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National survey of utilization of continuous water quality monitors in water supply systems in Japan

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ABSTRACT

An investigation of the utilization of water quality monitors at water purification plants throughout Japan was conducted via questionnaire from August to October 2015. The number of types of monitors installed at more than one water purification plant was 34. Chlorine, high sensitivity turbidity, pH, and turbidity monitors were (highly) recommended for installation in four water purification processes (rapid sand filtration, chlorination only, slow sand filtration and membrane treatment), except for high sensitivity turbidity of chlorination only. The number of installations of the monitors recommended and their installation points were dependent upon the processes. Highly recommended points of turbidity were raw water and sedimentation points, which were set for (critical) control points in water safety plans. That of high sensitivity turbidity was the rapid sand filtration point for confirmation of *Cryptosporidium* control. Chlorine monitors were applied for automatic control, regardless of the water purification processes. Some interesting monitors, such as those for musty odor compounds and trihalomethane, were newly developed and utilized. The results of this study showed that water quality monitors were important for water quality management systems based on water safety plans in Japan.

Key words | questionnaire investigation, surrogate parameter, water purification process, water quality monitor, water safety plan

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INTRODUCTION

The safety of drinking water is generally verified through regular examination of the drinking water. In Japan, the number of current standard items in drinking water regulations is 51 (Ministry of Health, Labour and Welfare (MHLW 2015)), and the regular time intervals of water examination depend on the water quality items (from more than once per day to more than once per three months). On the other hand, water quality monitors are installed at several

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points in water supply systems and the target items of such are continuously monitored. Data from water quality monitors are utilized for several purposes. The types of water quality monitors are limited, and their detection/quantification limits are generally higher than those by water examination.

For example, the index values of the concentrations of chlorine in finished water (Asano *et al.* 2016) and dissolved ozone at the outlet of ozone reactors (Nakamura *et al.* 2017) have been set and maintained using chlorine and dissolved ozone monitors, respectively. Warning systems in drinking water distribution networks by monitoring several water quality items have also been reported (Perelman & Ostfeld 2013; Oliker & Ostfeld 2015). In addition, in Japan, water quality management based on water safety plans (WSPs) is recommended by MHLW (2008), and continuous monitoring of target items (i.e., hazardous items and/or their surrogates) at (critical) control points (CPs) is the preferred method of monitoring in many of the WSPs.

To date, information on utilization of water quality monitors (e.g., the types of water quality monitors installed, installation points of the monitors, and utilization of the data from the monitors) is limited and only available for individual water utilities (Kawaguchi *et al.* 2010). In addition, it seemed that such information was dependent upon the types of water purification processes and scale of facility capacity of water purification plants (WPPs). Moreover, detailed analytical results regarding utilization of the water quality monitors have not been reported. Such information is useful for enhancing water quality management during water purification processes based on WSPs. In this study, the utilization of water quality monitors in water supply systems throughout Japan was investigated via questionnaire and its association with WSPs was evaluated.

MATERIALS AND METHODS

A questionnaire investigation for 331 water utilities throughout Japan was conducted via e-mail from August to October 2015. The water utilities were selected based on the types of water purification processes (rapid sand filtration (RSF), chlorination only, slow sand filtration (SSF), and membrane treatment) of their WPPs. Membrane treatment was with microfiltration or ultrafiltration, excluding one case that used microfiltration followed by reverse osmosis. The numbers of respondent WPPs that employed RSF, chlorination only, SSF, and membrane treatment were 177, 46, 16, and 19, respectively. The distributions of the facility capacity of the WPPs using individual purification processes are summarized in Table S1 in the Supplementary Material (SM) (available with the online version of this paper). It is of note that the presence of chlorine in tap water is required in Japan; chlorination is conducted in all four purification processes. Additionally, some WPPs categorized as membrane treatment also apply RSF or SSF (Table S2 in the SM, available online). The ranges of facility capacity were several tens to more than one million m^3/day. Most of the facility capacities of the WPPs investigated were $<30 \times 10^3$ m^3/day, except for those employing RSF ($<500 \times 10^3$ m^3/day). In the questionnaire investigation, the water supply system was divided into three elements, i.e., catchment, water purification process, and distribution, as installation points of the water quality monitors, and water purification processes were further divided into water intake, raw water, unit processes, and finished water. In the questionnaire, installation points were asked for target WPPs. For example, there were seven installation points (catchment, water intake, raw water, sedimentation, filtration, finished water, and distribution) in WPPs utilizing RSF when the percentage of target WPPs having individual installation points was $\geq$50% (Table S2 in the SM). It is of note that several WPPs responding for the questionnaire did not answer for the installation of monitors in distribution in their systems.

