming (MILP), network model, optimization of water operation, water distribution system

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INTRODUCTION

The amount of electric power used in Japan's water utility services is approximately 1% of total nationwide electricity usage. Water utilities in recent years have been making aggressive efforts to save energy in water facilities. They have been installing inverter controllers in pumping equipment, are working to save energy by optimizing water operations, and are taking other steps to reduce electric power usage (MHLW 2003).

Ever since fiscal year (FY) 1995, the amount of water supplied in Japan has been trending downward. Electric power usage, however, has mostly held steady since around FY 1994. (In FY 2008 power usage was 7.64 billion kWh.) Power usage, in other words, has not decreased even as the water supply volume has declined. In fact, the amount of power use per unit water supplied (called the energy consumption rate in this research) has been rising slightly; it was 0.508 kWh/m^3 in FY 2008. In coming years many water utilities are expected to introduce advanced water treatment facilities aimed at supplying high-quality water to customers. Power usage is likely to rise even further as a result. In reducing power usage by today's water systems, it will therefore be important to achieve power usage reductions in the water distribution system, which accounts for the majority (from 60 to 70%) of power use in water services as a whole (Walski 1993; Wu *et al.* 2012).

METHODS

Electric power usage [kWh] and its unit (energy consumption rate) [kWh/m^3]

The scatter chart in Figure 1 shows the relation between flow rate Q [m^3] of service reservoir Y and energy consumption rate e [kWh/m^3]. It uses hourly distribution pump data for the period from April to July 2010. Similarly, Figure 2 plots the relation between flow rate Q and electric power usage P [kWh]. Looking at the relation of e to Q in Figure 1 tells us that as flow rate Q decreases, the observed values of energy consumption rate e become significantly larger than

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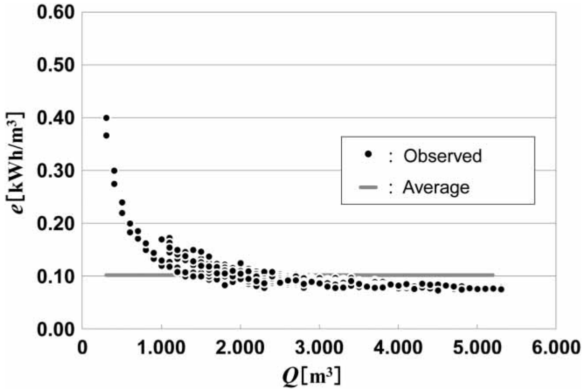

Figure 1 | An example of electric power consumption rate [kWh/m^3].

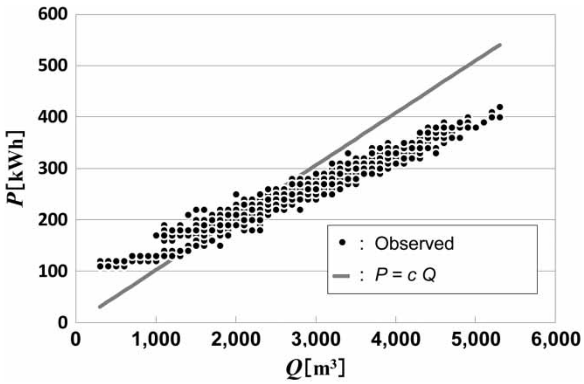

Figure 2 | An example of electric power usage [kWh].

the average e values. The relation between P and Q in Figure 2, meanwhile, is such that as flow rate decreases, the observed values become greater than those derived from the electric power usage estimation equation $p = c\ Q$. When flow rate Q increases, on the other hand, energy consumption rate e falls below the average. The phenomenon evident here is that changes in distribution flow rate cause the observed values to diverge from $p = c\ Q$. The amount of electric power needed to distribute 1 m^3 of water changes as the flow rate rises or drops (Masuko *et al.* 2012). In this paper we define the above trend as the dependence of energy consumption rate [kWh/m^3] on water distribution flow rate.

