A Feasibility Study on the Water Quality Improvement by Making Use of Underground Water in Hakata Bay

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***Abstract*- Hakata Bay is an enclosed bay adjacent to Fukuoka City and the eutrophication of the bay water has been getting serious by the sewage contamination in recent years. In this study, we propose a plan to improve the water quality by making use of the underground water upwelling by plunged pipes into the bottom of the bay. The density of the underground water is smaller than sea water that the vertical circulation and the upwelling of the bottom water by the entrainment effects will be generated in the bay, which may improve the water quality of the bay. Field measurement results of the water quality and the quantity of the underground water together with the laboratory experiments and numerical simulations of the diffusion of the underground water in the bay are presented in this paper.**

I. INTRODUCTION

Hakata Bay is an enclosed bay adjacent to Fukuoka City. Its sea area is 126.1km^2 and the mean depth is 10.7m and the volume of water is 1346.6×10^6m^3. The eutrophication of the bay water has been getting serious by the sewage contamination in recent years. Abnormal growth of sea lettuce from September to November creates an environmental problem of the bay by the bad smell when the sea lettuce decays at the end. The hypoxia water is created in the sea bottom in summer, which is caused by the consumption of oxygen in the bottom layer. To solve this problem, the dredging sludge of the entire bay is needed but it is not realistic because of the area of the bay.

In this study, we propose a plan to improve the water quality by making use of the underground water upwelling by plunged pipes into the bottom of the bay. The pull up method of groundwater is not difficult, if we plunged a long pipe into the sea bottom until the end of pipe reaches sand-layer under the thick mad layer of about 8m, then the groundwater comes up spontaneously through the pipe. We tested at 5 spots using PVC (polyvinyl chloride) pipes in the bay and we measured the flux of the groundwater, temperature, salinity, dissolved oxygen and water quality of the groundwater.

Through field measurements of the groundwater, we found that the flux depends on the sea level, which might be explained by the reason that the groundwater was lifted up by the difference of the pressure heads between groundwater and sea water. We applied the Darcy's law for seepage flow. We determined the permeability coefficient from the observation data and estimated the flux of underground water per pipe was about 1 m^3/day.

The results of water quality of the groundwater are presented in figures, where the temperature of groundwater was stable throughout the year and it was around 19 degrees C and the salinity of the groundwater was around 15 PSU almost half of sea water, therefore the density of the groundwater was smaller than sea water even in summer. The DO was very low and the nutrients were rich compared with the bay water.

We tried to simulate the diffusion of the groundwater in the bay. Because, the groundwater comes up from the bottom therefore the non-hydrostatic model is needed. Our interests are the diffusion process in wide area in the bay, and then we applied the MEC Ocean model, which consists of two models, hydrostatic model in wider area and non-hydrostatic or full-3D model in small domain. The small area of 100m by 100m was analyzed by the full-3D model and the entire bay was covered by the hydrostatic model. We considered the tide at the open boundary. The numerical results of the salinity distribution in the vertical plane and the horizontal plane after 68 hours from the discharge of groundwater are presented by the graphics.

II. SAMPLING OF GROUND WATER AND WATER QUALITY[1)

A. Experimental site and the method

Location of the observation and sampling groundwater, which was started from 2005, was under the Bridge between Uminonakamichi and Island City in Fig.1. The length of the

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bridge is about 600m. Our observation site was about 15m from the North end of the bridge, where the water depth was about 3m. According the Shirouzu[2], the ground structure under the sea bottom is consisted of the silt layer of about 10m thickness and the Suzaki sand layer under it. Suzaki sand layer is thought to spread along Umi and Sue-rivers at the East, and Naka-river at the West, and it appears at the ground surface near Dazaifu city, approximately 20km south of Hakata Bay[3]. Therefore, the groundwater permeates from the ground surface through Suzaki sand layer.

Fig.2 shows five spots of the pipes to make upwelling the groundwater through the PVC pipes of 65 mm diameter, with some drilling holes at the bottom end as the strainer. Setting the pipes at the site was relatively easy, because the sea bottom was covered with the soft sludge that the pipe easily penetrated the soil by using high pressured water jet from top side of the pipe.

Sampling the groundwater was conducted by the flexible pipe and a small electric-pump. The groundwater was stored in the bucket on the ship and it was contained in the bottle. The CTD (Conductivity, Temperature, and Depth) and DO (Dissolved Oxygen) of the groundwater were measured in the bucket.

