Water supply control system for smarter electricity power usage adopting demand-response scheme
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ABSTRACT
Demand-Response is a scheme in which electricity suppliers and consumers collaborate for smarter usage of electricity aiming to mitigate gap between supply and demand. It makes electricity consumers receive incentives through curtailing or increasing power demand during a certain period subject to the request from the power infrastructure. Water utilities, as heavy electricity consumers, could participate in the scheme through shifting power demand by modifying pumps operation schedule utilizing reservoirs’ buffering stock capability. We developed conveyance/transmission pumps scheduling algorithm to be applied in the scheme that requires quick modification of pumping schedule to respond the request. In addition, we made test bedding through simulation approach utilizing actual data of Osaka Water Supply Authority to show the scheme’s potential for waterworks and effectiveness of the algorithm.

Key words | Demand-Response, mathematical programming, pumps operation scheduling

INTRODUCTION
According to Japan Water Works Association, water utilities are heavy consumers of electricity that use close to 1% of total energy consumption in Japan, and reducing electricity charges is one of the key issues. Especially conveyance/transmission pumps account for much portion of it. On the other hand, electric power companies have been required to manage electric supply and demand balance, which is getting less controllable due to the increase of renewable energy. As a mean to mitigate gaps between electricity supply and demand, the Demand-Response (hereinafter called ‘DR’) scheme is under consideration. It makes electricity consumers receive incentives through curtailing or increasing power demand during a certain period subject to the request from the power infrastructure. That is beneficial not only for the electric power companies but electricity consumers. Water utilities, which consume much amount of electricity, could contribute the DR scheme by making conveyance/transmission pumps operation schedule utilizing reservoirs’ buffering stock capability without increasing reservoirs’ capacity.

The water utilities make daily pumps operation schedule to fulfill water demand that varies according to the time of the day, day of the week, weather etc. In addition, for the better operation schedule, stable water supply and lowering energy consumption are to be considered. To make the daily schedule in automatic, various mathematical programming
techniques have been adopted (Ulanicki et al. 2007; Puig et al. 2012) such as multi-objective optimization (Kurek & Ostfeld 2014; Odan et al. 2015). This kind of scheduling problem is formulated as mixed-integer programming (MIP) (Bunn & Reynolds 2009) which is known as time consuming. Biinspired algorithms such as Genetic algorithm (GA) and Particle Swarm Optimization (PSO) (Kang 2014; Bohorquez et al. 2015; Castro-Gama et al. 2017; Brentan et al. 2018; Khatavkar & Mays 2018) were utilized to overcome this, but it still requires much time to obtain near optimal solution. AI approach like Neural Network has also been made (Wu & Behandish 2012), which uses much amount of data to reach practical solution. To solve the problems above, we have developed a scheduling algorithm, which is an approximate optimization method combining linear programming (LP) and heuristic method (Tadokoro et al. 2015).

When water utilities participate in the DR scheme, they need to consider curtailing or increasing pumping during the requested period from power infrastructure, which makes the scheduling problem more complicated. Moreover, the request would come short period in advance (e.g. 15 minutes). Accordingly, it is a key to develop a new scheduling algorithm to handle curtailing or increasing power demand during requested timeslots as well as criteria such as meeting varying water demand, stable water supply and lowering energy consumption within limited computation time. We enhanced our scheduling algorithm by introducing minimum-maximum optimization, so as to meet the requirements above in demand curtailment case (Takahashi et al. 2017).

This paper describes the developed method improving to be utilized also in demand increasing case, and shows test bedding results applied to a large water utility.

**WATER SUPPLY CONTROL SYSTEM AND DEMAND-RESPONSE SCHEME**

**Water supply control system overview**

A water supply control system, which is configured as a sub-system of supervisory control and data acquisition (SCADA) system, manages daily schedule of water production, conveyance/transmission and distribution in a water utility. The system remotely monitors and controls geographically dispersed facilities in a water supply network such as purification plants, reservoirs and pumping stations (Figure 1). The system has two main functions that are water demand forecast and pumping operation scheduling.

The first function forecasts daily water demand in each distribution area in time series (e.g. every 30 minutes) by multiple regression analysis with using weather, temperature, and daily water demand as explanatory variables. The second function plans optimal daily conveyance/transmission schedule that minimizes objective functions including power consumption and fluctuation in flow rates, while fulfilling water demand under constraints of facilities such as production capacity of purification plants, pumping capacity in pumping stations and water level of reservoirs. The schedule describes a time series of water flow rate and water level for every time step in a scheduling period, for example, every 30 minutes in 24 hours. It is drafted basically once in a day, and modified on an ad hoc basis to countermeasure the situation like troubles in facilities.

