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Groundwater characteristics of the Saga Plain, Japan

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ABSTRACT

The Saga Plain is located in the west of Kyushu Island, Japan. The area is seriously affected by overdraft of groundwater. Land subsidence has been evident since 1957, and it was quite significant in 1960. The groundwater head varies seasonally depending on discharge and precipitation.

According to the geological properties of the Saga Plain, a single layer two-dimensional plane model was adopted to simulate the seasonal fluctuation of the groundwater head. Based on the Darcy's Law and continuity principle, the following differential equation was used to describe the groundwater flow:

$$T\frac{\partial^2 h}{\partial x^2} + T\frac{\partial^2 h}{\partial y^2} = S\frac{\partial h}{\partial t} + Q(x, y, t)$$

where T is the transmissivity of aquifer; S is the storage coefficient; Q is the net recharge; and h is the groundwater head.

By comparing the pattern of the Hexa diagram in different areas and different aquifers, it was found that saltwater intrusion occurred in the Saga Plain due to over-pumping. Water quality and quantity are affected not only by the recharge and soil utilisation but also by the surrounding geological conditions.

Tritium concentration analysis was used for estimating the age of groundwater in the Saga Plain. The Saga Plain is divided into the Saga District and Shiroyishi District. In the Saga District, the groundwater showed a young age in the shallow wells of inland as well as costal areas. The young age in the inland areas was attributed to the recharge of groundwater from the northern mountains. For the coastal areas, it was thought as the effect of saltwater intrusion from the Ariake Sea. Meanwhile, measurements showed that the groundwater in deep aquifers was of old age in the Saga District. Those results were also supported by the chemical analyses of the components of groundwater in the Saga Plain. In the Shiroyishi District, the old groundwater was encountered both in deep and shallow aquifers. The analyses of chemical components showed that the groundwater is affected mainly by the fossil water in the Shiroyishi District.

INTRODUCTION

Groundwater is a valuable but limited natural resource. Its existence depends mainly on rainfall. Many environmental problems such as water exhaustion, land subsidence, and water pollution often occur in the world owing to its overdraft. Hence, the protection of groundwater resource becomes a very important subject in the environmental field. The Saga Plain (Fig. 1) is typical lowland. Land subsidence due to overdraft is the most serious problem in the Saga Plain. Since 1957, the subsidence has reached a maximum value of 110 mm. At present, it has become very critical with the values of 20–40 mm per year in the southwest area of the Saga Plain (Saga Prefecture Office and Saga University 1997). Observations showed that the land subsidence was closely related to the fluctuation of groundwater head, which in turn is related to the amount of pumping. Land subsidence has been observed since 1960, even though a restriction was put into effect in 1974. In addition, saltwater intrusion also occurred in this area probably due to over-pumping. These combined problems seriously affect the natural environment and human activities in the area.

Generally, properties of groundwater depend on regional geological conditions. But the water quality and quantity are also strongly affected by the recharge and land use. This study focuses on the groundwater characteristics of the Saga Plain such as their quality, quantity, and surrounding geological conditions.

GEOLOGICAL SETTING

The Saga Plain is made up of alluvial deposits. It is surrounded with mountains in the north, east, and west (Fig. 2). In the north, there is Mt Sefuri, which is composed of Mesozoic granite and the Sangun metamorphic rocks and serpentinites. In the east, there are Mt Minou and Chikushi, which are made up of the Sangun metamorphic rocks. In the west, there are Mt Oninohanayama, Kishimayama, and Taradake, containing Palaeocene sediments and Neogene

