Application of Water Supply Operation System to Improve Efficiency of Hydraulic Power Generation

T. Tanaka*, S. Kaneko, N. Aoyama***, Y. Toriyama******

* Water Supply Operation Center, Bureau of Waterworks, Tokyo Metropolitan Government 2-8-1, Nishishinjyuku, Shinjuku-ku, Tokyo, Japan, tanaka-toshihiko@waterworks.metro.tokyo.jp
** Purification Division, Bureau of Waterworks, Tokyo Metropolitan Government 2-8-1, Nishishinjyuku, Shinjuku-ku, Tokyo, Japan, kaneko-seiji@waterworks.metro.tokyo.jp
*** Purification Division, Bureau of Waterworks, Tokyo Metropolitan Government 2-8-1, Nishishinjyuku, Shinjuku-ku, Tokyo, Japan, aoyama-noboru@waterworks.metro.tokyo.jp
**** Purification Division, Bureau of Waterworks, Tokyo Metropolitan Government 2-8-1, Nishishinjyuku, Shinjuku-ku, Tokyo, Japan, toriyama-yasuhiro@waterworks.metro.tokyo.jp

Abstract: At various locations with different landscapes and conditions, the excess pressure of water that flows into the distribution reservoirs of water supply stations is adjusted through pressure reducing valves and becomes unused energy. Due to this, we are promoting the installation of hydraulic power generation equipment in place of the pressure reducing valves. This is one of the renewable energy uses since this method does not produce greenhouse gases and reduces the use of fossil fuels. For the operation of the hydraulic power generation equipment, we have conducted research so that our water supply operation system could control the inflow rate towards the most optimal rate for power generation. This ensures the long-term inflow of water that allows for power generation without affecting stable supply of water. With this, we succeeded in increasing the power generation amount and the early recovery of the total cost. In short, we have demonstrated that the equipment utilization factor and the power generation efficiency could be improved by combining the hydraulic power generation equipment and the capacity of distribution reservoirs. Consequently, generation of greenhouse gases will be repressed and the waterworks utilities will be more sustainable.

Keywords: water supply operation; hydraulic power generation; excess pressure; renewable energy

Introduction

With the water supply area of 1,239 m² and the population of 13.295 million, Tokyo is an extremely congested metropolis (FY2017). In order to supply water throughout the metropolis, transmission/distribution pipes have the total length of 27,038 km, which is greater than two thirds of the circumference of the Earth. Also, in order to increase resilience to demand fluctuations and disasters, we maintain a number of water supply stations, and the majority of transmission pipes constitute the dual supply network. The water transmission/distribution requires immense electrical power. Therefore, in order to improve the sustainability of our waterworks utilities, we strive to improve better efficiency of equipment, operate our services with consideration to energy saving, and make use of renewable energy sources (Bureau of Waterworks, Tokyo Metropolitan Government, 2017; 2016a; 2016b; 2016c; 2014).

On one hand, Tokyo is characterized by complex terrain with coastal lowlands, undulating plains, plateaus and mountainous regions. When transmitting water to far supply stations in the complicated network, the pressure can be excessive and pressure reducing valves are installed at the supply stations located in the middle of the network. In other words, the excess pressure of water that flows into supply stations is adjusted by pressure reducing valves and becomes unused energy. Due to this, we are promoting the installation of hydraulic power generation equipment in place of pressure reducing valves. This equipment collects the excess pressure to use as electrical energy. This is a kind of renewable energy uses since it does not produce greenhouse gasses and reduces the use of fossil fuels (Tanaka, 2017; Masuko, 2011).

When installing the hydraulic power generation equipment, we examine the data on the inflow rate and inflow pressure at each water supply station, and determine the specifications for the turbine design and the power generation output. In the examination, we make full use of the past data accumulated by the water supply operation system developed independently by us. We also take into consideration the future plans of new water supply stations and transmission/distribution pipes. However, the complete prediction of those changes in the future is difficult. Thus it was concerned that the power generation would not be processed as planned. Accordingly we conducted research so that the water supply operation system with demand estimation and distribution reservoir operation functionalities would be able to control the optimal inflow rate for power generation. This secures sufficient inflow of water for power generation on the long-term basis while not affecting the stable supply of water. Hereby, more effective usage of excess pressure has become possible, thus we report it here.