**Demand-response scheme**

USA’s Federal Energy Regulatory Commission defines DR as ‘Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market price or when system reliability is...”

![Figure 1](https://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2019.143/609662/ws2019143.pdf)
In the DR scheme that is under consideration in Japan, an electricity power company communicates with electric consumers via aggregators to ask for curtailment or increase of power demand during a certain period, and consumers get incentives by responding the requests (Figure 2). The aggregators accumulate responses from consumers and deal with electricity power companies. In introducing DR scheme that timely shifts or cuts power demand, power infrastructure can manage not only its peak demand periods without setting up or up-scaling facilities, but also utilize renewable energy efficiently in case the generated electricity exceeds the demand without installing batteries.

Water utilities that are heavy electricity consumers can participate in the scheme through modifying the daily water supply operation schedule utilizing reservoirs' buffering capability. They can shift power demand in response to the requests from aggregators and contribute smarter energy usage of their community. However, following issues are to be discussed for them to participate.

1. Primarily for water utilities, stable and reliable water supply is the must, and reservoirs’ capacity is designed as preparations for abnormalities such as troubles in water supply facilities, sudden electricity outage, accordingly they are required to consider risks to respond DR requests.
2. Since DR requests might be sent on an ad hoc basis, 15 to 30 minutes in advance in the least case, water utilities are required to modify their schedule near real-time.

To solve the issues, we had developed scheduling algorithm for water supply control systems. It was designed to solve the computation time problem based on the heuristic approach narrowing down MIP search space, and we enhanced the algorithm so as to be utilized in DR scheme as follows.

1. Making the whole time pumping schedule that is not considered DR request. It is an optimal schedule without DR scheme. This schedule is made by Multi-Objective Programming (MOP) and Quasi-optimal Routing System (QRS) (Tadokoro et al. 2013). MOP solves the problem using Linear Programming (LP) to make computation time short and selects the most satisfactory schedule. QRS is based on heuristic rules. It discretizes the schedule of the fixed pumps that is not well modified in LP.
2. Modifying the schedule during DR requested period, MIP is used to minimize maximum demand power in demand curtailment, and maximize minimum demand power in demand increase. The problem that plans an optimal pump operation schedule during the time period of DR is formulated as follows.

Expression (1) is the objective function. $E_t(X)$ is demand power for every 30 minutes of which the power company evaluates it at a time step. $X$, that is described in expression (4), denotes a matrix of the numbers of driving pumps at each pump station and $t$ denotes time with a time step of 30 minutes. The objective function is set for determining $X$ to minimize maximum demand power.

$$
\min_X \max_E E_t(X)
$$

$$
E_t(X) = \frac{1}{2} \left( e_{t-1}(x_{t-1}) + e_{t}(x_{t}) \right) \quad (1 \leq t \leq T)
$$

$$
e_{t}(x_{t'}) = a \cdot x_{t'} + b \cdot 1 \quad (1 \leq t' \leq 2T)
$$

$$
X = [x_1, x_2, \ldots, x_{2T}]
$$

$$
x_{t'} = \begin{bmatrix} x_{1,t'} \\ x_{2,t'} \\ \vdots \\ x_{n,t'} \end{bmatrix}
$$
power at $t$. Expression (2) is a formula to calculate every 30 minutes of demand power by averaging 15 minutes of it. Expression (3) is a formula to calculate every 15 minutes of demand power. Where $e_r(x_r)$ denotes demand power at time $t'$ and $x_r$, that is described in expression (5), denotes a vector of the numbers of driving pumps at pump station $n$ at time $t'$, and $t'$ denotes a time step of 15 minutes. We used a short time step of 15 minutes for scheduling to reduce or increase peak power as much as possible. $a$ and $b$ denote constant vectors. The numbers of driving pumps $X$ are determined under some constraints below.

$$l_{i,t} = l_{i,t-1} + \frac{\Delta t}{S_i} \cdot (c_{1i} \cdot f_r + c_{2i} \cdot f_{0r} - d_{i,t}) \quad (1 \leq t' \leq 2T + T_0) \quad (6)$$

$$l_{\text{min},i,t} \leq l_{i,t} \leq l_{\text{max},i} \quad (1 \leq t' \leq 2T) \quad (7)$$

$$l_{\text{min},i,t} \leq l_{i,t} \leq (2T + 1 \leq t' \leq 2T + T_0) \quad (8)$$

$$l_{\text{min},i,t} = \frac{\Delta t \sum_{t' = 0}^{T-1} d_{i,t}}{S_i} \quad (9)$$

$$f_r = a_1 \cdot x_r + b_1 \quad (1 \leq t' \leq 2T) \quad (10)$$

$$f_r = f_{\text{max},r} \quad (2T + 1 \leq t' \leq 2T + T_0) \quad (11)$$

$$f_r = \begin{bmatrix} f_{1,r} \\ f_{2,r} \\ \vdots \\ f_{n,r} \end{bmatrix}, \quad f_{0r} = \begin{bmatrix} f_{0,1,r} \\ f_{0,2,r} \\ \vdots \\ f_{0,m,r} \end{bmatrix} \quad (12)$$

