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Quantitative Analysis of Nutrient Inflow from River and Groundwater to Imazu Bay in Fukuoka, Japan

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Abstract**—**Imazu Bay plays an important role for endangered species such as horseshoe crabs and black-faced spoonbills that stay in the bay for spawning or the passing of winter. However, this bay is semi-enclosed with slow water exchange, which could lead to eutrophication under the condition of excess nutrient inflow to the bay. Therefore, quantification of nutrient inflow is of great importance. Generally, analysis of nutrient inflow to the bays takes into consideration nutrient inflow from only the river, but that from groundwater should not be ignored for more accurate results. The main objective of this study is to estimate the amounts of nutrient inflow from river and groundwater to Imazu Bay by analyzing water budget in Zuibaiji River Basin and loads of T-N, T-P, NO_3-N and NH_4-N. The water budget computation in the basin is performed using groundwater recharge model and quasi three-dimensional two-phase groundwater flow model, and the multiplication of the measured amount of nutrient inflow with the computed discharge gives the total amount of nutrient inflow to the bay. In addition, in order to evaluate nutrient inflow to the bay, the result is compared with nutrient inflow from geologically similar river basins. The result shows that the discharge is 3.50×107 m3/year from the river and 1.04×107 m3/year from groundwater. The submarine groundwater discharge accounts for approximately 23 % of the total discharge, which is large compared to the other river basins. It is also revealed that the total nutrient inflow is not particularly large. The sum of NO3-N and NH4-N loadings from groundwater is less than 10 % of that from the river because of denitrification in groundwater. The Shin Seibu Sewage Treatment Plant located below the observation points discharges treated water of 15,400 m3/day and plans to increase it. However, the loads of T-N and T-P from the treatment plant are 3.9 mg/L and 0.19 mg/L, so that it does not contribute a lot to eutrophication.

Keywords**—**Eutrophication, groundwater recharge model, nutrient inflow, quasi three-dimensional two-phase groundwater flow model, Submarine groundwater discharge.

I. Introduction

IN semi-enclosed bays with slow water exchange, high nutrient loading causes eutrophication. For example, pollution loads flowing into Tokyo Bay increased during the period of high economic growth, which resulted in outbreaks of red tide and poor oxygen water mass [1]. Water quality in Tokyo Bay has been improved by the regulation of COD, phosphorus and nitrogen based on the Water Pollution Prevention Law, but tideland or seaweed bed cannot be restored after eutrophication occurs.

A semi-enclosed bay, located in Fukuoka City, is a suitable place for wild birds to live. Approximately 180 kinds of birds, such as sandpipers or ducks, come to this bay and spawning horseshoe crabs have been reported in the beach of the bay. Thus, it is obvious that Imazu Bay biologically plays an important role. On the other hand, the bay does not have active water exchange and it is very possible that eutrophication occurs. Accordingly, it is needed to prevent eutrophication, which is mainly caused by high nutrient loadings, and therefore, the quantification of the nutrient loadings into the bay is of great importance. Generally, analysis of the nutrient inflow into a bay takes into consideration the nutrient loadings from the river only; however, recent research has shown that submarine groundwater discharge is also a significant pathway of nutrient loading to the sea [2].

In this paper, the main objective is estimate nutrient loadings from river and groundwater into Imazu Bay. First, the water budget in Zuibaiji River Basin, whose water is flowing into Imazu Bay is analyzed using various models. Next, the measured nutrient loadings are multiplied with the computed discharge from Zuibaiji River Basin into the bay to estimate nutrient inflow. Finally, in order to evaluate nutrient loading into Imazu Bay, the result is compared with the nutrient loadings from geologically similar river basin to bays.

II. Method and Materials

A. Study Area and Observations

Zuibaiji River is a second grade river which flows through the western part of Fukuoka and Itoshima City, Japan. It is 13.2 km long and its basin covers an area of 52.9 km^2. Zuibaiji Dam is located upstream of the river and helps to supply drinking water to Fukuoka and Itoshima City. The basin is composed of granodiorite in the upstream basin and transported sediments, such as mud, sand or gravel, in the downstream basin.