B. Measurement of quantity of upwelling groundwater

The quantity of upwelling groundwater per unit time was not so much that it was measured by direct collection of groundwater per one minute by a flexible bag from the top of the pipe in water. The observation date was selected November 22, 2006 in a flood tide, since the quantity of the groundwater seemed to have relation of the tidal level of the bay.

Fig.3 shows the quantities per one minute from 5 pipes. There was big difference between G2, G5 and G1, G4, but the reason was not clear. It may be the penetration condition of pipes into the sand layer. As shown in Fig.3, the upwelling groundwater was more quantity as the tidal level was lower, because it is driven by the difference of pressure head of sea water and the groundwater at the site. We assumed the following Darcy's low for permeable flow:

$$q = -K\partial h/\partial x = K_a(\zeta_0 - \zeta) \quad (1)$$

where K : permeability coefficient, $\partial h/\partial x$: hydraulic gradient, K_a : upwelling coefficient, ζ_0 : groundwater level, ζ : sea water level

From the observation results of G2, G3 and G5 in Fig.3, we obtained $K_a = 1.96 \times 10^{-3}(s^{-1})$. The maximum quantity of groundwater was 1000 cc/min which was equivalent to the flow velocity of 5mm/s.

Next, we estimated the groundwater quantity per day by (1). Results were depending on the tidal condition as follows:

1) 1,062 l/day on flood tide
2) 1,195 l/day on neap tide

Fig.1 Observation site in head of Hakata Bay

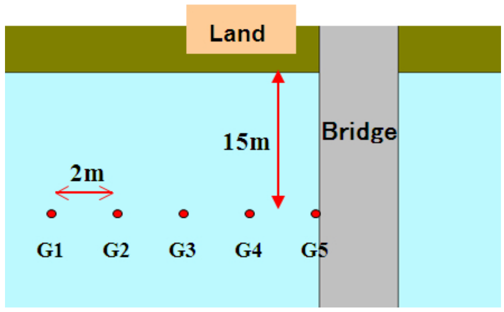


Fig.2 Observation points of sampling water

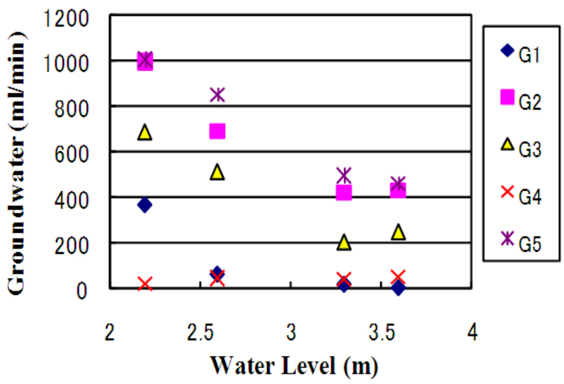


Fig.3 Water level vs. amount of groundwater at the site

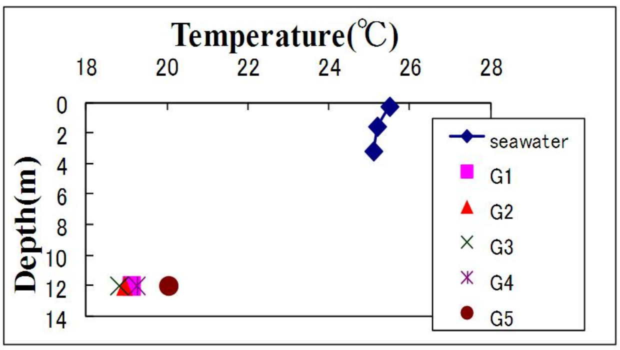


Fig.4 Temperature of seawater and groundwater at the site

From these results, we can say that groundwater is upwelling approximately 1 m^3 /day by a pipe of 65mm diameter, if the pipe penetrates into the sand layer firmly.

C. Physical properties and DO of groundwater

Fig.4 shows the distribution of the temperature of seawater and groundwater in depth from sea surface observed September 7, 2006. The temperature of groundwater was lower than seawater by 5 degrees C in this case but it was found that the groundwater temperature was stable over the year from other observation results. Fig.5 shows the distribution of salinity of seawater and groundwater. The salinity of groundwater was found to be almost half of the seawater in Fig.5.

