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598

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Application of water supply operation system to improve efficiency of hydraulic power generation

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Abstract

At various locations in Tokyo, the excess pressure of water entering the water supply distribution reservoirs is adjusted by pressure reducing valves, wasting unused energy. The installation of hydraulic power generation equipment is now promoted in place of the pressure reducing valves. This is a renewable energy source as the method produces no greenhouse gases and reduces fossil fuel use. The results of research into the operation of the hydraulic power generation equipment enable the water supply operating system to optimize the inflow rate for power generation without affecting the stability of the water supply. This has increased the amount of power generated and enabled earlier recovery of total costs.

Key words: excess pressure, hydraulic power generation, renewable energy, water supply operation

INTRODUCTION

With a water supply area of 1,239 km^2 and population of 13.295 million, Tokyo is an extremely congested metropolis (Bureau of Waterworks 2017). The water supply transmission/distribution pipes throughout the metropolis have a total length of 27,038 km: more than two thirds the earth's circumference. To increase resilience to demand fluctuations and disasters, a number of water supply stations are maintained and the majority of transmission pipes constitute a dual supply network. Water transmission/distribution requires large amounts of electrical power, so, to improve the waterworks utilities' sustainability, efforts are made to improve equipment efficiency, operate services with consideration to energy saving, and use renewable energy sources (Bureau of Waterworks 2017; 2016a; 2016b; 2016c; 2014).

Tokyo is characterized by complex terrain with coastal lowlands, undulating plains, plateaus and mountainous areas. When transmitting water to distant points, the pressure can be excessive and pressure reducing valves are installed at supply stations in the middle of the network. In other words, the excess pressure of water flowing into supply stations is adjusted and thus unused. To overcome this, the installation of hydraulic power generation equipment is being promoted in place of pressure reducing valves, to convert the excess pressure to electrical energy. This is a kind of renewable use as it does not produce greenhouse gases and reduces the use of fossil fuels (Masuko *et al.* 2011; Tanaka 2018).

When installing hydraulic power generation equipment, the data on inflow rate and pressure at each water supply station are examined, in order to determine the turbine design and power output specifications. During examination, full use is made of data accumulated by the water supply operating system developed for Tokyo. Research was conducted so that the water supply operating system would be able to control the optimal inflow rate for power generation. This ensures that sufficient inflow of water for power generation is secure in the long-term without affecting the stability of the water supply. As a result, more effective use can be made of excess pressure.

MATERIAL AND METHODS

Tokyo's water supply comes mostly from rivers – 78% from the Tone-Arakawa rivers, and 19% from the Tama River. Interchange between them is possible through the raw water connection pipelines. The aim is for effective use of water in relation to the condition of each river or dam, so, on the basis of this 'raw water plan', the daily volume of water distributed is predicted for the following month using results from previous years and seasonal changes.

Treatment plants are operated according to the predictions and the 'main pipeline operating plan' determined for transmitting water to water supply stations. If the transmission pipes are part of the dual network system, the routes used are determined on the basis of energy saving and maintenance conditions (Masuko *et al.* 2012).

Water station distribution pumps are operated on the basis of the 'distribution pump operating plan', which takes account of the pressure and volume patterns on weekdays and holidays. Distribution pipeline pressure is constantly maintained at over 20 m, allowing for pipe resistance and demand fluctuation.

The water supply operating system for the waterworks facilities integrates the 'raw water plan', the 'main pipeline operating plan' and the 'distribution pump operating plan' to improve demand prediction. The distribution reservoir operating function is derived from the demand prediction function as well as the water inflow plan. All of these plans are improved by taking into account factors such as the weather forecast, temperature, day of the week and national holidays. Revisions are also made constantly to adjust to real-time demand fluctuations. Figure 1 is an outline of the water supply