In the river basin, rainfall has been monitored at Ikeda and Zuibaiji Dam. The river flow rate and water quality was observed at Ikada in November, 2014. (Table I), and, groundwater quality was observed at four points (A, B, C and D) in October, 2011. (Table II)

TABLE I
River Water Quality at IKEDA

Parameters	
Water temperature (°C)	23.8
pH	7.1
EC(μS/cm)	193
ORP(mV)	275
T-N(mg/L)	1.6
T-P(mg/L)	0.086
NO_3^-(mg/L)	5.8
NO_4^+(mg/L)	«0.03

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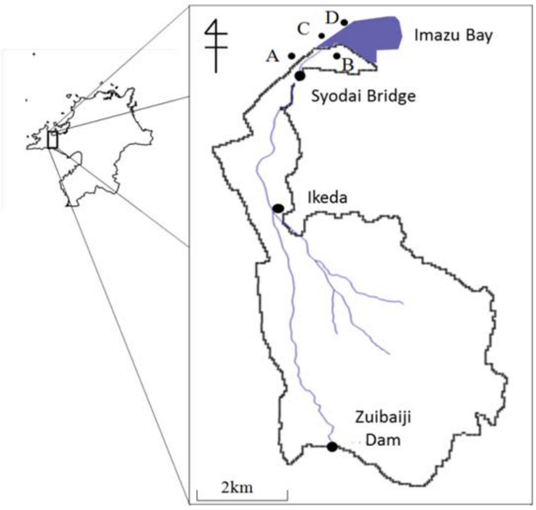

Fig. 1 Observation points

TABLE II
GROUNDWATER QUALITY AT THE 4 POINTS

Parameters	A	B	C	D
Water temperature (°C)	19.7	22.5	20.6	22.0
pH	7.20	7.41	6.89	6.64
EC(μS/cm)	2110	1870	6040	8040
DO(mg/L)	1.4	1.0	1.2	1.3
ORP(mV)	-179	-351	-209	-13
T-N(mg/L)				
T-P(mg/L)				
NO_3^-(mg/L)	ND	ND	ND	ND
NO_4^+(mg/L)	0.03	0.07	0.08	0.50

B. Estimation Methods

The two models, the groundwater recharge model and quasi three-dimensional two-phase groundwater model, are applied to estimate river discharge and submarine groundwater discharge, respectively. The study area is divided into 13,005 grids, with a grid length of 50 m in the x and y directions, and land use distribution data were assigned to all grids. The simulation period is three years from 2009 to 2012.

The groundwater recharge model is applied to calculate groundwater recharge, evapotranspiration and direct surface runoff from the input data, such as rainfall, temperature, topographical data and so on. The groundwater recharge calculated in the GRM is used as the input data for the quasi three-dimensional two-phase groundwater model which estimates groundwater discharge into river. The amount of river discharge is the summation of direct surface runoff and groundwater discharge into river, and the submarine groundwater discharge is the difference between groundwater recharge and groundwater discharge into the river.

After the simulation for the river discharge and the submarine groundwater discharge, the observed nutrient loads (T-N, T-P, NO_3-N and NH_4-N) in the river and groundwater are multiplied with the estimated discharge, resulting in the total nutrient loads from the river and groundwater to the bay.

III. Description of Models and Parameterization

A. Groundwater Recharge Mode

The conceptual groundwater recharge model is illustrated in Fig. 1. It functions as a vertical tank storage with an outlet at height R_0 and an outlet coefficient a_L. The R_0 corresponds to the field capacity of the soil and a_L controls the groundwater recharge rate $q_w(t)$ from the tank. The recharge induces a rise of the groundwater table. Further, the rainfall interception is denoted by $r_{int}(t)$ and rainfall that reaches the ground surface r(t) is calculated by $r(t) = r_{total}(t) - r_{int}(t)$, where $r_{total}(t)$ is the total rainfall intensity. For areas without trees, $r(t) = r_{total}(t)$.

