

Effect of advanced water treatment on behaviour of residual chlorine and development of chlorine control method in distribution systems

T. Fuchigami, M. Takeda and K. Terashima

ABSTRACT

The behaviour of residual chlorine concentration in drinking water treated by the mid-chlorination or the advanced water treatment (AWT) was investigated. The AWT removes dissolved organic matter more than the mid-chlorination, thus the rate of residual chlorine reduction is decreased. The analysis of chlorine concentration data measured by automated continuous monitoring devices revealed that the introduction of AWT reduced the maximum and mean chlorine concentration by 0.33 mg L^{-1} and 0.21 mg L^{-1} compared to the mid-chlorination respectively, while the minimum concentration was maintained at around 0.3 mg L^{-1} in the whole city. The overall chlorine reduction rate coefficient in the AWT was reduced to approximately half of that in the mid-chlorination. Volatilization of chlorine from a water surface could be expressed by the zero-order rate of reaction from laboratory experiments. The rate of volatilization increases with increasing water temperature and shallower water depth. The residual chlorine prediction models were developed based on the results of data monitoring and laboratory experiments. The accuracy of simulated values is good and almost all of the predicted concentrations are in the range of $\pm 0.1 \text{ mg L}^{-1}$ of measured concentrations. The models are very effective to control residual chlorine concentration at predetermined target value.

Key words | advanced water treatment, distribution system, reduction rate coefficient, residual chlorine, simulation

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INTRODUCTION

In Japan, the article 22 of the water works law describes sanitary measures of drinking water. Based on the article, the ordinance for enforcement of the water works law defines as “All water works authorities shall disinfect water by chlorine so that tap water shall contain 0.1 mg L^{-1} free residual chlorine or more”. The Guidelines for Drinking-Water Quality published by World Health Organization describes that prevention of waterborne diseases is one of the most important purposes of the water quality control (WHO 2004). It mentions that enough disinfectant should be kept in a water distribution network. Propato and Uber reported that the product of residual chlorine concentration and residence time is crucial for the control of infectious

disease outbreaks (Propato & Uber 2004). On the other hand, the off-flavour caused by chlorination is one of the reasons of consumers' complaints (Mackey *et al.* 2004). Off-flavour substances are produced by chemical reactions between dissolved matters and chlorine (Kajino *et al.* 1999; Freuze *et al.* 2005). Therefore, it is desired by consumers for being supplied comfort tap water to eliminate off-flavour precursors by treating water and to maintain the minimum but necessary amount of chlorine concentration for micro-organism disinfection.

Residual chlorine concentration in distribution networks decreases due to reactions of chlorine and organics in water, inner wall of water supply pipes, etc

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(Vasconcelos *et al.* 1996; Clark & Grayman 1998; Ki  n   *et al.* 1998). Thus, the accurate prediction of the chlorine concentration decrease in distribution networks is essential to set an adequate target value of chlorine concentration at water purification plants, so that chlorine concentration at taps can be controlled properly.

Osaka Municipal Waterworks Bureau (OMWB) switched its water treatment process from the mid-chlorination water treatment (MCWT) process to the latest advanced water treatment (AWT) process from 1998 through 2000. Automated continuous monitoring devices (telemeters: TMs) have been measuring free chlorine concentrations in the water supply area, and the data collected by TMs before and after the introduction of AWT were analysed. The analysis result shows that the behaviour of residual chlorine in the distribution system obviously changed when the water treatment method was changed.

This paper reports the behaviour of residual free chlorine in the supply network, especially on the effects of the AWT process introduction and the change in free chlorine concentration reduction rate. The residual chlorine simulation system has been developed based on the chlorine behaviour research mentioned above and the results of laboratory experiments. This paper also reports its details.

WATER PURIFICATION PROCESS AND AUTOMATED WATER QUALITY REMOTE MONITORING SYSTEM OF OSAKA CITY

Osaka city, which has an area of about 222 km² and about 2.6 million population, is located close to the centre of Japan. OMWB has three purification plants, Kunijima (capacity: 1.18 million m³ day⁻¹), Niwakubo (capacity: 0.80 million m³ day⁻¹) and Toyono (capacity: 0.45 million m³ day⁻¹). The quality of raw water from the

Yodo River was good until about the 1950s, but it has worsened since then. So with a view to improving the comprehensive quality of tap water, especially for eliminating musty odour and reducing trihalomethane, OMWB has changed the water purification method to the AWT with a two-stage process of ozonation and granular activated carbon (GAC) treatment. The conventional MCWT and AWT processes are shown in Figure 1. Mid-chlorine was injected before rapid sand filtration in the MCWT; it removed manganese by contact oxidation. Instead of mid-chlorine, ozone is injected before filtration to oxidise inorganic and organic substances in the AWT. GAC is also effective to remove dissolved organics by physical adsorption and biological activity. Therefore, the AWT decreases not only trihalomethane concentration but also all kinds of organic substances. Musty odour substances are removed by post-ozonation and GAC completely. Sodium hypochlorite solution is injected at the final process as disinfectant.