'Efficient range' and 'inefficient range' of pump operation

Analyzing the e-Q and P-Q scatter charts, we find that they can be classified into three patterns as shown in Figure 3. These results are based on the April to July 2010 data on an hourly basis for energy consumption rate and electric power usage of 48 distribution pumps in city T (Arai *et al.* 2012). The three patterns, as represented on the e-Q graphs at the top of Figure 3, are as follows:

(1) When there is no dependence on water distribution flow rate (energy consumption rate remains practically flat).
(2) When energy consumption rate rises with increased flow rate (positive dependence).
(3) When energy consumption rate rises with decreased flow rate (negative dependence).

Controlling the flow rate range so that the energy consumption rate is below average c can be considered good water management from the standpoint of energy efficiency. If, however, pumps are operated in the range in which energy consumption rate rises above average c, this is undesirable from the standpoint of reducing electric power usage. In this study we define the former as the 'efficient range' and the latter as the 'inefficient range'.

Mathematical formulation

In this study we introduce a dummy variable (integer variable) δ_{ij} concerning the choice of water flow rate range j (Aiyoshi & Yasuda 2007). The purpose of the variable is to divide the water flow rate ranges into an efficient range and inefficient range. δ_{i1} and δ_{i2} are variables representing the choice in facility i of flow rate range $j = 1$ and flow rate range $j = 2$. The variable δ_{i0} represents the stoppage of water flow. Each of the choices takes value 1 if chosen or value 0 if not chosen. As the division between water flow rate ranges we use the point where the observed data sets intersect the average energy consumption rate. (See the graphs in Figure 3 above showing the e-Q relation. This intersection point is defined as the point where a function approximating the observed values curve $y = ax^b$ crosses $e = c$ (fixed).) The minimum water flow rate of the observed values (lower bound) is represented by q_{iL} [m^3] and the maximum water flow rate (upper bound) is q_{iU} [m^3]. The water flow rate range to the left of the medium flow rate (division point) q_{iM} [m^3], namely $q_{iL} \leqq Q_i \leqq q_{iM}$, is $j = 1$, and that to the right of q_{iM} [m^3], namely $q_{iM} \leqq Q_i \leqq q_{iU}$, is $j = 2$. The

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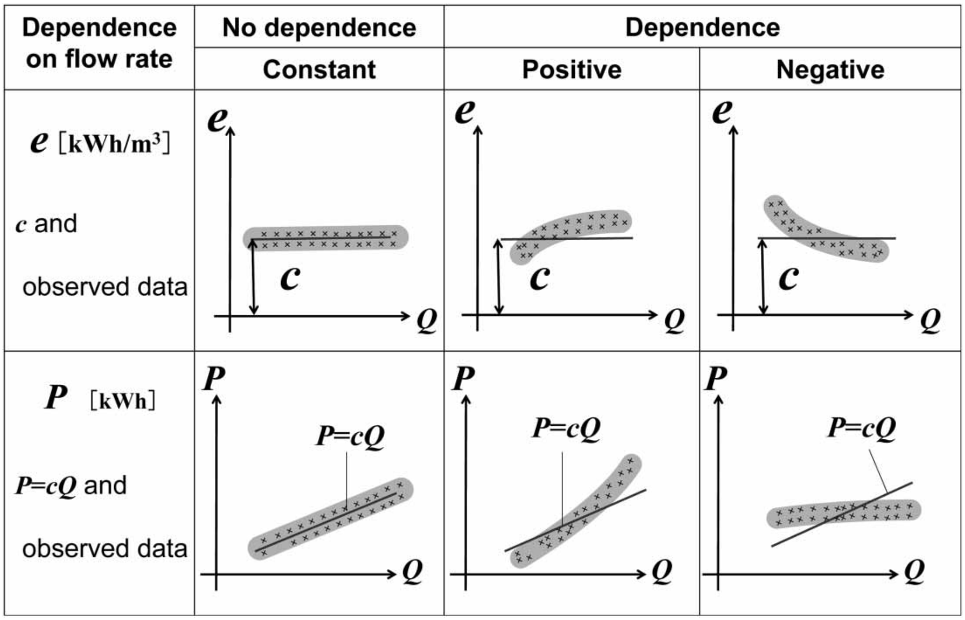