The rainfall that reaches the ground surface is then separated into two components: the surface runoff, whose rate is given as $F(r)\cdot r(t)$ and the infiltration, with the rate $[1 - F(r)]\cdot r(t)$, as shown in Fig. 1. Here, F(r) denotes the surface runoff coefficient as a function of rainfall intensity.

$$F(r)=\frac{r(t)}{r(t)+(r)_{1/2}}\cdot F_\infty \quad (1)$$

where $(r)_{1/2}$ is the value of r(t), when Fi(r) is equal to $F_{i\infty}/2$. If typical $F_{i\infty}$ values are adopted, such as exemplified in Table I, then only $(r)_{1/2}$ is an undetermined parameter in the equation.

Evapotranspiration reduces water stored in the tank by $EVT_1(t)$. If the water in the tank is exhausted, evapotranspiration can still occur by water uptake denoted by $EVT_2(t)$ from the groundwater through the unsaturated zone and the root zone, as explained by Bouwer (1978) [3]. This may occur if the vertical distance between the ground surface and the unconfined groundwater table is less than the extinction depth Hg*, which needs to be evaluated separately. A similar approach was introduced by Anderson & Woessner (1992) [4], who considered the water uptake rate from the groundwater as a linear function of depth of the water table less than Hg*. The actual evapotranspiration can thus be estimated as the sum of $r_{int}(t)$, $EVT_1(t)$ and $EVT_2(t)$. It is obvious that the actual evapotranspiration by the present procedure varies over the region depending on the tank properties and the groundwater level.

The following equations describe the change in water level stored in the tank as illustrated in Fig. 2. Equation (2) expresses the change in the tank water level, $h_w(t)$, and (3) gives the recharge rate to the unconfined groundwater:

$$\frac{dh_w}{dt}=\{1-F(r)\}\cdot r(t)-q_w(t)-EVT_1(t) \quad (2)$$

$$q_w(t)=a_L\cdot\{h_w(t)-R_0\}\times Y[h_w(t)-R_0] \quad (3)$$

where $Y\{h_w(t) - R_0\}$ is a step function equal to 1 for $hw(t)>R_0$ and 0 for $h_w(t)<R_0$. The outlet coefficient a_L has the unit h-1, and $q_w(t)$ is the recharge rate to groundwater. The $q_w(t)$ divided by effective porosity n_e can be approximated as the groundwater table rising rate.

The parameters n_e, a_L, R_0, F_∞, $(r)_{1/2}$, were assigned values depending on land use (Table III) to represent its effect to direct runoff, infiltration, and groundwater recharge from a previous study by [5].

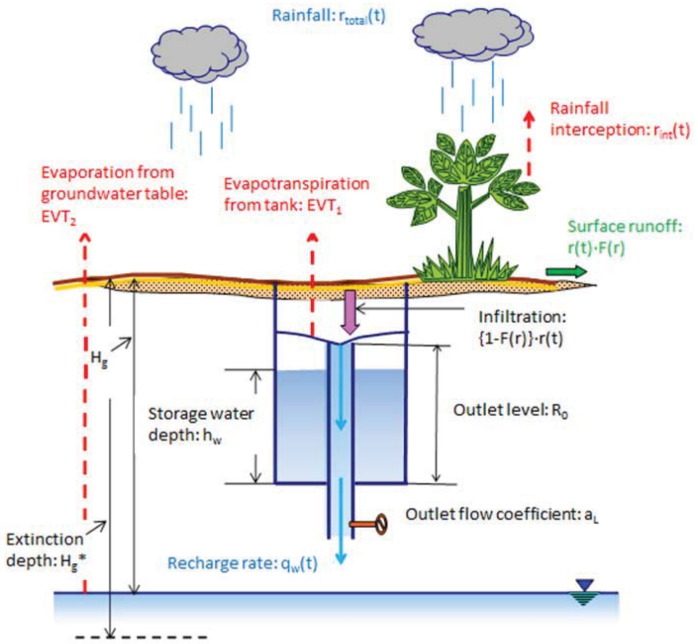

Fig. 2 Groundwater recharge model

TABLE III
PARAMETERS FOR LAND USE

Land use	n_e	a_L	R_0	$r_{(1/2)}$	F_∞
Paddy field	0.175	0.39	7	9	0.2
Agriculture field	0.175	0.19	5	5.7	0.2
Forest area	0.225	0.13	17	6.6	0.3
Building area	0.225	0.3	19	4.5	0.3
Golf field	0.08	0.5	8	12	0.1
Lake or river	0.08	0	0	0	1
Unused bare area	0.08	0.43	7	2.5	0.3