OMWB has the automated water quality remote monitoring system in order to continuously check the tap water quality and control free residual chlorine at the proper concentration in the distribution network. This monitoring system consists of 40 telemeters; 31 telemeters are located at taps, and nine telemeters are at outflows of water distribution plants. Each telemeter measures six water quality items (free residual chlorine, water temperature, turbidity, colour, pH value, and electric conductivity) and transmits data to Water Examination Laboratory and Water Distribution Information Centre using the dedicated line. The display device installed in the laboratory shows trend lines, data list tables, put data on maps, etc. on the monitor screen. All data measured by TMs are updated at intervals of 1 min. All water quality instruments equipped in each telemeter keep accurate measurements by monthly routine maintenance and a yearly precise checkup.

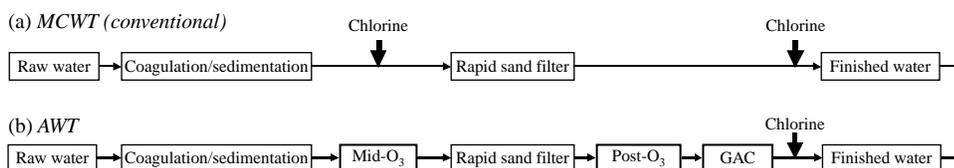


Figure 1 | Flow chart of water purification treatment in Osaka city.

ESTIMATION OF OVERALL RATE COEFFICIENT FOR THE REDUCTION IN RESIDUAL FREE CHLORINE CONCENTRATION IN THE WATER DISTRIBUTION PROCESS

The reduction of chlorine concentration in water distribution systems was analysed using a first-order rate equation based on the results of telemeter measurement (Elton *et al.* 1995). Figure 2 shows the water distribution system investigated on kinetics of chlorine reduction. Sodium hypochlorite is added to water at Niwakubo Water Purification Plant. A telemeter (Al-Jasser 2007) was installed at the outflow site of Tatsumi Water Distribution Plant, and telemeters (Clark & Grayman 1998;

Al-Omari *et al.* 2004) were at the taps. The residence times from the outflow site of water purification plant to telemeter (Clark & Grayman 1998; Al-Omari *et al.* 2004; Al-Jasser 2007) were 6.5, 8.8 and 17.0 h, respectively (when the water supply from Niwakubo Water Purification Plant is $364,400 \text{ m}^3 \text{ day}^{-1}$).

The reduction rate of free chlorine concentration in the water distribution system, r_{all} , is expressed by the following equation:

$$r_{\text{all}} = -\frac{dC}{dt} = k_{\text{all}} C \quad (1)$$

C is a free chlorine concentration measured by each telemeter installed in the water distribution system, t is the residence time from the outflow site of the water purification plant to each telemeter, and k_{all} is the observed reduction rate coefficient of free chlorine concentration in the water distribution system. k_{all} is estimated as the slope of the regression line obtained from plotting $\ln C/C_0$ against t , where C_0 is initial chlorine concentration measured at the water released from the purification plant.

