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Practical Paper

Development of sustainable operational technologies of the water treatment plant for stable water supply

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ABSTRACT

For the continuous and stable supply of safe drinking water, it is essential to not only design suitable water treatment plants that can handle the characteristics of raw water quality but also appropriately operate and control them. Controlling complicated water treatment systems using fewer operators essentially requires hazard identification and the establishment of the operation and control of the systems by a simple method of selecting the relevant data. Therefore, the Hanshin Water Supply Authority has supported operators by adding an advanced operation supporting feature to the renewed information-processing equipment in water treatment plants. Moreover, the Authority has investigated the problem of bromate, examined measures for its reduction, and applied the control measures to the information-processing equipment so that operators can promptly cope with the problem. This supporting system is effective in terms of the Water Safety Plan. The successive development of technologies while considering the aspects of operation and control is important for realizing a continuous stable water supply.

Key words | bromate reduction, information-processing, operation and control, ozonation, successive development, water-quality management

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INTRODUCTION

The role of water utilities is to continuously supply a sufficient amount of safe drinking water. The water treatment plant (WTP) must be designed to be capable of removing risk factors associated with raw water, each of which has unique characteristics, in order to satisfy the water-quality standards of drinking water. In addition, such plants must be appropriately operated and controlled to achieve their designed performance and to always maintain the quality of drinking water at the outlet of the supply system.

Meanwhile, consumers have been increasingly concerned about the drinking water quality and have requested the supply of safe and palatable water. Under such circumstances, coupled with the improvement of analysis technology and the advancement of technology for evaluating toxicity, the number of items included in the water quality standards for drinking water in Japan has now increased to 51, and these items are expected to be successively revised upon future scientific findings. In addition, more plants have adopted advanced water treatment technologies, such as ozonation and GAC (granular activated carbon) adsorption, to cope with the deterioration of raw water quality, increasing the complexity of water treatment systems. Nevertheless, advanced instrumentation technology has made WTPs more automatic, enabling their operation and control with fewer operators. Operators are

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required to monitor and control a WTP to ensure its normal operation; for this purpose, they must understand the operating state of the plant from the huge amount of data collected by the monitoring and control equipment, promptly detect any abnormalities, and take appropriate measures. Recently, water facilities in Japan have faced a new problem, a flurry of retirements of experienced workers; thus, the transfer of operator skills should be considered an urgent priority.

In 1993, the Authority modified the conventional water treatment system by introducing ozonation and GAC adsorption systems, with the aim of improving taste and odour and reducing disinfection by-products. After the adoption of these systems, the generation of bromate as an ozone disinfection by-product became the focus of attention. The Authority explored various measures for reducing bromate and applied the measures to techniques of the operation and control of WTPs.

In this study, we report the introduction of the bromate reduction protocol to the information-processing equipment, along with the conditions of water-quality control, from the viewpoint of the operation and control of the WTP.

WATER QUALITY CONTROL

Water quality control in WTP

The Authority takes raw water at the furthest point downstream of the Yodo River of the Lake Biwa-Yodo River system, and purifies and supplies it as drinking water to the four cities of Kobe, Amagasaki, Nishinomiya and Ashiya in the Hanshin area (between Osaka and Kobe). Figure 1 shows the water treatment flow in the Authority.

Table 1 summarizes the maximum values of characteristics used in water-quality control by the Authority that are given in the water-quality standards and guidelines and were detected or measured in raw and supplied water in 2004–2006. The following substances and indicators in raw water were detected or measured to be in excess of the values in the water quality standards: standard plate count, *Escherichia coli*, aluminium, iron, manganese, substances responsible for musty odour, geosmin, colour, turbidity and nitrite nitrogen. Moreover, disinfection by-products generated in the WTP (bromate, trihalomethane (THM) and chlorate), although not exceeding their maximum allowable values, still require attention. Toxic substances that could enter the water supply through an accident or terrorist attack, oil and *Cryptosporidium*, which are usually not detected, also need monitoring and control because, if detected, they may seriously harm the drinking water to be supplied.

Table 2 summarizes the main control measures involved in monitoring the above risk factors at intake and their control in the WTP. A continuous and stable water supply may be realized by focusing the monitoring on these factors and preparing appropriate measures in the WTP.

Table 3 shows the sites where the water quality is monitored automatically in the Inagawa WTP. The plant is controlled by operators who check the data on water quality, the operating condition of the equipment, flow rate, pressure and other factors that are input into the monitoring and control equipment in the central control room. The huge amount of data obtained from as many as 6,000 monitoring sites are processed by computers; therefore, a simple method for operators to extract the necessary information from the data is essential for the stable operation of the WTP.