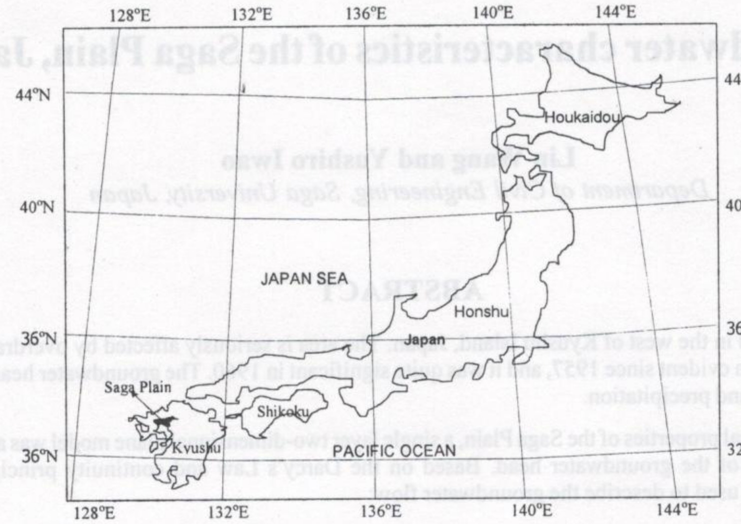

Fig. 1: Location of the study area

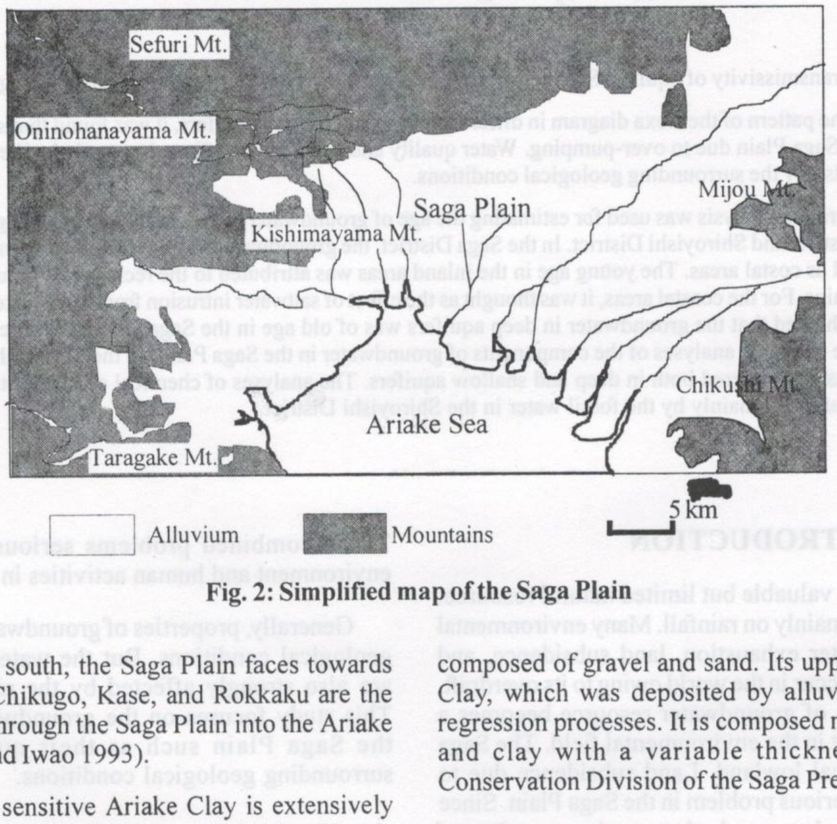

Fig. 2: Simplified map of the Saga Plain

volcanic rocks. In the south, the Saga Plain faces towards the Ariake Sea. The Chikugo, Kase, and Rokkaku are the main rivers that flow through the Saga Plain into the Ariake Sea (Khamehchiyan and Iwao 1993).

The very soft and sensitive Ariake Clay is extensively distributed in the area. The thickness of Ariake Clay is generally 10–20 m, and reaches a maximum of 30 m. There are marine sand and mud beds in the lower parts of the Ariake Clay.

The beds are divided into the A, B, C, D, E, and F units (Table 1). The lower part of the D, E, and F units consists of marine sand, which was deposited in Pliocene epoch. Unit C contains pumice-bearing volcanic ash derived from the pyroclastic flows of Mt Aso about 33 thousands years ago. Unit B is named as the Shimabara Bay Formation. It is composed of gravel and sand. Its upper layer is the Ariake Clay, which was deposited by alluvial transgression and regression processes. It is composed mainly of very soft silt and clay with a variable thickness (Environmental Conservation Division of the Saga Prefecture Office 1990).

