Original Article

Questionnaire Survey on Installation of Online Water Quality Monitors and Data Utilization for Water Supply Systems in Japan

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ABSTRACT

In recent years, Japanese water utilities are facing pressing problems like staff shortage and climate-induced water quality deterioration. Utilization of online water quality monitoring data have received increasing attention to address these problems. A questionnaire survey was carried out for 32 water utilities to comprehend current situation of online water quality monitors (OWQMs), including installation of OWQMs and critical obstacles, water quality items monitored, utilization of water quality dataset, and future challenges. Turbidity, pH, and chlorine were mostly monitored using OWQMs from source to tap, for determining operating conditions of water purification process. Turbidity, pH, toxic substance, musty-odor substance, and residual chlorine were regarded as highly significant for both operational management and risk management. Initial/operational costs, measurement accuracy, and maintenance work volume were typical obstacles of OWQM installation. Nineteen out of the 32 water utilities have utilized water quality dataset obtained by OWQMs for predicting residual chlorine/bromate concentration, and for determining injection ratio of chemical coagulant and powdered activate carbon. Further OWQM installation and data utilization would be the key to strengthen the basis of water supply systems in Japan.

Keywords: online monitoring, data utilization, water quality, water supply

INTRODUCTION

While almost 100% water supply coverage has been achieved [1], Japanese water utilities are now facing pressing problems like technical staff shortage and climate-induced water quality issues including deterioration of raw water quality and increase in disinfection by-products in the course of water distribution networks [2]. To address these problems, installation of online water quality monitors (OWQMs) and utilization of the continuous water quality dataset has received increasing attention in recent years. Novel technologies have been developed and applied in the field of water supply system, such as continuous monitoring of water quality items using compact water quality sensors,

and early prediction of water quality using machine learning techniques.

Currently, more than 250 manufactures provide instruments for the automated measurement of over 100 water quality parameters in water and wastewater industries around the world [3]. Among these, typical water quality parameters applied to the online monitoring were pH, electrical conductivity (EC), oxidation reduction potential (ORP), dissolved oxygen (DO), turbidity, alkalinity, free and total chlorine, fluoride, ammonia, nitrate, ozone, particulate count, absorbance, and total organic carbon [3]. Advantages of introducing the OWQMs include time and cost reduction by replacing laboratory tests, utilization of the monitoring data for treatment process control, compliance with regula-

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Received: June 21, 2021, Accepted: December 13, 2021, Published online: February 10, 2022

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tions regarding national water quality standards, detection of faults and contaminations, and customer services. On the other hand, disadvantages of the OWQMs were lack of technical staff with experience in online monitoring, additional costs and labors for the operation and maintenance of monitoring instruments, inapplicability to remote areas, quality assurance/quality control of the water quality measurement data, and issues on water quality regulations that require laboratory testing [3].

Kosaka *et al.* conducted a nationwide questionnaire survey on the installation of OWQMs and utilization of their dataset among 331 small-/mid-scale Japanese water utilities in 2015. In total, thirty-four water quality items were obtained by the OWQMs at least one water utility. Chlorine, turbidity, and pH were critical water quality items for treatment process control, *i.e.*, rapid sand filtration, slow sand filtration, and membrane filtration processes [4]. They concluded that the installation of OWQMs and utilization of the dataset were significant for securing water quality management based on Water Safety Plan methodology, recommended by World Health Organization [5].

Several applications of OWQM dataset with machine learning techniques for water quality management have been reported worldwide. Zhang *et al.* successfully developed a hybrid statistic model combining artificial neural network with genetic algorithm for forecasting the overall performance of drinking water treatment plants in China [6]. Delpla *et al.* applied an artificial neural network model for the prediction of significant turbidity events in the main drinking water source of the city of Quebec, Canada, and was able to predict the mean levels of turbidity at the drinking water intake [7].

By utilizing these novel technologies for continuous water quality monitoring and prediction from the water sources to the water taps, more efficient and advanced water quality management would be achievable simultaneously, even with a limited number of technical staffs. For example, Takeuchi *et al.* applied an artificial neural network model with continuous water quality dataset for predicting residual chlorine decay during water distribution network at a small water supply system in Japan. They concluded that this approach could significantly reduce workload of daily water quality management by water utilities [8].

The present study aims to figure out current situation of OWQMs supporting water supply systems in Japan, including dominant water quality items and their significance in water quality management, obstacles in installation, utilization of the water quality dataset, and future challenges.