Expression (6) is a formula to calculate water level during the DR period and until a certain time period $T_0$ after the DR. Where $l_{i,t}$ denotes the water level at distribution reservoir $i$ at time $t'$. $\Delta t$ denotes a time step of scheduling that is 15 minute and $S_i$ denotes a cross-sectional area of reservoir $i$. $c_{1i}$ and $c_{2i}$ denote constant vectors. $f_r$ denotes a vector of flow rates under DR operations at pump station $n$ at time $t'$, $f_{0r}$ denotes a vector of flow rates under normal operations at pump station $m$ at time $t'$ which are described in expression (12). $d_{i,t}$ denotes a flow rate of water distributed from reservoir $i$. The water level need to satisfy with constraints described in Expression (7) and (8). Where $l_{\text{min},i,t}$ denotes the lower limit of the water level at reservoir $i$ at time $t'$, and $l_{\text{max},i}$ denotes the upper limit of it. The lower limit of the water level during the DR and after the DR is described in expression (9). It guarantees to keep the water level for water demand until after 12 hours. Expression (10) and (11) are formula to calculate flow rate. $a_1$ and $b_1$ denote constant vectors. The flow rate is set by the numbers of driving pumps during the DR period and maximum flow rate $f_{\text{max},t'}$ at each pump station after the DR period. Initial conditions, water level and flow rates at the start of DR period, are given from the schedule that is made (1).

(3) Re-schedule the whole times operation by applying same method as (1). The pumping schedule during DR periods are given as additional constraints.

By using this developed algorithm, the schedule during DR period are optimized for DR and the other period are optimized for conventional objectives (energy savings, balance of intakes, etc.). The problem of computation time can be solved by applying MIP only to the DR period.

**FEASIBILITY STUDY**

To investigate potential of the DR scheme in waterworks and verify effectiveness of the developed scheduling algorithm, we made a case study in the water conveyance network. This study was performed as a part of subsidy project by The New Energy Promotion Council and conducted with Osaka Water Supply Authority as a test bedding field. The authority is the bulk water supplier to 42 municipalities in the prefecture, and its daily supply capacity is 2,330,000 m$^3$. Studied conveyance network consists of 3 purification plants, 6 reservoirs, and 15 pumping facilities (Figure 3). 116 connection points to the municipalities are grouped in 21 demand points. We evaluated 8 cases of DR potential (4 cases in summer/ 4 cases in winter). DR requested periods are 2 or 3 consecutive hours during 15:00 to 18:00 in summer and 17:00 to 20:00 in winter, which are peak times of electricity demand so it is very likely to be requested demand curtailment. The same consecutive hours during 12:00 to 15:00, which are hours possibly renewable energy supply exceeds demand so it is very likely to be requested demand increase.
Conveyance network of Osaka Water Supply Authority ('P' represents pumping facility).

Figure 3 | Conveyance network of Osaka Water Supply Authority ('P' represents pumping facility).
Each simulation makes 30 minutes’ time series schedule for 48 hours. The schedule in DR case is required to comply with the following condition same as usual operation to ensure secure and stable water supply. Although the authority has applied the time of use (TOU) electricity pricing that is similar to the DR, we did not consider TOU to estimate DR potential properly.

- Flow rates in water purification plants are considered to be as constant as possible in purification process operation
- Each conveyance line has its upper and lower limit in flow rate
- Each reservoir has upper and lower limit in water level for keeping safety stock of water, and the water level recovers close to upper limit at 7:00 enabling to cope with sharp water demand increase in the morning
- Supplying flow rate to each municipality is equal to usual operation case

**RESULTS**

Demand curtailment simulation results are shown in Table 1. The DR potential is the total curtailment of power demand in the conveyance network. To evaluate the DR potential, the DR operation schedule compared to the usual operation schedule. The DR potential is evaluated at time step of 30 minutes but average value during the DR period is shown in the table. It shows that the water supply system can reduce 2,221 to 3,592 kW of power demand during the DR period. In case 1, the usual power demand during the DR period was 32,080 kW (not shown) accordingly 11.2% of power demand can be reduced. The computation time of the simulation by PC (CPU: Intel Core i5-4590 3.30 GHz, RAM: 4GB) was approximately 1 minute. It shows the computation time is reasonable even if the developed algorithm is applied large water network.

