Influence on coagulant dose in high color raw water is shown in Figure 3. A-WTP needs much more coagulant dose at almost the same pH and temperature than C-WTP which uses raw water of low color (less than about 10 degrees). The data of WTPs shows that high turbidity raw water of high color consumes lots of coagulant, as is reported in the research on turbidity with color by Tambo (1984) and Hozumi et al. (1994). This suggests that color is an important indicator of coagulant dose control for high turbidity raw water, especially at small water utilities using high color raw water sources.

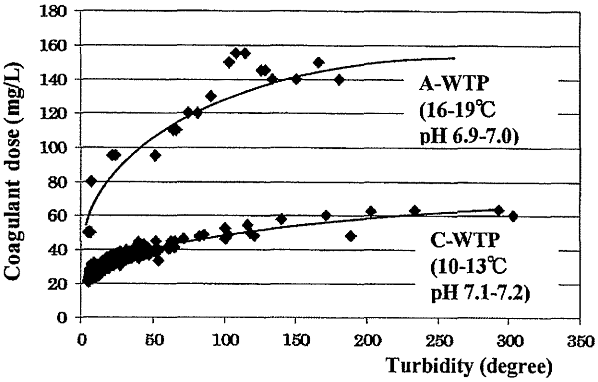

Figure 3. Correlation between coagulant dose and turbidity of raw water

Behavior of Alkalinity during high turbidity. Alkalinity is an important factor for optimum coagulation (David Hendricks 2006, Tseng et al. 2000), and it is necessary to understand alkalinity changes during high turbidity periods. Figure 4 shows a correlation between alkalinity and turbidity; as the turbidity increases, the alkalinity decreases for both D-WTP and F-WTP, which use high alkalinity raw water and low alkalinity raw water, respectively. On the other hand, the alkalinity at E-WTP does not change even if the turbidity of raw water increases. This indicates that alkalinity changes during high turbidity periods depend on the raw water source. From these results, it is suggested that alkalinity measurement of raw water is very important for high turbidity raw water in order to control optimal coagulation.

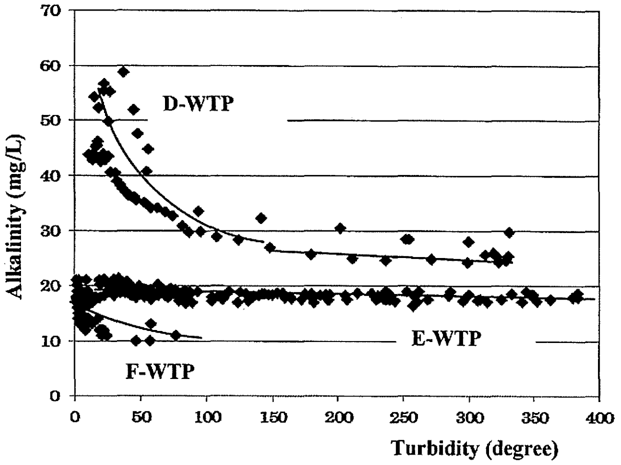

Figure 4. Correlation between alkalinity and turbidity of raw water

Alkalinity consumption by coagulant. Alkalinity consumption is calculated to be 0.15mg/L for 1mg/L of PACl (10%) and 0.24mg/L for 1mg/L of aluminum chloride (alum, 8%). Figure 5 plots the alkalinity consumption by PACl and alum for D-WTP and F-WTP. Poor correlations exist between the two plants' consumption patterns, and the 0.18mg/L for PACl and 0.33mg/L for alum in Figure 5 are a little higher than 0.15mg/L and 0.24mg/L. It is clear from these results that coagulants consume alkalinity constantly. Therefore, considering that the alkalinity reduces as the turbidity increases, monitoring alkalinity is indispensable for controlling coagulant dose when raw water has high level of turbidity.

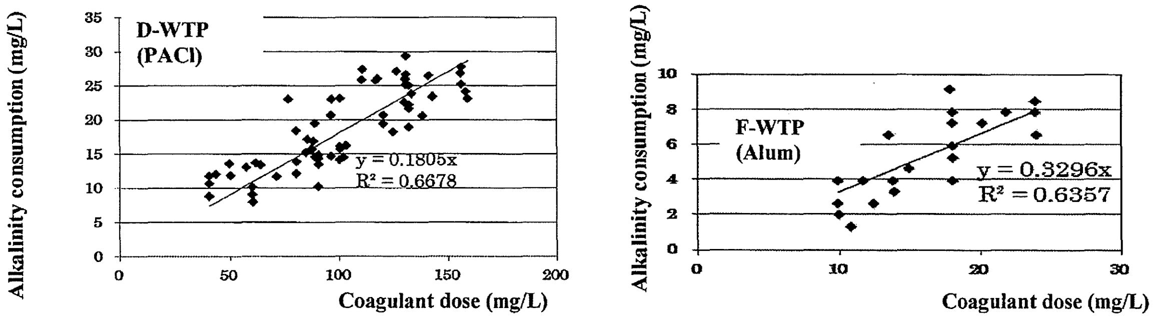

Figure 5. Correlation between alkalinity consumption and coagulant dose

EC as alternative indicator of alkalinity. In spite of being an important indicator for coagulation process, alkalinity is not analyzed at WTPs in small water utilities in Japan, due to time-consuming analysis. Also, automatic analyzers of alkalinity are not introduced to small water utilities because of the high cost and the difficulty of maintenance. Therefore, small water utilities need alternative indicators of alkalinity. Because electric conductivity (EC) automatic analyzer is widely used for monitoring of raw water, correlation between EC and alkalinity was analyzed for four WTPs using different raw water sources to see the EC's feasibility as an alternative indicator of alkalinity (Figure 6). The raw water of each WTP has high correlation between EC and alkalinity. On the other hand, as the figure shows, a close overall correlation is found for D-, E-, and F-WTPs except C-WTP. This result shows that EC would be an alternative indicator of alkalinity for each WTP's raw water, though a correlation equation between EC and alkalinity in each WTP would be necessary. Overall, EC measurement as alternative indicator of alkalinity would be a sufficiently reliable indicator of coagulation and sedimentation control in small water utilities.

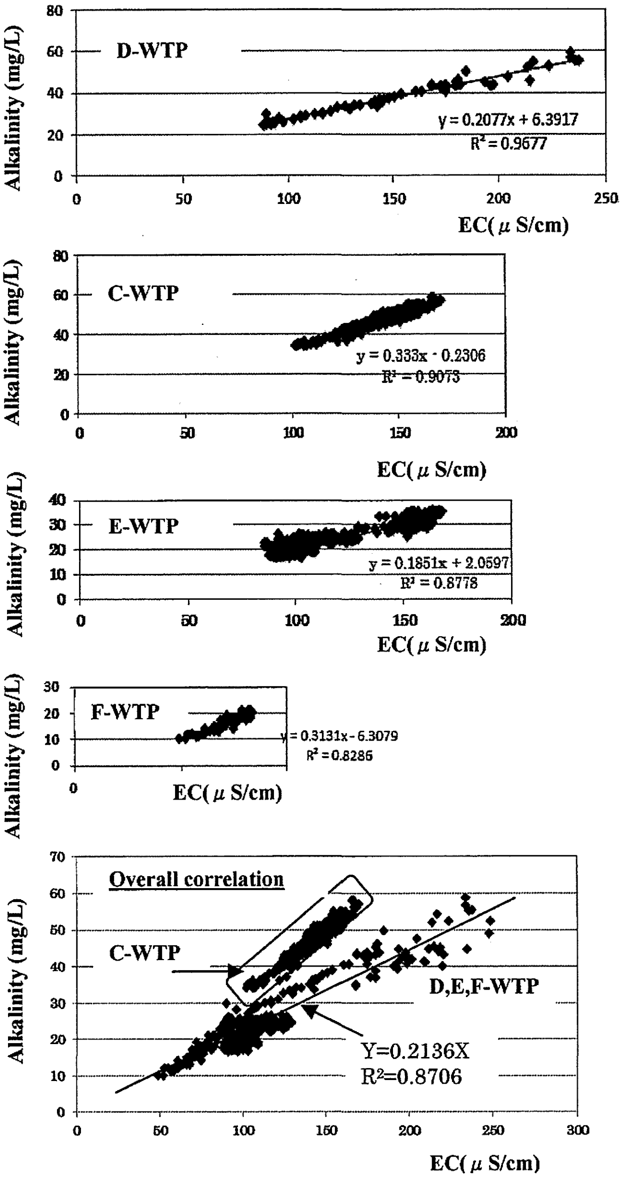

Figure 6. Correlation between EC and alkalinity for raw water of some WTPs

Optimal coagulant dose for pH variation. Figure 7 shows the results of coagulant dose by pH adjustments with and without acid. Raw waters at C-WTP and D-WTP are from different lakes affected by eutrophication and the pH goes up to about 8.0 or more. C-WTP adjusts pH by sulfuric acid and D-WTP does not use acid. Compared with C-WTP, D-WTP consumes more than twice as much of coagulant PACl to keep optimal coagulation conditions. This result proves that pH adjustment by acid is an effective and easy way to control coagulation and sedimentation for high pH raw water during high turbidity periods, as explained in the coagulation theory by Weber Jr. (1972).

