Establishing a 3D model of groundwater advection and diffusion at Fushimi ward in Kyoto basin

Takafumi Kitaoka [1], Makoto Nakamura [2] and Harushige Kusumi [3]

[1] Graduate school of Science and Engineering, Kansai University
E-mail : k111781@kansai-u.ac.jp
[2] Newjec Co.Ltd.
E-mail : nakamuramk@newjec.co.jp
[3] Dept. of Civil and Environment Engineering, Kansai University
E-mail : kusumi@kansai-u.ac.jp

Kyoto city has various traditional cultures and industries. One of them is the production of Japanese sake, for which Fushimi Ward in Kyoto is famous. The purpose of our study is to maintain the groundwater resource that supports the life and culture of people in Fushimi ward. Firstly, we measured the groundwater level and came to understand the groundwater properties in this area. Next, we analyzed the 3D simulation of groundwater while using those data. Having arranged the bore data, we then constructed an accurate stratum model necessary for analyzing. We then analyzed the seepage flow in order to reproduce the groundwater flow. Finally, we assumed how contamination occurred in groundwater by using the result of the seepage flow analysis with maximum accuracy, and subsequently carried out the advection and diffusion analysis. For the purpose of groundwater conservation, we would like to use this simulation model as a general assessment to protect the resource and the environment of groundwater.

1. INTRODUCTION

Fushimi Ward located in the south of Kyoto City is composed of the plains part surrounded by three rivers and the mountain range. Fushimi's groundwater has long supported Kyoto's traditional industries. One of them is the production of Japanese sake, for which Fushimi Ward in Kyoto is famous. This area has a plentiful supply of good quality groundwater suited to making Japanese sake, and consequently. As the survey area is a part of the Kyoto basin, it is considered to be rich in groundwater. The purpose of our study is to maintain the groundwater resource that supports the life and culture of people in Fushimi ward. Firstly, we measured the groundwater level and came to understand the groundwater properties in this area. Next, we analyzed the 3D simulation of groundwater while using those data. Previous research recreated the groundwater behavior over a wide area in the shallow-strata[1)]. In this research, we assumed how contamination occurred in groundwater by using the result of the seepage flow analysis with maximum accuracy, and subsequently carried out the advection and diffusion analysis. By doing the advection and diffusion analysis, we predicted how an assumed pollutant spreads in 5 years when pollution is generated in the concerned region. For the purpose of groundwater conservation, we would like to use this simulation model as a general assessment to protect the resource and the environment of groundwater.

2. GEOLOGICAL CONDITIONS

Fig.1 shows the geologic map of the surrounding examined region[2)]. Kyoto basin is surrounded by

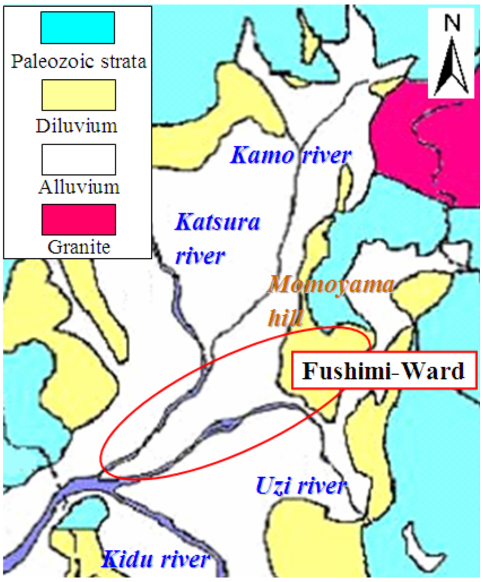

Figure 1 Geologic map of Kyoto

mountains formed by a bowl shaped depression in the paleozoic stratum and granite. The paleozoic strata basin rock is an impermeable bed upon which there is a permeable, diluvial layer and then alluvial layer. In the strata of the Kyoto basin, in the majority of areas a gravel layer can be seen. The area above this is covered by fine-grained soil (sand, silt and clay). The N-value of the gravel layer is, as a rule, greater than 50. In the geological structure of the subject area a gravel layer corresponding to the diluvial layer has build up. This is covered by an alluvial layer of a depth of approximately 10 meters.