MATERIALS AND METHODS

A questionnaire survey was carried out from the beginning of November to the end of December 2020. Questionnaires were sent to 32 mid-/large-scale water utilities in Japan, selected to cover most regions and populations in Japan evenly. Small-scale water utilities were not included because OWQMs were sometimes not available at these utilities [2]. Total population served by the 32 water utilities accounted for approximately 43% of the total population served by municipal water supply services in Japan. Detailed information of each water utility, *i.e.*, number of water purification facilities per type water purification process and total design water supply capacities, was obtained from the latest “Statistics on Water Supply” [9] and provided as Supplementary Materials (**Table S1**). Range of the total design water supply capacities of the target water utilities was 42,499–8,846,697 [m³/day]. Assuming that all the water sources of the facilities with chlorine disinfection only were groundwater and that of other facilities were surface water, most water utilities obtained their source water from surface water. On the other hand, ratio of groundwater source for five middle-scale water utilities were in the range of 0.4 or above (**Table S1**).

The questionnaire survey consisted of following six categories: (1) water quality items currently monitored by OWQMs, instruments used, locations, frequency, significance to operation/risk management, and issues on operation and water quality management, (2) water quality items to be monitored by OWQMs in near future, expected outcomes, and challenges/obstacles in installation, (3) expectations for future technological development on OWQMs, *e.g.*, desirable water quality items to be continuously monitored, and functions that enable further labor-/cost-savings, (4) water quality dataset obtained by OWQMs currently utilized for daily operational/risk management, and also advanced water quality management, *e.g.*, prediction of raw/finished water quality items, (5) handling of the water quality dataset regarding access restriction to internal staffs, storage period, storage devices used, providing the dataset to external agencies, and (6) research and development needs on the future OWQMs.

Among these, water quality items currently (or to be) monitored using OWQMs, locations, significance to operation/risk management, and utilization for daily operational/risk management were multiple-choice questions and others were open ended-questions. The questionnaire form was made with Microsoft Excel spreadsheet and sent to/received from contact person of each water utility as an attached file. English translation of the questionnaire form is available

as Supplementary Materials (**Fig. S1**). The authors have received answers from all the target water utilities; thus, a response ratio was 100%.

RESULTS AND DISCUSSION

Water quality items obtained by OWQMs and their significance for operational management and risk management

As a result of the questionnaire survey, OWQMs were available at all the target 32 water utilities. Numbers of water quality items obtained by OWQMs by each water utility are shown in **Fig. 1**. Variety of the numbers was observed among the target 32 water utilities. Average numbers of the water quality items obtained at water source, water purification process, and water distribution network/faucet were 6.7, 4.8, and 4.3, respectively. **Table 1** shows thirteen dominant water quality items monitored by OWQMs and numbers of water utilities. Turbidity, pH, water temperature, electric conductivity, and alkalinity were mostly monitored at water sources or intakes of water purification plants. Other water quality items observed at water sources were cyanide, chromium, fluoride, phenol, total organic carbon (TOC), chemical oxygen demand (COD), volatile organic compound

(VOC), oxidation-reduction potential (ORP), ultraviolet absorption, and particle count. On the other hand, residual chlorine, turbidity, color, pH, water temperature, and electric conductivity were mostly observed by OWQMs in the course of water purification processes, water distribution networks, and faucets.

Significances of these thirteen water quality items for operational management and risk management were evaluated by respondents of the questionnaire survey by rating each item as highly significant: 3, moderately significant: 2, and less significant: 1. Average rating of the significance of water quality items were shown in **Table 2**. Water quality items significant for daily operational management that rated more than 2.5 on average were residual chlorine, turbidity, pH, musty-odor substance, chlorine demand, and toxic substance in descending order, and that for risk management were toxic substance, oil, turbidity, residual chlorine, musty-odor substance, and pH. Thus, five water quality items (turbidity, pH, toxic substance, musty-odor substance, and residual chlorine) were regarded as highly significant for both operational management as well as risk management for the water utilities. According to responses to an open-ended question, primary reasons for the significance of each water quality item were as follows:

Fig. 1 Numbers of water quality items obtained by online water quality monitors (OWQMs).

Table 1 Number of water utilities monitoring each water quality item using OWQMs.