Material and Methods

The water resources in Tokyo come mostly from rivers. 78% of this is sourced from Tone-Arakawa Rivers, and 19% is from Tama River. Mutual accommodation between these water resources is possible through the raw water connection pipelines. We aim for the effective usage of valuable raw water considering the condition of each river or dam. On the basis of this “raw water plan”, we predict the amount of water distribution per day for the following month via results from previous years and seasonal changes.

At purification plants, we perform purification procedures according to the prediction and determine the “main pipeline operation plan” for transmitting water to water supply stations. If transmission pipes have the dual network system, the transmission routes are determined upon consideration of energy saving and the maintenance conditions (Kaneko, 2014; Iwasaki, 2012; Masuko, 2012).

The distribution pumps at stations are operated based on the “distribution pump operation plan” which has been programmed with the pressure and water amount patterns on weekdays and holidays. Over 20 m of pressure in the distribution pipelines is constantly maintained whilst considering pipe resistances and demand fluctuations.

The water supply operation system makes the operation plan of waterworks facilities by integrating the “raw water plan”, the “main pipeline operation plan” and the “distribution pump operation plan” to increase the accuracy in demand prediction. The distribution reservoir operation function is derived from this demand prediction function as well as the water inflow plan. In the distribution reservoir operation, the storage volume, distribution amount, inflow rate and distribution pressure on any given day and its following day are controlled for every 15 minutes. All of these plans are estimated by further precision by basing such factors as the weather forecast for the following day, temperature, day of the week and national holidays. Furthermore, revisions are constantly made adjusting to the real-time fluctuations in demand. An outline of the water supply operation system is shown in **Figure 1**. By entering the conditions of the inflow water that can maximize the potential of the hydraulic power generation equipment, efficient power generation becomes possible.

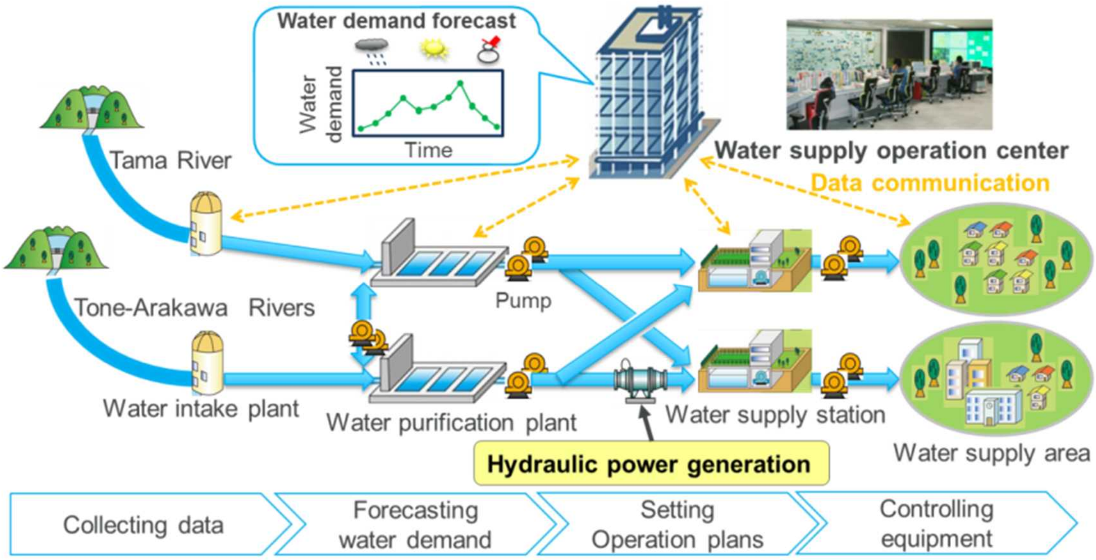

Figure 1 Water supply operation system

Table 1 Outline of hydraulic power generation equipment

Supply station name	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 (m)	28.5	30	25.5	35.0
Turbine design	Diagonal flow (horizontal axis)		Francis (horizontal axis)	
Launched Month/Year	March 2005	April 2008	April 2010	October 2013
Installation status				