B. Quasi Three-Dimensional Two-Phase Groundwater Flow Model

The quasi three-dimensional salt- and freshwater two-phase groundwater flow model was applied to the present simulation, since one of the main interests was to calculate outflow from groundwater into the river. Not only freshwater, but also saltwater is taken into consideration in the model. The model employs basic groundwater flow equations for unconfined aquifer and confined aquifer. Figs. 3 and 4 show the quasi three-dimensional two-phase groundwater flow model for unconfined aquifer and confined aquifer.

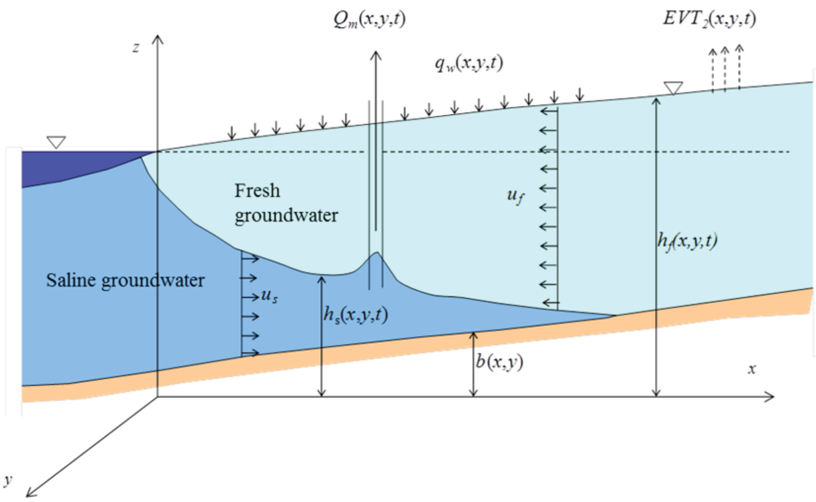

Fig. 3 Quasi three-dimensional two-phase groundwater flow model for unconfined aquifer

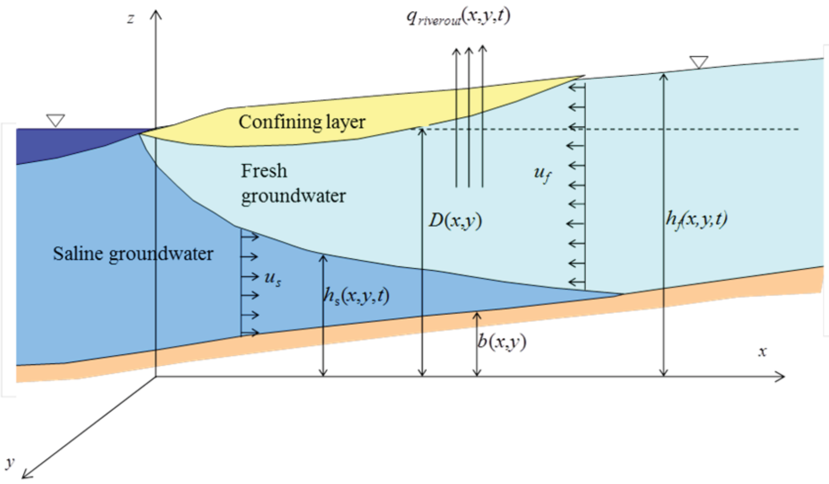

Fig. 4 Quasi three dimensional two-phase groundwater flow model for confined aquifer

The basic groundwater flow equations in the unconfined aquifer are;

- Freshwater phase:

$$n_e \frac{\partial(h_f - h_s)}{\partial t} = -\frac{\partial\{(h_f - h_s)\cdot u_f\}}{\partial x} - \frac{\partial\{(h_f - h_s)\cdot v_f\}}{\partial y} - \sum_m \begin{matrix} Q_m(x,y,t)\delta(x-x_m)\delta(y-y_m) \\ +q_w(x,y,t) - EVT_2(x,y,t) \end{matrix} \quad (4)$$