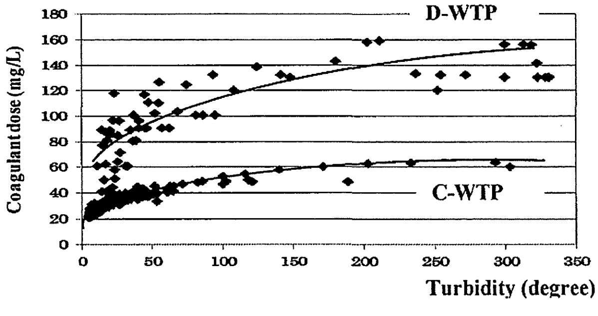

Figure 7. Optimization of coagulant dose by pH adjustment with acid

Calculation method for optimal coagulant dose. In larger water utilities, coagulant dose is determined by performing jar test for high turbidity raw water. It is difficult, however, for small water utilities to perform jar test during high turbidity periods, due to limited work force. Hence it is necessary to propose a simple and comprehensive coagulant dose method not requiring jar test, to assist small water utilities. As one of the factors for optimal coagulation, the ratio of Al (coagulant dose) / T (turbidity) is reported by Tambo et al. (1972), but this factor is rarely utilized in Japanese WTPs. To evaluate this method, the data of four WTPs are plotted by Al/T ratio and T in Figure 8. The figure shows that each WTP has a higher correlation up to 600 degrees of turbidity. This result indicates that an exponentiation equation for AL/T ratio and T could be adopted as a control method of coagulant dose for high turbidity in small water utilities using various raw water sources. The figure also shows the results when PACl was used as coagulant. The same results are obtained in other WTPs using alum as coagulant. Each exponentiation equation obtained from Figure 8 is as follows.

$Y=a \cdot X^b$ ------- (1)

Y : Al/T Al (Coagulant dose(mg/L))

T (Turbidity(degree))

X : Turbidity(T)

a, *b* : coefficient

$Al=a \cdot T^{b+1}$ ------- (2)

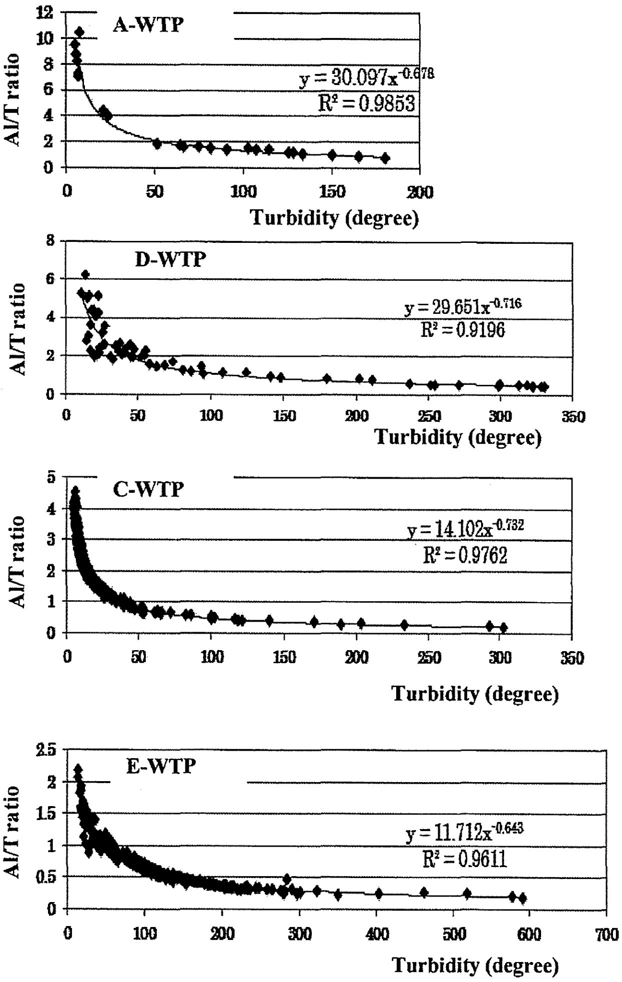

Figure 8. Correlation between Al/T ratio and T for raw water of some WTPs

To evaluate what kind of water quality for various raw waters affects coefficients *a* and *b*, coefficients *a* and *b*, which are calculated from Figure 8, and characteristics of raw water for each WTP are shown in Table 2. As shown in Figure 8, the Al/T ratio of A-WTP, which has high color , is twice higher than that of E-WTP with low color, and coefficients *b* in A-WTP and E-WTP are very close and coefficient *a* differs considerably between A-WTP and E-WTP. This result shows that coefficient *a* is much affected by color. Similarly, as coefficients *b* in D-WTP and C-WTP are close, coefficient *a* might be affected by pH of coagulation. The comparison between low coefficients *b* such as observed at A-WTP and E-WTP and high coefficient *b* such as observed at D-WTP and C-WTP indicates that coefficient *b* might be affected by alkalinity of raw water. To summarize the evaluations above, it is suggested that factors of water quality associated with coefficient *a* are color and pH, and that factor of water quality associated with coefficient *b* is alkalinity. These results indicate possibility to make overall calculation method of coagulant dose for various raw waters.

Table 2. Coefficients a and b and characteristics of raw water

WTP	Exponentiation equation coefficients: a	Exponentiation equation coefficients: b	Characteristics of raw water: color	Characteristics of raw water: alkalinity	Characteristics of raw water: pH
A	30.097	-0.678	high	low	medium
D	29.651	-0.716	low	high	high
C	14.102	-0.732	low	high	high (acid adding)
E	11.712	-0.643	low	low	medium

From these results, it is demonstrated that the exponentiation equation ($Al=a \cdot T^{b+1}$) for each WTP is more successful to decide coagulant dose less than 600 degrees of raw water turbidity than many other coagulant dose equations (Nakamura 1974), though it is necessary to calculate coefficients *a* and *b* for each WTP by plotting Al/T ratio and T as shown in Figure 8. Therefore it is considered that the exponentiation equation would help small water utilities which have difficulty of performing jar test during high turbidity periods.

Easy method to guarantee stable treatment of raw water with high turbidity

Evaluation for re-coagulation (two-step coagulation) method in actual facilities. Re-coagulation (two-step coagulation) is a method that adds a little dose of coagulant to settled water between sedimentation and filtration processes. This method has been introduced to some of the Japanese WTPs lately, as on-site trials, for the purpose of measuring algae and controlling turbidity of sand filtered water. In this study this method's effectiveness during high turbidity periods was tested, based on WTPs' data. Figure 9 shows filtrate treatability of turbidity and particle numbers at 0.5mg/L and 1.0mg/L of coagulant dose (as PACl) as re-coagulation trials in A-WTP during different high turbidity periods. It is clear from turbidity and particles numbers that a 1mg/L dose of PACl as a re-coagulation coagulant obtains a better filtrate water quality than in case of 0.5mg/L, and the filtrated water is very stable under 0.01 degrees of turbidity by 1mg/L of PACl dose. In WTP having introduced re-coagulation, it is important to confirm the increase of the head loss of sand filter and aluminum outbreak to filtered water. In some results of A-WTP, a little increase of head loss of sand filter is shown to occur, but it is actually not affected for filtration and backwash interval in case of under 1mg/L coagulant dose. Also, aluminum outbreak of filtered water with re-coagulation is almost as low level as that with conventional coagulation. Mixing intensity in some WTPs was also investigated. It is indicated that an additional mechanical mixing is not necessary and that coagulant only dropped at effluent of sedimentation basin before sand filtration. Re-coagulation has a great effect on the stabilization of turbidity of sand filtered water. It is expected that re-coagulation will be applied in small water utilities for the backup against imperfect coagulation and sedimentation to deal with high turbidity raw water.

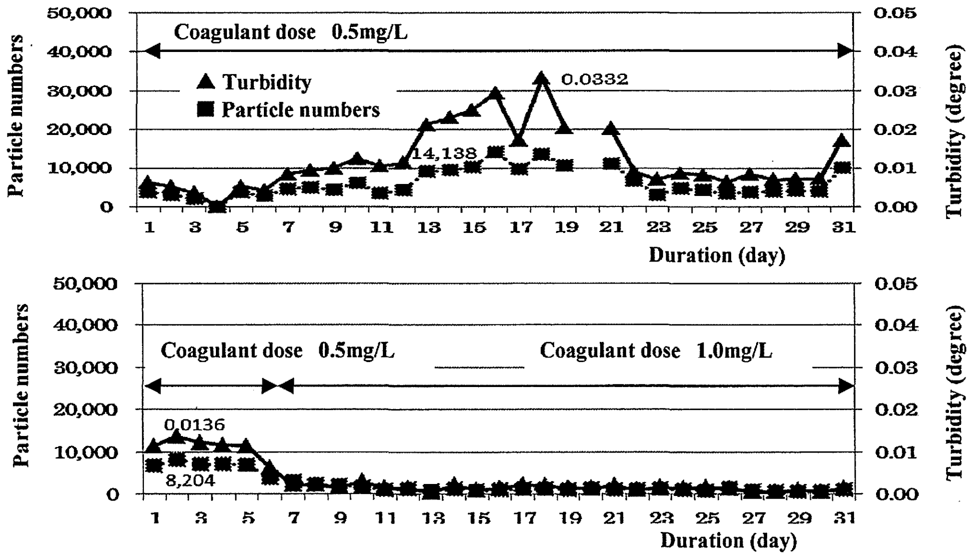

Figure 9. Treatability of turbidity and particle numbers by re-coagulation in actual facility

Identification of re-coagulation (two-step coagulation) method by the pilot plant. The pilot plant experiment by using equipment shown in Figure 1 was conducted in order to get the backup data in detail. The experiment conditions are shown in Figure 10. Setup turbidity is 5 degrees for the regular raw water and 1000 degrees as the highest turbidity. Process of turbidity is 5 degrees for 90min., 1000 degrees for one hour, 500 degrees for 90min., 200 degrees for 90min., and 50 degrees for two hours as show in Figure 10. 100 times diluted PACl is prepared. In case of re-coagulation (two-step coagulation), 1000 times diluted PACl is added at the constant dose of 2mg/L on the outlet of sedimentation tank. Optimal coagulation dose was determined by jar test. Figure 11 presents the results of Case 1 (optimal coagulant dose), Case 2 (insufficient coagulant dose), Case 3 (insufficient coagulant dose + re-coagulation). Figure 12 presents the results of Case 1 (optimal dose), Case 4 (imperfect sedimentation), Case 5 (imperfect sedimentation + re-coagulation).