Fig.6 shows the density of seawater and groundwater calculated from the temperature and salinity. As shown in Fig.6, the density of groundwater was smaller than seawater. The reason is clear that the salinity of groundwater was almost half of seawater. This was the result of summer season but the same thing is true over the year, because the seawater becomes heavier in winter by the decrease in temperature. Therefore, we can expect the vertical circulation of seawater throughout the year if the groundwater is upwelling from the sea bottom.

Fig.7 shows the concentration of DO of seawater and groundwater. We understand the groundwater was hypoxia which was harmful to the benthos in bottom soil, but fortunately, the groundwater may come up to water surface in a short time because it is lighter than adjacent seawater.

D. Water quality of groundwater and seawater

Fig.8 shows the distribution of the concentration of the ammonia nitrogen (NH_4-N), which was sampled in September 7, 2006. The concentration of the groundwater was found to be almost 10 times higher than seawater, which is usually bad for the water quality of the bay. On the other hand, Fig.9 and Fig.10 show the concentration of the nitrite (NO_2-N) and nitrate (NO_3-N) nitrogen. The groundwater was found lower than seawater with respect to nitrite and nitrate nitrogen.

Fig.11 shows the concentration of phosphate phosphorus (PO_4-P) of the groundwater and seawater. Although the concentration of the groundwater scattered depending on the spot, the concentration of groundwater was lower than seawater except G4, where the quantity of groundwater was very small.

Fig.12 shows the concentration of total nitrogen (TN) consisting organic and inorganic nitrogen. Referring to Figs.8, 9 and 10, we understand that most part of TN was occupied by inorganic nitrogen. On the contrary, Fig.13 shows the concentration of total phosphorus (TP). Comparing it with Fig.11, we understand the most part of TP consisted of organic phosphorus. From these results of water quality, the age of groundwater was much older than seawater, because of the DO and the composition ratio of the inorganic nitrogen.