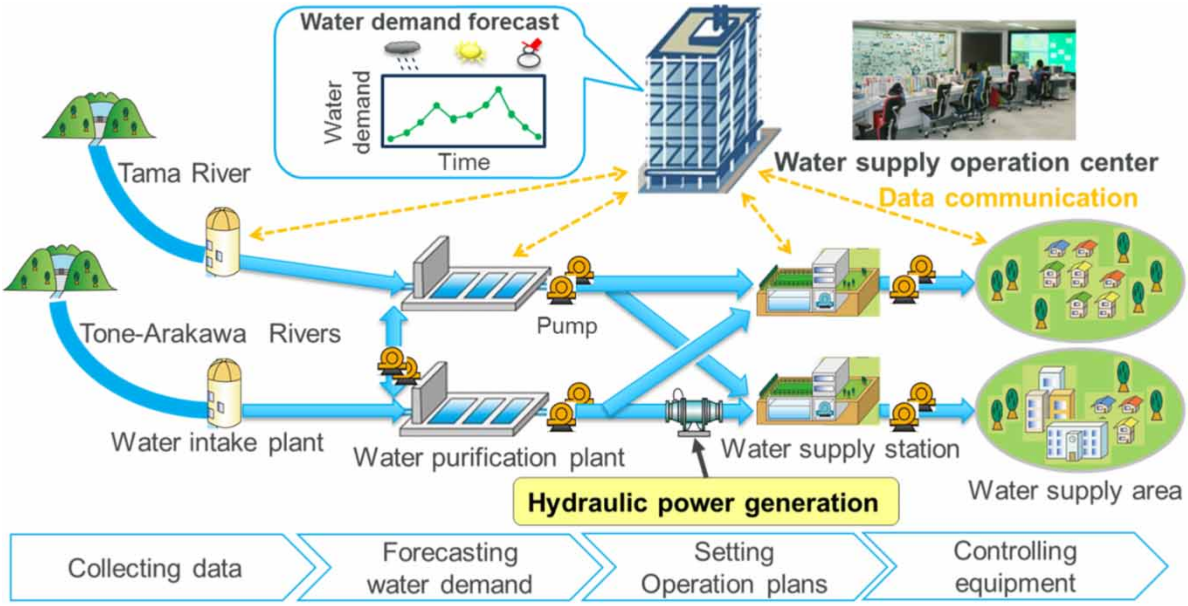


Figure 1 | Water supply operating system.

operating system. Using influent conditions to maximize the hydraulic power generation equipment's potential, makes efficient power generation possible.

The hydraulic power generation equipment has been installed at four water supply stations where sufficient space was readily available – see Table 1.

Table 1 | Hydraulic power generation equipment

Supply station	**Minami-Senju**	**Kameido**	**Yakumo**	**Kasai**
Max output (kW)	95	90	300	340
Max inflow rate (m^3/s)	0.422	0.416	1.5	1.4
Max effective drop in excess pressure (m)	28.5	30	25.5	35.0
Turbine design	Diagonal flow (horizontal axis)		Francis (horizontal axis)	
First power generated month/year	March 2005	April 2008	April 2010	October 2013
Installation status				

Figure 2 shows the excess pressure status at Kasai water supply station, which is midway between Kanamachi treatment plant and Tokai water supply station. On average there is about 30 m excess pressure in the portion around Kasai water supply station. To operate the equipment, the influent rate possible for power generation has been determined by considering both turbine efficiency, fluctuations in influent pressure, and vibrations and noise in the turbine due to cavitation. The upper limit is 1.26 m^3/s (4,550 m^3/h), which is 90% of the maximum usage of 1.4 m^3/s and the lower limit 0.58 m^3/s (2,100 m^3/h), or 42%.

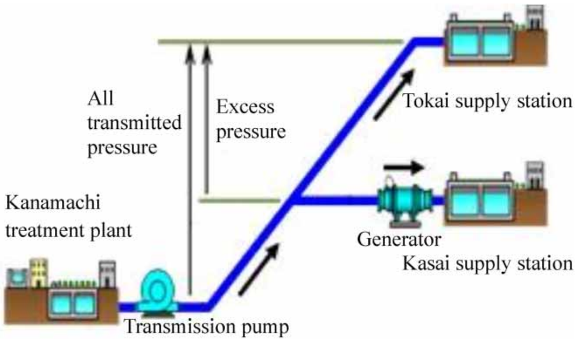


Figure 2 | Status of excess pressure at Kasai.

Before installing the hydraulic power generation equipment, the distribution reservoir operation controlled the reservoir inflow rate in line with changing demand. As a result, the distribution reservoir level was kept constant – see Figure 3 (left). With this operating style and flow rates below the power generation threshold, the influent was bypassed and the energy in the excess pressure was unused. At flow rates above the upper power generation threshold, residual influent was also bypassed and energy in the excess pressure remained unused.