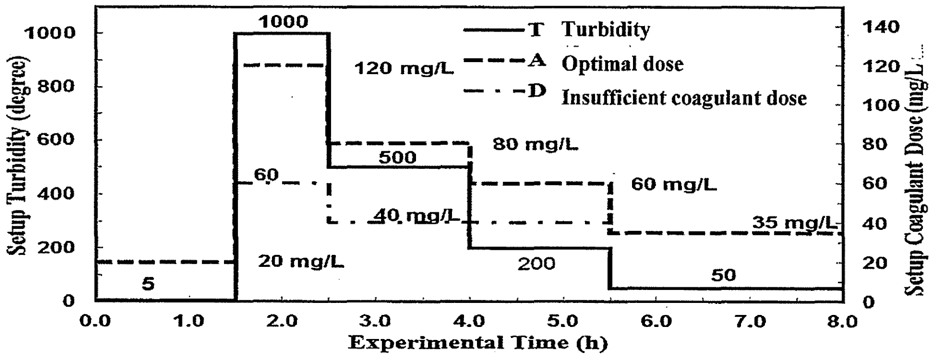

Figure 10. Setup turbidity and coagulant dosage (as PACl)

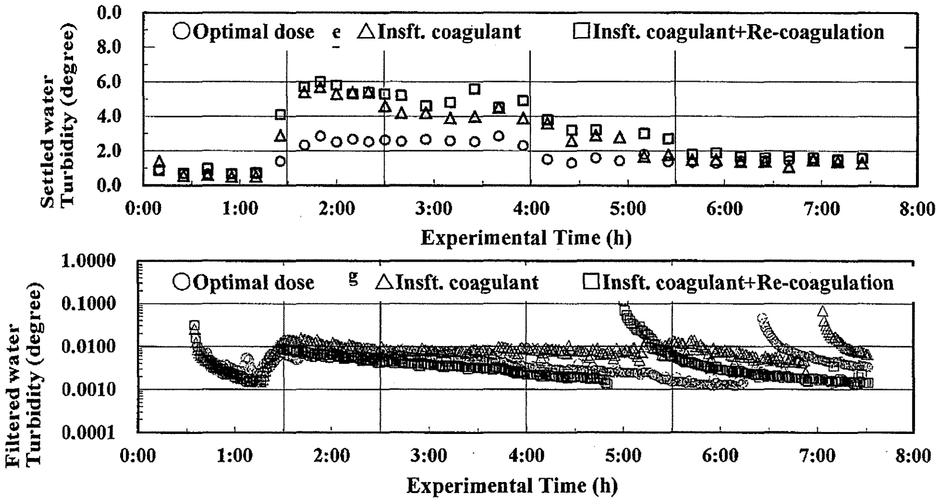

Figure 11. Comparison between optimal dose and insufficient dose of coagulant with/without re-coagulation

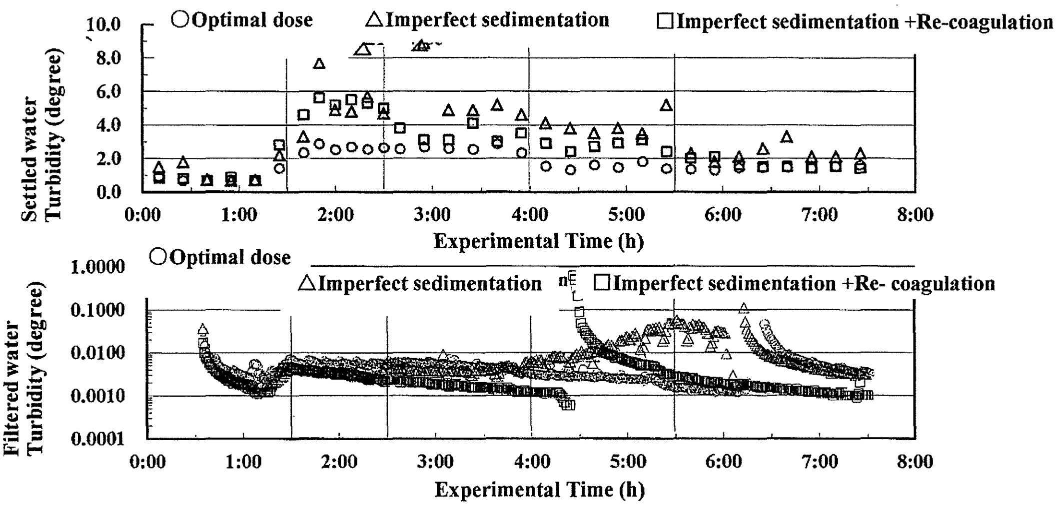

Figure 12. Comparison between optimal dose and imperfect sedimentation with/without re-coagulation

Results of insufficient coagulant dose are shown in Figure 11. The settled water turbidity increased around 2 times of optimal coagulant dose in the range from 1000-200.The filtrate turbidity also increased highly in case of 1000-degree raw water turbidity and it decreased in case of 50-degree raw water turbidity. In re-coagulation, settled water shows that the coagulant dose is insufficient but that filtrate turbidity decreases more than in case of optimal coagulant dose. However, filtrate duration time tends to be short in case of 2mg/L dose rate. In Figure 12, in the conditions of imperfect sedimentation, the change of sedimentation turbidity is around the same as the case of insufficient coagulant dose. But the filtrate turbidity tends to increase during the filtration time. By the pilot plant test it is also proved that re-coagulation (two-step coagulation) is effective to guarantee stable treatment of raw water with high turbidity with decreasing filtrate turbidity.

CONCLUSIONS

Based on the data from the actual and pilot plants, this study concludes that (1) Turbidity, Alkalinity, color (organics originated to peat) and pH are important indicators that mainly affect coagulation and sedimentation control during high turbidity as data analysis for various raw water, (2) EC is available for alternative indicator of alkalinity to manage coagulation and sedimentation, (3) exponentiation equation ($Al=a \cdot T^{b+1}$) by calculating coefficient *a* and *b* in each WTP could be adopted to control the automatic coagulant dose without jar test, and (4) re-coagulation (two-step coagulation) is an easy and effective measures for small water utilities to guarantee stable treatment of raw water with high turbidity.

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Water Quality Surveys of Shallow Wells Damaged by Tsunami in the Great East Japan Earthquake
～Case of Minamisanriku-cho in Miyagi prefecture～

Nobuteru Mizuno*, Masahiko Suzuki*, Takashi Onuma**,
Kenji Taira**, Takako Aizawa***

ABSTRACT

There are many shallow wells used as a water source near the coast of Minamisanriku-cho in Miyagi prefecture. However, most of them were damaged by seawater of the tsunami resulting from the Great East Japan Earthquake that occurred on 11 March, 2011. Most of the damaged water sources thus proved difficult to use as water supplies because of increased chloride ion concentrations and possibility of contamination.

Therefore, The Yokohama waterworks bureau assigned water quality survey teams to the sites to survey their water quality and the possibility of them being used in the future in accordance with a request from the "Waterworks reconstruction support for the Great East Japan Earthquake liaison council."

The survey was implemented 4 times from August to November of 2011. Result of the survey confirmed there to be no contamination except chloride ion. However, the downward tendency of chloride ion was not uniform, and it might be affected by sodium remaining in the surrounding soil and changes in the tide level. For this reason, continuous survey is conducted to ascertain these effects, although chloride ion concentration is decreased to drinkable level.

The results of the above mentioned surveys and future outlook are reported in this paper.

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1. Background and purpose

There are a number of shallow wells that are used as sources of water near the coast of Minamisanriku-cho in Miyagi prefecture (about 2 km area from the coast) (figure 1), with the majority of them having been damaged by seawater from the tsunami which resulted from the Great East Japan Earthquake of March 11, 2011. Most of the damaged water sources have therefore proved difficult to use as water supplies because of increased chloride ion concentrations. In addition, a number of gas stations and fish farms were located near those water sources and the possibility exists that toxic substances from those facilities also contaminated them.

The water and sewage services division of Minamisanriku-cho,, which manages the damaged water sources, therefore requested the "Liaison Council for Supporting the Restoration of Water Supply Facilities Affected by the Great East Japan Earthquake" (established by the Ministry of Health, Labour and Welfare as a framework to use in providing technical support in the damaged area) to dispatch a "Field Water Quality Survey Team" and investigate the water quality as part of a water treatment facility restoration plan.