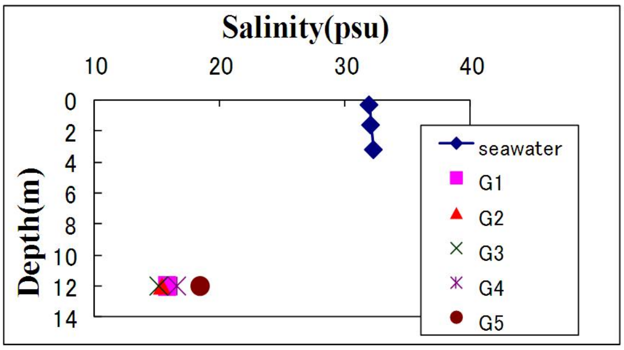


Fig.5 Salinity of seawater and groundwater at the site

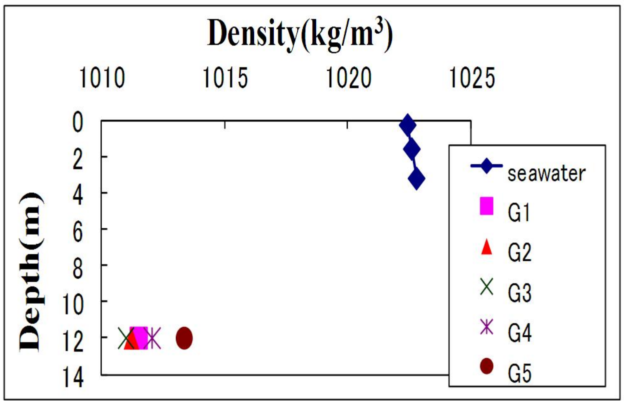


Fig.6 Density of seawater and groundwater at the site

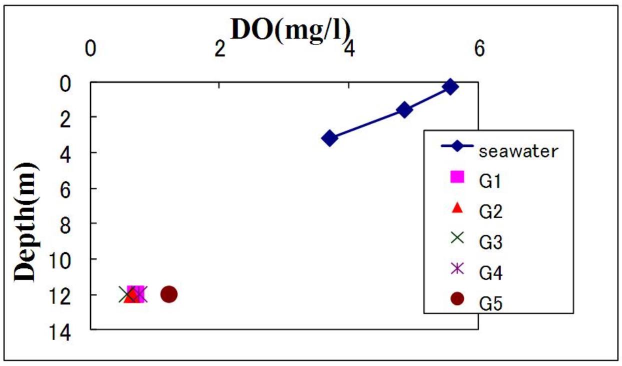


Fig.7 DO of seawater and groundwater at the site

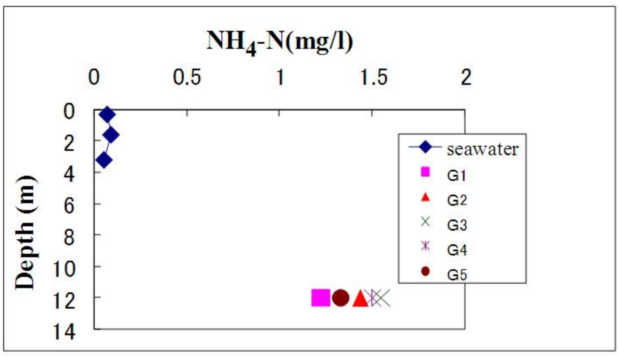


Fig.8 NH_4-N of seawater and groundwater at the site

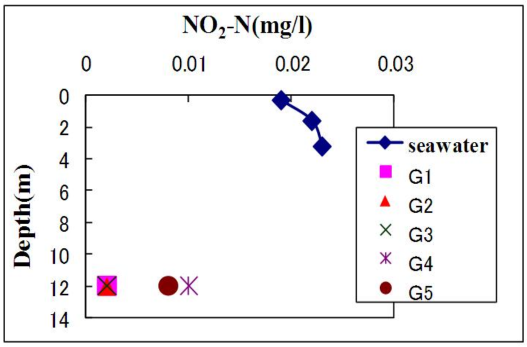


Fig.9 NO_2-N of seawater and groundwater at the site

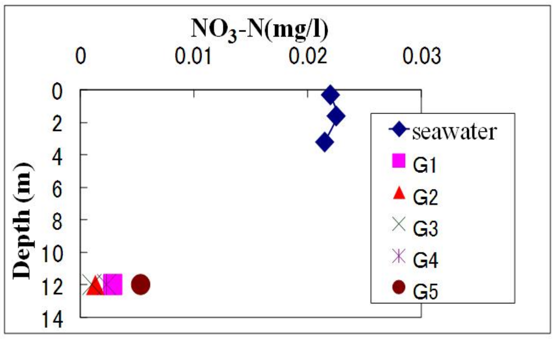


Fig.10 NO_3-N of seawater and groundwater at the site

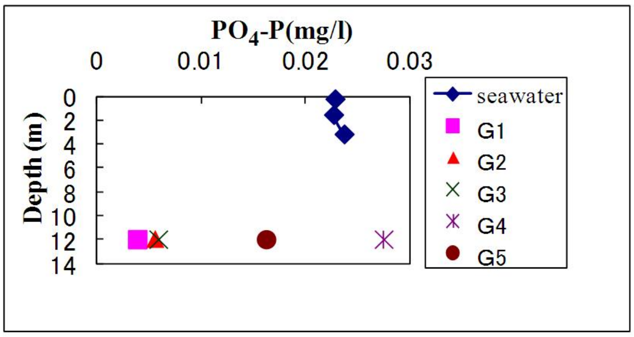


Fig.11 PO_4-P of seawater and groundwater at the site

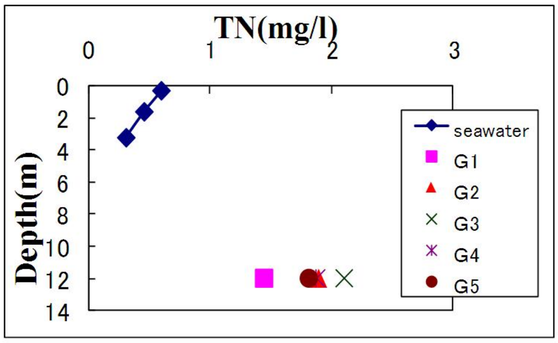


Fig.12 TN of seawater and groundwater at the site

III. Diffusion experiments of low density water from bottom in a circulating water channel[6)]

We tried to observe the diffusion of low density water from bottom in a circulating water channel since it would be difficult to see how the groundwater diffused in the real sea. It would help us to understand the phenomenon and to check our numerical simulations.