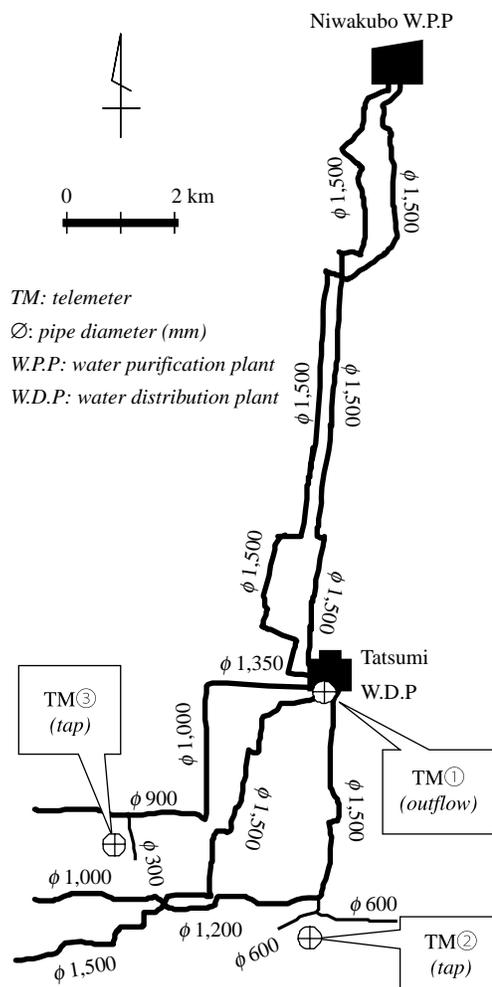


Figure 2 | Water distribution system investigated.

LABORATORY EXPERIMENTS

It was assumed that the improvement of water quality by the change of the purification method gave good effect on the consumption rate of residual chlorine in tap water. On the other hand, it was considered that residual chlorine decreased by volatilisation from surface into air in a distribution reservoir. Considering these results, the two factors that reduce free chlorine concentration in a water distribution system were investigated separately by laboratory experiments, i.e. (a) bulk phase free chlorine consumption caused by the reaction between free chlorine and dissolved organic matters (Hua *et al.* 1999; Powell *et al.* 2000; Hallam *et al.* 2003; Al-Omari *et al.* 2004; Vieira *et al.* 2004), (b) reduction in free chlorine concentration caused by volatilisation from a water surface. Free chlorine concentrations were measured by the N,N' -diphenyl- p -phenylenediamine colorimetric method using a UV-Vis spectrophotometer

(Shimadzu Corp.; UV-mini 1240). Dissolved organic carbon (DOC) concentrations were measured by the combustion catalytic oxidation/NDIR method using a total organic carbon analyser (Shimadzu Corp.; TOC-V_{CSH}).

Test waters

All experiments were carried out using waters treated by the MCWT or AWT at Niwakubo Water Purification Plant. Each finished water was stored for several hours in the reservoir after the chlorine injection, so the initial fast and drastic decrease of chlorine concentration could be neglected (Sung *et al.* 2001; Gang *et al.* 2003; Warton *et al.* 2006). Purified water with added chlorine solution and the pH adjusted to 7.5 with dilute NaOH or H₂SO₄ solution was also tested.

Apparatus and reagents

25 mL glass-stoppered test tubes and 2,000 mL beakers (inner diameter: 125 mm, height: 200 mm) were used for the experiment. This glass apparatus was soaked in sodium hypochlorite solution prior to the experiment to prevent free chlorine consumption on the glass surface. To prepare the chlorine solution, chlorine gas was generated from sodium hypochlorite and absorbed in NaOH solution. Subsequently, the solution was adjusted to pH 8 with H₂SO₄ and diluted with purified water. Milli-Q water (Millipore Corp.) was used as purified water.

Methods

Experiment on the free chlorine consumption in bulk phase

Several test tubes were filled with water sample and sealed. Subsequently, the test tubes were kept dark in a constant-temperature oven at a specified temperature. At the same time, free chlorine concentration in one of the test tubes was measured and regarded as the initial concentration (C_0). Free chlorine concentration in each tube was measured at predetermined time intervals.

Experiment on the reduction in free chlorine concentration caused by volatilisation from a water surface

About 1,500 mL of purified water was put into a 2,000 mL beaker and the beaker was kept dark in a constant-temperature oven to attain the predetermined temperature. Subsequently, a chlorine solution was added to purified water up to the predetermined free chlorine concentration and stirred. Several test tubes were filled with the mixture in the beaker and sealed. After adjusting the volume of sample water in the beaker to 1,000 mL, the water was stirred continuously. The beaker and test tubes were kept dark in a constant-temperature oven. Free chlorine concentration was measured simultaneously and regarded as the initial concentration (C_0). After the predetermined period, each 20 mL water sample was collected from the beaker and the free chlorine concentration was measured.