This paper provides an outline of the surveys that were conducted by the Yokohama Waterworks Bureau, which dispatched water quality survey teams to the sites in accordance to the request made by the "Liaison Council for Supporting the Restoration of Water Supply Facilities Affected by the Great East Japan Earthquake".

The purpose of the surveys was to investigate any water sources affected by the seawater from the tsunami, assess the water quality and situation with damage at each of them, and determine a future plan that includes the possibility of them being used in the future or the need to change water sources and construct new water treatment facilities.

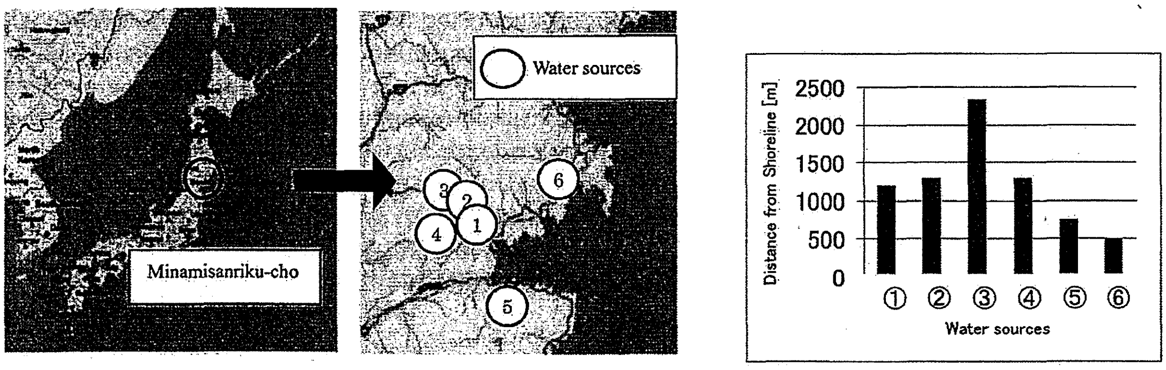


Figure 1. Location of damaged water sources and their distance from shoreline
(Water source name:①Sukezukuri No.1②Sukedukuri No.2③Komori④Tajiribatake⑤Tokura⑥Isatomae)

2. DETAILS OF THE SURVEY

(1) Outline of damaged water sources

The six water sources that were surveyed and the situation with the facilities surrounding them are explained below. Seawater from the tsunami reached upstream of all the water sources. A number of gas stations and other facilities were also located nearby.

a. Sukezukuri No.1 and No.2 water sources (figure 2)

The Sukezukuri water source consists of a No.1 water source, which is about 1.2 km away from the coast, and a No.2 water source, which is about 100m closer inland than the No.1 water source. The Sukezukuri water source was used as the primary water source for the Sukezukuri Water Treatment Facility, which provided water to about 2,700 households in the Shizugawa area where administrative bodies that included the Minamisanriku-cho town hall were located. Water pumped from the water source was simply chlorinated before then being made available for use. The treatment capability was 4,896 m^3/day (3,633 m^3/day in fiscal 2009), or quite a large volume of water.

*b. Komori water source (figure 2) *developed after the disaster*

Located 1km closer inland than the Sukezukuri No.1 water source and which was developed as an alternative source to the Sukezukuri water source, which was severely damaged by tsunami and therefore incapable of being used. The Komori water source was originally used with a pump dedicated for use with a trout and salmon farm, but the farm ceased operating after the earthquake and is in current use as a secondary water source.

*c. Tajiribatake water source (figure 2) *developed after the disaster*

Located about 1.3km inland from the coast and which was developed as an alternative source to the Sukezukuri water source, similar to the abovementioned Komori water source. One well had already been excavated prior to the disaster for use as a secondary water source but no intake pump had been installed. After the disaster two new wells (No.2 and No.3) were then excavated and pumps installed to utilize the water from all three.

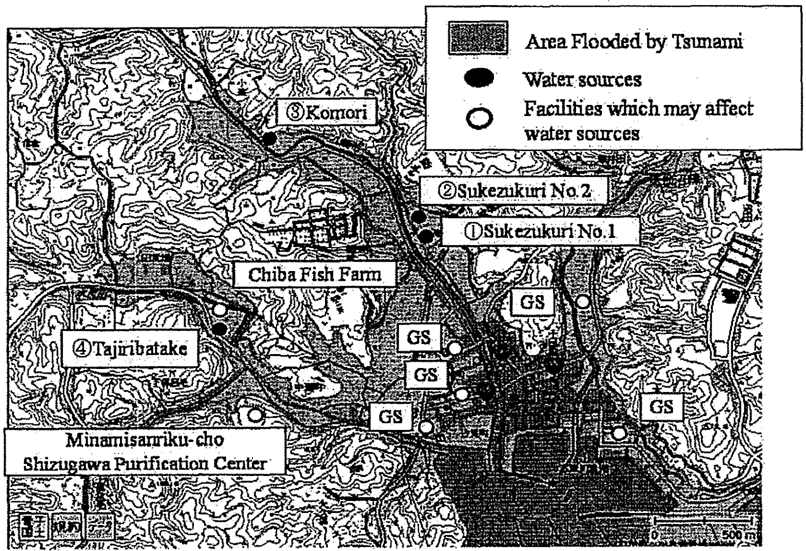


Figure 2. Location of Sukezukuri・Komori・Tajiribatake water source
(Reference: Association of Japanese Geographers HP)

d. Isatomae water source (figure 3)

Located about 700m inland from the coast and which was used as a primary water source for the Isatomae Water Treatment Facility, which provided water to about 1,450 households within the former Utatsumachi before the towns and villages were combined. Water pumped from the water source was chlorinated before being made available. The treatment capability was 2,300 m^3/day (1,800 m^3/day in fiscal 2009), or quite a large volume of water.

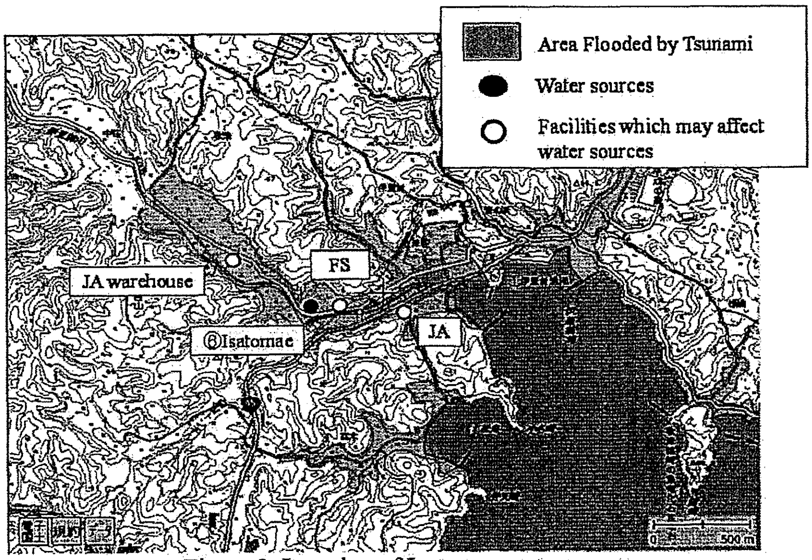


Figure 3. Location of Isatomae water source
(Reference: Association of Japanese Geographers HP)

e. Tokura water source (figure 4)

Located about 500m inland from the coast and which was used as a primary water source for the Tokura Water Treatment Facility, which provided water to about 680 households in the Tokura area which stretches to the east and west (from Rikuzen Tokura station to Kamiwarizaki station on the Kesennuma line). Water pumped from the water source was immediately chlorinated before then being made available to households. The treatment capability was 1,057 m^3/day (614 m^3/day in fiscal 2009), or quite a large volume of water.

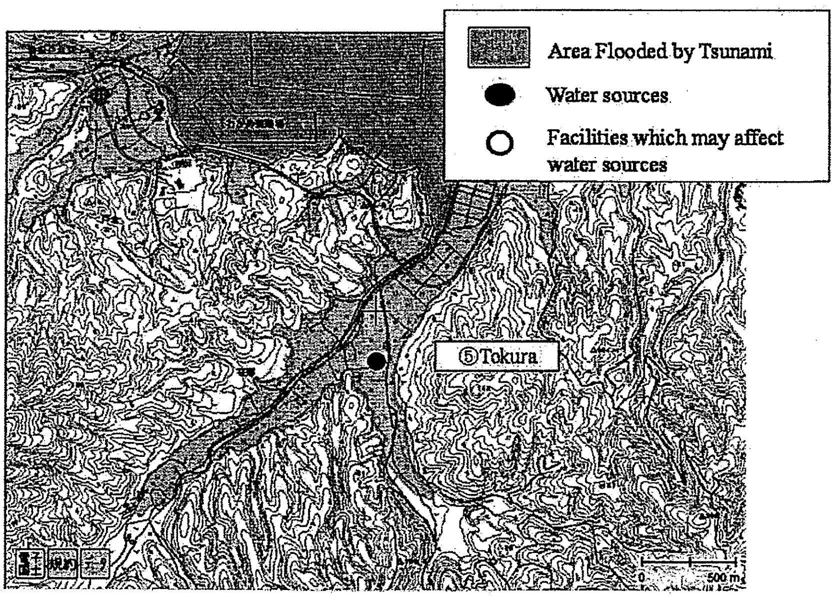


Figure 4. Location of Tokura water source
(Reference: Association of Japanese Geographers HP)

(2) Expected effects of the tsunami on the water sources

The tsunami resulting from the Great East Japan Earthquake, as reported by the Japan Metrological Agency, rose as high as 15m in Minamisanriku-cho. The areas we surveyed are mostly at most about 10m above sea level (as predicted by a digital map provided by the Geospatial Information Authority of Japan). All the wooden buildings in the areas were completely destroyed. Only the frames of reinforced concrete and steel frame buildings remained and we couldn't tell what they actually looked like prior to the disaster. Every existing water source was completely flooded by the tsunami and the total amount of chloride ions had increased, and gasoline, pesticides, and human excreta had also possibly contaminated the water sources from nearby gas stations and houses.