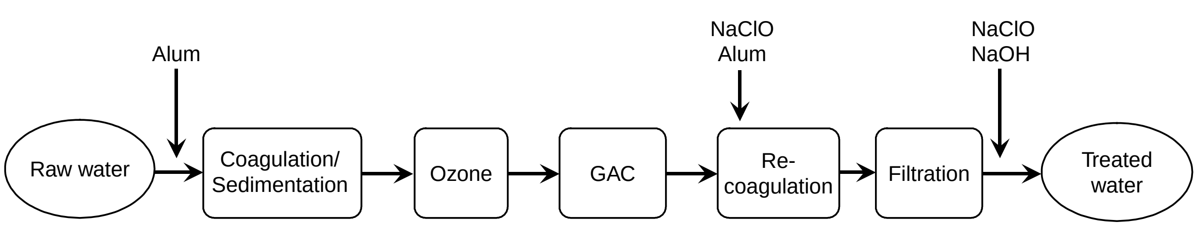

Figure 1 | Water treatment flow of the Hanshin water supply authority.

Table 1 | Maximum values of characteristics of raw and supplied water quality in 2004–2006

		Raw water		Supplied water	
Items	STD (mg/L)	Max. (mg/L)	Max./STD (%)	Max. (mg/L)	Max./STD (%)
Standard plate count	100	57,000	57,000	1	1.0
E. coli	0	7,900		0	0.0
Lead	0.01	0.002	20.0	< 0.001	0.0
Arsenic	0.01	0.002	20.0	< 0.001	0.0
Nitrate nitrogen and nitrite nitrogen	10	1.87	18.7	1.76	17.6
Fluoride	0.8	0.13	16.3	0.12	15.0
Bromate	0.01	–	–	0.0058	58.0
Total THM	0.1	–	–	0.016	16.0
Aluminium	0.2	1.06	530	0.08	40.0
Iron	0.3	0.73	243	< 0.01	0.0
Sodium	200	19.2	9.6	24.8	12.4
Manganese	0.05	0.060	120	< 0.005	0.0
Chloride ion	200	21.9	11.0	22.3	11.2
Hardness	300	52.0	17.3	52.1	17.4
Total solid	500	140	28.0	150	30.0
Anionic surface active agent	0.2	0.04	20.0	< 0.02	0.0
Geosmin	0.00001	0.000320	3,200	< 0.000001	0.0
2-MIB	0.00001	0.000005	50.0	< 0.000001	0.0
TOC	5	2.6	52.0	1.3	26.0
Color	5	55	1,100	0.5	10.0
Turbidity	2	42	2,100	< 0.1	0.0
Nickel	0.01	0.003	30.0	0.001	10.0
Nitrite nitrogen	0.05	0.068	136	< 0.001	0.0
Chlorate	0.6	–	–	0.17	28.3
Free carbon dioxide	20	3.2	16.0	2.4	12.0
$KMnO_4$ consumption	10	8.2	82.0	1.3	13.0

Information-processing equipment at Inagawa WTP

Figure 2 shows the system configuration of the information-processing equipment renewed in 2002 at the Inagawa WTP. The equipment consists of an information-processing server, a work station for controlling the facility and terminals for controlling the facility, reading data and preparing daily reports.

Figure 3 shows the features of the information-processing equipment. Each type of data collected by the monitoring and control equipment with a period of 1 min is subjected to the arithmetic operations and a closing process, and subsequently stored in a database to be used for each feature.

Table 2 | Monitoring or control measures in the intake and WTP

Items	Monitoring or control technologies
Toxic substances	Monitoring using bioassay (at intake)
VOC, Oil	GC–MS automatic monitor (at intake)
SPC, *E. coli*	Residual chlorine control, contact time
Turbidity, aluminum	Alum injection dose control, pH control
Manganese	Break-point chlorine control, monitoring of color
Organic compounds, musty order, DBP	Ozone dose control, GAC adsorption
Cryptosporidium	Monitoring of turbidity of filtered water

VOC: volatile organic carbon; SPC: standard plate count; *E. coli*: *Eschericia coli*; DBP: disinfection by-products; GAC: granular activated carbon.