To be used as basic monitors, 23 water quality monitors were selected (Table 1), and other monitors were added if they were installed. In the table, the principle of high sensitivity turbidity monitors was mainly the particle counting method, followed by the transmitting and scattering methods. Questions regarding the installation of the water quality monitors and their utilization were asked. In particular, in distribution, multiple water quality monitors that can analyze several water quality items (e.g., chlorine, pH, and turbidity) simultaneously were installed. In that case, it was considered that water quality monitors for individual items were installed.

Table 1 | Installation percentages of water quality monitors at water purification plants employing individual purification processes

Water quality monitor	Rapid sand filtration	Chlorination only	Slow sand filtration	Membrane treatment
Alkalinity[a]	50	0	6.3	11
Ammonia[a]	13	0	0	11
Biological[a]	55	11	19	47
Chlorine[a]	98	98	94	100
Chlorine demand[a]	16	0	0	0
Chromium[a]	0.6	0	0	0
Color[a]	47	43	19	26
Cyanide[a]	7.9	0	0	0
Dissolved oxygen[a]	7.9	0	6.3	0
Dissolved ozone[a]	6.2	0	0	0
Electrical conductivity[a]	60	22	25	37
High sensitivity turbidity[a]	86	35	75	89
Musty odor[a]	5.1	0	0	5.3
Oil[a]	18	0	6.3	16
Oil film[a]	11	0	6.3	5.3
pH[a]	97	57	63	95
Phenol[a]	0.6	0	0	0
TOC[a]	4.0	0	0	0
Trihalomethane[a]	2.3	0	0	0
Turbidity[a]	95	63	81	79
UV absorbance[a]	17	0	6.3	5.3
VOC[a]	1.1	0	0	0
Water temperature[a]	71	39	44	74
Boron	0	0	0	5.3
Chlorophyll	0.6	0	0	0
COD	0.6	0	0	0
Continuous odor	1.7	0	0	0
Dissolved manganese	0.6	0	0	0
Fluorescence	0.6	0	0	0
ORP	0.6	0	0	5.3
SDI	0	0	0	5.3
Total phosphorus	0.6	0	0	0
Trichloramine	0.6	0	0	0
Water treatment process	0.6	0	0	0

[a]Twenty-three basic water quality monitors; TOC: total organic carbon; UV: ultraviolet; VOC: volatile organic compound; COD: chemical oxygen demand; ORP: oxidation–reduction potential; SDI: silt density index.

RESULTS AND DISCUSSION

Installation of water quality monitors at water purification plants employing rapid sand filtration

Table 1 shows the installation percentages of individual water quality monitors in WPPs using RSF. The number of types of water quality monitors installed was 32, and the installation percentages of individual monitors ranged from 0.6% to 98%. The percentage of WPPs that installed more than one of the 32 types of water quality monitors was 99%. The nine monitors in addition to the 23 basic monitors were chemical oxygen demand (COD), chlorophyll, continuous odor, dissolved manganese, fluorescence, oxidation–reduction potential (ORP), total phosphate, trichloramine, and water treatment process monitors (Table 1).

The installation percentages of four water quality monitors (i.e., chlorine, high sensitivity turbidity, pH, and turbidity) were ≥80%. It was shown that these monitors were needed for installation in the RSF process. In particular, the monitors of chlorine, pH, and turbidity were the main monitors for process monitoring and control because they were installed at three to four points at many WPPs. Five water quality monitors (alkalinity, biological, color, electrical conductivity, and water temperature) were installed at ≥50%. These monitors are recommended to be installed in the RSF process. Regarding biological monitors, the types of monitors were mostly monitoring equipment using fishes. Upon querying of the types of fishes used, the most frequent answers were killifish species and goldfish (Figure S1 in the SM, available with the online version of this paper).

Figure 1 shows installation percentages of the four monitors at individual installation points in WPPs. For turbidity, turbidity monitors at raw water and sedimentation points and high sensitivity turbidity monitors at rapid filtration points were installed at ≥80%. In a study on analysis of WSPs developed (Sasaki *et al.* 2016), the CPs of turbidity, a hazardous item, were raw water and sedimentation points when the hazardous event was rain. This indicated that the turbidity data of the two points were used as turbidity control (e.g., setting coagulant dosage), particularly automatic control (i.e., feedforward control) in raw water