In addition, the ground level near every water source had sunk 0.6 to 0.7m after the Great East Japan Earthquake. This then led to the possibility of the underground water source having been changed, and the effect of a change in the tide level was causing the chloride ion concentration to fluctuate.

For this reason we concentrated on surveying the situation with contamination at each of the water sources via use of water quality tests and monitored the change in chloride ion concentrations.

(3) Period and content of the survey

The period and main content of the survey are shown in table 1. Surveys took place a total of four times during August through to November in 2011 via water quality survey teams being dispatched to the field. The surveys mainly focused on water quality analysis, and during the 1st and 2nd surveys the teams conducted simplified tests in the field (on the chloride ion concentrations, smell, turbidity, pH, etc.) and returned with some samples to the Yokohama Waterworks Bureau for detailed examination of water quality standard items and agricultural chemicals, and to check for the possibility of contamination. During the 3rd and 4th surveys a decreasing tendency with the chloride ion concentration was mainly investigated, and a conductivity meter installed as an alternative indicator at the water sources in thereby enabling the concentration level to be constantly monitored.

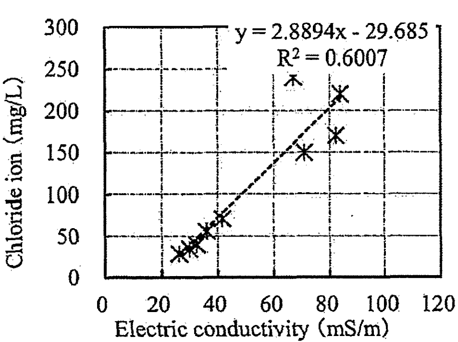
With any of the water sources whose chloride ion concentrations had not decreased enough (Sukezukuri and Isatomae water sources) the decision was made to continue to monitor the transition of the concentration levels after December 2011, with the water and sewage services division of Minamisanriku-cho then being entrusted to install a compact conductivity meter and continue the survey.

TABLE Ⅰ. Period and main content of each survey

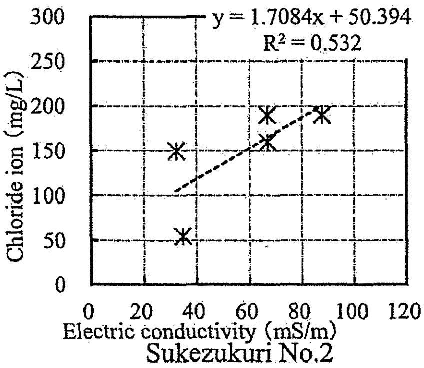
	1st Survey	2nd Survey	3rd Survey	4th Survey	Continuous Survey
Period	2011.8.8～8.12	2011.9.26～9.30	2011.10.17～10.21	2011.11.13～11.16	2011.12～2013.3
Method	Dispatched survey team to the site and examined water quality				Constant monitoring of electric conductivity was conducted by compact conductivity meters
Target water source	Sukezukuri No.1,Sukezukuri No.2, Isatomae				
	Tajiribatake, Tokura				▨
	Komori			▨	▨
Item of water examination	• Water quality standard items(27items) •Salt concentration, etc.(5items) •Anaerobic spore-forming bacteria •Agrichemicals (70items)	• Water quality standard items (23items) •Langelier's index •Salt concentration, etc.(6items) •Radioactive substances (3items)	• Water quality standard items(23items) •Salt concentration, etc.(5items)	• Water quality standard items(13items) •Salt concentration, etc.(4items)	•Chlorine ion, Sodium ion
Other Survey		•Constant monitoring of electric conductivity (Sukezukuri No.1)	•Constant monitoring of electric conductivity (Sukezukuri No.1,No.2, Isatomae)	•Constant monitoring of electric conductivity (Sukezukuri No.2, Isatomae)	• Constant monitoring of electric conductivity (Sukezukuri No.1,No.2,Isatomae)

(4) Electric conductivity measurement as an alternative indicator of chloride ion concentrations

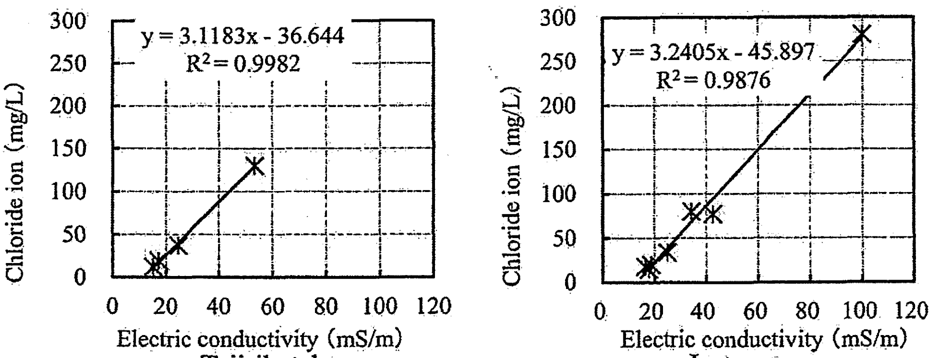
Figure 5 shows the correlation between the chloride ion concentration and electric conductivity. As the figure reveals there is a high correlation between the chloride ion concentration and electric conductivity, with the slope being about 3. This confirms that electric conductivity can be used as an indicator of the chloride ion concentration. The decision was therefore made to install compact electric conductivity meters at the water sources in thereby enabling constant measurement of the transition in the chloride ion concentration, being in addition to periodic manual analysis.



Sukezukuri No.1

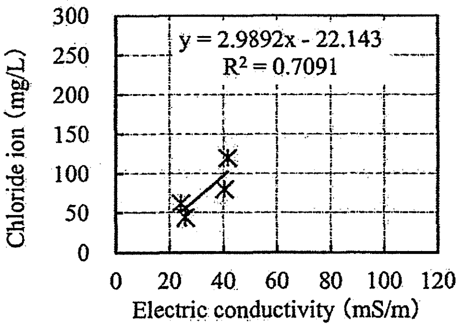


Sukezukuri No.2



Tajiribatake

Isatomae



Tokura

Figure 5. Correlation between chloride ion concentration and electric conductivity

3. RESULTS OF THE SURVEY

(1) Outline of the situation with contamination from nearby facilities.

The results of surveying the situation with contamination from nearby facilities are as follows:

a. Contamination from toxic substances

Surveys made by Minamisanriku-cho revealed the Sukezukuri No.1 and No.2 water sources to contain 0.002mg/L of arsenic immediately after the disaster (11 April, 2011). However, the first survey, which was conducted on August 2011, detected no toxic substances at all the water sources, and hence the increase in concentration was considered temporary and due to diastrophism from the disaster.

In thereby investigating the situation with contamination from radioactive substances released during the accident that occurred at the Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station the second survey measured the concentrations of 3 radioactive nuclides (namely Cs134, CsI137, and I131). The results revealed no radioactive substances (detection limit 10Bq/kg) and thus confirmed that there was no effect from radioactive substance contamination.

b. Contamination from pesticides or human excreta

The first survey that took place in August 2011 revealed no pesticides in any of the water sources. No anaerobic spore-forming bacteria, which indicate contamination from human excreta, etc. to have occurred, were detected either and the ammonium nitrogen level was less than 0.1mg/L. For this reason the possibility of the raw water having been contaminated by pesticides or human excreta was considered to be very low.

c. Contamination from gasoline

No petroleum components were identified in any of the water sources, thus confirming contamination from gasoline to be negligible.

d. Effects of water hardness on the piping

All the water sources were of higher hardness levels due to the effect of the seawater, thus making separation of the hardness components within the piping system a matter of concern. The Langelier Saturation Index was therefore calculated as part of the second survey. The results, however, were between -1.3 and -1.4, thereby indicating no separation would occur.

We concluded that none of the water sources had been contaminated by the nearby facilities. The results indicate that the water sources can be reused again once their chloride ion concentrations have decreased.

(2) Situation with the chloride ion concentration

Table 2 and Figure 6 reveal the trends of the chloride ion concentrations of the 6 water sources surveyed. After the disaster all the water sources had higher chloride ion concentrations than water quality standards allow for (200mg/L) due to the effect of the tsunami, but later on they gradually decreased, and 8 months after the disaster (November 2011) they were below the water quality standards at all the water sources.