Figure 3 | Relation of energy consumption rate and electric power usage to flow rate Q.

estimation equation for electric power usage P_i in a facility is shown in Figure 4. This estimation equation was devised by dividing water flow rates into ranges $j = 1$ and $j = 2$ ($Q_i = q_{i1} + q_{i2}$), and approximating for each of these ranges the relation of electric power usage P and flow rate Q by means of a linear function. The estimation equation for electric power usage when $j = 1$ is $P_i = a_{i1}\, q_{i1} + b_{i1}$ and that for $j = 2$ is $P_i = a_{i2}\, q_{i2} + b_{i2}$.

Electric power usage in facility i (P_i) is expressed by Equation (1). The constraints governing the choice of flow rate range $j = 1$ and $j = 2$ are expressed by Equation (2) and Equation (3), respectively. Dummy variable δ_{ij} takes the values 0 or 1. Since for dummy variable δ_{ij} either one or the other must always be chosen, Equation (4) is obtained.

$$P_i = (a_{i1}q_{i1} + b_{i1}\delta_{i1}) + (a_{i2}q_{i2} + b_{i2}\delta_{i2}) \quad (1)$$

$$q_{iL}\delta_{i1},\ q_{i1},\ q_{iM}\delta_{i1} \quad (2)$$

$$q_{iL}\delta_{i2},\ q_{i2},\ q_{iM}\delta_{i2} \quad (3)$$

$$\delta_{i0} + \delta_{i1} + \delta_{i2} = 1 \quad (4)$$

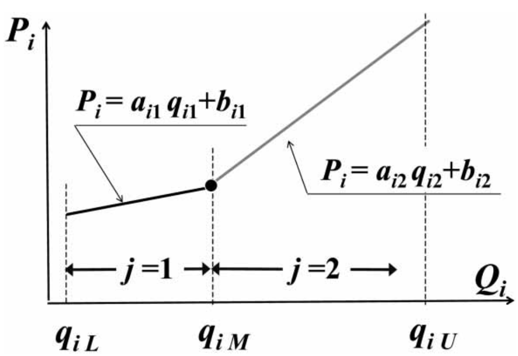

Figure 4 | Equation used to estimate electric power usage at facility i for water flow rate range j.

In the next section we attempt a case study for a network consisting of multiple treatment plants and service reservoirs. Equation (5) is an objective function aimed at minimizing electric power usage TE [kWh] in the system as a whole. Equation (6) expresses the constraints on water demand D. In the following we define a mixed integer linear programming (MILP) model that formulates these.

$$\mathrm{TE} = \Sigma P_i \rightarrow \min \quad (5)$$

$$\Sigma Q_i > D \quad (6)$$

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RESULTS AND DISCUSSION

The studied water distribution network

The water distribution system that is the object of this study is shown in Figure 5. In this system, water is sent to service reservoir K from three water distribution stations, treatment plant H ($i = 1$), treatment plant A ($i = 2$), and water-supply plant N ($i = 3$). The water flow rate of pumps in a facility is given as Q_i ($=q_{i1} + q_{i2}$) [m^3]. The water flow rate in each facility for sending water to other than service reservoir K is defined as O_i [m^3]. Flow rate Q_i [m^3] is equal to the total of water directly flowing into service reservoir K, given as q_{i3} [m^3], and water sent to other systems, O_i [m^3] (flow conservation condition: $Q_i = q_{i3} + O_i$). The data used for estimating electric power usage P_i are those for the period from April to July 2010. Figure 6 shows an approximation of electric power usage in each facility.