- Saltwater phase

$$n_e \frac{\partial h_s}{\partial t} = -\frac{\partial[\{h_s - b(x,y)\}\cdot u_s]}{\partial x} - \frac{\partial[\{h_s - b(x,y)\}\cdot v_s]}{\partial y} \quad (5)$$

The basic groundwater flow equations in the confined aquifer are;

- Freshwater phase

$$S\cdot\frac{\partial h_s}{\partial t} - n_e\frac{\partial h_s}{\partial t} = -\frac{\partial[\{D(x,y) - h_s\}\cdot u_f]}{\partial x} - \frac{\partial[\{D(x,y) - h_s\}\cdot v_f]}{\partial y} - \sum_m \begin{matrix} Q_m(x,y,t)\delta(x-x_m)\delta(y-y_m) \\ -q_{riverout}(x,y,t)\delta(x-x_{out})\delta(y-y_{out}) \end{matrix} \quad (6)$$

- Saltwater phase

$$n_e \frac{\partial h_s}{\partial t} = -\frac{\partial[\{h_s - b(x,y)\}\cdot u_s]}{\partial x} - \frac{\partial[\{h_s - b(x,y)\}\cdot v_s]}{\partial y} \quad (7)$$

where $h_f(x,y,t)$, $h_s(x,y,t)$, $b(x,y)$ and $D(x,y)$ are fresh groundwater elevation, two-phase interface elevation, impermeable base elevation taken from the reference level and the elevation of the base of the confining layer taken from the reference level, respectively. The term $Q_m(x,y,t)$ is the water extraction rate by pumping at location (x_m,y_m) at time t. The delta functions $\delta(x-x_m)$ and $\delta(y-y_m)$ represent the location of the pumping well. The term $q_w(x,y,t)$ represents the groundwater recharge. The term $q_{riverout}$ is the groundwater discharge into the river at location (x_{out},y_{out}).

Darcy's law gives the relationship as shown in (8).

$$u_f = -k\frac{\partial\phi_f}{\partial x}, v_f = -k\frac{\partial\phi_f}{\partial y}, \phi_f = h_f$$
$$u_s = -k\frac{\partial\phi_s}{\partial x}, v_s = -k\frac{\partial\phi_s}{\partial y}, \phi_s = \frac{\rho_f}{\rho_s}\cdot h_f + \frac{\Delta\rho}{\rho_s}\cdot h_s \quad (8)$$

where the terms u_f, u_s, and v_s, v_f represent the velocity components in x- and y- direction. The subscripts s and f denote saltwater and freshwater, respectively. The terms ϕ_f and ϕ_s are the piezometric heads, and the density difference is written as $\Delta\rho=\rho_s-\rho_f$ at the saltwater intrusion area. The permeability k varies spatially but is assumed uniform in the vertical direction.

C. Water Balance Analysis

Based on the result of the simulations, several hydrological components are investigated. As seen in Fig. 5, river discharge and submarine groundwater discharge can be estimated as;

$$Q_r = q_r + q_{riverout} \quad (9)$$

$$q_{riverout} = q_w - q_{riverout} \quad (10)$$

IV. Results and Discussion

A. Simulation Results

The annual river discharge and groundwater discharge are $3.50\times10^7 m^3$/year and $1.04\times10^7 m^3$/year, accounting for approximately 77 % and 23 %. Taniguchi (2001) [6] reported that the percentage of submarine groundwater discharge is generally approximately a few percent to 10 percent. Thus, the submarine groundwater discharge into Imazu Bay is larger than average, the cause of which is much spring water in the area.