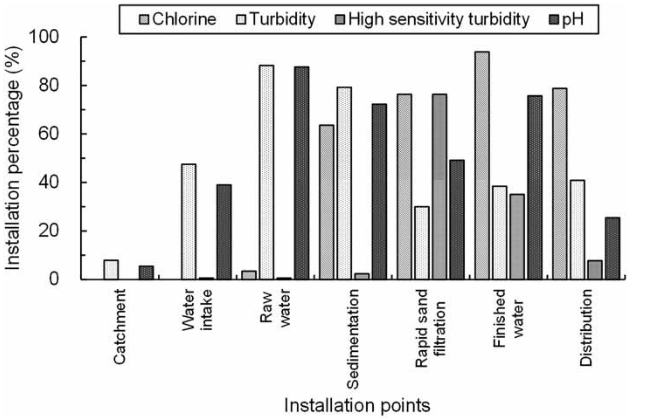

Figure 1 | Installation percentages of chlorine, turbidity, high sensitivity turbidity, and pH monitors at individual installation points in water purification plants employing rapid sand filtration. Individual installation points were adopted at ≥50% of the WPPs investigated.

(Figure S2 in the SM, available online). Also, as an index for controlling *Cryptosporidium*, <0.1 Japanese turbidity unit (JTU) of turbidity is required after filtration in Japan when bacteria selected as indicators of *Cryptosporidium* are found in raw water (MHLW 2007). Thus, it was found that raw water and sedimentation points for turbidity monitors and rapid filtration points for high sensitivity turbidity monitors were highly recommended installation points in RSF. In addition, water intake points and finished water/distribution were also recommended installation points because turbidity monitors were generally installed at three to four points. According to the data analysis of water quality monitors at 20 WPPs, 98% of turbidity data after sedimentation were <1.0 JTU and >99% of turbidity data after RSF were <0.03 JTU, regardless of turbidity levels in raw water (Asano *et al.* 2016). It was confirmed that turbidity was well controlled in RSF processes in Japan.

For chlorine control, the chlorine monitors were installed at ≥60% for the sedimentation, RSF, finished water, and distribution points. Excluding distribution, the levels of chlorine determined via chlorine monitors were used for automatic control at relatively high percentages (30–40%) (Figure S2 in the SM). Prechlorination or intermittent chlorination is applied for many WPPs employing RSF. It was reported that in the WSPs developed, the critical CP of chlorine levels was finished water (0.5–1 mg/L) and the general CPs of chlorine levels were sedimentation and RSF points (0.3–1.0 and 0.3–1.2 mg/L, respectively) (Sasaki *et al.* 2016). It was also reported that the medians of fluctuations of 4 h chlorine levels in finished water at 20 WPPs were <0.1 mg/L (Asano *et al.* 2016). Thus, it was found that sedimentation, RSF, and finished water points were recommended installation points of chlorine monitors to control chlorine levels in process waters and feedback controls at these points were desirable. In addition, installation of the chlorine monitors at distribution points was also recommended to confirm the chlorine levels in drinking water.

A basic water quality item is pH, and this affects the treatment efficiencies of some unit processes (e.g., coagulation and chlorination). From installation percentages, for pH monitors, highly recommended installation points were raw water, sedimentation, and finished water, and a recommended installation point was RSF (Figure 1). The percentages applying automatic control (probably feedback control) at individual installation points ranged from about 10% to 20% (Figure S2 in the SM).

Figure 2 shows the number of installation points of turbidity monitors in WPPs when WPPs were separated per facility capacity. The number of installation points of the monitors was greater when the facility capacities of the WPPs were larger. As described above, installation of the turbidity monitors at three to four points was recommended. However, the number of installation points was up to two at ≥50% of WPPs with facility capacities of $<30\times10^3$ m^3/day. Similarly, the number of installation points of chlorine and pH monitors

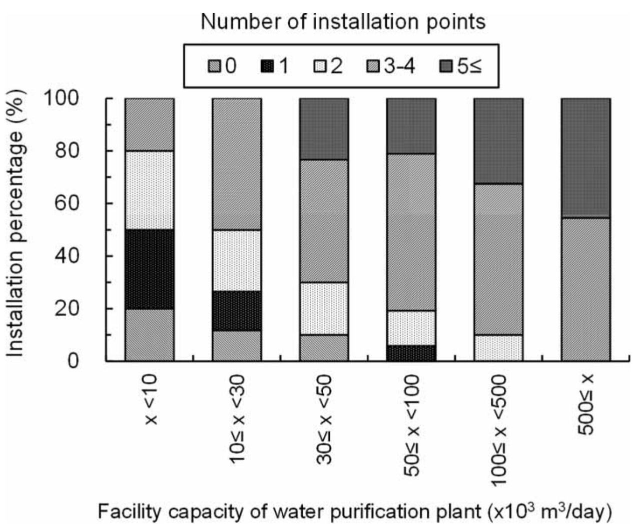

Figure 2 | Installation percentages of turbidity monitors at water purification plants employing rapid sand filtration, separated based on facility capacity.

was lower than the recommendation at $<30 \times 10^3$ m^3/day (Figure S3 in the SM, available online). The monitors are generally expensive and water utilities with WPPs of smaller facility capacities may not have sufficient budgets to install them. Even in such circumstances, it was suggested that there is room for improvement of process monitoring and control using water quality monitors at such smaller WPPs.

