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Plant capacity affects some basic indices of treated water quality: multivariate statistical analysis of drinking water treatment plants in Japan

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ABSTRACT

The quality of treated water produced by a drinking water treatment plant (DWTP) is affected by many factors. Relative impacts of various factors that affect the following treated water quality indices—turbidity, color, aluminum concentration and aggregate organic constituents—were investigated. Multivariate statistical analysis based on Hayashi's Quantification Theory Type 1 was performed on a dataset comprised of statistics on raw and treated water quality collected from thousands of DWTPs throughout Japan. Explanatory factors were the source of the raw water, water treatment process employed, plant capacity, total plant capacity of the water supplier (TCWS), raw water quality and pH of treated water. The statistical analyses mainly revealed that not only did obvious factors such as raw water quality affect treated water quality, but also more obscure factors such as plant capacity and TCWS. The results also imply that the larger the water supplier a DWTP of a given size belongs to, the higher the quality of treated water will be.
Key words | aluminum, color, quantification theory, TOC, turbidity

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INTRODUCTION

The coverage of the water supply system in Japan has reached a high level, serving over 97% of its population (JWWA 2007*a*). Concurrently, drinking water treatment technologies have advanced. However, treated water quality fluctuates within a drinking water treatment plant (DWTP), and it also varies among DWTPs. Treated water quality may be affected by various factors such as raw water quality. The effects of raw water quality on the performance of drinking water treatment processes have been widely investigated: they include the effects of pH on coagulation process (Qin *et al.* 2006) and on floc formation and granular media filtration (Gregory & Carlson 2003). The effects of types and dose of coagulants as well as pH during coagulation on natural organic matter removal and residual aluminum were also investigated (Yan *et al.* 2008). There may be, however, other factors that affect treated water quality. Trained DWTP operators comprehend the characteristics of raw water as well as the treatment system of their own DWTP, and can appropriately operate the system and control treated water quality despite fluctuations in raw water quality. It may be difficult, however, for them to predict the effects on the treated water quality of changing the raw water source or the application of a new treatment process. That is to say, treated water quality is probably affected not only by explicit factors that can be studied relatively easily by plant operators, such as raw water quality, but also by implicit factors that are invisible to plant operators, including treatment processes and raw water sources. The effects of these factors remain uncertain unless performance is compared among DWTPs.

The size of a DWTP and the scale of a water supplier may also be factors that affect treated water quality.

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WHO (2004) pointed out in its drinking water quality guidelines for aluminum: “Small facilities (e.g., those serving fewer than 10,000 people) might experience some difficulties in attaining this level (0.1 mg/L aluminum), because the small size of the plant provides little buffering for fluctuation in operation; moreover, such facilities often have little resources and limited access to the expertise needed to solve specific operational problems”. It has also been pointed out that the lack of appropriately trained operators and the low numbers of personnel in small-scale operations may lead to insufficient management of water quality and finance (NRC 1997; Ogasawara 2008).

In the present study, we aimed to elucidate and discuss what factors affect treated water quality, and by how much. Multivariate statistical analysis was conducted with the data from *Statistics on Water Supply* (*Suidou Toukei* in Japanese), the annually published report containing data on treated water in Japan. The report contains data on both raw and treated water quality of DWTPs nationwide, as well as their facility data, such as plant capacity and treatment process employed.

Multiple regression analysis is the most commonly applied method of multivariate statistical analysis. Standard multiple regression analysis requires the use of quantitative data. However, factors that affect treated water quality are not always quantitative; qualitative factors such as the water treatment process employed may also have an impact. Therefore, Hayashi's Quantification Theory (Hayashi 1950, 1952) was employed as the multivariate statistical analysis method. Employing this theory, the effects of qualitative explanatory items can be quantified. Furthermore, this theory does not require a linear relationship between explanatory and response variables by categorizing the explanatory variables. For example, pH does not linearly affect the performance of coagulation; near-neutral pH is more preferable than extremely acidic or basic pH in the case of general drinking water treatment. Therefore, by categorizing the quantitative variables that are not normally distributed, like pH, the theory can quantify the effects of such quantitative variables.

Five indices on treated water quality; turbidity, color, potassium permanganate ($KMnO_4$) consumption, total organic carbon (TOC) and aluminum concentration were treated as the response variables. These variables were selected because we focused on the solid–liquid separation performance of DWTPs in this study. Turbidity and color are the basic indicators of the performance. Aluminum is used as a coagulant in almost all DWTPs in Japan, and control of residual aluminum in treated water is crucial because high residual aluminum in treated water indicates inadequate coagulation. $KMnO_4$ consumption is an indicator of aggregate organic constituents in drinking water, with a measurement method similar to that of chemical oxygen demand using $KMnO_4$ as the oxidizing agent (JWWA 2001); $KMnO_4$ consumption was a drinking water quality standard unique to Japan until its replacement by TOC in the current standard, which took effect in fiscal year (FY) 2004. Therefore, multiple regression analysis on TOC with the data of FY 2004 and 2005 was also performed. We investigated which of the explanatory items may affect the five treated water quality indices.