The experiments were conducted in a circulating water channel of the Institute for Applied Mechanics, Kyushu University, the size of the observation part is as follows: L x B x D = 4.4m x 1.5m x 1.6m. Fig.14 shows the outline of experimental setup, a narrow channel of 0.4m breadth was made by the white plate (2m x 1m) in the back of observation window. The bottom plate was also set by the white plate in the narrow channel. Three holes were opened at the centerline of bottom plate and an acrylic pipe was attached at each hole. The bottom hole was connected by a plastic tube with a bottle, which was filled with warm water colored by aniline blue.

We observed the diffusion pattern of the low density colored water ejected from the bottom. Since it is not allowed to use salt water in the circulating water channel, we used warm water adjusted the density difference as same as sea water and groundwater in the Hakata Bay. Experiments were conducted twice; No.1 experiments in July, 2008 and No.2 experiments in October, 2008.

No.1 experiments were intended to observe the diffusion pattern in the wide area and three pipes with outlet diameter of

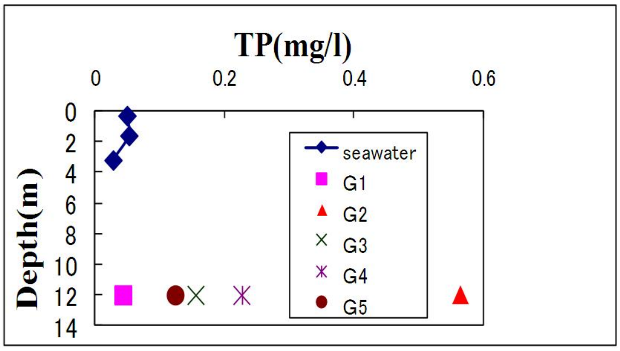


Fig.13 TP of seawater and groundwater at the site

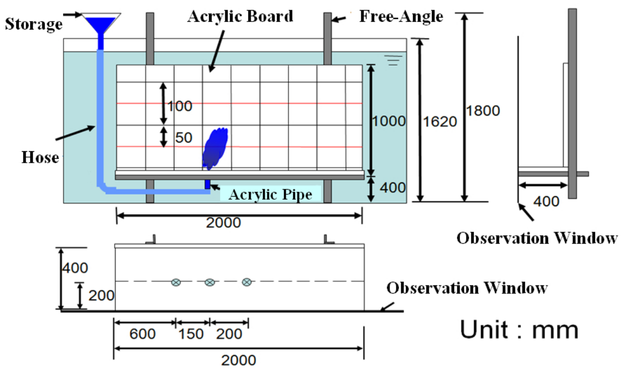
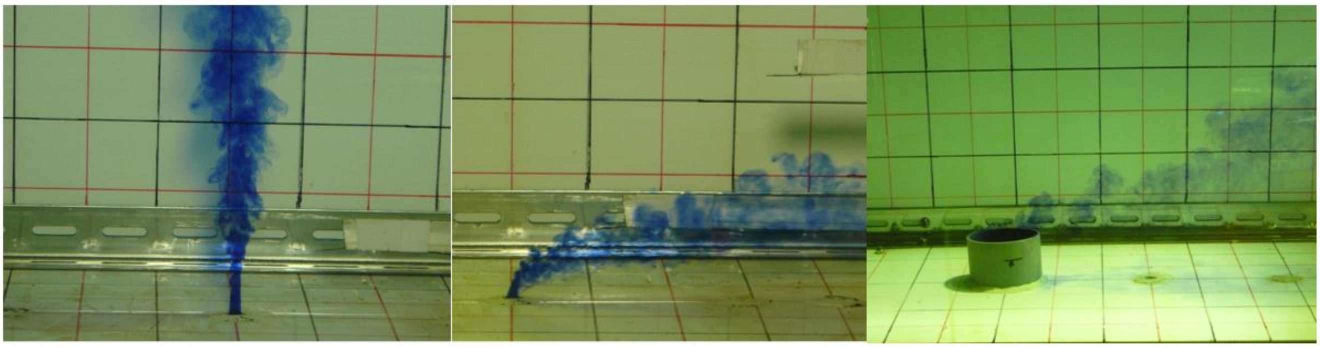
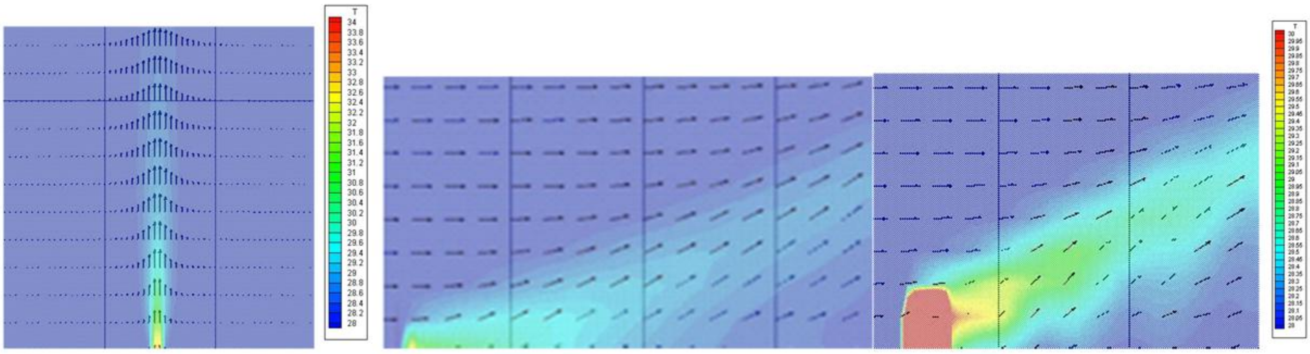