SIMULATION OF THE FLUCTUATION OF GROUNDWATER HEAD

Administratively, the Saga Plain is divided into the Saga District and Shiroyishi District. In the Saga District, 80 per cent of pumping is for industrial purposes whereas, in the Shiroyishi District, about 70 per cent of pumping is for agricultural purposes. In summer, drawdown and reduction of aquifer pressure is related basically to the increased use of water for air-conditioning and irrigation, inducing the land

Table 1: Stratigraphy of the Saga Plain

Geological age	Shiroyishi District			Saga District		
	Stratum	Thickness	Lithofacies	Stratum	Thickness	Lithofacies
Holocene	Ariake Clay	0~28 m	Silty clay	A	0~30 m	Silty clay
Pleistocene	Shimabara layer	10 m±	Transgressive deposit	B	0~10 m	Alternation of silt and sand
	Aso welded tuff	1~5 m	Tuff-bearing volcanic ash	C	10~20 m	Sand mingled with pumice Yame clay layer
	? Undifferentiated diluvium layer	10 m±	Silt mingled with sand	D	50 m±	Upper part: loam and clay; Lower part: sand and gravel
	? Undifferentiated diluvium layer	120 m±	Alternation of silt and sand	E	120 m±	Alternation of sand and silt layers
	? Undifferentiated diluvium layer	100 m±	Alternation of silt and sand	F		Mudstone

subsidence. However, in winter, the water head resumes its height due to the decrease in pumping amount. Fig. 3 shows the fluctuation of groundwater head and monthly pumping from 1985 to 1990. From the available data, it was found that the land subsidence was remarkable when pumping amount was large. Even though the land subsidence has became small and the ground has shown a tendency to recover after the restrictions imposed on groundwater extraction, the complete recovery of the ground has not taken place.

Aquifer model

The fluctuation of groundwater head was simulated in order to study the quantity of groundwater variation due to pumping. According to the geological conditions of the Saga Plain, the aquifer model was simplified to a one-layer, two-dimensional aquifer (Fig. 4). In the model, the upper impermeable Ariake Clay layer is considered as a confining layer and the lower portion as a unit of confined aquifer.

Because the aquifer thickness (200 m) is much less than its extension in horizontal direction (20 km × 22 km), it is reasonable to neglect the groundwater flow in vertical direction. Based on the Darcy's Law and continuity principle, the following differential equation was used to describe the groundwater flow:

$$T\frac{\partial^2 h}{\partial x^2} + T\frac{\partial^2 h}{\partial y^2} = S\frac{\partial h}{\partial t} + Q(x,y,t) \qquad (1)$$

where T is the transmissivity of aquifer, S is the storage coefficient, Q is the net recharge, and h is the groundwater head.

Cell division and hydrological coefficients

Fig. 5 depicts the cell division of the study area. The study area is about 624 km^2. It was divided into 624 meshes (each of 1 km^2). The cells were grouped into 4 zones according to the following hydrological conditions (Fig. 5).

T_1=1400m^2/day, S_1=0.30
T_2= 800 m^2/day, S_2=0.16
T_3= 500 m^2/day, S_3=0.35
T_4= 200 m^2/day, S_4=0.36

Initial condition and boundary conditions

The groundwater heads measured in March 1985 were used as the initial condition of water head. Because the northern and western boundaries were mountains and the Ariake Clay was absent there, it was reasonable to think the aquifer as unconfined one. The surface water from the mountains was assumed to be the recharge source of groundwater. In addition, the groundwater head near the mountains was about 0 m and did not vary significantly with time (Esaki et al. 1996). Hence the boundary conditions for the mountain areas were fixed at 0 m. In the east, the aquifer continued beyond the study area. Due to the fluctuating flows in those areas, the water head was fixed at its initial value. The southern boundary was the Ariake Sea where the groundwater head was considered independent of pumping, and in those areas the water head was fixed at sea level.

Finite difference method

Finite differential model was adopted in the simulation. The water balance around one cell is shown in Fig. 6 and is described as follows:

It was assumed that the water flow occurred only between neighbouring cells (Wolfgang 1986), and all of the cells could be considered as multi-linked small tanks.

Simulation result and discussion

With time step as 6 days, the fluctuation of groundwater head in five years (from March 1985 to March 1990) was simulated. The comparison of calculated results with the observed ones in the wells Tanjin A-1 and Shiroyishi C-1 are shown in Fig. 7. The main tendency of groundwater head fluctuation is similar. This model matches well with the actual