METHODS

Statistical data source

Statistics on Water Supply of FY 2001–2005 (JWWA 2003, 2004, 2005, 2006, 2007*b*) were used. The statistics include data on the quality and quantity of both raw and treated water from thousands of DWTPs in Japan. Treated water quality of the indices applied in this study was measured at a treated water reservoir or a distribution reservoir at each DWTP. There are many DWTPs where only chlorination is performed as a drinking water treatment process. These DWTPs are generally very small and located in rural areas, but they are large in number. The data from these DWTPs were excluded because our focus was the performance of solid–liquid separation processes. The data of FY 2001–2005 were compiled into a single dataset; each single-year dataset was also analyzed separately.

Multivariate statistical analysis

Hayashi's Quantification Theory Type 1 (HQTT1; Hayashi 1952) was applied as the method of multivariate analysis. This method is equivalent to multiple regression analysis using dummy (0/1) variables. Both qualitative and quantitative explanatory items were categorized as shown in Table 1. Explanatory items were the source of the raw water, water treatment process, plant capacity (DWTP size), total plant capacity of the water supplier (TCWS), raw water quality defined in terms of the response variables (except aluminum) and pH of treated water. Water treatment process is actually an aggregate item; each treatment process shown in Table 1 is regarded as an independent explanatory item. We assigned dummy variables, which consisted of negative (0) or positive (1) responses, for every subcategory; the subcategories were treated as explanatory variables (x). The response variables (y) were quantitative treated water quality indices and included turbidity (Japanese Turbidity Unit; JTU), color (Japanese Color Unit; JCU), $KMnO_4$ consumption (mg $KMnO_4$/L), TOC (mg C/L) and aluminum concentration (mg/L). The unit of JTU is similar to Nephelometric

Table 1 | Response variables (y), explanatory items and subcategories as explanatory variables (x)

Response variables (y)	Explanatory items		Subcategories (x) and their descriptions
Turbidity (Japanese turbidity unit; JTU)	Source of raw water		Surface water*
			Lake water†
Color (Japanese color unit; JCU)			Groundwater‡
	Drinking water treatment process	Granular activated carbon§	Employed (1)
$KMnO_4$ consumption (mg $KMnO_4$/L)			Not employed (0)
		Powdered activated carbon	1/0
TOC (mg C/L)		Ozonation	1/0
Aluminum (mg/L)		Biological treatment	1/0
		Membrane filtration	1/0
		Slow filtration	1/0
		Rapid filtration	1/0
	Plant capacity (m^3/d) (DWTP size)		<500
			500–1,000
			1,000–2,000
			2,000–5,000
			5,000–10,000
			10,000–20,000
			20,000–50,000
			$>50,000$
	Total plant capacity of the water supplier (TCWS) (m^3/d)		$<1,000$
			1,000–2,000
			2,000–5,000
			5,000–10,000
			10,000–50,000
			50,000–100,000
			$>100,000$
	Raw water quality		Depends‖
	pH of treated water		<6.75
			6.75–7.00
			7.00–7.25
			7.25–7.50
			7.50–7.75
			>7.75

*Includes water discharged from dams and lakes.
†Includes water collected directly from dams.
‡Includes riverbed water.
§Includes biological activated carbon filtration.
‖Range and division of the subcategories of the raw water quality item depend on the response variable. This item was not employed for aluminum because only a small number of DWTPs reported aluminum concentration in raw water.

Table 2 | Basic statistics and Japanese drinking water quality standard values for the response variables

Response variable	Measurement unit	Years of the dataset (FY)	Number of cases (*N*)	Treated water quality: Mean	Treated water quality: Standard deviation	Standard value until FY 2004	Standard value after FY 2004*
Turbidity	JTU	2001–2005	11,918	0.09	0.12	2	2
Color	JCU	2001–2005	11,987	0.61	0.56	5	5
$KMnO_4$ consumption	mg $KMnO_4$/L	2001–2004	10,782	1.26	0.78	10	–
TOC	mg C/L	2004–2005	2,376	0.61	0.39	–	5
Aluminum	mg/L	2001–2005	7,389	0.03	0.04	0.2†	0.2

*The Japanese drinking water quality standard was revised for FY 2004.
†It was not a legally binding standard value, but a complementary guideline value.

Turbidity Units (NTU), but the standard substance is not formazin but mixed polystyrene particles. Regarding the unit of JCU, 1 JCU corresponds to the color of a standard solution that contains 1 mg/L of platinum and 0.5 mg/L of cobalt. The annual mean value of each treated water quality index was input as the response variable for each DWTP. There are cases where the annual mean value of a certain water quality index in a DWTP was lower than the quantification limit. In these cases, we substituted the 50% value of the quantification limit.

Basic statistics and Japanese drinking water quality standard values for these indices are summarized in Table 2. The number of cases (*N*) of TOC and aluminum are smaller than those of other water quality indices. This is because they were newly incorporated into the drinking water quality standard in FY 2004; measurement and reporting of TOC and aluminum has become obligatory since then. Standard deviation is similar to or higher than the mean value for some water quality indices, which implies the distribution shape of the data is not a normal distribution and is skewed because the values of these water quality indices cannot be lower than zero.