RESULTS AND DISCUSSION

Change of residual chlorine concentration in Osaka city after the introduction of AWT

Table 1 shows the maximum, minimum, mean and standard deviation values of monthly mean free chlorine concentrations measured in FY1997 and FY2000 at 20 telemeters in whole city area. These telemeters were installed at taps, not at water distribution plants. The data of FY1997 were obtained before the AWT was introduced, whereas the data of FY2000 were obtained after completion of the supply of the AWT water throughout the whole city. As can be seen from Table 1, the minimum free chlorine concentrations in FY1997 and FY2000 were almost equal, because we controlled that the minimum value of free chlorine

Table 1 | Comparison of the residual free chlorine concentrations measured by telemeters in Osaka city

		MCWT (FY1997)	AWT (FY2000)
Max	mg L ⁻¹	0.98	0.65
Min	mg L ⁻¹	0.31	0.30
Mean	mg L ⁻¹	0.64	0.43
SD	mg L ⁻¹	0.14	0.06

SD: Standard deviation.

concentration at each telemeter would be maintained at 0.3 mg L^{-1} in both fiscal years. The maximum and yearly mean concentrations in FY1997 were higher than in FY2000 with differences of 0.33 mg L^{-1} and 0.21 mg L^{-1} , respectively. The standard deviation, a statistical measure of data dispersion, was also higher in FY1997 than in FY2000.

To clarify the effects of water quality improvement due to the introduction of AWT process on the change of deviation of residual chlorine concentration in supply area, we compared both free chlorine concentrations measured by nine telemeters supplied by the Niwakubo Purification Plant in summer season (water temperature; $27\text{--}30^\circ\text{C}$). The results are shown in Figure 3. It shows the histograms of daily mean concentrations with graduations of 0.05 mg L^{-1} , which were measured in August of 1998 and 2000. In August 1998, this plant still treated water using the MCWT process, but it operated the AWT in August 2000, and each chlorine concentration of water released from the plant during those months was controlled to a constant value of 1.0 mg L^{-1} and 0.8 mg L^{-1} , respectively. As is evident from Figure 3, the histogram for the conventional MCWT water exhibited a flat, wide distribution pattern with a low peak value, whereas the histogram for AWT water showed a narrow distribution pattern with a mode of approximately 0.4 mg L^{-1} . Assuming that both histograms exhibited normal distribution patterns, each distribution of free residual chlorine in summer season could be estimated from the standard deviations shown in the Figure.

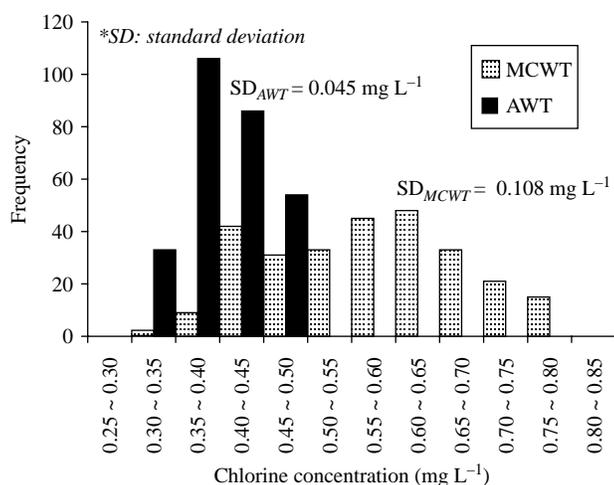


Figure 3 | Comparison of the histograms of free chlorine concentrations between the conventional MCWT and AWT water.

As a result, it was determined that for the MCWT process during the summer season, 95% of the free chlorine concentration in the investigated supply area had stayed within the range of $0.56 \pm 0.22 \text{ mg L}^{-1}$, whereas for the AWT process, the concentration had remained within the range of $0.40 \pm 0.09 \text{ mg L}^{-1}$. These results indicate that water quality improvement by the AWT is helpful in lowering and levelling residual free chlorine concentration.

Changes of overall free chlorine reduction rate in water distribution process after the introduction of AWT

To investigate change in the reduction rate of free chlorine concentration after the introduction of AWT, the data measured by telemeters in the water distribution system shown in Figure 2 was analysed using a first-order rate equation. The overall reduction rate coefficient of free chlorine concentration, k_{all} (h^{-1}), was estimated everyday from the free chlorine concentration measured at the outflow of Niwakubo Water Purification Plant, the outflow of Tatsumi Water Distribution Plant (telemeter (Al-Jasser 2007)) and the taps (telemeter (Clark & Grayman 1998; Al-Omari *et al.* 2004)), C (mg L^{-1}), and the residence time from the water purification plant to each point, t (h). The relationship between k_{all} and water temperature T ($^\circ\text{C}$) in the MCWT and AWT is shown in Figure 4(a,b), respectively. Initial chlorine concentration at the water releasing point of the purification plant in the MCWT or AWT, C_0 was $0.8\text{--}1.2$ and $0.7\text{--}0.8 \text{ mg L}^{-1}$, respectively, and t was recalculated separately each day using the ratio of water supply quantity.