As an example, schedule of Banpaku Pumping Station (Banpaku) and Senri Reservoir Station (Senri), whose location is dotted area in Figure 3, in Case 1 are shown in Figure 4(a) and 4(b). Senri receives water from Banpaku and Onohara Pumping Station (Onohara). Schedule of Onohara during the DR period is same as usual (not shown). Usual Banpaku’s flow rate during the DR period is 6,085 m³/h (17:00 to 18:00) and 6,213 m³/h (18:00 to 19:00) that equals to a large pump operation. The simulation shows that flow rate can be reduced to 2,750 m³/h (a small pump operation) at that period. The change of pump operation corresponds to 1,053 kW. Senri’s water level does not fall below lower limit during the DR period and after the DR. So it can be said that Banpaku has 1,053 kW DR potential. In evaluating other facilities, 4 facilities (Murano, Niwakubo, Fujiidera, and Sayama) also have DR potential.

Table 2 shows demand increase simulation results. The DR operation schedule can increase 7,304 to 8,624 kW of power demand. In case 5, the usual power demand during the DR period was 31,823 kW (not shown) accordingly 27.1% of power demand can be increased. Computation time of all the simulation was less than 1 minute.

As an example, schedule of Banpaku and Senri in Case 5 are shown in Figure 5(a) and 5(b). The usual Banpaku’s flow rate during the DR period is 6,284 m³/h (12:00 to 13:00) and 6,054 m³/h (13:00 to 14:00) that equals to a large pump operation. The flow rates can be increased to 10,800 m³/h (two large pumps operation) at that period. The change of pump operation corresponds to 1,444 kW. In evaluating other facilities, all of them except two pumping facilities (Onohara and Fujiidera) have DR potential.

**Table 1 | Demand curtailment potential and computation time at Osaka Water Supply Authority**

<table>
<thead>
<tr>
<th>Season</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR period</td>
<td>17:00–19:00</td>
<td>17:00–20:00</td>
<td>15:00–17:00</td>
<td>15:00–18:00</td>
</tr>
<tr>
<td>DR potential (kW)</td>
<td>3,592</td>
<td>2,221</td>
<td>3,185</td>
<td>3,511</td>
</tr>
<tr>
<td>Computation time (sec)</td>
<td>43.162</td>
<td>38.366</td>
<td>68.293</td>
<td>53.972</td>
</tr>
</tbody>
</table>

*Average value during the DR period.
CONCLUSIONS

The feasibility study shows that Osaka Water Supply Authority has potential to be a resource provider through modifying their pumping schedule and utilizing reservoirs’ buffering stock capability. There are many water utilities that have similar conveyance/transmission system to the authority can be also applied the DR scheme.

In participating the DR scheme, water utilities might need to modify the schedule in near real-time while sustaining secure and stable water supply. The proposed scheduling algorithm made daily pumping schedule under DR scheme

Figure 4 | (a) The pumping schedule of DR operation and usual in Banpaku in Case 1. (b) The water level changes of DR operation and usual in Senri in Case 1.

Table 2 | Demand increase potential and computation time at Osaka Water Supply Authority

<table>
<thead>
<tr>
<th></th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>Winter</td>
<td>Winter</td>
<td>Summer</td>
<td>Summer</td>
</tr>
<tr>
<td>DR period</td>
<td>12:00–14:00</td>
<td>12:00–15:00</td>
<td>12:00–14:00</td>
<td>12:00–15:00</td>
</tr>
<tr>
<td>DR potential (kW)</td>
<td>8,624</td>
<td>7,459</td>
<td>8,544</td>
<td>7,304</td>
</tr>
<tr>
<td>Computation Time (sec)</td>
<td>43.482</td>
<td>47.030</td>
<td>47.068</td>
<td>42.672</td>
</tr>
</tbody>
</table>

*Average value during the DR period.

Figure 5 | (a) The pumping schedule of DR operation and usual in Banpaku in Case 5. (b) The water level changes of DR operation and usual in Senri in Case 5.
around 1 min even in case of large water utility. In addition, the schedules did not violate operational conditions such as water demand and control ranges of water level. It shows that the algorithm can strongly support water utilities to join the DR scheme.

REFERENCES