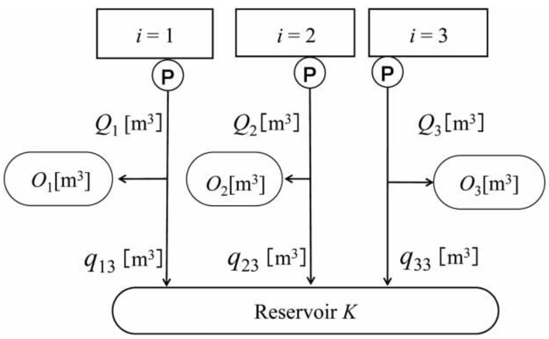

Figure 5 | The water distribution network studied.

Optimization results and analysis

The day chosen for the analysis was July 24, the day of maximum water demand during the data period. After transforming Equation (6) to $\Sigma q_{i3} \geq D$, optimal solutions (Q_i) were found by applying the proposed MILP model to each hour from 12:00 a.m. to 11:00 p.m. Then the electric power usage was estimated based on these solutions, with the results as shown in Figure 7. In this figure the 'observed values' are those obtained by substituting the actual water flow rates on that day in the equation given in Figure 6 for estimating electric power usage ($P_i = a_{i1}\, q_{i1} + b_{i1}$ or $P_i = a_{i2}\, q_{i2} + b_{i2}$). Similarly, the values for 'LP model' in the figure are values obtained by finding solutions using as objective function the straight line (LP model) and substituting these in the equation given in Figure 6 for estimating electric power usage.

Comparing the electric power usage at each time, the MILP model values are all smaller than the observed values. The minimum difference is 2.1% ($t = 9$) and maximum is 21.2% ($t = 5$). Calculating the electric power usage for one day suggests that the MILP model can reduce usage by 8.23%. The results of optimization by the LP model also indicate the possibility of nearly the same amount of reduction in electric power usage. The expected reduction for the LP model is 7.98%. In order to confirm the superiority of the MILP model over the LP model, we compared their respective optimal solutions at each time t, as a result of which we determined that they fall into the four operation modes shown in Figure 8. These four modes are: (1) times when ΣQ_i is 80,000 [m^3] or greater ($t = 9$, 10, 11, 12, 13, 14, 15, and 20); (2) times when ΣQ_i is in the 70,000 [m^3] range ($t =$ 8, 16, 17, 18, 19, 21, and 22); (3) times when ΣQ_i is from

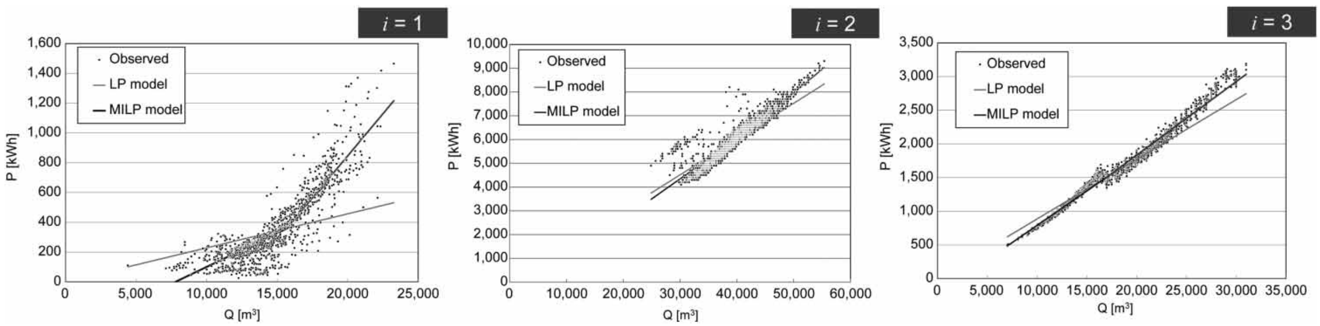

Figure 6 | Results of electric power usage estimation.