RESULTS AND DISCUSSION

Distribution reservoir operation is now implemented, taking the hydraulic power generation equipment into consideration in the planning function of the water supply operating system. As a result,

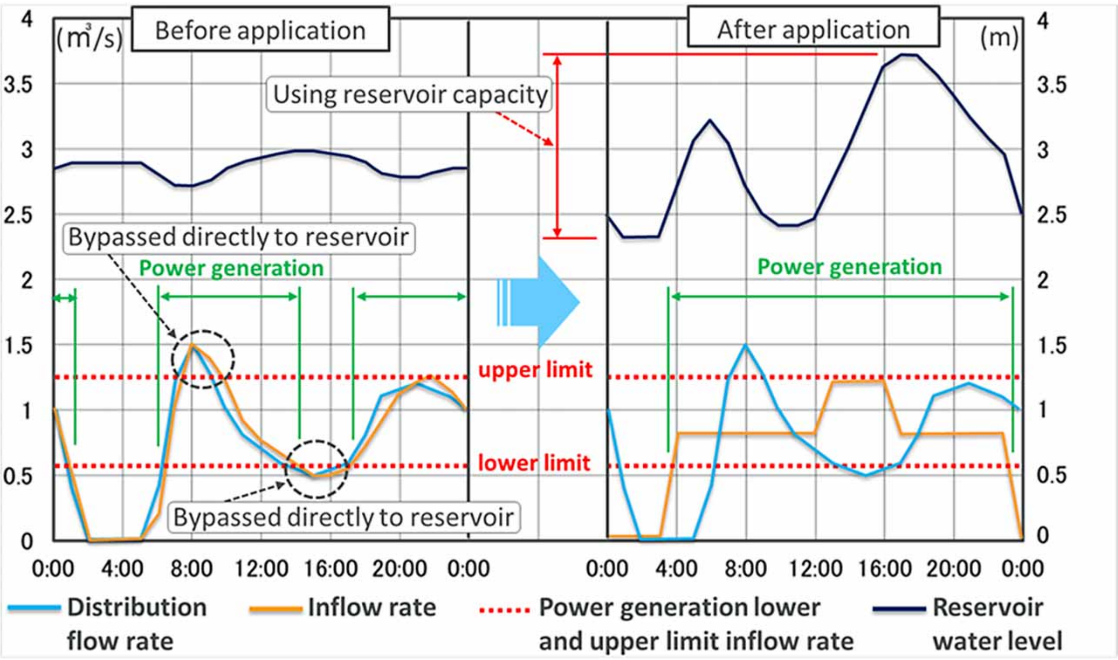
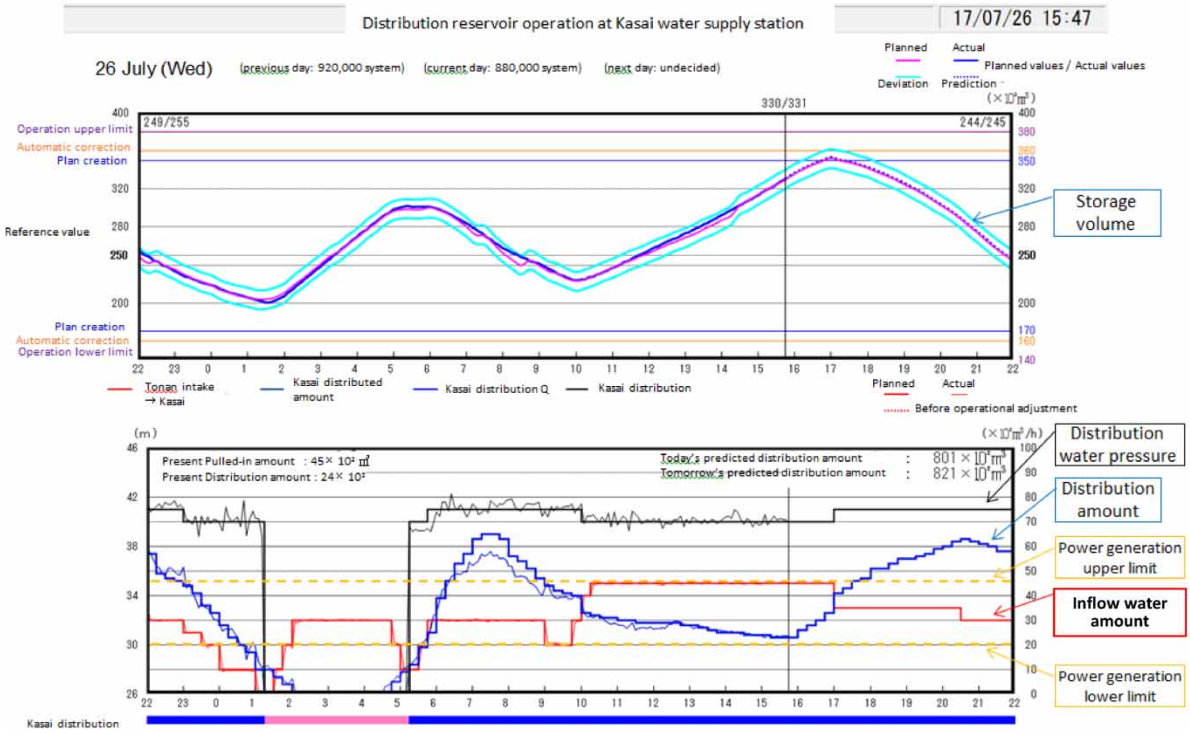