3. GROUNDWATER PROPERTY

(1) Introduction

Fig.2 shows the expansion of the area around Fushimi Brewery companies. We set up 27 observation wells in this area. And, we set the auto-water meter in 27 places. In this area there are about 50 pumping wells providing water for sake-making. Based on the measurements, water level fluctuations in the comparatively shallow aquifers in which underground structures exist, and deeper aquifers in which pumping takes place were investigated. Based on these measurement results, it was confirmed whether shallow strata groundwater is influenced by pumping or not.

(2) Soil profile

In order to establish the structure of the strata of the area under examination, we made a cross-section map from the boring data. Fig.3 shows the area covered by the soil profile. Fig.4 shows the soil profile. We then, based on the soil profile, divided the strata into aquifer and aquiclude strata. From the ground surface we defined the aquifer strata as Dg1, Dg2 and Dg3 and the aquiclude strata as Dc1, Dc2 and Dc3. Layers deeper than this are treated as the deepest layer and a mixture of aquifer and aquiclude. Further, by marking the position of the strainers we were able to establish which aquifer strata the wells were pumping from, and which strata's water level changes the observation wells were measuring.

(3) Pumping discharge

Fig.5 shows the per aquifer stratum average daily pumping amounts from each brewery well. It was established that there is a lot of pumping in the Dg3 stratum that has a depth of 50 meters. In particular, 70% of pumping was from areas west of the Shintakase river.