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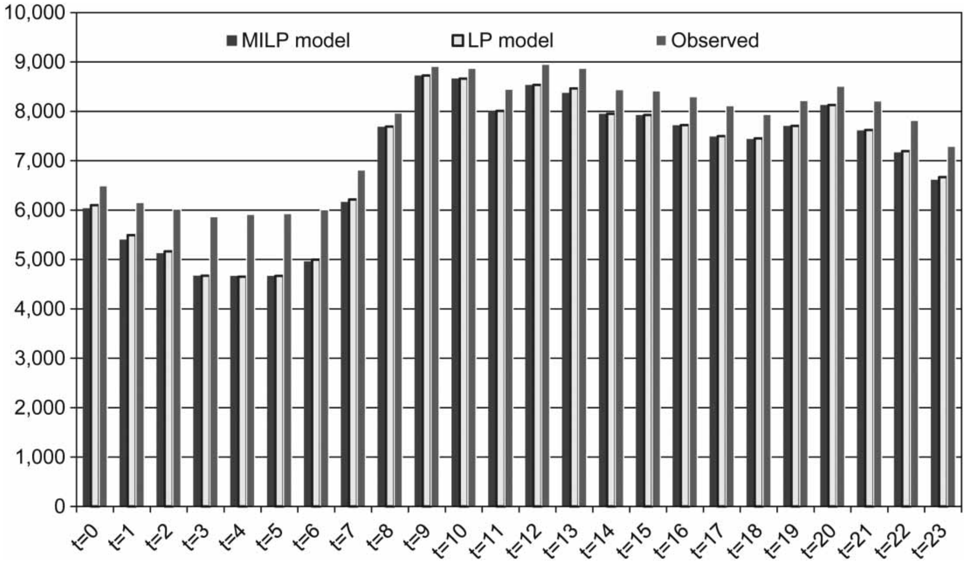

Figure 7 | Estimation of electric power usage [kWh] from optimization models.

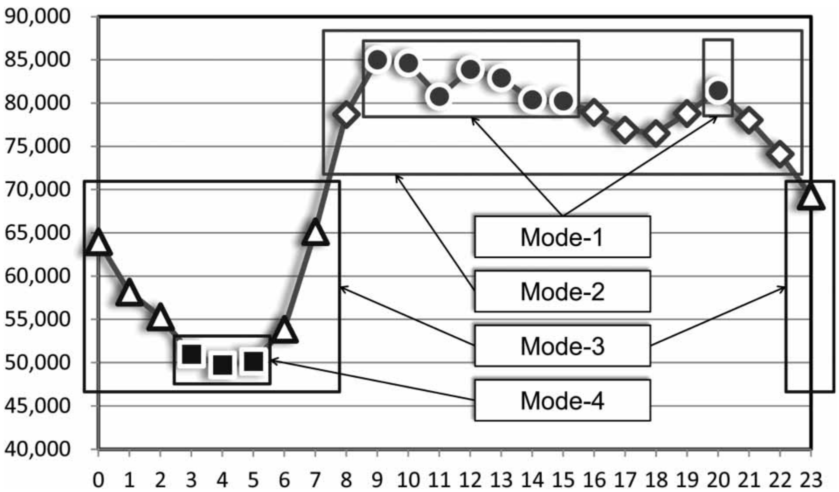

Figure 8 | Four operation modes (horizontal axis: time t, vertical axis: ΣQ_i [m^3]).

around 55,000 [m^3] to just under 70,000 [m^3] ($t = 0$, 1, 2, 6, 7, and 23); and (4) time of minimum flow rate when ΣQ_i is around 50,000 [m^3] ($t = 3$, 4, and 5). Selecting times representative of each mode, we can show the optimal solutions for each mode as in Figure 9.

The optimization strategies of the MILP model and LP model in Mode-1 to Mode-4 can be summarized as follows.