Figure 3 | Changes in distribution reservoir operation.

the period when the inflow rate is suitable for power generation is now longer (Figure 3, right). In addition, the influent that was 'bypassed' previously is now available for power generation. Effective use is thus made of the reservoir's capacity, like a hydroelectric dam, without affecting water supply stability, although the reservoir water level changes significantly. An example of the monitoring screen for this type of operation is shown in Figure 4.


Distribution reservoir operation at Kasai water supply station

17/07/26 15:47

26 July (Wed) (previous day: 920,000 system) (current day: 880,000 system) (next day: undecided)

Present Pulled-in amount : 45× 10² m³
Present Distribution amount : 24× 10²

Today's predicted distribution amount : 801 × 10⁴m³
Tomorrow's predicted distribution amount : 821 × 10⁴m³

Figure 4 | Distribution reservoir operation at Kasai.

If the actual level of demand begins to deviate from the predicted volume, the operating system automatically corrects the operating plan. This occurs even when the power generation equipment is running, which ensures both the stability of the water supply and use of the excess energy.

Table 2 shows the performance of the hydraulic power generation equipment at Kasai water supply station. In the estimate based on the inflow rate prior to equipment installation, an annual power generation of 1.4 million kWh was expected. Because the distribution reservoir was operated on the basis of the water inflow plan taking account of power generation starting in FY2015, annual power generation exceeded 1.5 million kWh, some 0.1 million kWh more than expected. Annual power generation can be represented using Equation (1).

$$\mathrm{E\,(kWh/year)} = \mathrm{P\,(kW)} \times 24\,\mathrm{(hour)} \times 365\,\mathrm{(day)} \times \mathrm{F} \tag{1}$$

where:

E = annual power generation mount (kWh/year)
P = maximum output (kW)
F = equipment utilization factor

where

$$\mathrm{F} = \frac{\mathrm{E\ \ (kWh/year)}}{\mathrm{P\,(kW)} \times 24\,\mathrm{(hour)} \times 365\,\mathrm{(day)}} \tag{2}$$

Table 2 | Performance of hydraulic power generation equipment at Kasai

Item	Unit	FY2013*,**	FY2014	FY2015	FY2016	FY2017	Total
Power generated	million kWh	0.68	1.27	1.58	1.50	1.51	6.54
Influent volume	10,000 m^3	1,429	2,643	3,009	2,968	2,887	12,936
Original power generation	Wh/m^3	48	48	53	51	52	–
Power market price	yen/kWh	31.60	33.73	32.12	29.00	29.00	–
Power revenue	10,000 yen	2,148	4,291	5,087	4,357	4,390	20,273
CO_2 conversion amount***	t-CO_2	333	621	773	734	738	3,199
Equipment utilization factor	%	45.8	42.7	53.0	50.4	50.8	–

*The Japanese financial year (FY) starts in April and ends in March.
**The values for FY2013 start from October, when the hydraulic power generation equipment went into operation.
***The CO_2 conversion factor is 0.489 t-CO_2/million kWh (Bureau of Environment 2018).