The multiple regression models for predicting the response variables can be described as follows:

$$\hat{Y} = C + \sum_i \sum_j b_{i,j} X_{i,j} \quad (1)$$

where $\hat{Y}$ is a predicted value of a response variable, C is a constant, $b_{i,j}$ is a partial regression coefficient and $X_{i,j}$ is a categorized dummy (0/1) variable for the *i*th item in the *j*th subcategory. The kinds of explanatory items and their subcategories are described in Table 1. In this study, there are five water quality indices treated as response variables, and five independent regression models are used.

In HQTT1, the sum of dummy variables in each explanatory item must be 1. In this case, variables within an explanatory item contain redundant information. For example, when an item has k subcategories and the

Table 3 | Ranges of partial regression coefficients for each explanatory item

Explanatory items	Response variables/partial regression coefficients: Turbidity (JTU)	Color (JCU)	$KMnO_4$ consumption (mg $KMnO_4$/L)	TOC (mg C/L)	Aluminum (mg/L)
Source of raw water	0.010	0.152	0.175	0.104	0.003
Water treatment process*	0.045	0.434	0.404	0.076	0.025
Plant capacity (DWTP size)	0.040	0.224	0.196	0.097	0.008
Total plant capacity of the water supplier (TCWS)	0.044	0.194	0.236	0.126	0.014
Raw water quality	0.051	0.681	1.822	0.753	–
pH of treated water	0.043	0.295	0.083	0.077	0.020

*The water treatment process item is not a single item but an aggregated one, and thus the magnitude of the range should not be directly compared with other explanatory items.

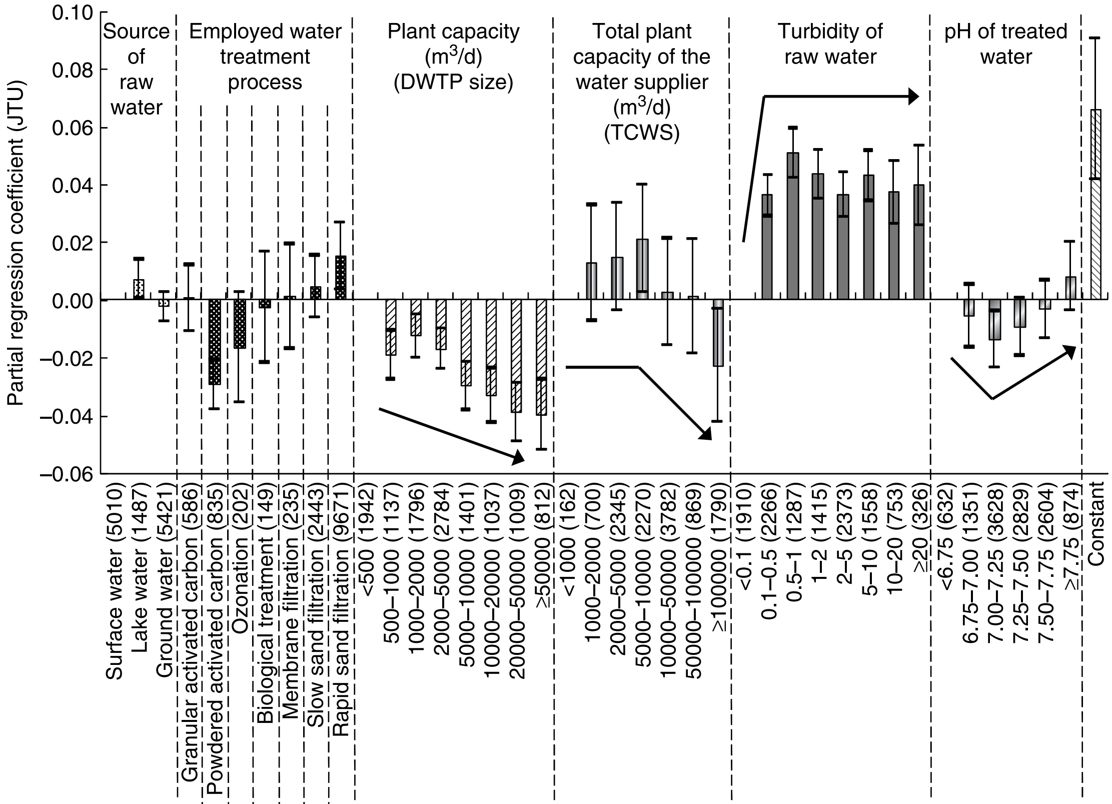

Figure 1 | Partial regression coefficients for the turbidity of treated water. Vertical line segments with attached bars indicate 95% confidence intervals. Subcategories where no bar is shown indicate the arbitrarily selected standard (zero value) for each explanatory item. Values in parentheses give the number of DWTPs belonging to each subcategory. Arrows indicate the tendency with increase of the explanatory variables. An arrow pointing obliquely upward, for example, indicates that turbidity increases with increase of the explanatory variable. If an arrowed line is horizontal, there is no significant change of turbidity with increase of the explanatory variable. The tendency changes where the slope of an arrowed line changes. Detailed description of the tendency is given in the text.

value 0 is assigned to $k - 1$ subcategories, the value 1 is consequently assigned to the remaining subcategory. To avoid this kind of redundancy, one subcategory in each item should be deleted. The deleted subcategory can be arbitrarily determined, and we principally deleted the first subcategory. The deleted subcategory becomes the standard for partial regression coefficients in that item, meaning that the partial regression coefficient of the deleted subcategory becomes 0. Thus, the other subcategories within the same item can be compared by the magnitude of each partial regression coefficient. For the items describing treatment processes, we assigned the dummy variables as employed (1) and not employed (0); that is, each treatment process was treated as an independent explanatory item.