Installation percentages of the remaining 24 water quality monitors were <20% and their installation points were mainly raw water or water intake points. It was considered that most of the monitors were used for contamination monitoring of specific target items in source water. Oil release accidents are the most frequent types of water quality accidents (MHLW 2016). To detect oil contamination, oil and oil film monitors are applied. For musty odor substances and volatile organic compounds (VOCs), the monitors using purge and trap (or headspace) gas chromatography with mass spectrometry and with flame ionization detection have newly been developed, respectively. Musty odor compounds (i.e., 2-methylisoborneol and geosmin) are standard items in drinking water regulation in Japan (MHLW 2015). As for VOC monitors, it was reported that they could be used to monitor oil release accidents (Kita *et al.* 2016). In general, the types of the target compounds of water quality monitors are limited, and their detection/quantification limits are higher than those by water examination. However, in case of the water quality monitors using chromatography, it is possible to analyze many types of target compounds and achieve lower detection/quantification limits. Thus, water quality monitors using chromatography (e.g., liquid chromatography/gas chromatography and mass spectrometry) may become more common in the future.

Moreover, recently, water quality monitors of disinfection byproducts (trihalomethane and trichloramine) have also been developed. As for ozonation, dissolved ozone monitors were installed after ozonation at all 12 WPPs applying ozonation. Automatic control was used at seven out of the 12 WPPs. Bromate is a disinfection byproduct upon ozonation and a standard item in drinking water. It was found that feedback control of dissolved ozone levels using the monitors was one good option to control bromate formation during ozonation. For example, dissolved ozone levels were controlled at 0.25 mg/L (0.02 mg/L in some cases) to keep bromate levels at <5 μg/L (Nakamura *et al.* 2017).

Installation of water quality monitors in water purification plants employing chlorination only, slow sand filtration, and membrane treatment

The number of types of water quality monitors installed in WPPs employing chlorination only, SSF, and membrane treatment were eight, 13, and 17, respectively (Table 1). For monitors installed in WPPs employing membrane treatment, in addition to the 23 basic monitors listed in Table 1 were: ORP; silt density index (SDI), an index for fouling of membrane; and boron monitors. The percentages of WPPs employing chlorination only, SSF, and membrane treatment that installed water quality monitors were 98%, 100%, and 100%, respectively. Thus, it was shown that water quality monitors were used at almost all the WPPs investigated. Types of the monitors installed at high percentages were similar to those of RSF. That is, chlorine, high sensitivity turbidity, pH and turbidity monitors were (highly) recommended monitors, excluding high sensitivity turbidity for chlorination only.

Installation percentages of chlorine monitors among the four water purification processes are shown in Figure 3. Those of turbidity and pH monitors are shown in Figure S4 in the SM (available online). The number of installation points in WPPs employing chlorination only was mainly one and that employing SSF was one or two when installed. Installation points were mainly finished water, except for turbidity of SSF. Percentages of automatic control of chlorine monitors in finished water were 21% for chlorination only and 53% for

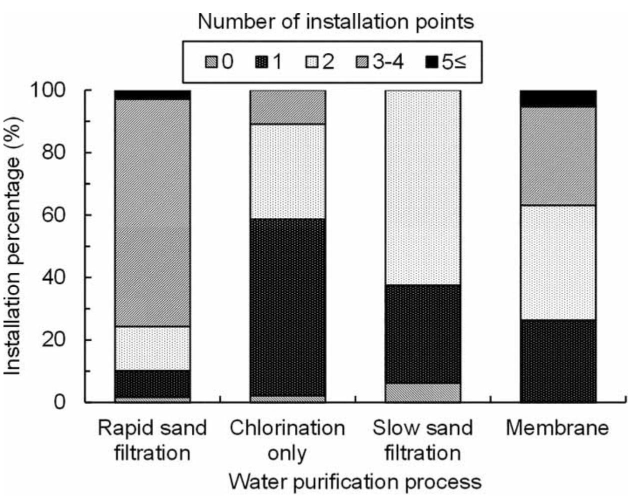

Figure 3 | Installation percentages of chlorine monitors among the four water purification processes.