The equipment utilization factor, F, is the ratio of the actual annual power generation to the potential generation if the equipment was operated continuously at its maximum output throughout the year. In general in Japan, for hydraulic power generation equipment, the ratio is around 40 to 50%, although it differs depending on flow conditions (Nagatomi & Yamamoto 2016). From FY2015 onwards, the equipment utilization factor for the hydraulic power generation equipment at Kasai has exceeded 50% (Table 2): an outstanding result. The power generated can be represented by Equation (3).

$$\mathrm{P\,(kW)} = 9.8\,(\mathrm{m/s^2}) \times \mathrm{Q}\,(\mathrm{m^3/s}) \times \mathrm{He\,(m)} \times \eta \tag{3}$$

where:

P = power generated (kW)
9.8 = gravitational acceleration constant (m/s^2)
Q = inflow rate (m^3/s)
He = effective pressure drop (m)
η = power generation efficiency

Here, the inflow rate Q in Equation (3) can be said to be controlled to the optimum for power generation. Depending on the turbine design, the power generation efficiency, η, is affected by the inflow rate, Q. This is particularly true for the Francis turbine, whose characteristic curve has a maximum – see Figure 5. In this case, it is possible to control the inflow rate, Q, so that η becomes optimal for power generation. The indicator that shows power generation efficiency is the original power generation unit, Wh/m^3, i.e., the power generated per unit inflow (Wh/m^3) increased in FY2015 compared to FY2014 and earlier. Power generation increased between FY2016 and FY2017, despite the decrease in flow volume – i.e., increasing power generation depends not only on increasing inflow volume but also on improving generation efficiency.

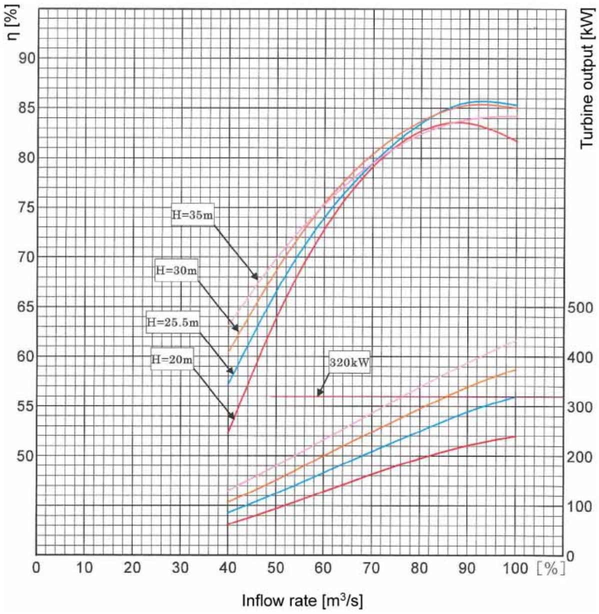


Figure 5 | Characteristic power generation efficiency curves.

Where the transmission pipes are twinned, distribution reservoir operation is also possible. This is done by ensuring that the transmission pipe flow rate to the hydraulic power generation equipment is optimal for power generation while controlling the rate in the twin transmission pipe. These simple principles are enabling improvements in equipment utilization and power generation efficiency.

For the hydraulic power generation equipment at Kasai, the recovery period for the total cost – i.e., the sum of the equipment, construction and maintenance costs (CAPEX + OPEX) – through the gains from power generation was seven years. This period is based on the estimate prior to equipment installation and is expected to be reduced to six years.

The hydraulic power generation equipment at Minami-Senju and Kameido water supply stations was overhauled – Table 1 – 10 years after installation, in each case. No corrosion or abrasion defects were found and neither equipment set had ever broken down or experienced any other trouble. Even after total cost recovery, long-term power generation can be expected.

CONCLUSIONS

Application of the water supply operating system has enabled the amount of power generated to be increased and total costs to be recovered early. In other words, it has been demonstrated that the equipment utilization factor and power generation efficiency can be improved by combining the use of hydraulic power generation equipment and the capacity of distribution reservoirs. In addition, greenhouse gas emissions will be reduced for longer, and waterworks utility operations will be more sustainable.

As waterworks utilities become larger, purification plants and supply stations are also allocated to serve larger areas. This means that the use of pressure reducing valves, along with proper pump operation, becomes indispensable. Given Tokyo's undulating terrain, many pressure reducing valves are needed and the potential for hydraulic power generation is high. We will continue to install and use hydraulic power generation for the sustainable development.

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