The SPSS 14.0J (SPSS Japan Inc., Tokyo, Japan) software package was used for statistical analysis. We did not observe any multicollinearity problems in the regression analysis. The highest absolute value of correlation coefficient between two independent explanatory variables was 0.65, the correlation between plant capacity and TCWS. This correlation was not high enough to cause multicollinearity.

RESULTS AND DISCUSSION

The determination coefficients (R^2) for the multiple regression analyses of each response variable were 0.066 (turbidity), 0.13 (color), 0.38 ($KMnO_4$ consumption), 0.40 (TOC) and 0.069 (aluminum). The coefficients are not high, except for $KMnO_4$ consumption and TOC; therefore, the regression model is unlikely to be appropriate for

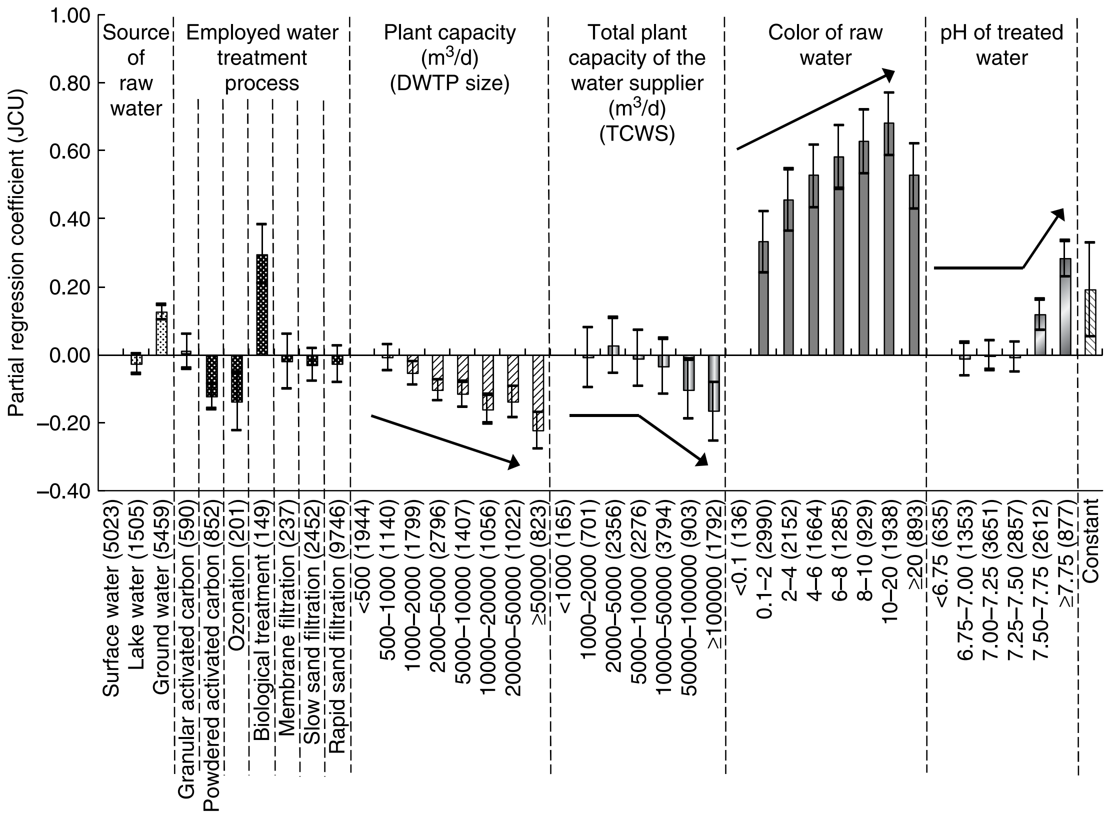

Figure 2 | Partial regression coefficients for color of treated water.

the quantitative prediction of treated water quality. Instead, we can clarify the dominant factors affecting the treated water quality by comparing partial regression coefficients. To compare the magnitude of the effect on treated water quality among explanatory items, we obtained the range of partial regression coefficients of each explanatory item by calculating the difference between the maximum and the minimum values within the same explanatory item (Table 3).

In general, the following tendencies were observed by comparing the magnitude of the ranges among explanatory items within the same response variable (water quality index). Raw water quality had quite a large effect on all of the treated water quality indices, except for aluminum, which was not included in the dataset in this study. Plant capacity and TCWS had a moderate impact on all the indices. The pH of treated water had a large impact on aluminum and also a moderate impact on turbidity and color. Each treated water quality index is, however, likely to have specific characteristics. Hereafter, we discuss the results for each water quality index individually.