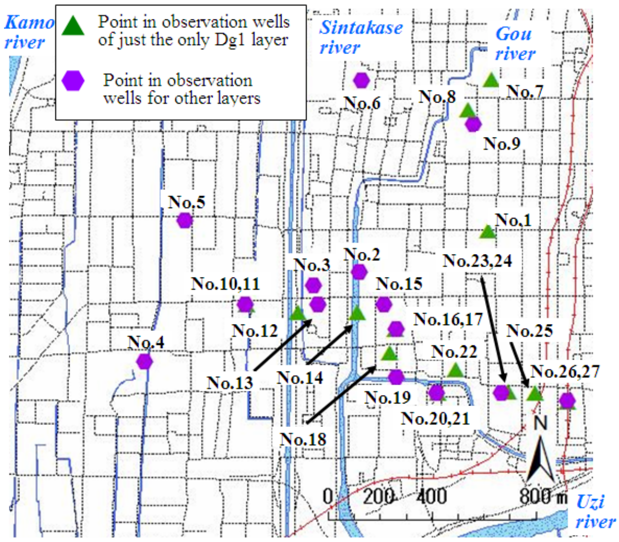

Figure 2 Location of observation wells

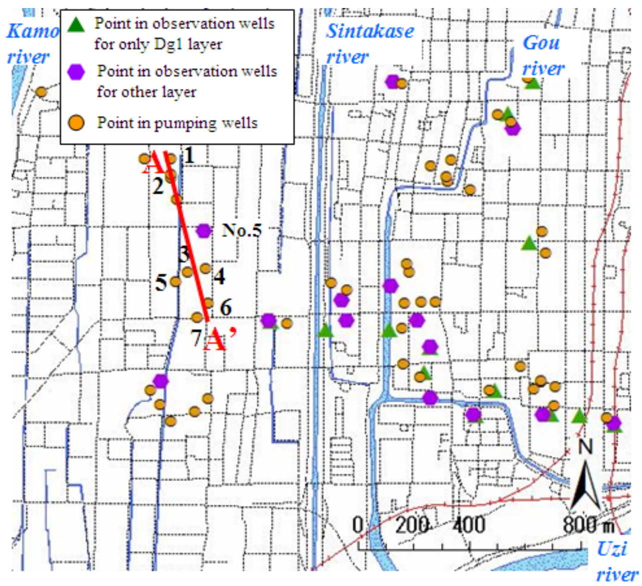

Table 3 Location of soil profile

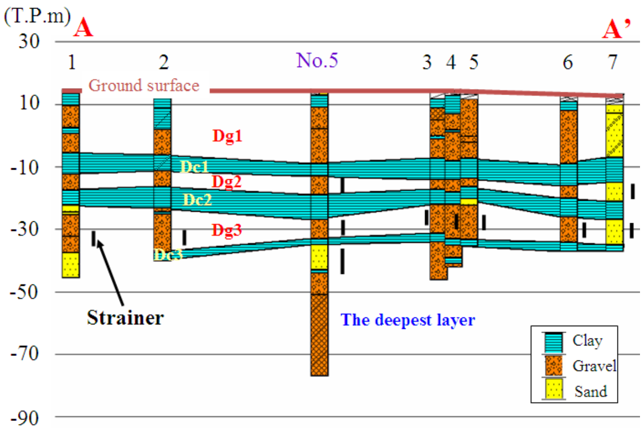

Figure 4 Soil profile

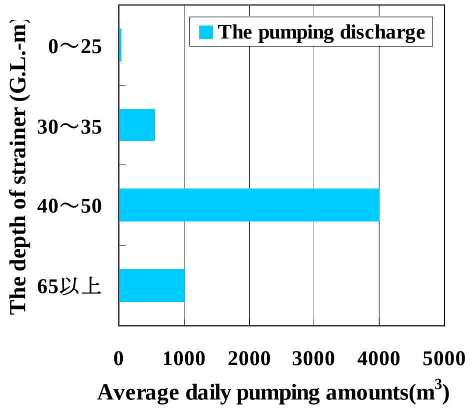

Figure 5 Average daily pumping amounts

(4) Water level changes in observation well

Fig.6 shows the relation between water level changes and rainfall in No.7 which has a strainer in Dg1. It can be seen from the graph that groundwater levels are influenced by rainfall. In the high rainfall period between late-May and mid-July, water levels increase markedly. Groundwater levels decrease corresponding with the decrease in rainfall after the rainy season. Fig.7 shows the relation between water level changes and rainfall in No.2 which has a strainer in the deepest layer. As the aquifer strata are influenced by pumping, water level changes can be seen. A shared property of the groundwater of the Dg1 strata in this region is that they are heavily influenced by rainfall. A shared property of the groundwater of the Dg2, Dg3 and deepest strata is that on days when pumping is not held, their levels stabilize. It is seen that water level changes in the western area, where pumping is most intense, are greatest. The margin of the water level changes varies depending on the location of the strainer doing the measuring, the amount of water being pumped in the surrounds and the distance between the measuring and pumping wells. Daily changes in this regions water level cannot be seen in the Dg1 aquifer strata. In other words, it can be taken that vertical flows due to pumping in the Dg1 strata are limited.

4. SEEPAGE FLOW ANALYSIS

(1) Introduction

In the past research, having arranged the bore data, we then constructed an accurate stratum model necessary for analyzing. Utilizing the model created through a seepage flow analysis considering saturation and undersaturation due to the finite element method, we recreated the groundwater flows of the entire target area. The ground-property values necessary for the analysis were established by repeated trial and error, until the measured water levels and analysis levels matched. The boundary of the model is set referring to the topographic map of three rivers and divides. Fig.8 shows the result of the seepage flow analysis of the wide-area model as the groundwater contour line. Roughly speaking, the groundwater flows toward the part where two rivers joined from a northeastern hilly district. The next step is to predict the behavior of the pollutants which are the cause of concern. However, given the calculation time and roughness of the mesh, an advection / diffusion analysis using a wide-area model cannot be expected to be particularly accurate. In order to increase the accuracy, we created a narrow-area model at locations pollutants will be added, subdividing the mesh and re-performing the seepage flow analysis on the narrow-area model.