Water quality item	Water source/ intake	Water purification process	Water distribution network/faucet
Turbidity	30	29	26
pH	30	28	22
Water temperature	27	13	17
Electric conductivity	24	7	13
Alkalinity	19	4	4
Oil	15	0	0
Toxic substance	13	2	0
Ammonia nitrogen	10	2	0
Dissolved oxygen	7	5	0
Chlorine demand	7	3	0
Musty-odor substance	7	2	3
Color	4	7	19
Residual chlorine	0	30	32

Table 2 Average rating of the significance of each water quality item. [highly significant: 3, moderately significant: 2, less significant: 1]

Water quality item	Operational management	Risk management
Turbidity	2.97	2.90
pH	2.87	2.52
Water temperature	2.20	1.54
Electric conductivity	2.27	2.15
Alkalinity	2.39	2.16
Oil	2.46	2.93
Toxic substance	2.55	3.00
Ammonia nitrogen	2.50	2.20
Dissolved oxygen	1.90	1.80
Chlorine demand	2.75	2.38
Musty-odor substance	2.86	2.57
Color	2.26	2.11
Residual chlorine	3.00	2.88

- Residual chlorine level in finished water is regulated by the Enforcement Regulation on the Waterworks Act [10] and shall be maintained above 0.1 mg/L at the end of water distribution network.
- Turbidity level in water after sand/membrane filtration shall be maintained below 0.1 degree by the Guidelines for Cryptosporidium and Giardia control in water supply [11], if the water source of the water purification plant contained fecal indicators, *i.e.*, *E. coli* and anaerobic spore-forming bacteria.
- pH monitoring is important to optimize chemical coagulation process.
- Concentrations of musty-odorous substances, *i.e.*, geosmin and 2-methylisoborneol (2-MIB), in water source are critical to determine injection ratio of powdered activated carbon at water intake or water receiving well.
- Monitoring of toxic substance in water source is crucial for risk management including decision on water intake interruption.

Future installation of OWQMs, expected outcomes, and obstacles

Future planning or vision of installing OWQMs regarding locations, target water quality items, and expected outcomes

are shown in **Table 3**. Several water utilities were considering the introduction of continuous measurement of residual chlorine concentration, turbidity, and color using OWQMs in water distribution networks and/or faucets to reduce the labor required for daily water quality testing required by the Enforcement Regulation on the Waterworks Act [10]. The OWQMs were also expected to ensure stable water quality management in water distribution network. Other water utilities were aiming to save labor and reduce reliance to human sense for odor substances by replacing the conventional organoleptic test to continuous instrumental analysis, and to predict residual chlorine concentration in the water distribution network with UV absorbance dataset.

Seven water utilities raised multiple obstacles in installing the OWQMs: (1) lack of financial support in initial/operational/maintenance costs [five responses], (2) increase in maintenance and inspection workload such as calibration of sensors [four responses], (3) low measurement accuracy [three responses], and (4) lack of space for installing the OWQMs and incidental equipment [one response].

Utilization of water quality dataset for advanced water quality management and data handling

Table 4 shows how the target water utilities were utilizing the water quality monitoring dataset obtained by OWQMs for their advanced water quality management. The most common way was to predict and control residual chlorine and/or bromate concentrations, and the second most was to help determine the injection ratio of powdered activated carbon and/or chemical coagulant. Nineteen water utilities have been already utilizing the water quality monitoring dataset for these advanced water quality management. Other thirteen utilities did not respond to this open-ended question, asking for any case examples of utilization of the water quality datasets for advanced water quality management (**Fig. S1**), and thus, their obstacles/challenges in this issue were not clear. Utilizing the water quality dataset would worth a lot for improving the efficiency of usual/emergent water quality management.

Most water utilities had an access control to the water quality dataset, by authorizing specific staffs and/or specific terminals, or by setting up a passcode. Most water utilities stored their data on HDDs or file servers, but some utilities used online storage devices or just paper media only. Storage

Table 3 Future planning or vision of installing OWQMs regarding location, target water quality item, and expected outcomes.

Location	Water quality item	Expected outcomes
Water source and intake	Alkalinity	Stable chemical coagulation control
	Ammonia nitrogen	Stable residual chlorine control
	Color	Labor-saving for water quality analysis
	Chlorine demand	Stable residual chlorine control
	Musty-odor substances	Rapid response to deterioration in source water quality
	Odor	Rapid response to deterioration in source water quality
	Oil	Rapid response to accidental source water pollution
	UV absorbance	Prediction of trihalomethane formation
Water purification Process	Disinfection by-products	Control of disinfection by-products
	Residual chlorine	Stable residual chlorine control
	UV absorbance	Labor-saving for water quality analysis, Prediction of residual chlorine level
Water distribution network and faucet	Color	Labor-saving for daily water quality analysis
	Residual chlorine	Labor-saving for daily water quality analysis Control of disinfection by-products
	Turbidity	Labor-saving for daily water quality analysis
	UV absorbance	Stable residual chlorine control
	Water pressure	Pipe network analysis
	Water temperature	Labor-saving for daily water quality analysis Prediction of residual chlorine

Table 4 Purpose of data utilization, number of water utilities, and water quality dataset applied.