- Mode-1: Both the MILP and LP models adopt a water management strategy of increasing the flow rates from facilities $i = 1$ and $i = 3$ to their upper bound in order to minimize the flow rate from facility $i = 2$.
- Mode-2: The results for facility $i = 2$ indicate a common approach in both models. That is, both adopt a strategy of limiting the flow rate from facility $i = 2$ to its lower bound. This strategy regarding facility $i = 2$ is common to all modes other than Mode-1. The two models differ, however, in water management at facilities $i = 1$ and $i = 3$. Whereas the LP model adopts a strategy of increasing the facility $i = 1$ flow rate to its upper bound, the

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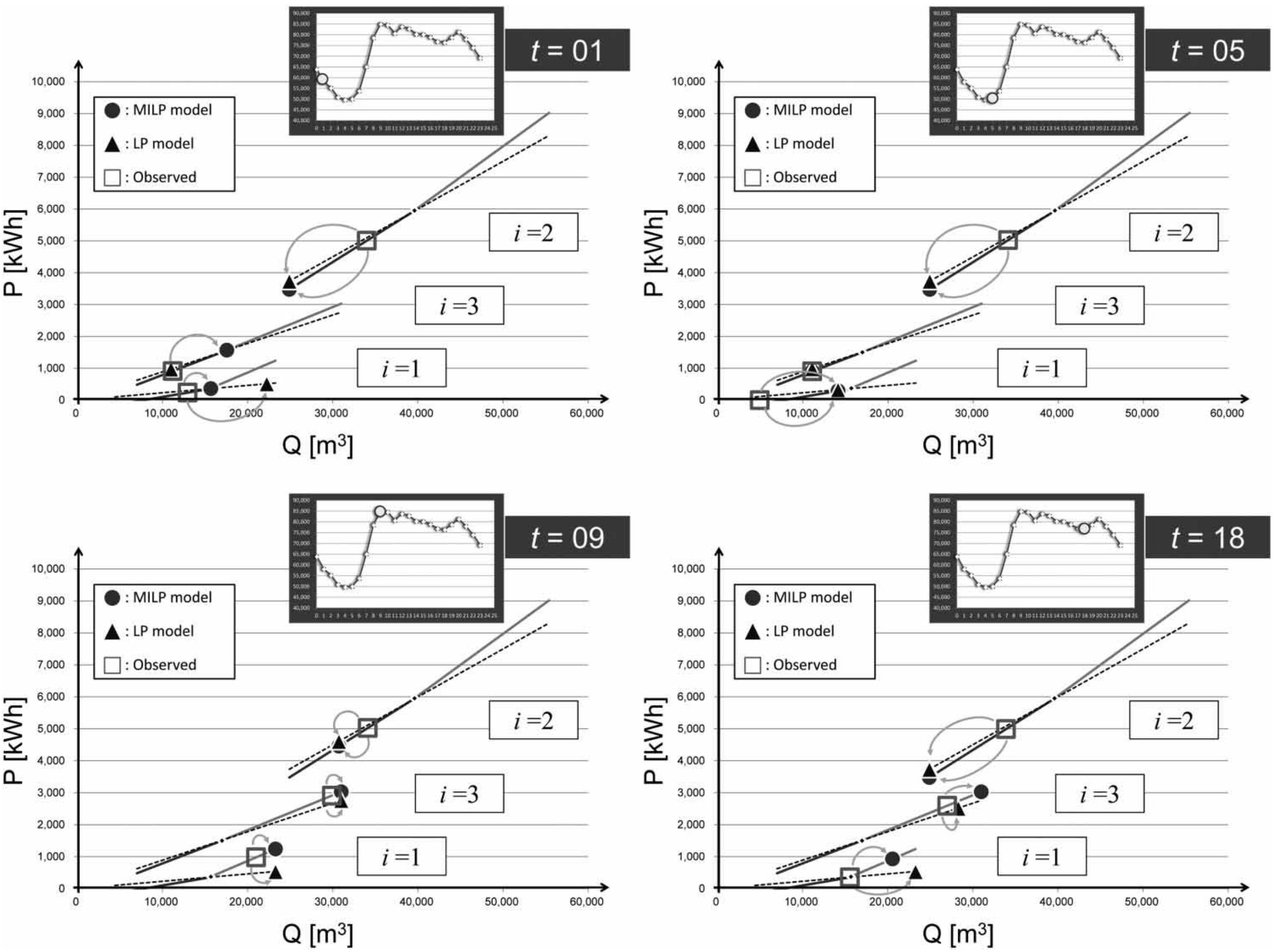

Figure 9 | Comparison of MILP model and LP model optimal solutions.