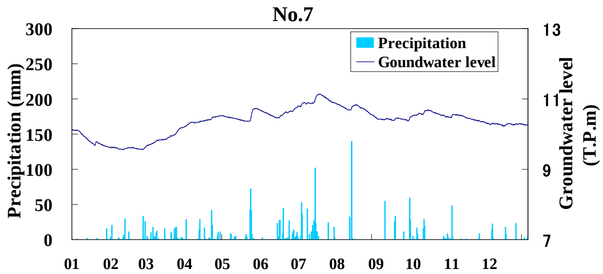

Figure 6 The amount of the rainfall and groundwater level of No.7

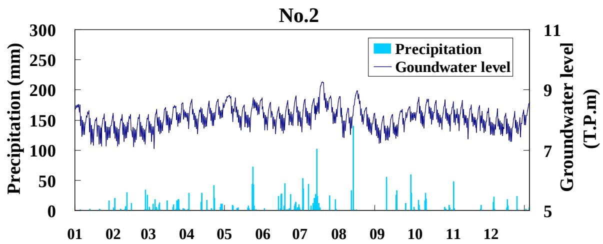

Figure 7 The amount of the rainfall and groundwater level of No.2

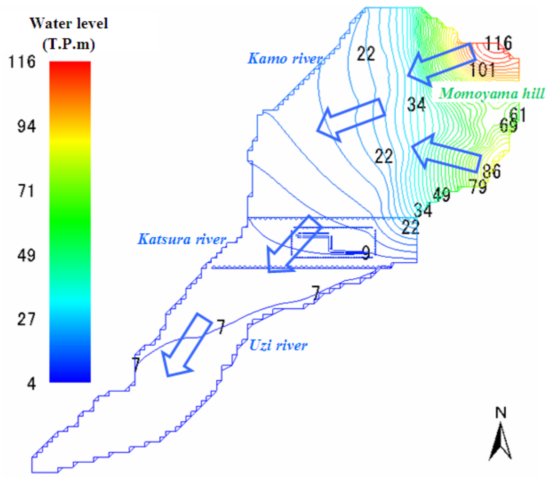

Figure 8 The results of the wide-area model

(2) A narrow-area model

Fig.9 shows the location of a narrow-area model. We stress that there are no pollutants actually being produced in these areas. Fig.10 shows the 3D mesh model. The number of nodes of analytical meshes is 30,027, and the number of elements is 27,133. Fig.11 shows the 3D stratum model. The stratal data came from the values established when making the wide-area model. The stratal data came from the values established when making the wide-area model. We examine down to the Dc1 layer which is assumed to be a comparatively shallow aquiclude stratum, with a depth of about 30m in plains / field areas. Based on T.P.-20m, we set a Dc1 layer at the bottom of the model under the alluvium and the Dg1 layer. The results of advection / diffusion analysis indicate that if pollutants do not spread to the lowest part of the model, the possibility of pollutants from the Dg1 strata seeping into the aquifer in which pumping is performed is low.

(3) Ground physicality parameter

Table.1 shows the ground physicality parameter. The soil-properties used were the same as those from the wide-area analysis. Although we are performing an analysis which considers saturation and undersaturation, at the current stage we are not examining the influence of the undersaturation characteristics on the results.

Table 1 Ground physicality parameter

	Coefficient of permeability (cm/s)	Specific storage (1/m)	Effective porosity (%)
Alluvium	5.00×10^{-4}	1.10×10^{-3}	10
Dg1	5.00×10^{-3}	7.10×10^{-6}	20
Dc1	5.00×10^{-5}	1.80×10^{-4}	10

(4) Boundary conditions

The boundary conditions were set using the water levels calculated from the wide-area model seepage flow analysis as a prescribed water head boundary to the north, south, east and west. As a result, in-flows were seen in the north side and east side. Accordingly, in the north side and east side condition as the prescribed flux condition, we set the flow rate values obtained from the analysis results using the prescribed head boundary. We re-performed the analysis. We set the rainfall values to surface nodes as a rainfall seepage boundary. In general, it is said that the amount of recharge of groundwater was about 29-33% of the rainfall. From this reason, the amount of recharge of groundwater is set at 30%.

(5) Result

Fig.12 shows the result of the 3D seepage flow analysis using the narrow-area model. From the analysis results we established that the groundwater flows from north-east to south-west, and were able to recreate more detailed flows. Due to the influence of the boundary conditions, the water flow velocities in the north-east and south-west regions of the model are overly-fast. In order to avoid this we add the pollutants in an area uninfluenced by the boundary conditions, where an appropriate flow velocity distribution can be established.