Consequently, k_{all} was estimated to be $0.015\text{--}0.059$ (h^{-1}) in the MCWT and $0.008\text{--}0.032$ (h^{-1}) after introducing the AWT, and it was confirmed that k_{all} in the AWT was reduced to almost half of that in the MCWT. Based on the results of exponential regression obtained from plotting representative k_{all} values in Figure 4(b), k_{all} after the introduction of AWT is represented by the following equation:

$$k_{\text{all}} = 0.0097 \exp(0.0388T) \quad (2)$$

Figure 4(b) also shows an observed reduction rate coefficient k_b (h^{-1}), which was estimated from analysis of

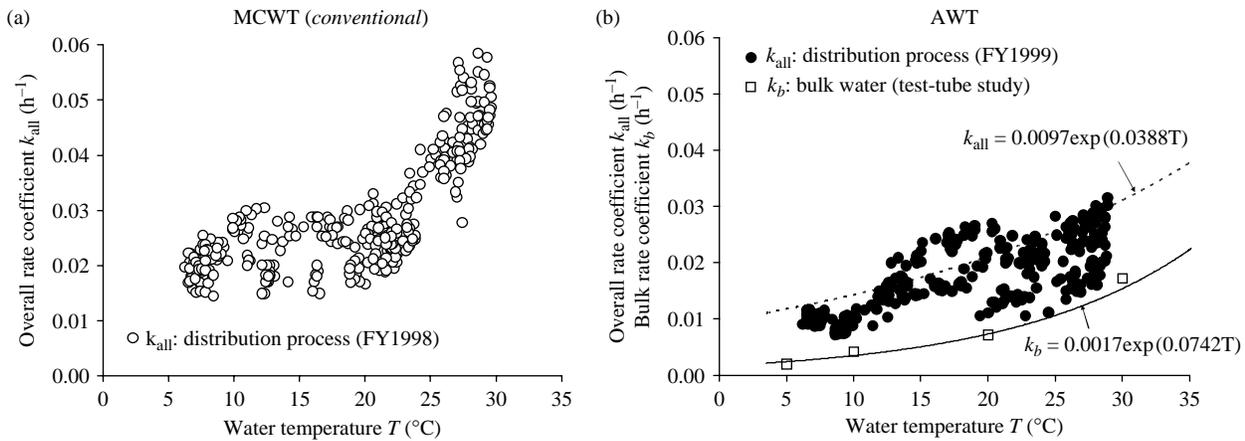


Figure 4 | Relationship between the overall reduction rate coefficients of chlorine concentration and water temperature in Osaka city (a: MCWT, b: AWT).

the reduction of free chlorine concentration in test tubes filled with the AWT water using a first-order rate equation. The relationship between k_b and water temperature is obtained based on the results of exponential regression shown in Figure 4(b). The k_b of the AWT water is represented by the following equation:

$$k_b = 0.0017 \exp(0.0742T) \quad (3)$$

The reduction rate due to free chlorine consumption in bulk phase r_b is represented by the following equation:

$$r_b = -\frac{dC}{dt} = k_b C \quad (4)$$

k_{all} was always greater than k_b , and the difference between k_{all} and k_b was probably derived from the reduction of free chlorine due to contact with the inner wall of pipes (Hallam et al. 2002; Clark & Haught 2005; DiGiano & Zhang 2005; Al-Jasser 2007) and volatilisation from the surface of reservoir water.

Influence of organic substances and volatilisation on chlorine reduction

Organic substances

The k_b (h^{-1}) of chlorine-added purified water, water in the MCWT, water immediately after the introduction of AWT, and water in the AWT after a lapse of 2 years and 5 months from the AWT introduction was estimated, and the results plotting these values against the concentration of DOC

(mg L^{-1}) in each water sample are shown in Figure 5. The k_b of water after the AWT introduction was always smaller than that of water in the MCWT, suggesting that the variance in k_b between samples depended on the difference in DOC. The DOC concentration immediately after the start of AWT operation was low because of the high adsorption performance of new GAC. The DOC concentration reached nearly constant level after the AWT worked for almost one year. The result shown in Figure 5 suggests that the reduction of DOC concentration by the AWT is one of the main factors to reduce the consumption of residual chlorine in drinking water.