Table 3 | Monitoring of water quality in the Inagawa WTP

Monitoring point	Raw	Rapid mixing	Sedimentation	Ozone	GAC	Re-coagulation	Filtration	Treated water
Turbidity	○		○				○	○
Color							○	○
pH	○	○				○	○	○
Conductivity	○							○
Temperature	○							○
Residual chlorine			○			○	○	○
UV260			○		○			
Residual ozone				○				
Dissolved oxygen	○							
Oxidation-reduction potential	○							
Bioassay			○		○			

The features shown in the bold boxes in Figure 3 were newly added in this study. The main features include an advanced operation supporting feature, a chemical dosing control feature, and an irregularity management supporting feature. The advanced operation supporting feature detects various irregularities and sends a signal to the irregularity management supporting feature. It is effective for monitoring rapid changes in turbidity at intake, the performance of organic substance treatment and the process of water treatment.

By monitoring rapid changes in turbidity at intake, a rapid increase in the turbidity can be detected at the intake located 13 km east of the Inagawa WTP (corresponding to approximately 3 hours for running water), enabling us to take prior control measures in the plant against high-turbidity raw water. When monitoring the performance of organic substance treatment, the advanced operation supporting feature sounds a warning when: 1) the UV value for GAC-treated water tends to increase; or 2) the UV value remains above the maximum permissible period for GAC-treated water, as calculated from the UV value for settled water, for more than a certain predetermined period. Regarding the monitoring of the process of water treatment, when it is necessary to change the operating number of settlers, ozone contactors, GAC adsorption tanks, or filters in use under unusual conditions, this feature can simulate the effect of the change on the process of water treatment.

The chemical dosing control feature calculates the dose rate of alum and can adjust the parameters to obtain an appropriate dose rate that reflects previous know-how and experience. The irregularity management supporting feature displays a warning message sent from the advanced operation supporting feature and informs the monitoring and control equipment of the warning. The message shows the details of the failure and the management procedure.

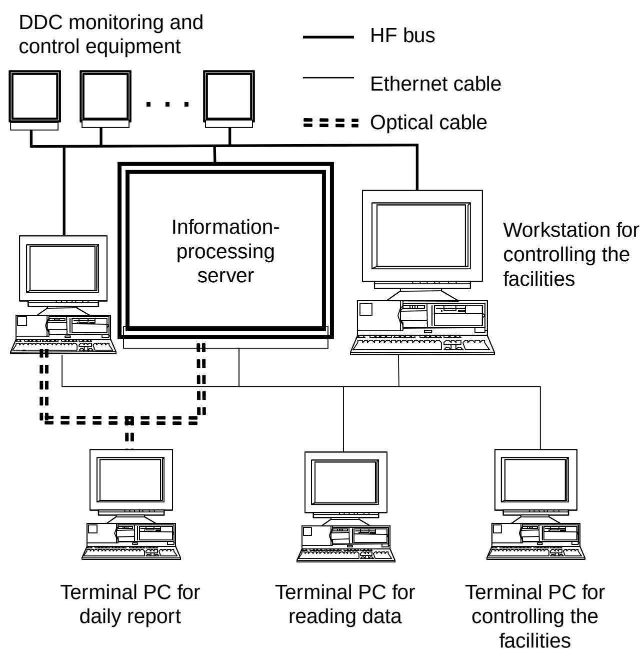

Figure 2 | System configuration of the information-processing equipment.

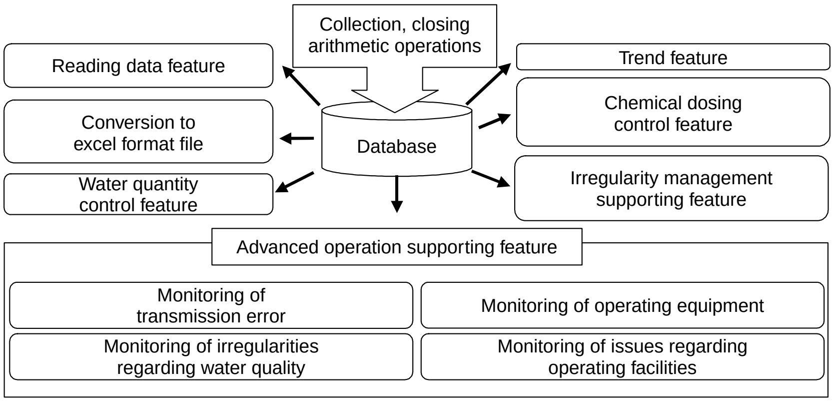

Figure 3 | Features of the information-processing equipment.