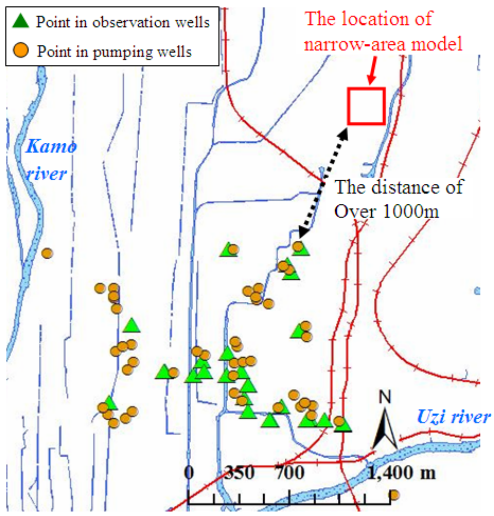

Figure 9 Location of narrow-area model

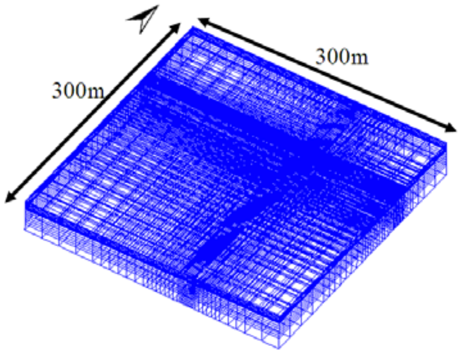

Figure 10　3D mesh model

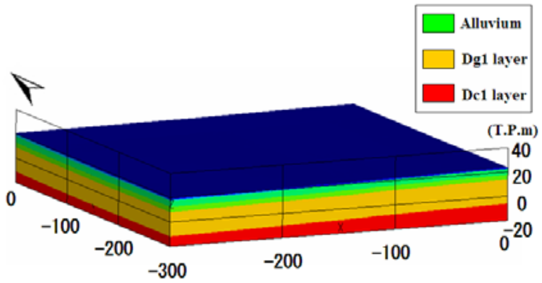

Figure 11　3D stratum model

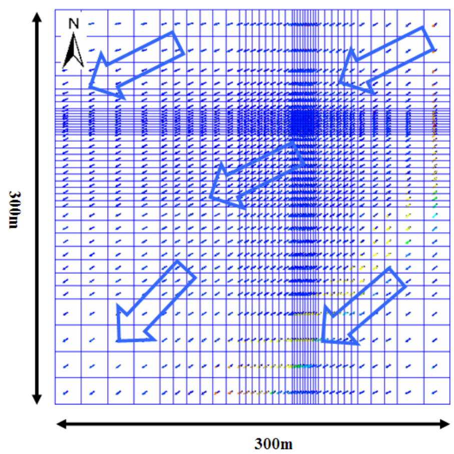

Figure 12　The result of the narrow-area model

5.　ADVECTION DIFFUSION ANALYSIS

(1) Introduction

In the Fushimi Ward area, we set a pollution outbreak and using the narrow-area model we performed a 3D advection / diffusion analysis. The present study predicts how 1 p.p.m source of the contamination spreads in 5 years in the Dg1 layer. As pollutants we used iron which in high-concentrations is undesirable for brewing, and Trichloroethylene, a volatile chloride compound. When iron/manganese levels increase problems such as 'worsened water quality' and 'increased coloring and turbidity' have been reported from each well.

(2) Ground physicality parameter

Table.2 and Table.3 shows the ground physicality parameter. Table.4 shows the representative chemical properties of iron and manganese. As establishing the material-properties of iron necessary for the advection / diffusion analysis is difficult, we used those of the chemically very similar manganese. As the period of manganese and iron is the same, their chemical traits are similar. Further, it is said that manganese often occurs together with iron.