The equipment generating with excess pressure has been installed at four water supply stations, Minami-Senju, Kameido, Yakumo and Kasai, where it was easy to secure installation space. **Table 1** shows the outline of these. As an example, **Figure 2** shows the status of excess pressure into the equipment installed at Kasai water supply station. Kasai water supply station is positioned midway through the transmission pipe running from Kanamachi purification plant to Tokai water supply station at the end. For this reason, the average of about 30 m of excess pressure exists in the portion pulled into Kasai water supply station. For the operation of the equipment, the inflow rate possible for power generation has been determined by considering not only turbine efficiency also fluctuations in inflow pressure, vibrations and noise of 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. The lower limit is 0.58 m^3/s (2,100 m^3/h), which is 42%.

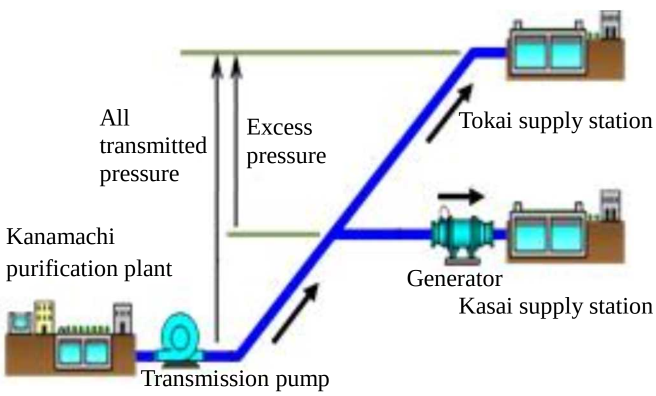

Figure 2 Status of excess pressure at Kasai

Before the installation of the hydraulic power generation equipment, the distribution reservoir operation controlled the amount of inflow water according to the change of distribution amount. As a result, the level of the distribution reservoir was kept constant as shown on the left side of **Figure 3**. With such operation, at a flow rate lower than the lower limit of power generation, all the inflow water was bypassed and energy of excess pressure was unused. At a flow rate higher than the upper limit of power generation, residual inflow water was also bypassed and energy of excess pressure was unused.