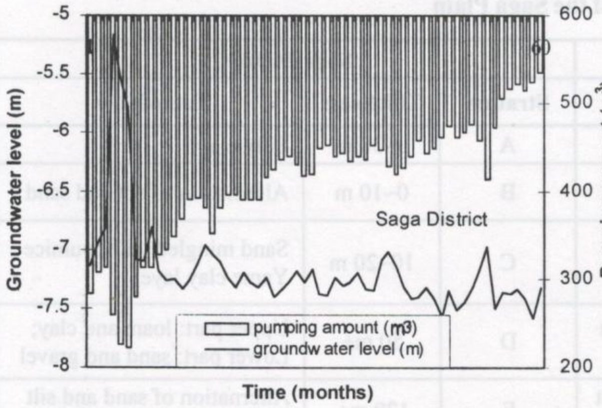

Fig. 3(a): Pumping amount and groundwater level in the Saga District

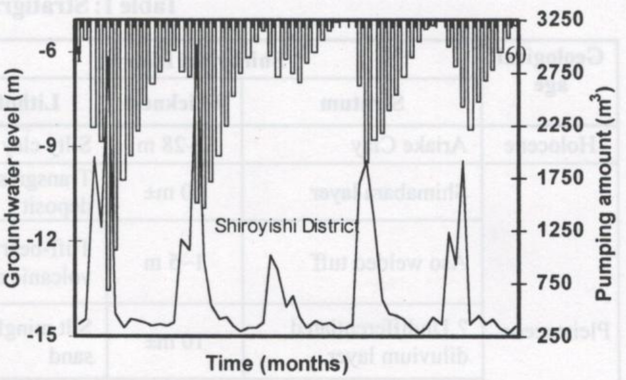

Fig. 3(b): Pumping amount and groundwater level in the Shiroyishi District

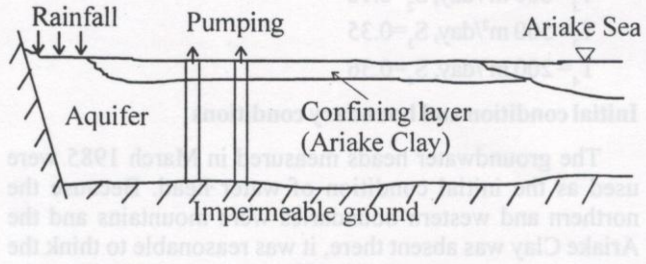

Fig. 4: Aquifer model of the Saga Plain

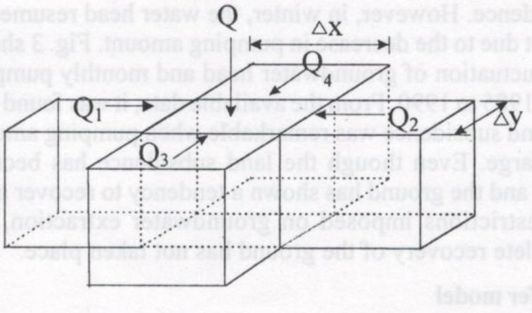

Fig. 6: Water balance around a cell

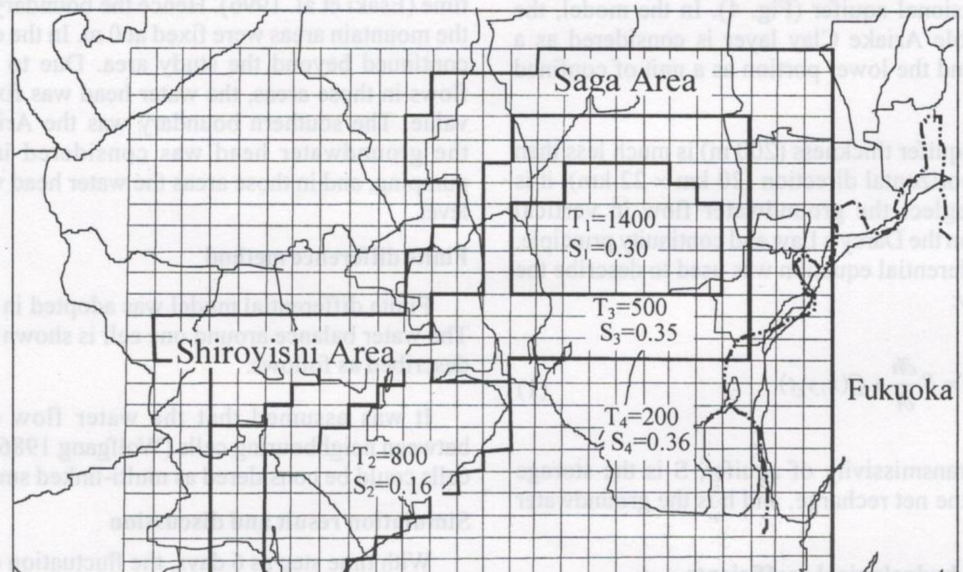

Fig. 5: Division of study area into 1 km x1 km cells for modelling

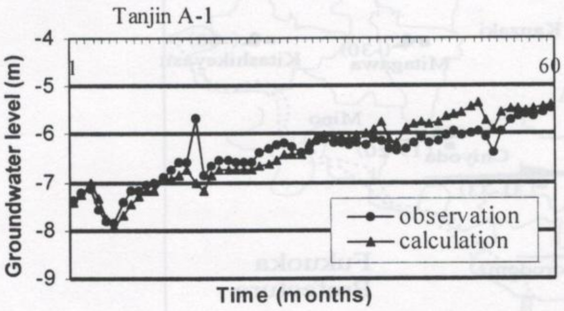

Fig. 7a: Comparison of simulation results with the observed data in the well Tanzin A-1

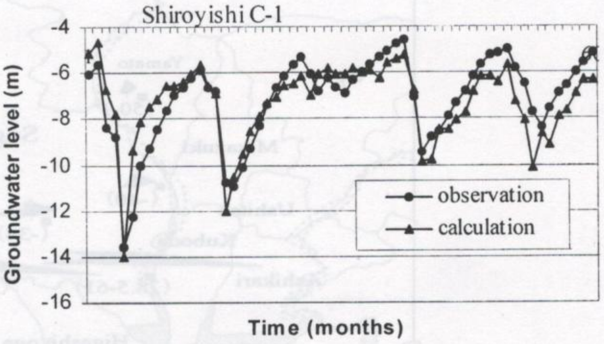

Fig. 7b: Comparison of simulation results with the observed data in the well Shiroyishi C-1

observations in the Saga Plain and can also be extended for the prediction of groundwater head fluctuation due to pumping.

THE DISTRIBUTION CHARACTERISTICS OF WATER QUALITY IN THE SAGA PLAIN

Generally, groundwater has regional characteristics. Different geological conditions and recharge rates give rise to different chemical composition of groundwater. The groundwater in the Saga Plain is the diluted fossil water that formed from the pore water (seawater) in the sedimentation period. The recharge source was infiltration and percolation of rainwater and river water from the mountain areas in the north and west.

The quantitative analysis of water quality in the Saga Plain was carried out for the following ions: Na^+, K^+, Ca^{2+}, Mg^{2+} and Cl^-, HCO_3^-, SO_4^{2-}. The ions of Na^+, K^+, Ca^{2+}, and Cl^- were analysed by electrode methods in the laboratory of Saga University, and the Saga Prefecture analysed the ions of Mg^{2+}, HCO_3^-, and SO_4^{2-}.