Purpose of data utilization	# of water utilities	Water quality dataset obtained by OWQMs
Prediction and control of residual chlorine concentration	9	Residual chlorine, water temperature, organic matters
Early detection of water quality incidents	4	electric conductivity and other items
Determining injection ratio of powdered activated carbon	3	Musty-odor substances, water temperature, ammonia nitrogen
Determining injection ratio of chemical coagulant	2	TOC, pH, electric conductivity
Prediction and control of bromate formation by ozonation	1	Water temperature, pH, dissolved ozone
pH adjustment	1	pH
Prediction of musty-odor substances in source water	1	Turbidity
Prediction of trihalomethane formation during water distribution	1	Residual chlorine and other items

periods of the dataset were mostly five to ten years. A few respondents answered they set up their HDDs so that old data would be deleted when the HDD capacity became full, or that they did not set up a specific storage period.

Eleven water utilities responded they were able to provide their monitoring dataset to outside entities, *e.g.*, universities and private companies, for the purpose of advanced data utilization like machine learning for accurate water quality prediction and control. Other eleven utilities described the data provision to the outside entities was negotiable, six utilities prohibited, and four utilities did not respond. One of the key issues for further data utilization would be the permission for data sharing inside and outside water utilities.

Research and development needs on the utilization of the water quality dataset

Five water utilities responded that it would be desirable to monitor various odorous substances in water source and water purification process continuously so that they could determine appropriate injection ratio of powdered activated carbon as soon as possible. Due to the decrease in technical staffs in charge of water quality testing, there were several opinions that they would expect the development of affordable OWQMs that can cover their small-scale distribution networks and can replace daily water quality testing conducted manually by their technical staffs or residents at the end of each network. Another opinion was that they hope OWQMs that can cover all water quality standard items in Japan. Cost- and/or labor-saving of the automatic water quality monitoring were big issues for the OWQMs. Total of 18 responses from multiple water utilities underscored that further cost- and/or labor-saving should be realized for the

monitoring equipment [four responses], installation of the equipment [one response], monitoring on residual chlorine and other items [six responses], routine operation and maintenance [six responses], and also data communication [one response]. In this regard, future development of low-cost and maintenance-free OWQMs was desirable.

CONCLUSION

The present study elucidated the current situation and issues on water quality management using OWQMs and utilizing water quality dataset, based on responses to the questionnaire survey by 32 water utilities in Japan. Most water utilities have installed OWQMs for variety of water quality items in water source, water purification process, water distribution network, and faucet. Among the water quality items, turbidity, pH, toxic substance, musty-odor substance, and residual chlorine were recognized as highly significant for both operational management and risk management. OWQMs have been also utilized for daily water quality testing required by the Enforcement Regulation on the Waterworks Act.

Utilization of the water quality dataset should be further promoted for strengthen the water quality management. Nineteen out of the 32 water utilities have made progress in utilization of the dataset, *e.g.*, prediction of residual chlorine and disinfection by-products in water distribution network. Provision of the dataset to outside entities could be also considered for advanced data utilization like machine learning for prediction and control of water quality.

Challenges in installing OWQMs were their high initial and maintenance costs, complicated maintenance and man-

agement with additional workload, low measurement accuracy, and the lack of space for installation. In other words, water utilities' needs on OWQMs were implementation of low-cost, less-labor, secured measurement accuracy, and smaller size/footprint.

Further research and development on OWQMs as well as the utilization of the water quality dataset would be the key to strengthen the basis of water supply systems in Japan.

ACKNOWLEDGEMENTS

This study was financially supported by the Health Labour Sciences Research Grant (MHLW20LA1004). The authors appreciate all the water utilities responded to the questionnaire survey.

SUPPLEMENTARY MATERIALS

Supplementary Materials file for this article is available at the link below.

https://www.jstage.jst.go.jp/article/jwet/20/1/20_21-085/_supplement/_download/20_21-085_1.pdf

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