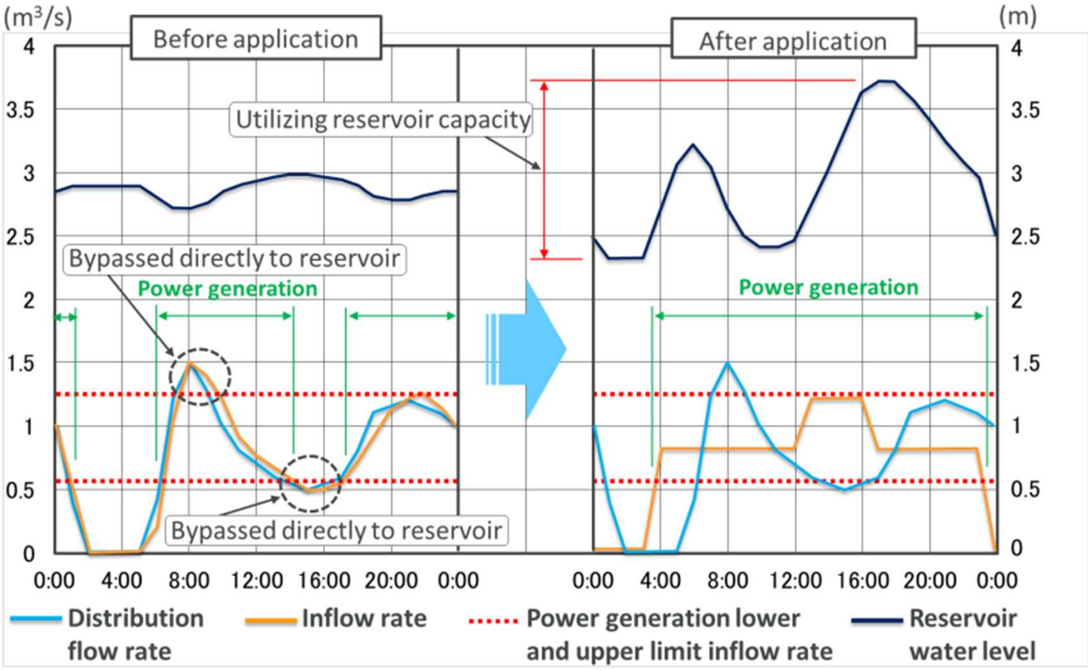

Figure 3 Changes in distribution reservoir operation

Results and Discussion

We have implemented the distribution reservoir operation taking the hydraulic power generation equipment into consideration by the planning function of the water supply operation system. As a result, the period in which the inflow rate is suitable for power generation has extended as shown on the right side of **Figure 3**. Also, the bypassed inflow water has become able to be used in power generation. With the operation, we made effective use of the capacity of the reservoir without affecting stable water supply although the water level of the reservoir changed greatly. With the operation, an example of monitoring screen is shown in **Figure 4.**

Moreover, in case a deviation between the predicted distribution amount and the actual data occurs due to abrupt changes in weather or particular events, the water supply operation system has the function to automatically correct the operation plan. This function is the same even if the hydroelectric power generation equipment is operated. With the system, we ensure both the stable supply of water and the utilization of unused energy.

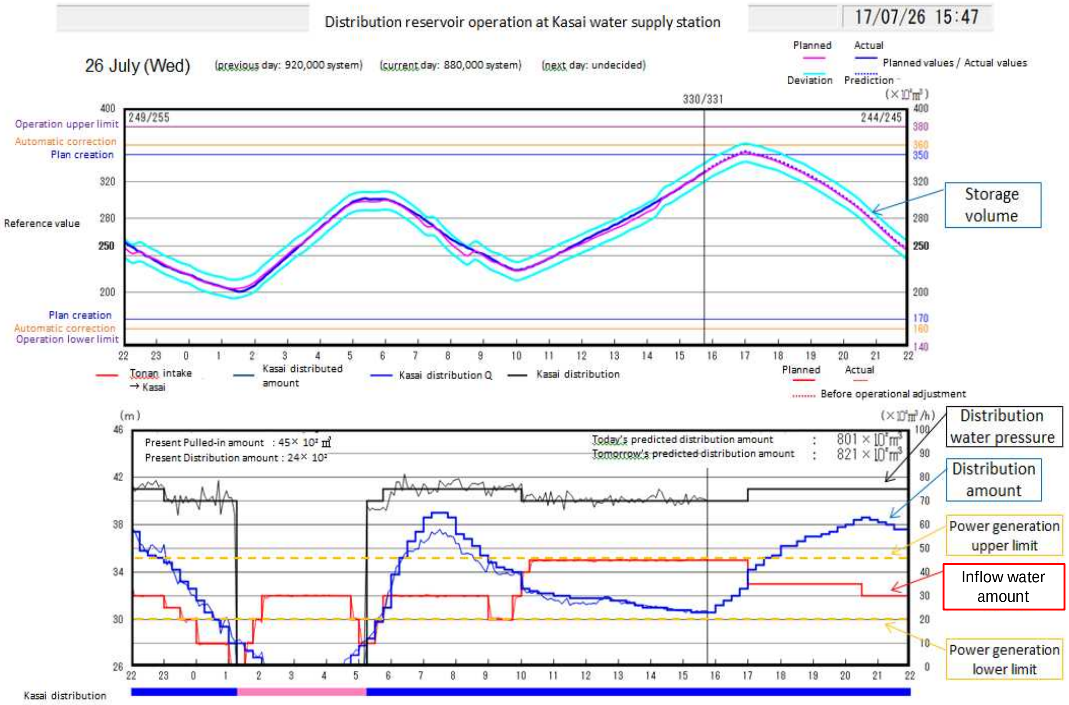

Figure 4 Distribution reservoir operation at Kasai

Table 2 Performance data of hydraulic power generation equipment at Kasai

Item	Unit	FY2013	FY 2014	FY 2015	FY 2016	FY 2017	Total
Power generation amount	10,000 kWh	68	127	158	150	151	654
Inflow water amount	10,000 m^3	1,429	2,643	3,009	2,968	2,887	12,936
Original unit of power generation	Wh/m^3	48	48	53	51	52	—
Power sell 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 of when the hydraulic power generation equipment was put into operation.
* The CO_2 conversion factor is 0.489 t-CO_2 / 1,000 kWh (Bureau of Environment, Tokyo Metropolitan Government, 2018).