Owing to the extension of the data storage period and the adoption of the analysis data collection tool, the electronic data in the database have become more readily available and useful for revealing long-term changes and elucidating the causes of various emergencies. Moreover, the system is equipped with the capability to detect and warn of system errors and unusual water quality and to provide a management procedure for them. Furthermore, this system adopts the previous achievements of the plant and the experience and knowledge of skilled workers, enabling the transfer of their technical skills to the next generation. With this renewed system, we can not only ensure the stable operation of the system under usual conditions but also provide prompt and appropriate responses under unusual conditions, greatly contributing to the safer and more stable operation and control of the plant.

Accommodation of new items regarding water quality

Bromate was added to the list of items in the water quality standards when they were revised in 2004. Bromate was not considered in the design of the current water treatment system because this system was installed in 1993. As shown in Table 1, the amount of bromate was thus more than half the standard value in some cases. We investigated suitable responses to this and added a bromate reduction feature to the advanced operation supporting feature of the information-processing equipment on the basis of the result, as described below.

BROMATE REDUCTION SUPPORTING FEATURE

Conditions of bromate in the WTP

Figure 4 shows the variation of bromate and water temperature in the Inagawa WTP in 2005. The concentration of bromate increased in the season with high water temperature, and although it did not exceed the standard value, it reached over half of that value some of the time. Therefore, we discussed measures for reducing bromate concentration.

In this discussion, we presupposed the retention of features such as the removal of the musty odour, the THM reduction and the inactivation of microorganisms, which are the purposes of the designed ozonation system. The target value of bromate at the Authority was set at 3 $\mu g\, l^{-1}$, which is 30% of the standard value. At the Inagawa WTP, the relationship between the concentration of bromate and the ozone CT value was examined to optimize the ozonation.

As shown in Table 4 and Figure 5, the ozone contactor in the Inagawa WTP is designed to employ the vertical-channel three-stage flowing method and is composed of an ozone generator using air as a source and diffuser tubes. Usually, ozone is uniformly diffused into all three stages in three (Systems I and II) or four (System III) tanks of each system. The standard contact and reaction times are 10 minutes each. The ozone injection is feedback-controlled automatically to maintain the concentration of the residual ozone at 0.25 $mg\, l^{-1}$ at the inlet of the GAC adsorption tank (Nagashio *et al.* 2000). Moreover, raw water is taken from the surface water of Yodo River, and the total capability of the plant with Systems I–III is 916,900 m^3/day.

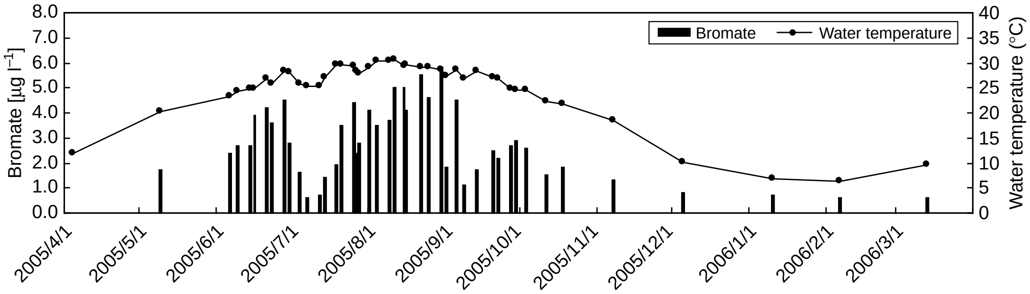

Figure 4 | Variation of bromate and water temperature for raw water in the Inagawa WTP.

Figure 6 shows the variation in the CT value in systems of the Inagawa WTP in fiscal year 2005. The concentration of dissolved ozone was actually measured for each stage, and the CT values were calculated using an estimation model (Uejima *et al.* 2004), assuming that the ozone is completely mixed in each stage of the ozone contactor. The ozone injection was carried out in accordance with the quality of raw water by maintaining the concentration of residual ozone, resulting in an annual average CT value of approximately 10 mg l^{-1} min. However, the CT value increased around June as the temperature of the raw water rose, and was almost double the average value towards the end of August. It was speculated, from this result, that the excess ozone was indirectly incorporated because of the increase in water temperature rather than being related to the quality of raw water.