Table 2　Ground physicality parameter

	Alluvium	Dg1	Dc1
DL	1.0	1.0	1.0
DT	0.1	0.1	0.1
Tortuosity	1.0	1.0	1.0
Effective porosity	10	20	10
Soil density	1.65	1.65	1.65

Table 3　Ground physicality parameter

	manganese	Trichloroethylene
Dispersion coefficient	5.0	0.15
Coefficient of molecular diffusion (ml/g)	1.725×10^{-2}	1.725×10^{-2}

Table 4　Chemical character

	manganese	iron
Atomic number	25	26
Atomic weight	54.94	55.85
Specific gravity	7.2	7.85

(3) Result

Fig.13 shows the initial state supposing the presence of pollutants. Fig.14 shows the result of manganese. Fig.15 and Fig.16 show the comparison of the concentration over time in the horizontal and vertical. In the horizontal direction, the extent of manganese contamination would expand to over 20m in the space of 5 years. In the vertical direction, compared to horizontal flows, the speed of downward flows is 2 orders lower, and it is estimated that it doesn't diffuse at a rate greater than 3 meters per 5 years. Fig. 17 shows the result of trichloroethylene. Fig. 18 and Fig. 19 show the comparison of the concentration over time in the horizontal and vertical. In the horizontal direction, the extent of manganese contamination would expand to over 70m in the space of 5 years. In the vertical direction, compared to horizontal flows, the speed of downward flows is 2 orders lower, and it is estimated that it doesn't diffuse at a rate greater than 5 meters per 5 years.