Turbidity

Turbidity in raw water had the largest impact on the turbidity of treated water (Figure 1, Table 3). However, these variables did not exhibit any quasi-linear relationship; lower turbidity was observed only when the raw water turbidity was less than 0.1 JTU. TCWS had the second largest impact. The plant capacity also appeared to be quite influential; the larger the plant capacity, the lower the treated water turbidity a DWTP achieved, especially when the plant capacity was larger than 1,000 m^3/d. TCWS does not appear to have a quasi-linear relationship to turbidity, but when we divide the subcategories of TCWS into two parts, $> 10{,}000$ and $< 10{,}000\,m^3$/d, it is obvious that larger DWTPs achieve lower turbidity in treated water. As mentioned above, multicollinearity was not observed in the analyses; therefore, it can be said that, among DWTPs of equal capacity, the larger the water supplier a DWTP belongs to, the better the treated water quality that is obtained, especially in the case TCWS $> 10{,}000\,m^3$/d.

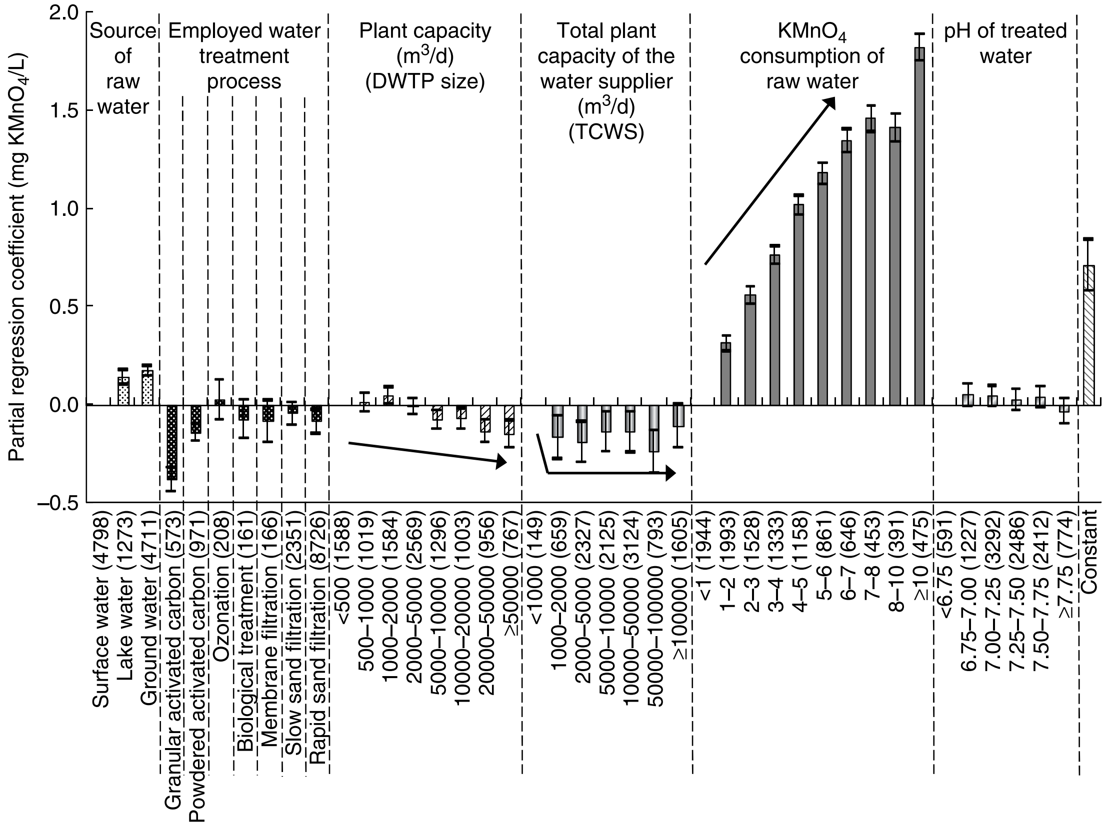

Figure 3 | Partial regression coefficients for $KMnO_4$ consumption of treated water.

Both plant capacity and TCWS had a range of partial regression coefficients of about 0.04 (Table 3); that is, turbidity may differ by up to 0.04 JTU depending on the capacity of the DWTP and that of the water supplier. This may be a large dependence, considering that the mean treated water turbidity is 0.09 JTU (Table 2).

Having treated water at a pH of about 7 can lower the turbidity; turbidity is higher at both lower and higher pH levels. Coagulation of clay particles by use of aluminum coagulant is best performed at a pH of approximately 7 (Tambo 1980). Therefore, a pH of about 7 was the most appropriate for removing turbidity, although the removal ability also depends on other factors such as organic substances in raw water. The statistical result on the effect of pH is consistent with the coagulation theory.