Figure 7 shows the relationship between the concentration of bromate in ozonated water and the CT value. The water was ozonated in the Inagawa WTP in 2005 and 2006. The concentration of bromate was reduced to below 3 μg l^{-1} through ozonation with a CT value of 11 mg l^{-1} min, or lower even during the hot season when water temperature is high. Figure 8 shows the relationship between the temperature of the raw water and the concentration of bromate detected. A bromate concentration above the target value (3 μg l^{-1}) was detected when the water temperature exceeded 25°C.

In Figure 8, the variation of the bromate concentration becomes large as the CT value increases. The following two reasons may lie behind this result. The CT value increases but the generation of bromate is reduced when the quality of raw water deteriorates (due to the increasing ammonia nitrogen and organic substances) at high water temperature. On the other hand, when a good quality of raw water is maintained even at a high water temperature, a high concentration of bromate is detected because the CT

Table 4 | Specifications of ozone facilities in the Inagawa WTP

Ozone contactor 10 basins			
Shape	I, II	W9.7 m × L12.0 m	3 × 2 basins
	III	W4.0 m × L24.0 m	4 basins
Type	Three-stage, bubble diffuser		
Structure	RC		
Effective depth	5 m		
Contact time	10 min		
Control	Feedback control by residual ozone at GAC influent		
Ozone generator 10 numbers			
Gas flow	I, II	620 m^3 (N)/h	3 × 2 Num
	III	500 m^3 (N)/h	4 Num
Ozone concentration		Max. 20 g/m^3(N)	
Raw material		Dried air	

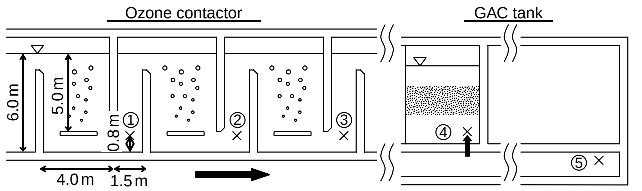

Figure 5 | Ozone contactor in the Inagawa WTP; 1–5, sampling points for dissolved ozone.

value is too high relative to the amount of ozone that must be injected. Namely, the generation of bromate is expected to be reduced by optimizing the ozone dosing such that the CT value can be appropriately controlled even at a high water temperature.

Establishment of bromate reduction supporting feature

Previous surveys on water quality suggested that the concentration of bromate exceeds the target value of $3\,\mu g\,l^{-1}$ when the CT value is over $11\,mg\,l^{-1}\,min$ at a water temperature of 25°C or higher. We confirmed that the generation of bromate can be reduced by lowering the residual ozone control value because the CT value is controlled to avoid it becoming excessively high during the season with high water temperature. Therefore, we examined the feasibility of adding a new feature to the advanced operation supporting feature, in order to adopt the measure of promptly reducing the concentration of residual ozone under conditions that will lead to an increase in the amount of bromate generated.

The main parameters of the new feature are water temperature and CT value. Although water temperature is always measured, the CT value requires the on-site measurement of the concentration of dissolved ozone in each stage of the ozone contactor, which is not always monitored by the monitoring and control equipment. Thus, we introduced an original alternative simplified CT value

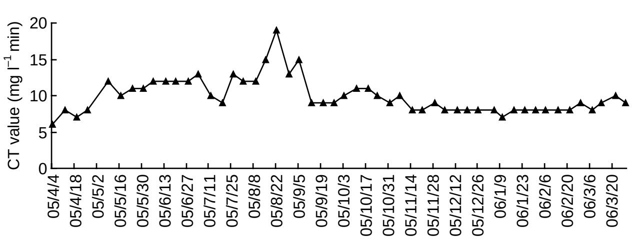

Figure 6 | Variation of CT value in the Inagawa WTP.

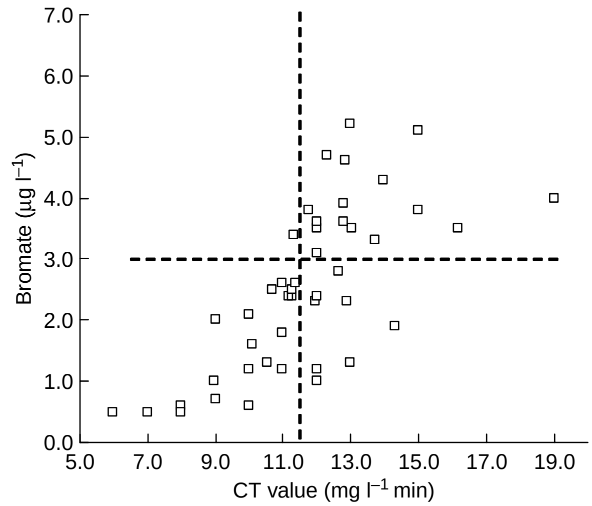

Figure 7 | Relationship between bromate and CT value.

for a water temperature of 25°C or higher, using the data collected by our computer. This is given by Equation (1).

$$S_{CT} = \frac{[((D_{ozone} + R_{ozone})/Q) + 2.99 \times 10^{-5}]}{1.86 \times 10^{-5}} \times E \qquad (1)$$

where S_{CT} is simplified CT value, D_{ozone} is ozone dose rate, R_{ozone} is residual ozone concentration, Q is flow rate and E is correction coefficient.