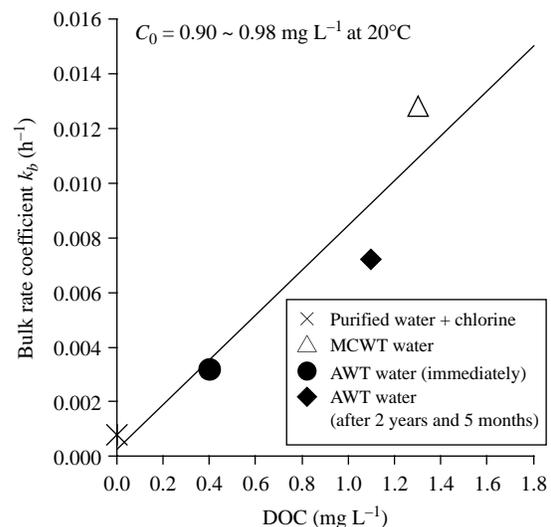


Figure 5 | Relationship between bulk reduction rate coefficient and DOC concentration.

Reduction in chlorine concentration caused by volatilisation from a water surface

The reduction in free chlorine concentration was determined in chlorine-added purified water in a beaker. Consequently, it was found that the results plotting the concentration C to time t fitted a linear regression quite well (Figure 6). On the other hand, almost no reduction was observed in the water in test tubes. When the reduction in free chlorine concentration is approximated by linear regression, the rate of free chlorine concentration caused by volatilisation r_v is represented by the following zero-order rate equation:

$$r_v = -\frac{dC}{dt} = k_v \quad (5)$$

k_v is an observed reduction rate coefficient of free chlorine reduction caused by volatilisation.

In addition, ΔC_v ($\text{mg L}^{-1} \text{h}^{-1}$) is defined as the slope of the regression line obtained when plotting $C_0 - C_t$ against t , where C_0 is the initial chlorine concentration and C_t is a concentration after t h. The surface area of 1 litre water sample in a beaker is estimated to be 0.012266 (m^2). Under these conditions, the mass of chlorine volatilising from 1 m^2 water surface per h, w ($\text{mg m}^{-2} \text{h}^{-1}$), is estimated by the

following equation:

$$w = \frac{\Delta C_v (\text{mg L}^{-1} \text{h}^{-1}) \times 1(\text{L})}{0.012266(\text{m}^2)} \quad (6)$$

When a water reservoir or tank is box- or cylindrical-shaped, the storage volume V (m^3) can be calculated as a product of the surface area of the water and the water depth, i.e. S (m^2) \times D (m). Therefore, k_v ($\text{mg L}^{-1} \text{h}^{-1}$) is represented by the following equation:

$$k_v = \frac{w(\text{mg m}^{-2} \text{h}^{-1}) \times S(\text{m}^2)}{V(\text{m}^3) \times 1000} = \frac{w \times S}{S \times D \times 1000} = \frac{w \times 10^{-3}}{D(\text{m})} \quad (7)$$

As shown above, k_v is proportional to w but inversely proportional to the water depth D . A similar experiment at a different water temperature T ($^{\circ}\text{C}$) was conducted and ΔC_v obtained was plotted against T , and w was estimated by Equation (6). Consequently, it was confirmed that w exponentially increased as water temperature T increased. Based on the results of the regression, k_v ($\text{mg L}^{-1} \text{h}^{-1}$) is represented by the following equation:

$$k_v = \frac{0.0004 \exp(0.0850T)}{D} \quad (8)$$

To be specific, residual free chlorine is likely to disappear more when the water depth is shallower and water temperature is higher under the same storage time.

Development of prediction models

Based on the results of telemeter measurements and laboratory experiments, models for simulating free residual chlorine concentrations in Osaka city water supply area were developed and the accuracy of prediction was assessed.

Overall model

This model is applied to the water distribution processes excluding reservoir water in secondary distribution plants.