The trend of a decrease, however, was not uniform. At the Sukezukuri No.1 and No.2 water sources the concentrations decreased exponentially, whereas concentration level at the other water sources significantly fluctuated for a while after the disaster. In addition, tests that took place after the heavy rain resulting from the typhoon of 27 September, 2011, revealed increased chloride ion concentrations at all the water sources. This then indicated the possibility of residual salt content in the soil having flowed into the underground water sources after the rainfall, thereby causing the chloride ion concentrations to repeatedly fluctuate.

At the Komori, Tajiribatake and Tokura water sources the chloride ion concentrations were below the water quality standard one month after the disaster (April 2011). At the Sukezukuri and Isatomae water sources, however, the concentrations had remained at relatively high levels. At the Sukezukuri water source, in particular, the concentration was about three times higher than before the disaster even 2 years after the earthquake (February 2013). This was considered likely to have resulted from the earthquake induced subsidence having caused the underground water source to have changed, thus leading to the water source being affected by the tide. If that were true then the chloride ion concentration may change in accordance with the change in tide level. Tidal changes include short-term changes in which the tide changes twice daily according to the Earth's rotation (daily change), mid-term changes which occur twice a month according to the revolutions of the moon (monthly change), and long-term changes of the period of one year according to the revolution of the earth (yearly change). The concentrations were likely to be affected by these tidal changes.

For this reason the assumption was made that the chloride ion concentration would fluctuate after rainfall or from tidal changes, and thus the decision was made to monitor the long term trend of the chloride ion concentration, and particularly at the Sukezukuri and Isatomae water sources where the chloride ion concentrations were high. The results of that are revealed on the following pages.

TABLE Ⅱ. Trends of chloride ion concentrations

Date	Chloride ion concentration(mg/L)					
	Shizugawa aria				Utatsu aria	Tokura aria
	Sukezukuri No.1	Sukezukuri No.2	Komori	Tajiribatake	Isatomae	Tokura
Before disaster (Average in 2010)	9	9	-	-	8	9
2011/3/26	302	-	-	545	248	239
2011/4/11	1330	1310	-	-	152	-
2011/4/18	921	980	22	70	127	-
2011/4/20	-	-	-	-	-	-
2011/4/25	826	990	164	144	-	-
2011/5/2	828	898	52	128	559	-
2011/5/11	815	776	23	55	238	-
2011/5/18	760	747	82	131	484	-
2011/5/25	707	726	29	-	225	-
2011/6/1	638	541	175	104	668	182
2011/6/8	611	503	99	160	325	211
2011/6/15	616	557	40	72	200	228
2011/6/21	531	419	25	49	134	212
2011/6/29	359	423	51	84	295	151
2011/7/6	417	392	53	57	205	-
2011/7/14	385	363	32	35	124	102
2011/7/22	332	314	31	27	87	-
2011/7/29	303	275	31	22	104	79

2011/8/11	240	190	26	19	80	62
2011/9/6	166	127	-	129	225	-
2011/9/27	220	160	160	130	280	120
2011/10/18	170	190	18	37	77	80
2011/11/14	150	150	-	12	34	44
2012/2/16	56	55	-	-	-	-
2012/3/22	71	-	-	-	-	-
2012/8/28	44	-	-	-	14	-
2012/10/16	35	-	-	-	15	-
2012/12/17	40	-	-	-	20	-
2013/2/26	29	-	-	-	18	-

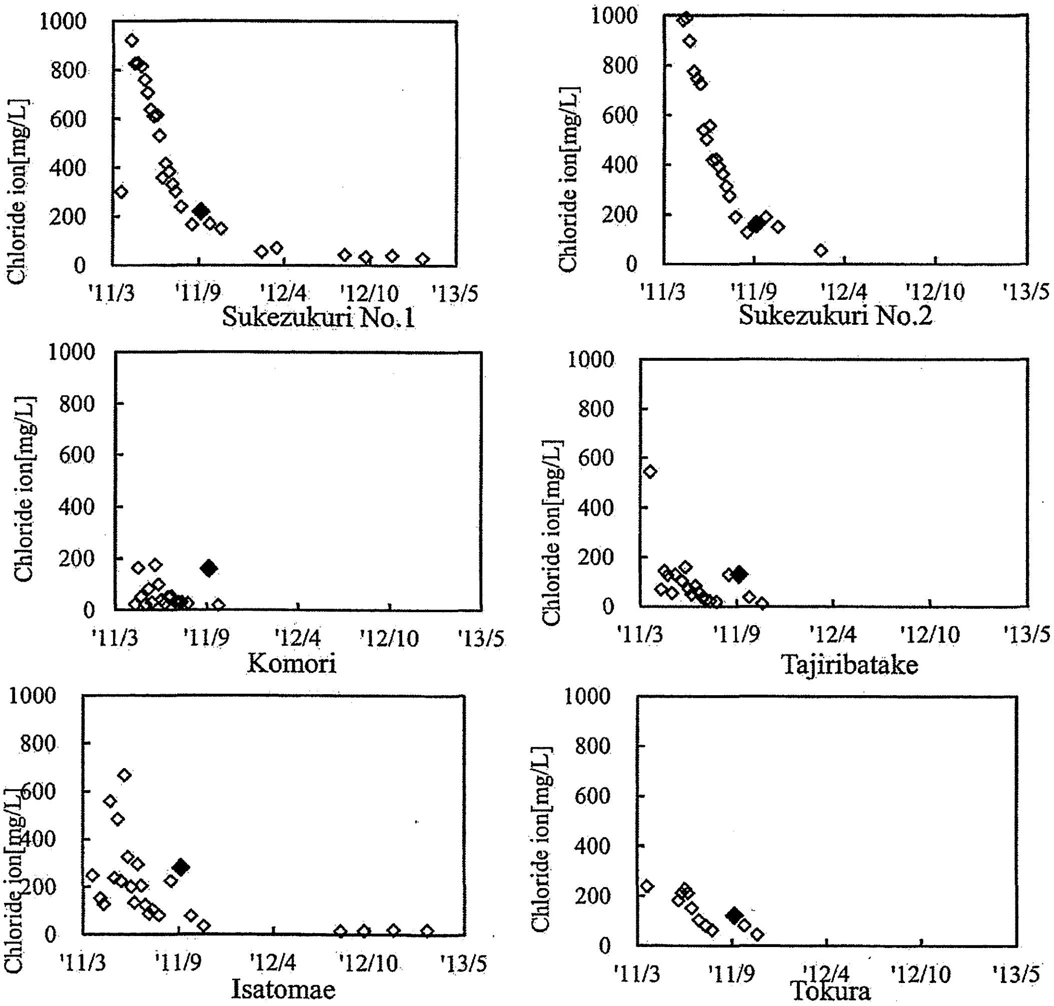


Figure 6. Trends of chloride ion concentrations
(Black mark indicates the data after the heavy rain resulting from the typhoon)

(3) Results of the surveys and future prospects with the water sources

a. Sukezukuri No.1 and No.2 water sources

Although the chloride ion concentration exponentially decreased at the Sukezukuri No.1 and No.2 water sources the level of concentration was still high when compared to other water sources, and still fluctuated around the water quality standards (200mg/L) 6 months after the disaster (November 2011). This was most likely to have been caused by the fact that the height above sea level near the Sukezukuri water source sank to the highest recorded historical tide level (1.6m) (according to a survey conducted by the Ministry of Land, Infrastructure, Transport and Tourism), thus causing the water source to be affected by the tide level. Therefore, and as an alternative indicator of the chloride ion concentration, we measured the electric conductivity of the Yahata River, which is close to the Sukezukuri water source. The result revealed the electric conductivity of the water source to be higher than that of the Yahata River, and thereby indicating the possibility of seawater reaching near the Sukezukuri water source (Figure 7).

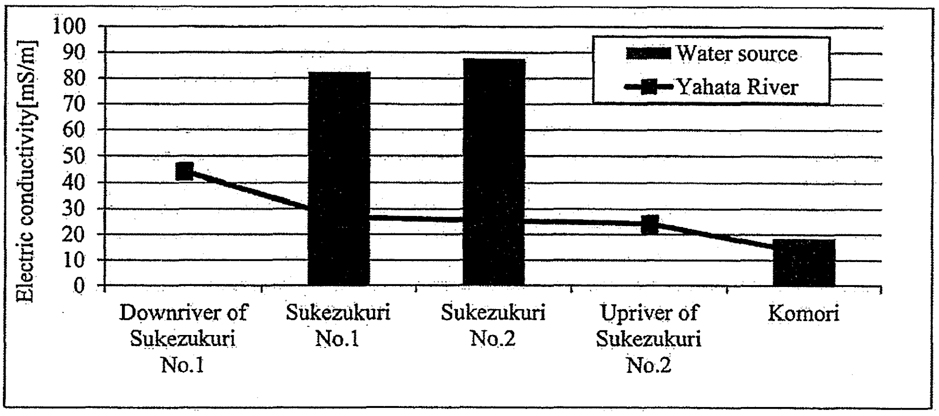


Figure 7. Electric conductivity at the Sukezukuri No.1, No.2, Komori water source and Yahata river(Located nearby these water sources) (measured on 18 October, 2011)

To measure the long term change in chloride ion concentration we installed an electric conductivity meter at the water source as an alternative indicator, and which enabled constant measurement of the concentration. Figure 8 shows the monthly fluctuations in the electric conductivity at the Sukezukuri water source and tide level, rainfall, and electric conductivity before the disaster (calculated from the chloride ion concentration before the disaster and based on the correlation equation provided in Figure 5).