SSF. Raw water quality of these processes is generally relatively stable and good. Thus, control of chlorine levels and monitoring of other items are most important in these processes.

On the other hand, the percentages of installation and the number of the monitors installed were higher for the RSF and membrane treatment processes (Figure 3 and Figure S4 in the SM). Regarding the process of RSF, raw water was mainly surface water and thus fluctuation in water quality was considered to be relatively higher. Therefore, it was considered that both continuous monitoring using water quality monitors and process control were needed. For the process of membrane treatment, recommended installation points were the raw water point for turbidity and pH monitors, membrane treatment point for high sensitivity turbidity monitors, and finished water point for chlorine and pH monitors. The percentages of the automatic control of the four monitors were high (Table S3 in the SM, available online) although the raw water comprised both surface water and groundwater. This suggests that water quality monitors play an important role in WPPs employing membrane treatment and this process may be applied for automatic control of situations to minimize human control.

Utilization of water quality monitors as surrogate parameters

Currently, the types of target items of water quality monitors are limited, although development of new monitors is in progress. Therefore, the data from water quality monitors are occasionally used as surrogates for other water quality parameters. Thirteen types of water quality monitors (i.e., ammonia, biological, chlorine, chlorine demand, color, electrical conductivity, high sensitivity turbidity, ORP, pH, SDI, turbidity, UV absorbance, and water temperature monitors) were used as surrogates for other water quality parameters. Among them, the major results of seven monitors at five installation points are shown in Table 2.

From the table, it is found that the monitors were used as surrogates in two aspects. One aspect is surrogates of specific parameters (e.g., levels of chlorine and chlorine demand were used as surrogates of ammonia). The other aspect is surrogates of comprehensive indices (e.g., biological monitors were used as a comprehensive index of toxic substances). The individual monitors are expensive, and thus the installation of many types of monitors is limited. It was considered that the usage of

Table 2 | The number of water purification plants utilizing water quality monitors as surrogate parameters

Water quality monitor	Water intake	Raw water	Sedimentation	Rapid sand filtration	Finished water
Biological	Toxic substances (8)	Toxic substances (9) Water pollution (2)	Toxic substances (1)	Toxic substances (1)	Toxic substances (4)
Chlorine	–	Ammonia (1)	Ammonia (1) Organic matter (1) Manganese (1) Chlorine demand (1) Odor (1)	Chlorine demand (1)	Ammonia (1) Nitrite (1)
Chlorine demand monitor	Ammonia (1)	Ammonia (6) Organic matter (1) Fish eggs (1)	–	–	–
Electrical conductivity	Toxic substances (1) Salts (3) Alkalinity (1)	Toxic substances (1) Salts (2) Alkalinity (1)	–	–	Alkalinity (1)
High sensitivity turbidity	–	–	–	*Cryptosporidium* (8) Alga (1)	*Cryptosporidium* (1)
pH	Alga (1) Turbidity (1) Toxic substances (1)	Alga (1) Turbidity (1) Aluminum (1)	Alga (1) Turbidity (1)	Alga (1)	
UV absorbance	Organic matter (2)	Organic matter (2) Chlorine demand (1)	Organic matter (2) Chlorine demand (1)	–	Organic matter (2)

Values in parentheses are the number of water purification plants utilizing the corresponding parameter; multiple respondents are included.

certain monitors for several objectives will become more important in the future. In addition, approaches to combine the data of several water quality monitors have been conducted (Oliker & Ostfeld 2015). Such approaches will also be more popular to extend data interpretation in the future.

This study was the first to investigate the utilization of water quality monitors at WPPs throughout Japan. It was shown that water quality monitors were closely related to monitoring and control measures of hazardous items presented in WSPs. Thus, it is expected that the insights obtained from this study will be used to enhance process control at WPPs.

CONCLUSIONS

(1) Water quality monitors were installed at most of the WPPs investigated. The number of types of monitors was 34. Chlorine, high sensitivity turbidity, pH, and turbidity monitors were (highly) recommended for installation in four water purification processes, except for high sensitivity turbidity of chlorination only.
(2) Regarding WPPs employing RSF, the number of the (highly) recommended installation points of chlorine, pH and turbidity monitors were three to four and they were used for process control. A recommended installation point of high sensitivity turbidity monitors was RSF for the confirmation of *Cryptosporidium* control.
(3) Recommended installation points of water quality monitors and their installation number were dependent upon the types of the water purification processes. Automatic control was also applied for some monitors; in particular, those chlorine monitors were applied, regardless of the water purification processes.
(4) Some water quality monitors were used as surrogates for comprehensive indices and/or specific water quality items.

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