MILP model strategy can be seen as one of increasing the flow rate from facility $i = 3$ to its upper bound. The strategy in Mode-2 is to make maximum use of either facility $i = 1$ or $i = 3$. The choice, however, differs between the two models.

- Mode-3: The LP model strategy is to make up for the decrease in flow rate from facility $i = 2$ by increasing the flow rate from facility $i = 1$ to its upper bound. The method in the MILP model is to raise the flow rate from facility $i = 1$ to the upper bound ($q_{1M} = 15{,}684$ [m^3]) of the efficient range ($j = 1$), and to make up for any remaining shortages by increasing the flow rate from facility $i = 3$. A feature of Mode-3 is that the method of making up for the decrease in flow rate from facility $i = 2$ always depends on increasing the flow only from facility $i = 1$. The significance of this tendency is that the LP model strategy is equivalent to a plan that simply compares average consumption rates [kWh/m^3] and gives priority to a facility with a low average ($i = 1$) over one with a high average ($i = 3$).
- Mode-4: Both the MILP model and LP model increase the flow rate from facility $i = 1$ to replace the amount of decrease in flow rate from facility $i = 2$.

We see from the above that differences between the MILP model and LP model arise in their optimization strategies for Mode-2 and Mode-3. The difference between the two models is greatest at time $t = 1$. Figure 10 shows a comparison between the LP and MILP models at time $t = 1$. Comparing the total electric power usage at facilities $i = 1$

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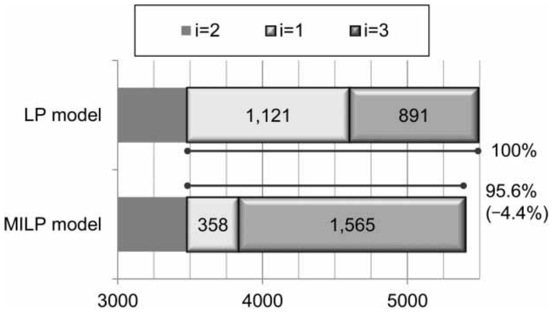

Figure 10 | Comparison of electric power usage [kWh/h] with the MILP model and LP model (at time $t = 1$). The values for electric power usage in the case of the LP model are based on the same estimation equation as that used in the MILP model for calculating power usage. It should be noted that the results for electric power usage by facility $i = 2$ are the same with both models.

and $i = 3$, the MILP model achieves a reduction that is 4.4% better than that with the LP model. Comparing consumption rate [kWh/m^3] averages, there ought to be an advantage to making extensive use of water from facility $i = 1$. In reality, however, a large facility $i = 1$ flow rate tends to result in a rise in the consumption rate [kWh/m^3] (i.e., a dependence on flow rate is seen), making it necessary to keep the facility $i = 1$ flow rate below the upper bound of the efficient range ($q_{1M} = 15,684$ [m^3] or below). The above analysis shows the MILP model to be a useful approach. Its superiority comes from incorporating the ability to request water distribution within the efficient range.

CONCLUSION

Noting the dependence of energy consumption rate on water flow rate, this study proposed an optimization method using an MILP model. We estimated the expected amount of reduction in electric power usage. As a result we showed that a reduction in electric power usage of around 8% per day can be achieved by changing the existing water flow rate distribution. We compared MILP and LP models, confirming the differences between the two approaches. We demonstrated the superiority of the MILP model, which aims for management within the efficient range of flow rates.

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