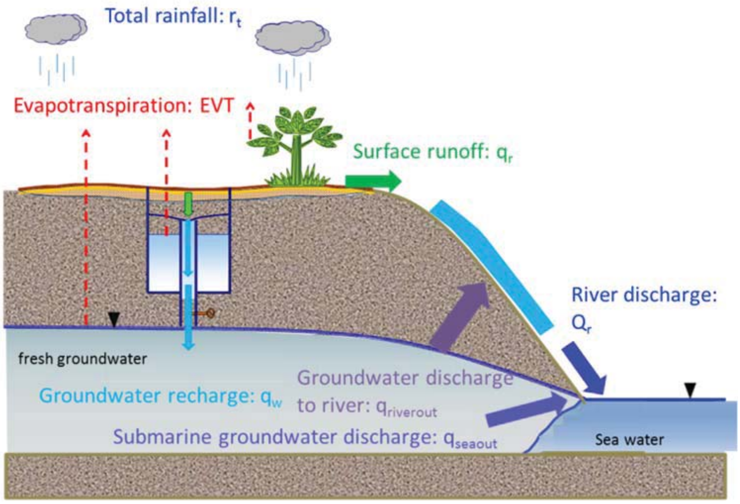

Fig. 5 Water balance in river basin

B. Validity of the Simulation

In order to verify the validity of the result, the simulated river discharge is compared with that which is observed at Ikeda. The comparison of the simulated specific discharge with the observed specific discharge is shown in Fig. 6. The simulated specific discharge is much smaller than the observed one. Generally, the h-q curve for the calculation of the observed discharge is defined where there are no sediments on the bottom. But, it is considered that the bottom level rise due to sedimentation caused the error, since the runoff rate which equals the observed river discharge divided by rainfall is more than one. Although there is a difference between the simulated value and the observed value, both values show the same tendency. Therefore, it is assumed that the simulated river discharge and groundwater discharge are valid and could be used for the estimation of nutrient loads.

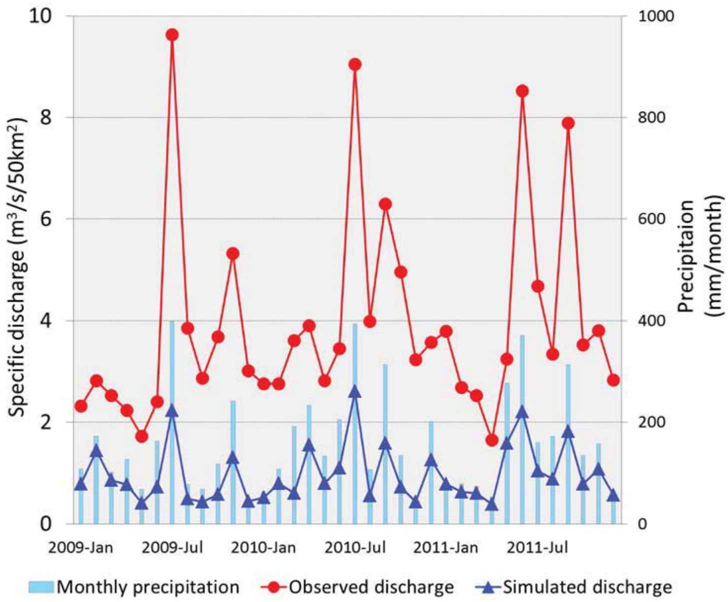

Fig. 6 Observed vs simulated river discharge

C. Estimated Nutrient Loads

Table IV shows the estimated nutrient loads flowing into Imazu Bay from river and groundwater.

1. Nutrient Loads from the River

There is a wastewater treatment plant named Shin Seibu Water Treatment Plant around Imazu Bay. The inflow into the wastewater plant was expected to increase due to urbanization resulting from the new campus of Kyushu University, and as such, the Shin Seibu Water Treatment Plant was established in

2014. The outflow from the treatment plant needs to be taken into consideration since it is located below the observation points. The treatment plant reported that the amount of treated water discharge is 15,400 m^3/day and loads of T-N and T-P from the plant are 3.9 mg/L and 0.19 mg/L, which indicates that the annual loads of T-N and T-P are 21.9 and 1.1 t/year [7]. These values are not too large to contribute to eutrophication in the bay.

The estimated nutrient loads are compared with those from other river basin with nearly same the areas as the study area. In Fukuoka City, there are the Mikasa River, Naka River, Okei River, besides the Zuibaiji River. Fukuoka City has already estimated the nutrient loads into Hakata Bay from the rivers [8]. The loads of T-N and T-P from Zuibaiji River are not large, compared with those from other rivers. (Fig. 7) Even if the loads from the treatment plant are added to those from Zuibaiji River, they are not considerable.