Chemical analysis of groundwater in the Saga District

According to their strainer depth, analysed wells were divided into three groups: shallow wells (strainer depth < 50 m), medium wells (strainer depth around 100 m), and deep wells (strainer depth around 200 m).

Fig. 8 shows the hexa diagram of groundwater samples from the Saga District. The samples of deep wells have a consistent pattern of Na-HCO_3 indicating the characteristics of normal stagnation. In medium wells, the samples from the southern coastal areas show a pattern of Na-Cl very different from that of Na-HCO_3 in the inland areas. The results of shallow wells show the tendency similar to those of medium wells, and the ion concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, and Cl^- show an increasing tendency from the inland areas to the coastal areas.

Fig. 9 depicts the concentration of Cl^- at various depths in the Saga District. It shows that the concentration values increase from deep to shallow wells. This trend is attributed to over-pumping of groundwater before the restrictions were imposed in 1974. During that period, a large quantity of groundwater was freely extracted from the shallow aquifer (first aquifer). As the groundwater head was almost the same for all the seasons, saltwater intrusion took place in the shallow aquifer due to drawdown. After the restrictions were imposed, the groundwater was extracted mainly from medium and deep aquifers (D and E layer), and the saltwater gradually intruded into the medium aquifer from the coastal areas.

The degree of saltwater intrusion was described by:

E_{Ca}=[ion concentration ratio of (Ca^{2+}/Cl^-) of groundwater]/[ion concentration ratio of (Ca^{2+}/Cl^-) of sea].