Fig.14 Experimental setup of upwelling of low density water in circulating water channel



(a) Diameter of outlet is 8mm, U=0 (b) Diameter of outlet is 8mm, U=3cm/s (c) Diameter of outlet is 70mm, U=3cm/s

Fig.15 Diffusion experiments of low density water from bottom with/without flow



(a) Sect. area of outlet is 1cm^2 (b) Sect. area of outlet is 1cm2, U=3cm/s (c) Sect. area of outlet is 36cm2, U=3cm/s

Fig.16 Simulation results of current and temperature distribution by MEC Ocean Model, color bar is for temp. distri.

6mm, 8mm and 10mm were used. Experiments were conducted under two conditions with/without uniform flow, which speed was 3cm/s. The temperature of background water was about 28 degrees C, then that of the ejected water from bottom was about 55 degrees C. Water temperature, density and density difference of experiments are arranged in Table 1.

In No.2 experiments, the outlet pipe was the same one used in the bay, of which diameter was 70mm. Uniform flow of 3cm/s was used as same as No.1 experiments. The temperature of background water was 21 degrees C and water of 52 degrees C was used as low density water.

The mean ejected speed of the low density water was about 1cm/s in No.1 experiments, and 0.5cm/s in No.2 experiments.

IV. Numerical simulations[7)]

In our project, we plan to generate the vertical current by the upwelling groundwater in the bay, which is expected to improve the water quality by breaking the stratification of water in summer. However, it is important to predict quantitatively what will really happen in the bay, if a certain amount of groundwater was upwelling. Therefore, we used the MEC Ocean Model[4), 5)], which is able to apply the full-3D solution in a narrow section in the wide field.

E. Numerical Simulations corresponding to Experiments

In order to validate the 3D model or non-hydrostatic part of MEC Ocean Model, diffusion simulations were conducted under the same conditions as experiments, where the density of water was considered by the temperature. Turbulence model was used by the SGS (Subscale Grid Size) model. The outlet area of the low density water was set 1cm^2(1cm x 1cm) or 36cm^2(6cm x 6cm), and the ejected speed of the low density water was set 1cm/s or 0.5cm/s. The background flow conditions were set same as experiments, zero or 3cm/s.

Fig.15 shows the experimental diffusion pattern of low density water from the bottom; left photo shows No.1

Table 1 Comparison of temperature, density and density difference of laboratory experiments with the site

	Temperature [℃]	Density [kg/m^3]	Density Difference [kg/m^3]
Seawater	**25.1**	**1021.29**	**10.534**
Groundwater	**19.2**	**1010.75**	
Tank Water	**28.0**	**996.24**	**10.937**
Warm Water	**55.0**	**985.77**	
Tank Water	**21.0**	**997.99**	**10.833**
Warm Water	**52.0**	**987.16**	