Among water treatment processes, powdered activated carbon (PAC) was the best for lowering treated water turbidity. Because the partial regression coefficient of PAC is approximately − 0.03, a turbidity decrease of 0.03 JTU is expected when PAC is employed. On the other hand, granular activated carbon (GAC) was found to be ineffective for lowering turbidity. Rapid sand filtration appears to cause increased turbidity in treated water, but the actual correlation lies between relatively high raw water turbidity and the choice of rapid sand filtration as a treatment technique. That is to say, when the water source is high in turbidity, rapid sand filtration is more likely to be chosen as the water treatment process, compared to slow sand filtration.

Color

Color in raw water had the greatest impact on the color of treated water (Figure 2, Table 3). A quasi-linear relationship between the color of raw and treated water was observed, unlike in the case of turbidity. The lower the color of the raw

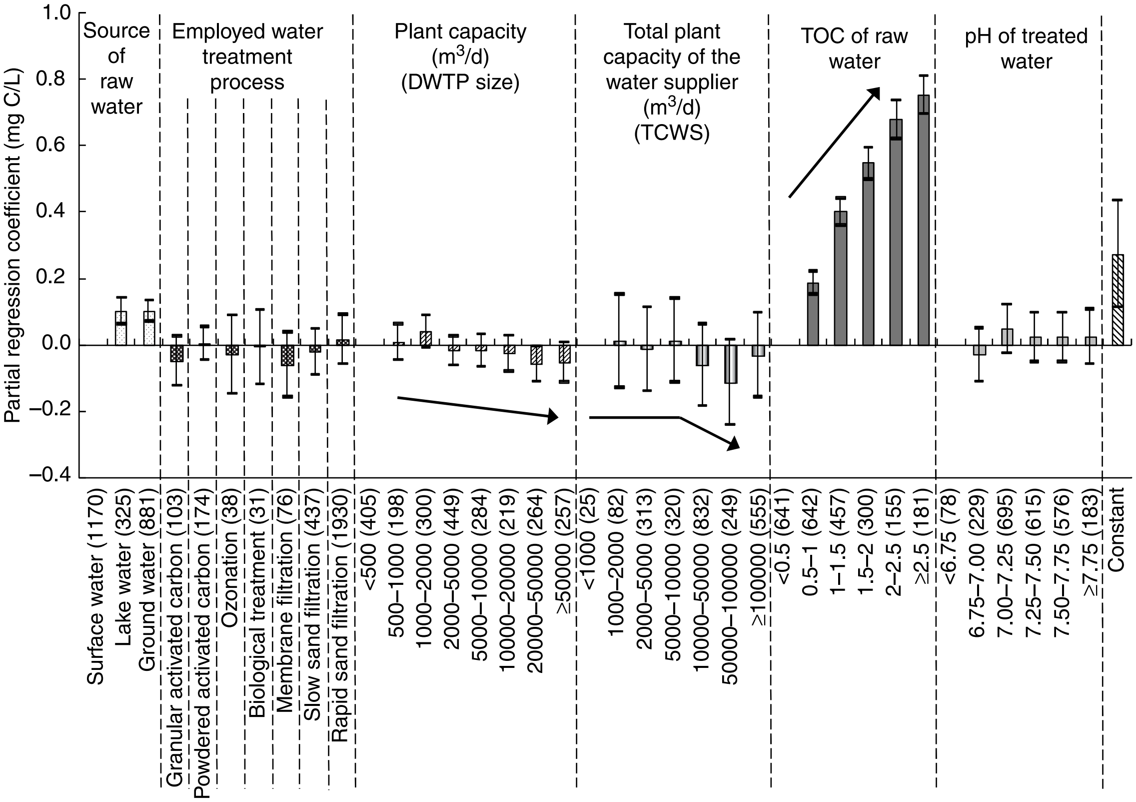

Figure 4 | Partial regression coefficients for TOC of treated water.

water, the lower that of the treated water, except when the color of the raw water was above 20 JCU. The color of the treated water was still much affected by the quality of the raw water despite advances in water treatment processes.

PAC and ozonation processes lowered color by about 0.1 JCU, whereas biological treatment was associated with increased color of about 0.3 JCU. One possible explanation for this increase is that the color of raw water is relatively high at DWTPs that use biological treatment processes because they are regarded as successful in removing organic matter but not in removing color. Another possible explanation is that organic substances produced by bacteria interfere with coagulation. This effect is further discussed in the section discussing aluminum.

GAC appeared to be ineffective in reducing color although PAC was effective. It may be due to the combined effects of the GAC process. Basically, GAC is an adsorption process. However, biological activity may also occur in GAC filters with time. It is because many microorganisms in water are attracted to particle surfaces, and they are also attracted to GAC particles (MWH 2005). As mentioned above, the adsorption process such as PAC could reduce the color, but a biological process increased the color. Since the GAC process is a mixture of an adsorption and biological process, a clear tendency could not be observed.

Similar to the case with turbidity, lower color is achieved as plant capacity increases and also as TCWS increases. This relationship between the color and the TCWS means that, even if a DWTP is small, lower treated water color can be achieved in the case that the DWTP belongs to a large water supplier.