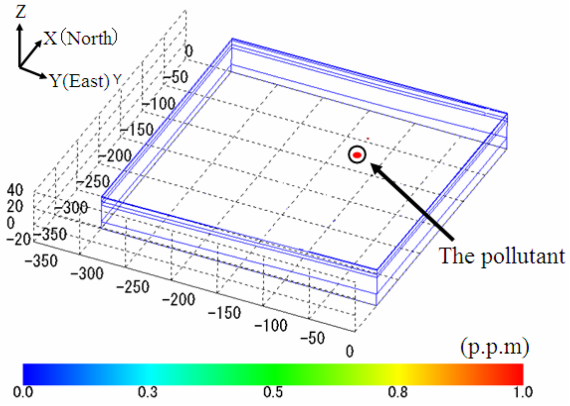

Figure 13 The initial state

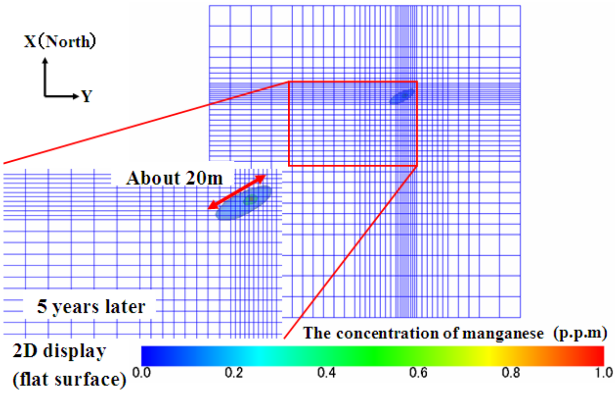

Figure 14 The results of mangneses

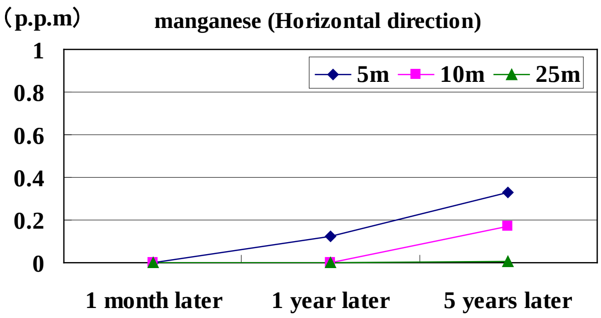

Figure 15 The concentration and time

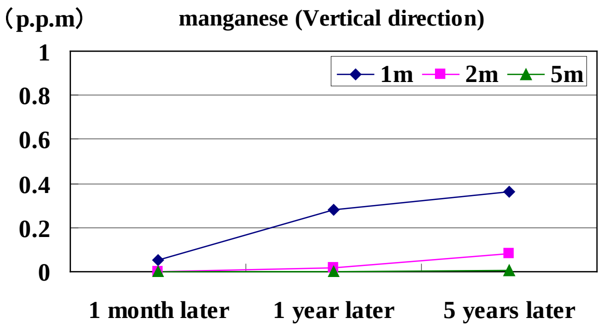

Figure 16 The concentration and time

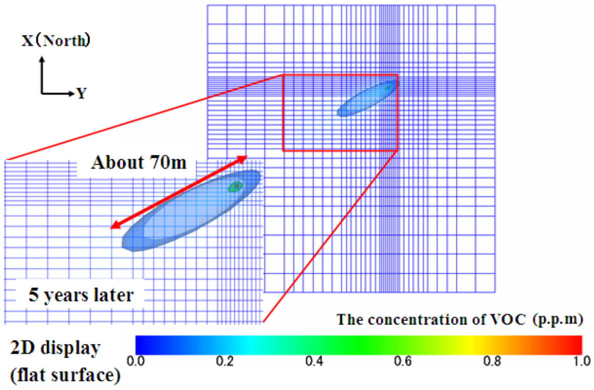

Figure 17 The results of VOC

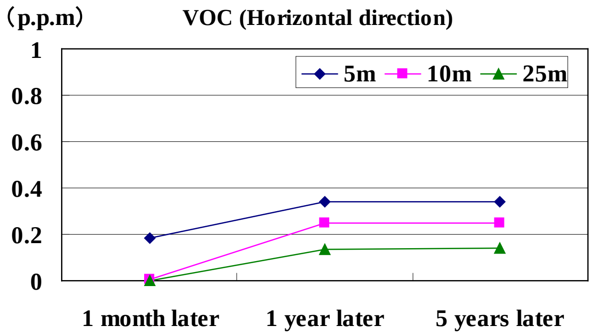

Figure 18 The concentration and time

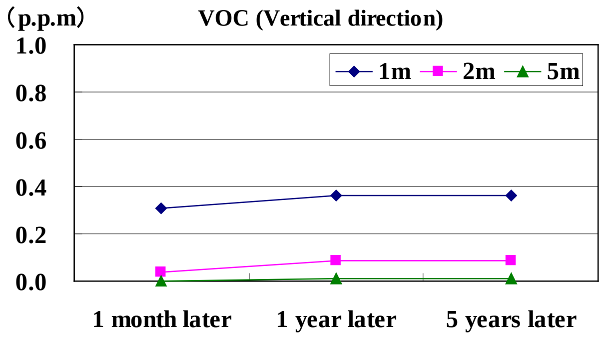

Figure 19 The concentration and time

3. CONCLUSIONS

Brewing utilizing groundwater has prospered in Fushimi Ward for many years. This research has focused on the Fushimi region which has long supported sake-brewing, a traditional industry of Kyoto. The results of this research are as per bellow. The groundwater in this area contains little iron and therefore suitable for making sake. Due to this, there are fears about a rise in iron concentrations due to the elution from underground structures. Through this research we established that the range of behavior of iron in this region is small. Further, as between the aquifer containing the underground structures, and the aquifer in which pumping is performed, there is a generally continuous clay aquiclude stratum, there is a low risk of an increase in iron concentration due to elution from underground structures in strata deeper than Dg2.

REFERENCES

Kitaoka, T., Kusumi, H. (2010): Examining the effects on Underground water levels of a subterranean construction using a 3D management model for underground water in Kyoto-City, Japan, Proc. of EIT-JSCE Symposium on Engineering for Geo-Hazards: Earthquakes and Landslides-for Surface and Subsurface Structures.

Kusumi, H., Nishimaki, S., and Furumiya T . (1995): Study on Actual Using Condition of Groundwater Resources in Minamiyamashiro District at Kyoto Prefecture, Proc. of Journal of groundwater hydrology, Vol.37(1), pp.55-67.