The ozone dose rate, concentration of residual ozone, and flow rate are the three parameters used to calculate the simplified CT value, and are continuously collected by the monitoring and control equipment. Figure 9 shows the relationship between the simplified CT value and the concentration of bromate generated. Similarly to the case of the CT value, it was confirmed, for the simplified CT value, that the concentration of bromate can generally be reduced to below $3\,\mu g\,l^{-1}$ by controlling the CT value to $11\,mg\,l^{-1}\,min$

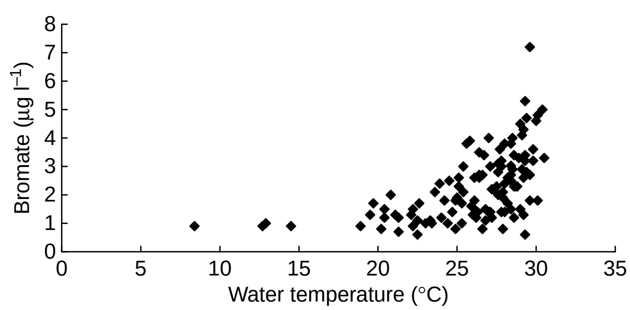

Figure 8 | Relationship between bromate and water temperature.

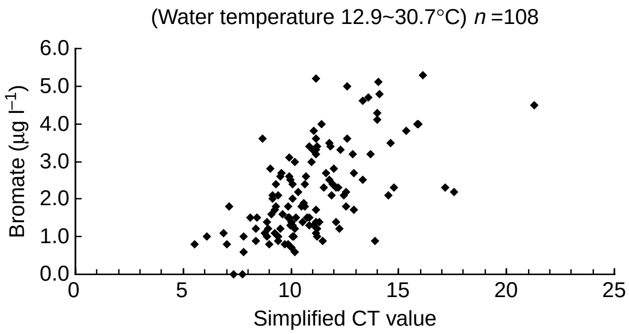

Figure 9 | Relationship between bromate and simplified CT value.

or lower. We developed a bromate reduction supporting feature on the basis of this result and incorporated it into the information-processing equipment. This equipment was modified so that operators can promptly take an appropriate measure. The system calculates the simplified CT value using Equation (1) and raises the alarm when detecting a simplified CT value of $11\,mg\,l^{-1}$ min or higher and a water temperature of 25°C or higher, enabling operators to take the appropriate measure of lowering the preset value of the residual ozone concentration on the monitor.

Moreover, an increased ozone demand is required as the water quality deteriorates, and the reduction in the amount of bromate with respect to the ozone dose rate was thus confirmed. Therefore, the system was designed to also warn of a raw water turbidity of 15 or higher, which is the maximum allowable value for stopping the bromate reduction supporting feature, thus supporting the feature by urging operators to return the changed value of the residual ozone concentration to the usual value.

CONCLUSIONS

The optimal operation and control of a water treatment facility, in addition to its appropriate design, is essential to continuously supply safe drinking water. Water facilities are now being managed using fewer operators, and the retirement of many experienced workers is expected. We are concerned that it will be very difficult to promptly obtain necessary information in accordance with various hazards if we only rely on highly experienced or highly skilled operators to operate and control the water treatment system. To cope with this, we have added an advanced operation supporting feature to the information-processing equipment, identified the important risk factors, and narrowed the targets of control, to realize more stable operation and control as well as to pass down operator skills. In particular, the intensive use of computing features enables us to even apply control measures against disinfection by-products with a complex reaction path to the operation and control techniques.

In the future, we plan to verify the effectiveness of these supporting features for actual conditions, and improve them as required. We will also survey and examine control measures against new risk factors and develop new features for the management of these factors to support the operation and control of the system. The result of adopting the bromate reduction feature in this study suggests that we should be concerned about its unsatisfactory performance resulting from only using residual ozone. We are now carrying out a review of the feature.

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