Treated water color increased when the pH was higher than 7.5. According to coagulation theory, colored substances have a high negative charge on their surfaces and can be best removed in a pH range of 5–6 because positively charged aluminum ions predominate at a pH of about 5 (Binnie et al. 2002). This pH value is relatively low compared to the optimal pH for the removal of turbidity. Our result by statistical analysis of real DWTPs corresponds to the coagulation theory.

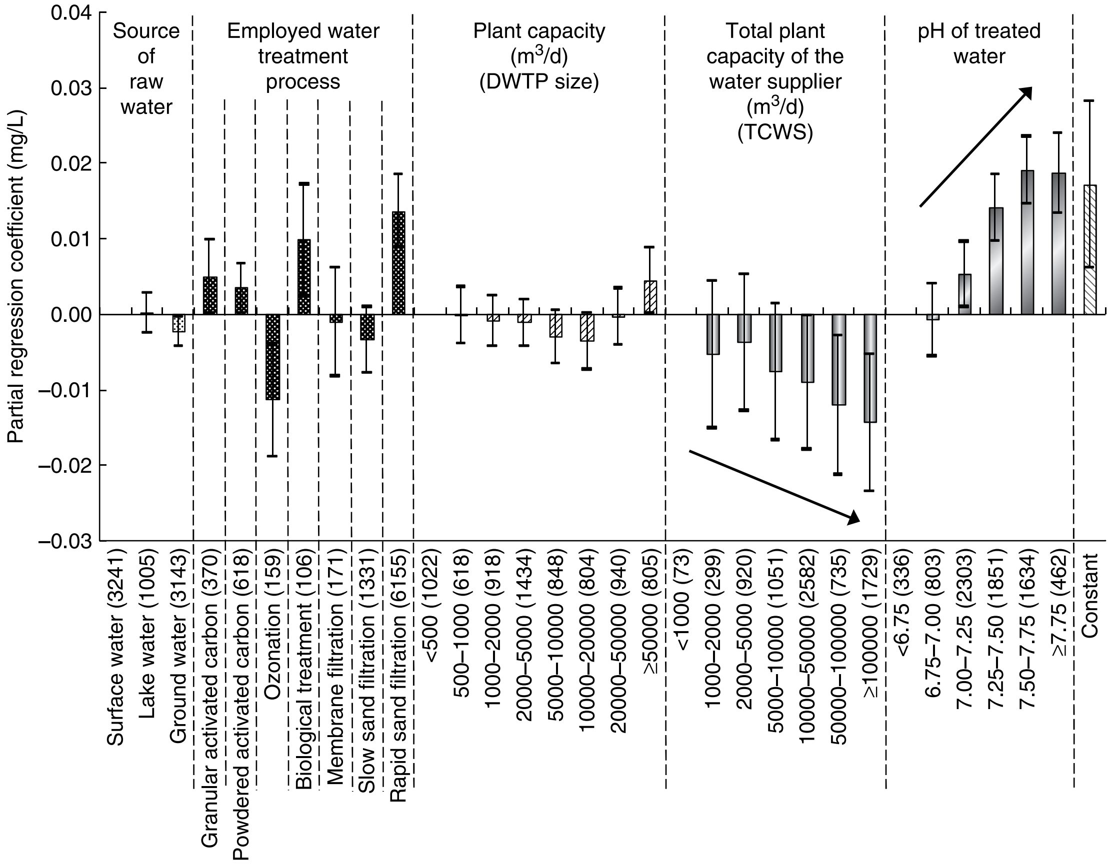

Figure 5 | Partial regression coefficients for aluminum of treated water.

$KMnO_4$ consumption

As was the case with turbidity and color, $KMnO_4$ consumption of raw water had the greatest impact on that of treated water (Figure 3). In the case of $KMnO_4$ consumption, the raw water quality had a much larger range of partial regression coefficients than other explanatory items (Table 3). A quasi-linear relationship is observed between $KMnO_4$ consumption in raw and in treated water. From these results and the relatively high R^2 value (0.38) mentioned previously, $KMnO_4$ consumption of treated water can be said to be determined, to a considerable degree, by the raw water quality. Although the values of other partial regression coefficients are small, larger DWTPs had lower $KMnO_4$ consumption. In addition, GAC and PAC processes reduce the $KMnO_4$ consumption. However, the partial regression coefficients of GAC and PAC are quite small compared to that of raw water $KMnO_4$ consumption, implying that the use of GAC and PAC for the reduction of $KMnO_4$ consumption is not very effective. TCWS higher than 1,000 m^3/d may slightly reduce the $KMnO_4$ consumption; pH was found to have no relationship with $KMnO_4$ consumption.