$$C_t = C_0 \exp(-k_{\text{all}} t) \quad (9)$$

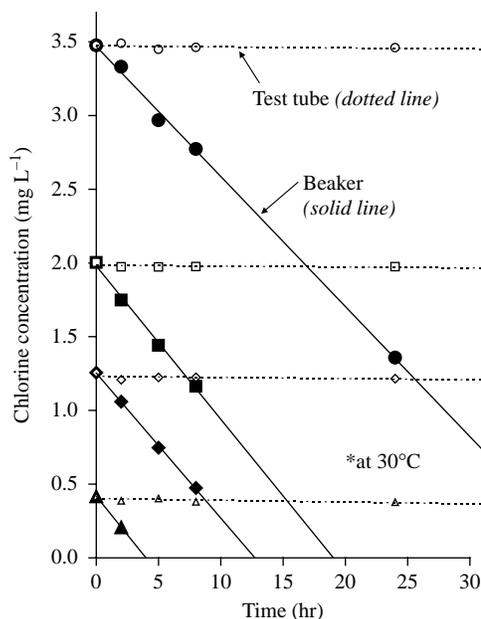


Figure 6 | Reduction in chlorine concentration by volatilisation from water surface.

where C_0 (mg L^{-1}) is the initial free chlorine concentration and C_t (mg L^{-1}) is free chlorine concentration after t (h). k_{all} (h^{-1}) is calculated from Equation (2).

Reservoir model

Under the assumption that free chlorine concentration in water stored in a reservoir is reduced by bulk free chlorine consumption and volatilisation from the water surface, the reduction rate of free chlorine concentration in stored water, r_r , is represented by the following equation based on Equations (4) and (5):

$$r_r = -\frac{dC}{dt} = r_b + r_v = k_b C + k_v = k_b \left(C + \frac{k_v}{k_b} \right) \quad (10)$$

By the integration of Equations (10) and (11) can be obtained.

$$C_{\text{out}} = \left(C_{\text{in}} + \frac{k_v}{k_b} \right) \exp(-k_b t) - \frac{k_v}{k_b} \quad (11)$$

C_{out} is free chlorine concentration of water leaving a distribution plant and C_{in} is free chlorine concentration of water entering a distribution plant. The k_b (h^{-1}) and k_v ($\text{mg L}^{-1} \text{h}^{-1}$) in Equation (11) are calculated from Equations (3) and (8), respectively. Equation (11) predicts the reduction of free chlorine concentration during storage in a reservoir. Equation (11), which is called the reservoir model, is applied to water stored in secondary distribution plants.

Accuracy of the prediction models

At OMWB, two mathematical models mentioned above are utilized for the prediction of free chlorine behaviour in the whole of Osaka city. As shown in Figure 7, the reservoir model is applied to water stored in secondary distribution plants, which have longer water residence time and shallower water depth in reservoirs compared to primary distribution plants. The overall model is applied to the rest of the water distribution process from purification plants to water taps.

The simulation method, which combines overall and reservoir models, has been used for the control of residual free chlorine concentration in Osaka city area for 4 years.

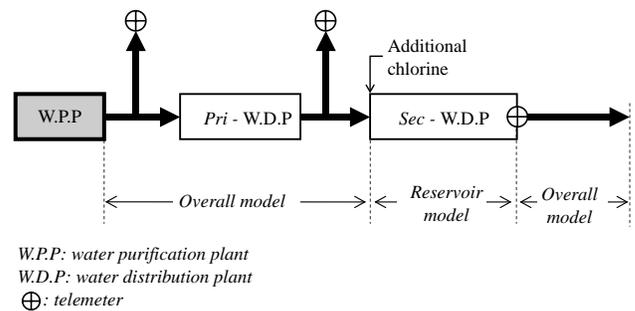


Figure 7 | Application method of prediction models.

These models can predict the behaviour of free chlorine accurately, so that we can control residual chlorine concentration in supply area above 0.1 mg L^{-1} which is defined as minimum concentration at every tap by a regulation. These are very effective to control the residual chlorine as low as possible all over supply area. Figure 8 shows the difference between measured and predicted daily concentrations of 19 telemeters using only overall model (bold line). The data plotted in Figure 8 were obtained in the year 2005 and the graduation in the figure is 0.02 mg L^{-1} . The data shown in the figure by bold line were observed at 19 telemeters, which are located in the whole city area of Osaka; therefore, the figure shows the accuracy of the prediction model about tap water supplied by three purification plants. The annual change in water temperature ranged from 6 to 30°C , and the whole year analysis shows that the differences between measured