Table 2 shows the performance data of the hydraulic power generation equipment at Kasai water supply station. In the estimation based on the inflow rate before the installation of the equipment, yearly power generation of 1.4 million kWh was expected. As a result of the distribution reservoir operation based on the water inflow plan considering the power generation starting in FY2015, the yearly power generation exceeded 1.5 million kWh, which was 0.1 million kWh more than expected amount. Moreover, the yearly power generation amount of **Table 2** can be represented as Eq. (1).

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

Here:

E = yearly power generation amount (kWh/year)

P = maximum output (kW)

F = equipment utilization factor

where

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

The equipment utilization factor F in Eq. (2) is a ratio of the actual yearly power generation amount to the yearly power generation amount when the equipment was continuously operated at its maximum output for a year. This research can be an effort to improve this factor. In general, for hydraulic power generation equipment in Japan, it is commonly around 50% to 95% though the factor differs depending on flow condition. From FY2015 onwards the equipment utilization factor of the hydraulic power generation equipment at Kasai water supply station has been surpassing 50% as shown in **Table 2**. This hydraulic power generation, having been affected by fluctuations in demand, can be said to suffer a worse flow condition. However, as hydraulic power generation equipment that is not built in a dam waterway specialized for power generation, it can be thought of having superior equipment utilization factor. Also, the power generation output can be represented as Eq. (3).

$$P\ (kW) = 9.8\ (m/s^2) \times Q\ (m^3/s) \times He\ (m) \times \eta \qquad (3)$$

Here:
P = power generation output (kW)
9.8 = gravitational acceleration (m/s^2)
Q = inflow rate (m^3/s)
He = effective drop in excess pressure (m)
η = power generation efficiency

In this research, the inflow rate Q in Eq. (3) can be said to be controlled to be the optimal value for power generation. Moreover, depending on the turbine design, the power generation efficiency η is prone to change due to the inflow rate Q. In particular, the Francis turbine has a large change, and its characteristic curve has a maximum. An example is shown in **Figure 5** .In this case, it is possible to control the inflow rate Q so that the power generation efficiency η becomes an optimal value for power generation. The indicator that simply shows the power generation efficiency is the original unit of power generation Wh/m^3, that is, the power generation amount Wh per inflow water amount 1 m^3. The original unit of power generation Wh/m^3 in **Table 2** has become high since FY2015 compared to FY2014 and before. Particularly, if one looks at the change from FY2016 to FY2017, the original unit of power generation is increasing, irrespective of the decreasing inflow water amount. Therefore, it is understood that the increase in power generation amount is not only dependent on the increase in inflow water amount but also on the improvement of power generation efficiency.

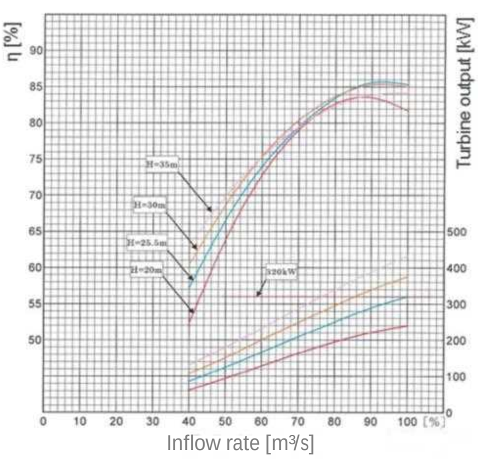

Figure 5 Characteristic curve of power generation efficiency

In the case the transmission pipes have the dual network system, distribution reservoir operation is also possible. This is done by fixing the inflow rate of transmission pipe in the hydraulic power generation equipment to be the optimal value for power generation, and controlling the inflow rate of the other transmission pipe. With these simple principles, the improvements on equipment utilization factor and power generation efficiency are being achieved.