TOC

Almost the same tendency was observed for treated water TOC as was observed for $KMnO_4$ consumption (Figure 4, Table 3). Treated water TOC is affected almost only by raw water TOC. The larger the DWTP and TCWS are, the lower the treated water TOC tends to be; these trends are similar to but smaller than those observed for $KMnO_4$ consumption. Unlike the case for $KMnO_4$ consumption, GAC and PAC appear to have little impact on treated water TOC. This suggests that there is organic matter that can be indicated by TOC but not by $KMnO_4$ consumption. However, there is a possibility that a small number of

Table 4 | Summary of the results*

		Drinking water treatment process								Total plant capacity of the water supplier		
Response variables	**Source of raw water**	**GAC**	**PAC**	**Ozonation**	**Biological treatment**	**Membrane filtration**	**Slow filtration**	**Rapid filtration**	**Plant capacity (DWTP size)**	**(TCWS)**	**Raw water quality**	**pH of treated water**
Turbidity (Figure 1)	Slightly higher turbidity with lake water		↘					↗	↘	→↘	Lower only when raw water turbidity < 0.1 ↗→	pH ≈ 7 is optimal ↘↗
Color (Figure 2)	Higher color with groundwater		↘	↘	↗				↘	→↘	↗	Increases when pH > 7.5 →↗
$KMnO_4$ consumption (Figure 3)	Lower $KMnO_4$ with surface water	↘	↘						Small impact ↘	Lower when TCWS > 1,000 (m^3/d) ↓→	Large impact ↗	
TOC (Figure 4)	Lower TOC with surface water								Small impact ↘	→↘	Large impact ↗	
Aluminum (Figure 5)	Slightly lower aluminum with groundwater			↘	↗			↗		↘	Insufficient data	Large impact ↗

*Direction of arrows correspond to the Figures 1–5. An arrow pointing upward, for example, means the value of the treated water quality index increases, i.e. the quality deteriorates, as the value of the explanatory item is higher or when the drinking water treatment process is employed. Blank sections indicate negligible impacts on treated water quality.

cases in the dataset ($N = 2,376$; Table 2) compared to other water quality indices may cause the statistically insignificant impact of GAC and PAC. Further data accumulation is necessary to clarify this effect.

Aluminum

The aluminum concentration in treated water was mainly influenced by treated water pH, TCWS, rapid sand filtration, ozonation and biological treatment (Figure 5). Higher treated water pH corresponded to higher aluminum concentration in treated water. This result agrees with solubility data for aluminum; aluminum has minimum solubility at about pH 6.2 at 25°C (MWH 2005). TCWS had a quasi-linear relationship with treated water aluminum, which suggests that aluminum was better controlled by larger water suppliers.

The ozonation treatment process seemed to decrease aluminum concentration although the results of statistical analysis using the single-year datasets were not stable. Ozonation was effective in the datasets of FY 2002 and 2003, but not in those of FY 2001, 2004 and 2005 (data not shown). Biological treatment and rapid sand filtration increased aluminum concentration in treated water. Biological treatment is an advanced drinking water treatment process; the aerobic treatment especially removes ammonium nitrogen, musty odor and algae (JWWA 2000). There are two plausible explanations for the undesired influence of biological treatment on the residual aluminum. One is that the raw water of DWTPs applying biological treatment may contain a lot of dissolved organic matter that binds easily to aluminum and keeps it in a soluble form. Another explanation is that the biological treatment itself may release such dissolved organic matter into the water. It is known that algogenic organic matter (AOM), especially extracellular organic matter (EOM), forms complexes with coagulant species and disturbs flocculation (Bernhardt *et al.* 1985). Intracellular organic matter (IOM) and EOM reduce coagulation efficiency (Takaara *et al.* 2007). Furthermore, some of the proteins isolated from IOM and EOM have a high affinity with aluminum hydrate, meaning that these proteins are able to form complex compounds with aluminum (Takaara *et al.* 2005; Pivokonsky *et al.* 2006). Therefore, this AOM may chelate aluminum coagulants, which then remain in treated water as dissolved residual aluminum. For the same reason that AOM interferes with coagulation, the biological treatment might increase the color of treated water as discussed above.

CONCLUSION

The results of our statistical analyses are summarized in Table 4. The following results were obtained:

1. The larger the plant capacity is, the better the treated water quality is in terms of turbidity, color, $KMnO_4$ consumption and TOC.
2. The larger the water supplier is, the better the treated water quality is in terms of turbidity, color, $KMnO_4$ consumption and aluminum concentration.
3. Raw water quality has the greatest impact on all treated water quality indices except aluminum. This result implies that treated water quality still depends on raw water quality despite advances in water treatment technology.
4. Treated water pH has the greatest impact on aluminum and some impact on turbidity and color. Treated water with $pH > 7$ gives more residual aluminum, $pH \approx 7$ gives the lowest turbidity and $pH > 7.5$ increases color.
5. The PAC water treatment process is very effective in reducing turbidity and color. Both PAC and GAC are effective in reducing $KMnO_4$ consumption, but they do not affect TOC. Treated water color and aluminum are higher in DWTPs with biological treatment as compared to DWTPs in which biological treatment is not employed.

Some of these results are in accordance with practical and theoretical understanding. On the other hand, some inherent factors, which cannot be revealed through individual DWTP experiences, also affect treated water quality. These factors include plant capacity and TCWS. The results imply that the larger the water supplier a DWTP of a given size belongs to, the higher the quality of treated water will be. Therefore, we suggest that it is a good strategy for small DWTPs to garner the cooperation of large water suppliers, especially regarding water treatment expertise and experience, to improve treated water quality.

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