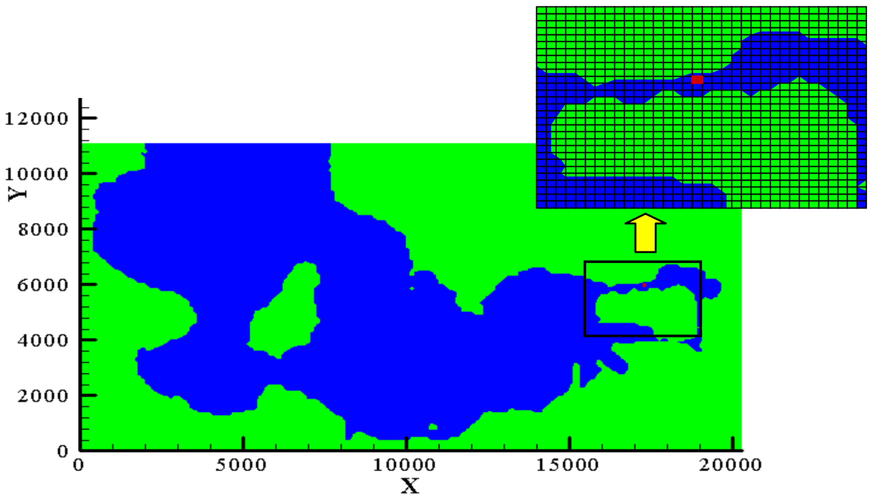


Fig.17 Calculation domain of Hakata Bay

experiment of 8mm pipe without uniform flow, middle photo is No.1 experiment of 8mm in 3cm/s uniform flow, the right photo shows No.2 experiment in 3cm/s uniform flow. Fig.16 shows the numerical simulation results corresponding to experiments in Fig.15. Color contours in Fig.16 show the water temperature. Comparing both results of Fig.15 and Fig.16, numerical simulations about flow and diffusion seem to agree well with mean flow and diffusions of experiments.

In case without uniform flow, the low density water went up straight from the outlet and the upwelling speed was more enhanced as higher the water went up. In case with uniform flow, the low density water flowed obliquely upward and the vertical velocity seemed larger as higher it went up. General flow pattern by the simulation seems to correspond to the experiments. Diffusion pattern of No.2 experiments was not continuous but cyclic, which was caused by the large size of outlet pipe. The superposition principle can be applied to the flow and diffusion pattern in the uniform flow with small speed in this study.

From these results, present simulation results agree well with experiments in both cases with/without horizontal flow. However, there are still some problems with the detailed diffusion pattern, which should be solved by adjusting the diffusion coefficients in future.

F. Numerical Simulations in Hakata Bay

In this study, we consider the environmental problems around Wajiro tideland in the head of the bay. Fig.17 shows the area for the numerical simulations, about 20km in EW and 10km in NS, from the bay entrance to head of the bay. Mesh size of the hydrostatic model was 100m x 100m in the horizontal plane and 16 layers were used in the vertical direction. Full 3D calculation was conducted in one hydrostatic mesh, where the sampling of groundwater was done. The full 3D mesh was set by 4m x 4m in horizontal plane, and 6 layers were set in vertical direction at about 3m water depth. Although the MEC model can be applied under

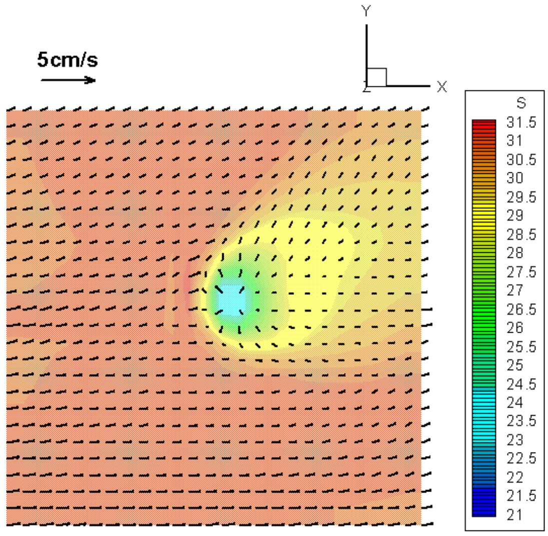


Fig.18 Horizontal distribution of salinity at water surface near outlet of groundwater, T=68 hours