Figure 8 reveals there to be no correlation between the electric conductivity and monthly tidal change, with the electric conductivity decreasing in a uniform manner. In addition, about 50 mm/day of rain fell on 3 December, 2011, but no change was observed in the electric conductivity, which then revealed that rainfall of about 50 mm/day had no effect on the electrical conductivity.

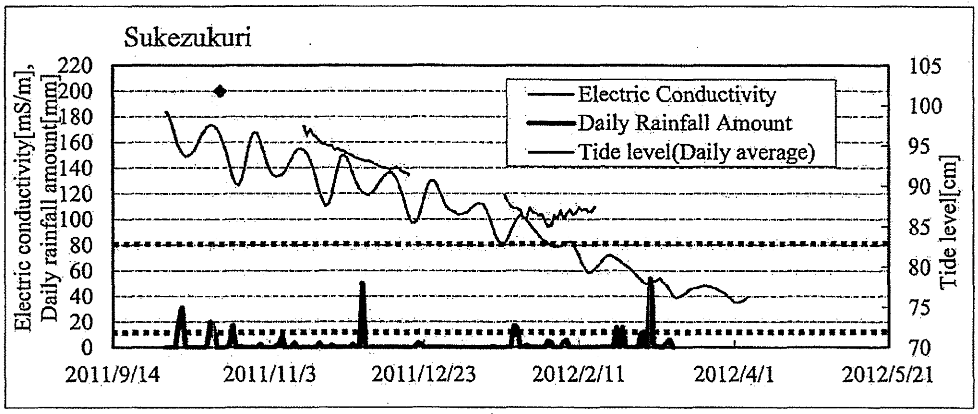


Figure 8. Electric conductivity of Sukezukuri water source, with rain fall amount(in Shidugawa) and tide level(in Ayukawa, daily average)※Black dotted line indicates electric conductivity at the water source before disaster, calculated from chloride ion concentration. Red dotted line indicates electric conductivity corresponding to water quality standard value of chloride ion.

Furthermore, the results of a survey on the correlation between the electric conductivity and annual change in tide level are shown in Figure 9. The results reveal that even in August, when the tide was at its highest level of the year, the electric conductivity didn't increase significantly and instead remained at basically the same level as in winter, or even lower, thus indicating that the tidal change has no major effect on the quality of water sources. Although no major change was recorded in the electrical conductivity during the above measurement period we weren't able to collect data during the heavy rain that fell in May and December 2012, and thus the effect of heavy rain has not been completely identified.

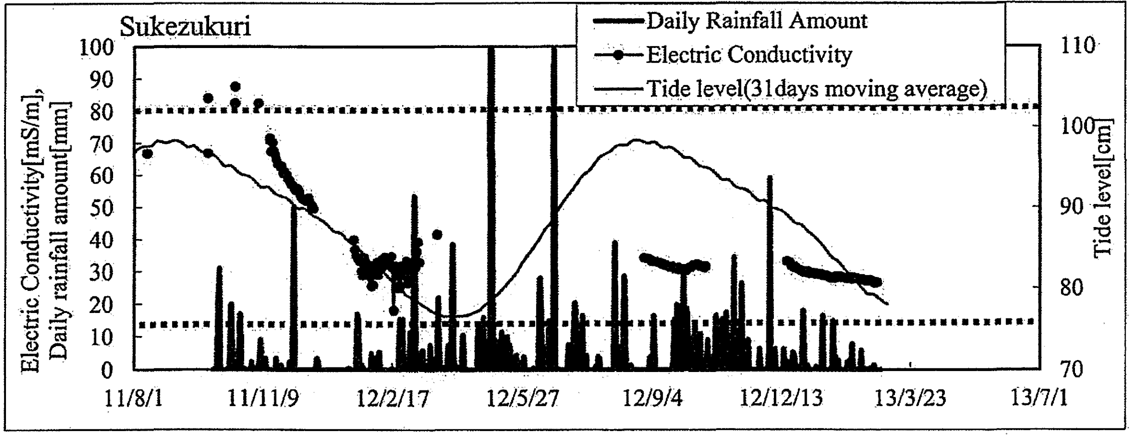


Figure 9. Electric conductivity at the Sukezukuri water source, with rain fall amount(at Shizugawa) and tide level(at Ayukawa, 31days moving average) ※Black dotted line indicates electric conductivity at the water source before disaster, calculated from chloride ion concentration. Red dotted line indicates electric conductivity corresponding to water quality standard value of chloride ion.

As revealed above, although the chloride ion concentration of the Sukezukuri water source was about three times higher than before the disaster the concentration level doesn't get significantly changed by a small amount of rainfall (about 50 mm/day) or via the tide level and it has been confirmed to be useable as a drinking water source as long as the chloride ion concentration doesn't significantly increase after heavy rain (100 mm/day).

b. Isatomae water source

After the disaster the chloride ion concentration level was way over water quality standards and continuously fluctuated. It then, however, started to decrease, although the fluctuation range of the chloride ion concentration was rather large, and the concentration level was near the water quality standard level (200 mg/L) 6 months after the disaster (September 2011). As with the Sukezukuri water resource, and to monitor the long-term fluctuations in the chloride ion concentration, we therefore installed an electric conductivity meter as an alternative indicator and constantly measured the concentration level.

Figure 10 shows the monthly fluctuations in the electric conductivity at the Isatomae water source and tide level, rainfall, and electric conductivity before the disaster (calculated from the chloride ion concentration before the disaster and based on the correlation equation provided in Figure 5). Figure 10 reveals there to be no correlation between the electrical conductivity and monthly tidal change, and the electric conductivity to have decreased in a uniform manner. However, a significant increase in the electric conductivity did occur during the rain that fell on 3 December, 2011 (about 50 mm/day). This therefore then confirmed that unlike the Sukezukuri water source the Isatomae water source is easily affected by rainfall.

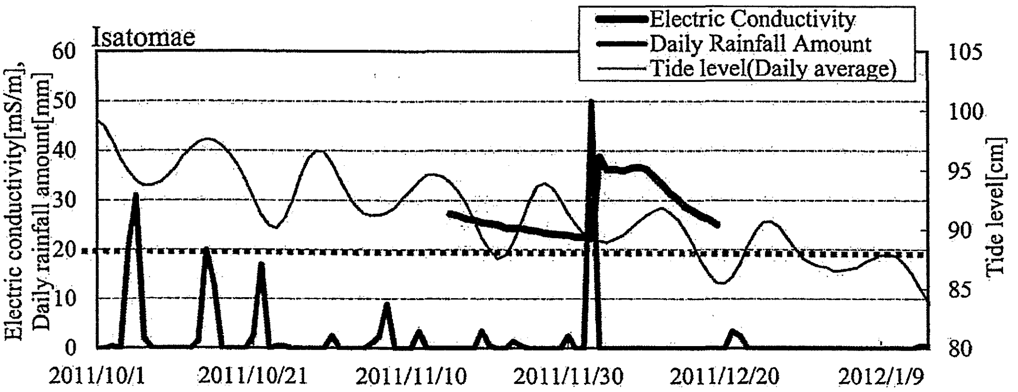


Figure 10. Electric conductivity at the Isatomae water source, with rain fall amount(at Shidugawa) and tide level(at Ayukawa, daily average)※Black dotted line indicates electric conductivity at the water source before disaster, calculated from chloride ion concentration. Red dotted line indicates electric conductivity corresponding to water quality standard value of chloride ion.

The results of a survey on the correlation between the annual fluctuations in electric conductivity and tide level and rainfall are shown in figure 11. The results reveal that even in August, when the tide was its highest level of the year, the electric conductivity didn't significantly increase and basically remained at the same value as in winter or even lower, thus indicating that the tidal change has no major effect on the quality of the water sources. As with the Sukezukuri water source we were unable to collect any data during the heavy rain that fell in May and December 2012, and hence the effect of heavy rain has not been completely identified.

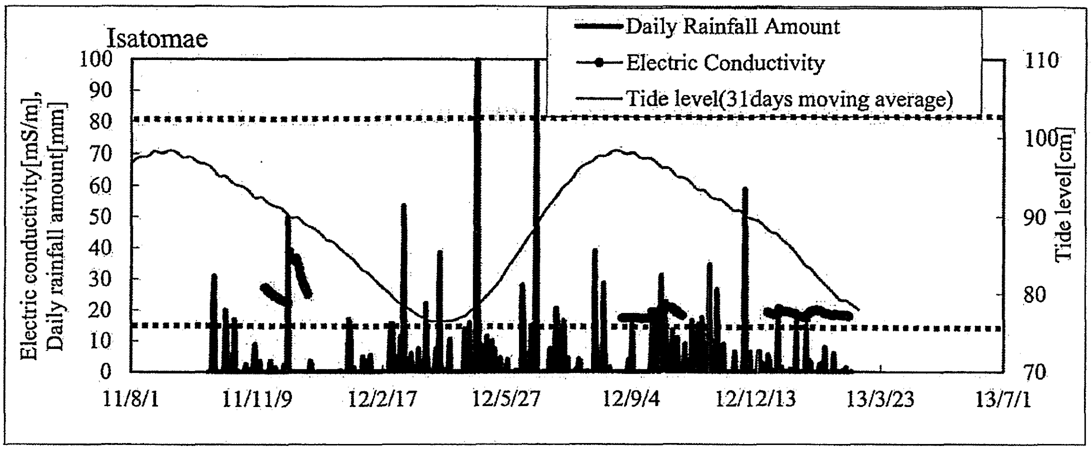


Figure 11. Electric conductivity at the Isatomae water source, with rain fall amount(at Shidugawa) and tide level(at Ayukawa, 31days moving average)※Black dotted line indicates electric conductivity at the water source before disaster, calculated from chloride ion concentration. Red dotted line indicates electric conductivity corresponding to water quality standard value of chloride ion.