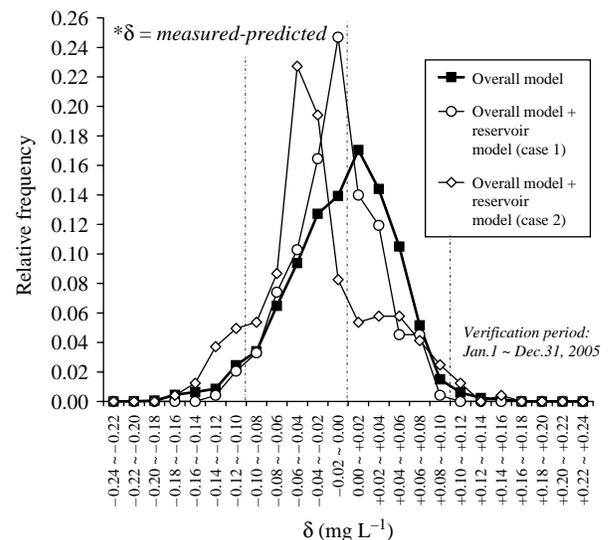


Figure 8 | Accuracy of the prediction models.

and predicted concentrations are almost in the range between $\pm 0.1 \text{ mg L}^{-1}$. In addition, the two results predicted using both overall and reservoir models are also shown in Figure 8 (solid lines). Each chlorine concentration was predicted at water releasing point of each secondary distribution plant. The storage times and water depths in two secondary distribution plants were 6 h and 2.3 m in Case 1, and 15 h and 2.4 m in Case 2, respectively. In the case of incorporating the reservoir model into the residual chlorine prediction, the prediction accuracy is as good as that using only overall model. It means that both models can predict the behaviour of chlorine caused by the change of temperature and residence time well.

Development of the annual residual chlorine control program based on the prediction models for setting chlorine control values in Osaka city

It is important to control residual chlorine concentration in water leaving water purification plants and water distribution plants adequately so that tap waters keep containing chlorine at target value. OMWB has been setting the whole year target value of concentration at all water purification plants and injection chlorine dose rates added at all secondary distribution plants. The target concentration and the injection rate are calculated by the prediction models. Mean daily temperatures obtained during the past 5 years are used for the calculation.

The examples of target value and injection rate are shown in Figure 9. Osaka city has controlled residual chlorine in whole supply area by the combination of the

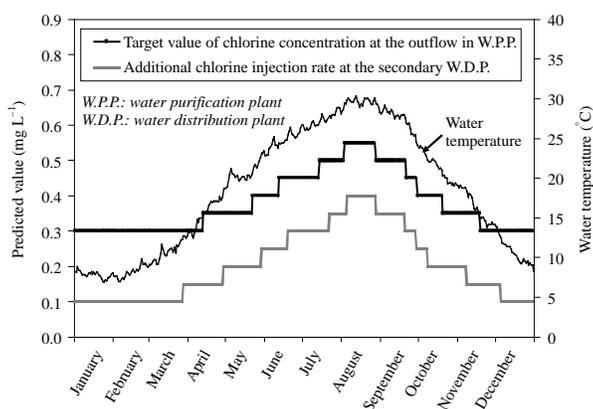


Figure 9 | Annual chlorine control program created using the prediction models for Osaka city.

annual residual chlorine control program shown in Figure 9 and readjustment of the target value or the injection rate based on the data measured by telemeters, if necessary.

CONCLUSIONS

This research reveals the following

- The introduction of advanced water treatment could reduce maximum and mean residual chlorine concentrations in the distribution area by 0.33 mg L^{-1} and 0.21 mg L^{-1} respectively, while minimum concentration of chlorine could be maintained at 0.3 mg L^{-1} . In addition to that, 95% of residual concentration at taps in summer season was assumed to be in the range of $0.40 \pm 0.09 \text{ mg L}^{-1}$. The overall reduction coefficient of chlorine was lowered to half of that in the time of mid-chlorination treatment. The reduction of dissolved organic matter in drinking water contributes to the control of residual chlorine for maintaining at constant concentration.
- It is estimated that the bulk phase chlorine consumption is shown in the first-order reaction and the decrease of chlorine by volatilisation is shown in the zero-order reaction. Those reduction rate coefficients increase with increasing of water temperature exponentially. In addition, the reduction rate coefficient of chlorine volatilisation is inversely proportional to the depth of reservoir water, so the chlorine concentration reduction will be greater if the water is shallower.
- The prediction models developed based on the reaction rate analyses of telemeter measurement data and laboratory experiments can predict whole year residual chlorine concentration at taps in distribution area within the range of $\pm 0.1 \text{ mg L}^{-1}$.
- The water temperature influences the extent of residual chlorine reduction in the distribution area greatly. The target chlorine concentration value at a water purification plant and injection rate of additional chlorine at a distribution plant should be changed based on the change of water temperature. The simulation method using two prediction models developed in this study is useful to set those target values properly.

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