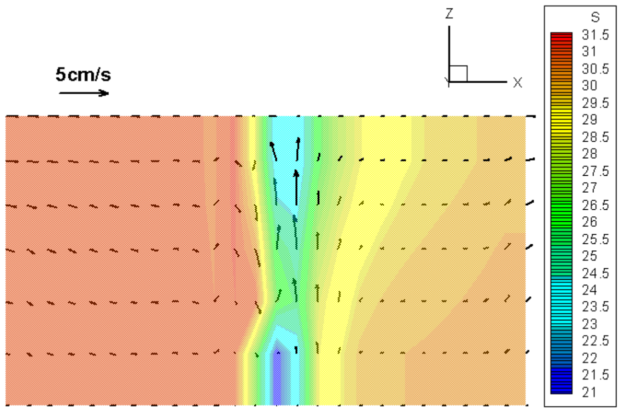


Fig.19 Vertical distribution of salinity near outlet of groundwater, T=68 hours

various meteorological and tidal conditions, we applied it to the simplified condition as follows:

1) Tide was given at the bay entrance by M2, of which amplitude and the period was assumed by 0.5m and 12 hours.
2) Fluxes of heat and salinity were not considered at every boundary and they were given by extrapolation at the open boundary.
3) Total amount of the groundwater was assumed as $100m^3$ and it was ejected from 4 meshes near center of 3D meshes.
4) Initial values of water temperature and salinity of the sea were assumed as 25.5 degrees C and 30 PSU, and those of groundwater were 15 degrees C and 15 PSU.

Fig.18 shows the concentration of salinity and the velocity vectors at water surface in 3D meshes after 68 hours from the start. There appeared some parts, where the salinity dropped to about 23 PSU. The low salinity area was spread in the north-east because the tidal current at this moment flowed to the same direction. Fig.19 shows the same things as Fig.18 in the vertical plane including the outlet of the groundwater. It can be understood that the groundwater is upwelling slowly from the outlet of pipes but it gradually increases its speed and the vertical circulation of maximum speed of 5cm/s is generated in the middle to surface of the water.

Fig.20 shows the distribution of salinity at the surface of water in the head of Hakata Bay after 68 hours from the ejection of groundwater. We understand that the area of low concentration of salinity is more spread in the center of the bay than the head of the bay, which seems quite natural because of the geometry around there. Therefore, we conclude that the MEC Ocean Model can be applied to this kind of problem, which consists of a full 3D problem in a small area surrounded by wide hydrostatic fields.

V. CONCLUSIONS

Judging from salinity, the groundwater about 8m below sea bottom in Hakata Bay is the mixture of sea water and freshwater. The density of groundwater is lower than sea water throughout the year therefore; there is a possibility to improve water quality by the vertical circulation generated by the upwelling groundwater.

Total volume of water in Hakata Bay is $1346.6 \times 10^6 m^3$. If we try upwelling of groundwater by 100 pipes, the volume of groundwater per year is estimated simply by 36,500 m^3/year, which corresponds to 0.0027% to the volume of water of the bay. Although the quantity of groundwater is negligible from the entire bay, it may effect on the local bay environments since the comparative strong vertical current is generated by the upwelling groundwater in the full-3D simulations. We want to conduct feasibility experiment by 100 pipes in the bay in near future.

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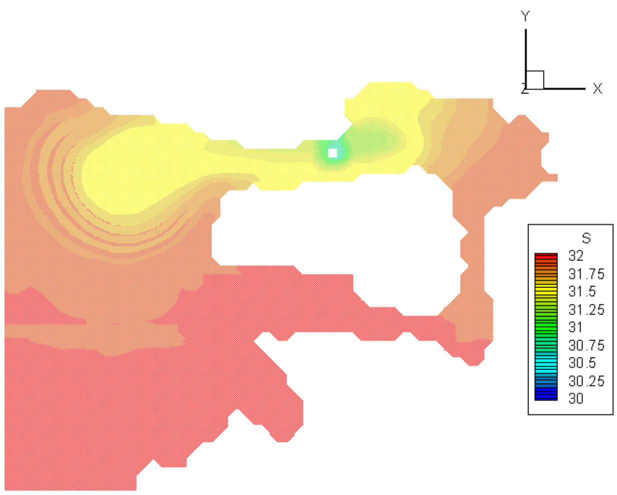

Fig.20 Horizontal distribution of salinity at water surface in head of Hakata Bay, T=68 hours