The sum of the equipment construction costs and maintenance costs are called the "total cost". For the hydraulic power generation equipment at Kasai water supply station, the recovery period of the total cost through the gains from power generation was seven years. This is based on the estimate before the installation of the equipment. It is expected that this will be reduced to six years.

For the hydraulic power generation equipment at Minami-Senju and Kameido water supply stations shown in **Table 1**, in ten years after their respective installations, an overhaul inspection was enforced. At this time, there were no defects such as corrosion or abrasion. Also, neither of the equipment had ever experienced a breakdown or any trouble so far. Even after the recovery of total costs, we can expect long-term power generation.

Conclusions

By application of the water supply operation system, we succeeded in increasing the power generation amount and the early recovery of the total cost. In other words, we have first demonstrated how equipment utilization factor and power generation efficiency can be improved by combining the hydraulic power generation equipment and the capacity of distribution reservoirs. In addition, greenhouse gas emission will be repressed for a longer period, and the waterworks utilities will be more sustainable.

As waterworks utilities grows larger, adjustment through pressure reducing valves, along with proper pump operation, becomes indispensable. Given the undulating terrain of Tokyo, many pressure reducing valves are necessary while this means the potential for the hydraulic power generation is high.

We also carry out hydraulic power generation by the gravitational flow of raw water. Including this, the power generation output ranges from 7 kW to 1,400 kW. Hence, it is a system that can be adapted in many different countries or regions regardless of the scale of waterworks utilities. Of course, the results of this research can be applied to any hydraulic power generation of any scale. We hope that our research can give ideas for the improvement of the resilience and sustainability of many different waterworks utilities. And we also believe it can contribute to unused energy in waterworks utilities around the world being turned into renewable energy, and reduces the use of fossil fuels and greenhouse gases.

References

Bureau of Environment, Tokyo Metropolitan Government. (2018). *Estimation Guidelines for Greenhouse Gas Emissions of Total Reduction Obligation and Emissions Trading Scheme*. Tokyo, Japan.

Bureau of Waterworks, Tokyo Metropolitan Government. (2017). *Environmental Report 2017*. Tokyo, Japan.

Bureau of Waterworks, Tokyo Metropolitan Government. (2016a). *Water Supply in Tokyo*. Tokyo, Japan.

Bureau of Waterworks, Tokyo Metropolitan Government. (2016b). *Tokyo Waterworks Management Plan 2016*. Tokyo, Japan.
Bureau of Waterworks, Tokyo Metropolitan Government. (2016c). *Tokyo Waterworks Innovation Project.* Tokyo, Japan.
Bureau of Waterworks, Tokyo Metropolitan Government. (2014). *Tokyo Waterworks 10 Year Plan for Energy Efficiency.* Tokyo, Japan.
Iwasaki K. (2012). *Construction of an Effective Water Supply System*. IWA World Water Congress, Busan, South Korea.
Kaneko, S. (2014). *Reduction of Power Consumption Using Power Monitoring System.* IWA World Water Congress, Lisbon, Portugal.
Masuko A., Hashimoto T., Ashida H., Tamura S., Arai Y. and Koizumi A. (2012). Study on the Minimization of the Total Electric Energy in the Water Distribution Process Based on the Analysis of Electrical Power Consumption Rate. *Journal of Japan Water Works Association*, **81**(3), 2-10.
Masuko A., Takagi J., Ashida H., Tamura S. and Koizumi A. (2011). Study on the Reduction of Water Distribution Energy by utilizing the remaining Water Pressure at a Reservoir considering the Water Quality preserving. *Journal of Japan Water Works Association*, **80**(6), 13-22.
Tanaka T. (2018). Utilization of Renewable Energy in Metropolitan Waterworks: Is Renewable Energy a Key to Solving Energy and Environmental Issues? *Water Science and Technology: Water Supply*, **18.3**, 1041-1050.