TABLE IV
NUTRIENT LOADS FROM RIVER AND GROUNDWATER

	T~N	NO_3~N	NH_4~N	T~P
River (t/year)	53	44	0.78	2.9
Groundwater (t/year)		0	0.28~4.73	

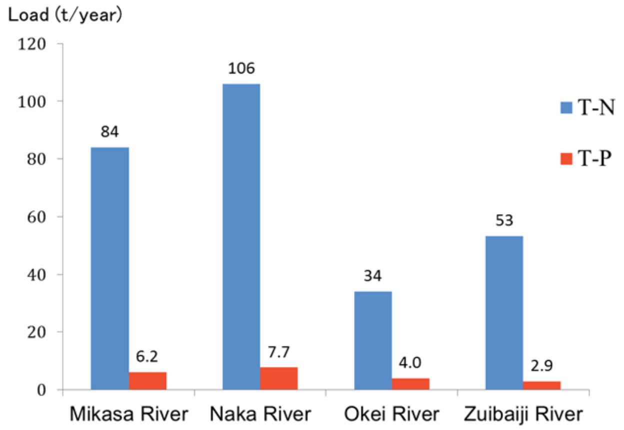

Fig. 7 Comparison of T-N and T-P loads from river

2. Nutrient Loads from Groundwater

Due to lack of data, the loads of T-N and T-P are not estimated. The load of NO_3-N is 0 t/year since the observed concentration of NO_3^- is lower than the detection limit as seen in Table II. The load of NH_4-N ranges from 0.28 to 4.73 t/year because of the different concentration of NH_4^+ depending on the observation points. Table III shows that the sum of NO_3-N and NH_4-N loadings from groundwater is less than 10 % of that from the river.

V. CONCLUSION

In this study, the nutrient loads into Imazu Bay from river and groundwater are respectively estimated using a groundwater recharge model coupled with a quasi three-dimensional two-phase groundwater model.

The following results were obtained:

- The percentage of submarine groundwater discharge to the total discharge into Imazu Bay is 23 %, which is larger than average according to Taniguchi.
- The summation of the NO_3-N and NH_4-N loads from groundwater is less than 1/10 of that from the river, which is mainly caused by that of the NO_3-N load is 0t/year due to the denitrification of the groundwater.
- Although a wastewater treatment plant is located around the bay, the loads of T-N and T-P from the treatment plant are 3.9 mg/L and 0.19 mg/L which do not contribute a lot to eutrophication in the bay. However, we need to pay attention to discharge from the plant since it plans to increase discharge.

REFERENCES

[1] K. Furukawa, "Eutrophication in Tokyo Bay," Eutrophication and Oligotrophication in Japanese Estuaries, 2015, pp. 5-37.
[2] W.S. Moore, Large groundwater inputs to coastal waters revealed by ^{26}Ra enrichments, *Nature* 380, 612-614.
[3] H. Bouwer, Groundwater Hydrology, 1978, 299-306.
[4] M. P. Anderson & W. W. Woessner, Applied Groundwater Modeling Simulation of Flow and Advective Transport.
[5] A. Tsutsumi, K. Jinno & R. Berndtsson, Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phrase flow model, 2004 *Hydrological Sciences-Journal-des Sciences Hydrologiques* 49(2), 205-226.
[6] M. Taniguchi, "Interaction between Groundwater and Surface Water/Sea Water ~4. Interaction between Groundwater and Sea Water," Groundwater Hydrology, vol.43(3), 2001, pp.189-199.
[7] Result of environmental monitoring in Shin Seibu Water Treatment Plant in 2014, Bureau of sewerage, Fukuoka City, (Available online, http://www.city.fukuoka.lg.jp/doro-gesuido/suishitsu/hp/01/index.html, accessed 22/02/2016).
[8] Result of monitoring for environmental conservation in Hakata Bay, Fukuoka City, 2012 (Available online, http://www.city.fukuoka.lg.jp/data/open/cnt/3/30216/1/24kekka.pdf, accessed 20/02/2016).