As revealed above no significant change was observed to have resulted from the tide level at the Isatomae water source, and the chloride ion concentration has decreased to near the level it was before the disaster. The concentration is unlikely to be affected by small amounts of rainfall (50 mm/day), but the fluctuation in chloride ion concentration does need to be constantly monitored after heavy rainfall as it is easily affected by rainfall.

c. Komori, Tajiribatake, and Tokura water sources

The chloride ion concentrations at the Komori, Tajiribatake, and Tokura water sources repeatedly fluctuated but were less than 200mg/L at an early stage, and remained within the water quality standards level after heavy rain resulting from a typhoon. We therefore considered that no issue of concern exists about using them as drinking water sources and thus stopped surveying them in November 2011 (fourth survey).

4. CONCLUSION

The results revealed no contamination from nearby facilities apart from chloride ion concentrations at all the water sources. The reason for this, we believe, is that there are no factories close enough which deal with chemicals and oil. The chloride ion concentration had gradually decreased and reached below the water quality standard level at all the water sources by 8 months after the disaster. The trend of the decrease in chloride ion concentration, however, was not uniform, and some of the water sources (Sukezukuri and Isatomae water sources) were possibly being affected by salt entering them from nearby soil or because of the tidal level due to land subsidence. Further surveys revealed no significant changes to have been caused by the tide level, although they did indicate the possibility of the chloride ion concentration increasing again after heavy rainfall.

For this reason we consider all the water sources to be useable as drinking water sources under normal conditions. However, with the Sukezukuri and Isatomae water sources, whose chloride ion concentrations remain high, it will be necessary to constantly monitor the levels of concentration via measuring the electrical conductivity, and to ensure to identify the fluctuation range of the chloride ion concentration after any heavy rainfall.

Verification of a Prediction Method of Earthquake Damage to Water Supply Pipeline by Using Damage Data of the 2011 Great East Japan Earthquake

Masakatsu Miyajima, Masahiro Fujiwara

ABSTRACT

This paper deals with a prediction method of earthquake damage to water supply pipeline. The 2011 Great East Japan Earthquake caused extensive damage to water supply pipeline at not only Tohoku region but also Kanto region. The authors collect damage data of water supply pipeline and make a database of not only the damage but also the ground condition and peak ground velocity at the damage site. The authors already have made a database of damage to the pipelines in the 2004 Niigata-ken Chuetsu Earthquake, the 2007 Niigata-ken Chuetsu-oki Earthquakes with additional data from the 1995 Hyogok-ken Nambu Earthquake, and proposed an equation to predict earthquake damage to the pipelines. The present study verifies the equation proposed by authors by using the database of the damage of the 2011 Great East Japan Earthquake.

Since comparison between the damage predicted by using the present equation and the actual damage occurred at strong ground motion areas in the 2011 Great East Japan Earthquake shows good agreement, the present method is verified. The damage to pipeline in liquefied areas is, however, not explained precisely by using the present prediction method because liquefaction occurred extensively at the area of relatively low peak ground velocity such as Urayasu City in Chiba Prefecture. Modified prediction method of damage to pipeline in liquefied area is, therefore, proposed based on the database of the damage in the 2011 Great East Japan Earthquake in this paper.

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INTRODUCTION

The 2011 Great East Japan Earthquake caused extensive damage to water supply pipeline at not only Tohoku region but also Kanto region. The authors collect damage data of pipelines and make a database of not only the damage but also the ground condition and peak ground velocity at the damage site. The authors already have developed a database of damage to water supply pipeline in the 2004 Niigata-ken Chuetsu Earthquake, the 2007 Niigata-ken Chuetsu-oki Earthquakes with additional data from the 1995 Hyogok-ken Nambu Earthquake, and proposed a prediction method of earthquake damage to pipeline. The present study verifies the prediction method proposed by authors by using the database of the damage of the 2011 Great East Japan Earthquake.

Since comparison between damage predicted by using the present equation proposed by authors and actual damage occurred at strong ground motion areas in the 2011 Great East Japan Earthquake shows good agreement, the present method proposed by authors is verified. The damage to pipeline in liquefied areas is, however, not explained precisely by using the present equation because liquefaction occurred extensively at the area of relatively low peak ground velocity such as Urayasu City in Chiba Prefecture. Modified prediction method of damage to pipeline in liquefied area is, therefore, proposed based on the database of the damage in the 2011 Great East Japan Earthquake in this paper.

EQUATION TO PREDICT EARTHQUAKE DAMAGE TO WATER SUPPLY PIPELINE

Attributes of Damaged Pipelines

We collected data on damaged pipelines in Kobe, Ashiya, and Nishinomiya (the 1995 Hyogo-ken Nambu Earthquake; n = 2170, n is number of data); Nagaoka and Ojiya (the 2004 Niigata-ken Chuetsu Earthquake; n = 277); and Kashiwazaki and Kariwa (the 2007 Niigata-ken Chuetsu-oki Earthquake; n = 491). We developed a database of damage locations in a geographical information system (GIS) and sorted the data by pipe attributes (pipe type, joint type, pipe diameter). The GIS database exported 250 m × 250 m cell data for analysis. We also developed a database of the peak ground velocity and microtopography types (drawn from the Japan Seismic Hazard Information Station: J-SHIS).

Reference Damage Rate

The reference damage rate was calculated from the approximate curve obtained by the least-squares regression equation relating the damage rate and the peak ground velocity. Equation 1 shows the reference damage rate obtained here. The calculation conditions reflected the fact that almost no pipelines were damaged by recent earthquakes at a peak ground velocity of <15 cm/s, and were based on measured maximum velocities. The rate of earthquake damage was estimated by multiplying the equation for the reference damage rate by the correction factors described below:

$$R(v) = 9.92 \times 10^{-3} \times (v - 15)^{1.14} \tag{1}$$

where $R(v)$ = reference damage rate (locations/km)
v = maximum surface velocity of ground vibration (cm/s) ($15 \leq v < 120$).

Determining the Correction Factors in the Damage Prediction Equation

The values of the correction factors were determined using cross-tabulation and multivariate analysis based on mathematical quantification theory class I. The valuables of the multivariate analysis were the damage rate (locations/km) obtained from pipe type, joint type, pipe diameter and microtopography respectively. To calculate the damage rates, cross-tabulation was used. Damage locations were plotted on the pipeline map in the GIS, and the damage rate (locations/km) was obtained from the plot by pipe type, joint type, and pipe diameter. The damage rate by microtopography type was also obtained by superimposing the microtopography map on the plot. Then we analyzed the relationship of pipe type, joint type, pipe diameter and microtopography class with the damage rate. The damage rate is the target variable. Since it is affected in a complex manner by pipe type, joint type, pipe diameter and microtopography type, a multivariate analysis was performed to analyze how much each attribute affects the damage rate. The correction factor for an attribute with insufficient samples was determined by taking into account cross-tabulation analysis, engineering knowledge, and a conventional correction factor.

The effect of liquefaction on pipeline damage was assumed to be nearly constant, once it had occurred, and independent of microtopography type. Taking into account the relationship of the correction factor for liquefaction in the conventional damage prediction equation and the correction factor for each microtopography type proposed in this study, if there is a risk of liquefaction, the correction factor for liquefaction is set to 6.0 for all microtopography types.

Table 1 shows the correction factors and the pipeline damage prediction equation based on the reference damage equation.

EVALUATION OF DAMAGE PREDICTION EQUATION

Database of Damaged Pipeline in the 2011 Great Japan Earthquake

We collected data on damaged pipelines in Sendai (n = 365; n is number of data), Ishinomaki (n = 278) and Tome (n = 164) in Miyagi Prefecture, Urayasu (n = 321) and Asahi (n = 60) in Chiba Prefecture in the 2011 Great East Japan Earthquake, developed a database of damage locations in GIS and stored the data by pipe attributes (pipe type, joint type, pipe diameter). Miyagi prefecture is close to the epicenter and Chiba Prefecture is far from the epicenter but extensive liquefaction occurred in Urayasu and Asahi Cities. We also developed a database of the peak ground velocity and microtopography types (drawn from the Japan Seismic Hazard Information Station: J-SHIS).

Comparison between Predicted Number of Damage and Actual One

The accuracy of the damage prediction equation was evaluated against data from the database mentioned above. Figure 1 shows the relation between a predicted number of damage and actual one in each 250m x 250m cell in Ishinomaki. A solid line in this figure indicates the ratio of the actual number of damage to the predicted one is 1.0. The ratios of 0.5 and 2.0 are also indicated as dotted lines in this figure. 57.7% of all data are plotted between two dotted lines. So, comparison of the predicted number of damage with the actual one shows relatively good agreement. However, some plots locate at area above 2.0 of the ratio and below 0.5. 35.1% of all data are plotted at the area above