As the value of E_{Ca} tends to 1, the groundwater resembles the saline water (Miura et al. 1986). Fig. 10 shows the distribution of E_{Ca} by ion concentration of Cl^-. In some areas of the Saga District, E_{Ca} was more than 1, implying the saltwater intrusion in those areas.

Chemical analysis of groundwater in the Shiroyishi District

Fig. 11 shows the hexa diagram of water samples in the Shiroyishi District. In the coastal areas, both the shallow and medium wells showed high concentrations of Na^+, K^+, and Cl^-. In the area along the Rokkaku River and Shiota River, the water samples also showed high values of Na^+, K^+, and Cl^-. In the inland areas, the medium wells exhibited Na-HCO_3 pattern, which was of normal stagnation, and was different from the pattern showed by the wells in the coastal areas. The difference is attributed to the large quantity of water extraction for agricultural use in the Shiroyishi District from ancient times. Seasonal drawdown of groundwater induced the saltwater intrusion from the coastal areas of the Ariake Sea. Meanwhile, the pollution of river by saltwater also affected the groundwater quality near the river.

Samples of deep wells in coastal areas showed characteristics of normal stagnation. The groundwater in the deep aquifer was not polluted by the saltwater yet.

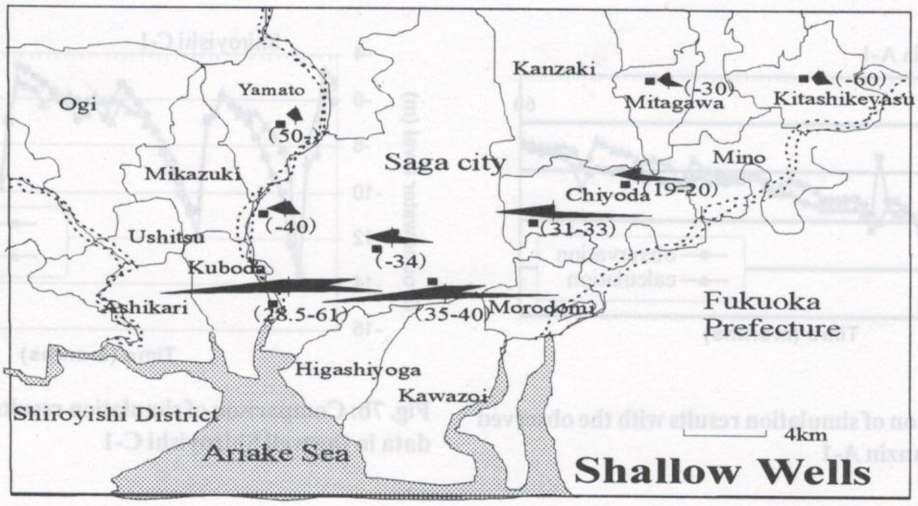

Fig. 8a: Hexa diagram of water samples from shallow wells in the Saga District

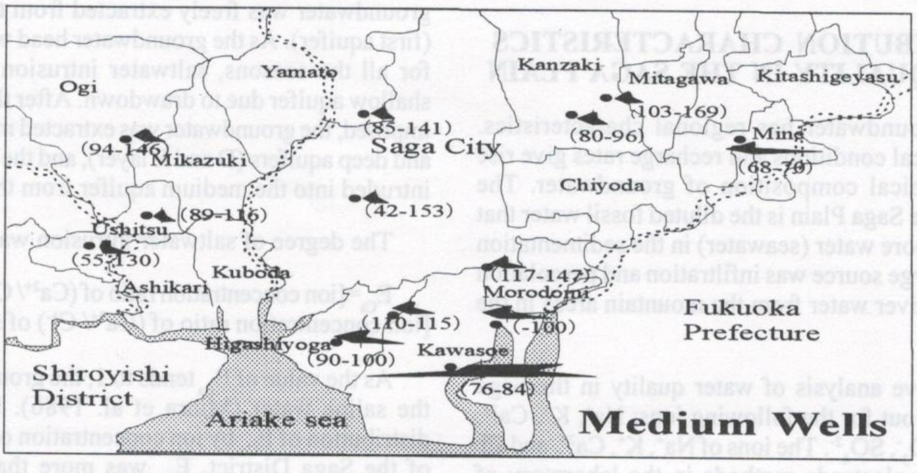

Fig. 8b: Hexa diagram of water samples from medium wells in the Saga District

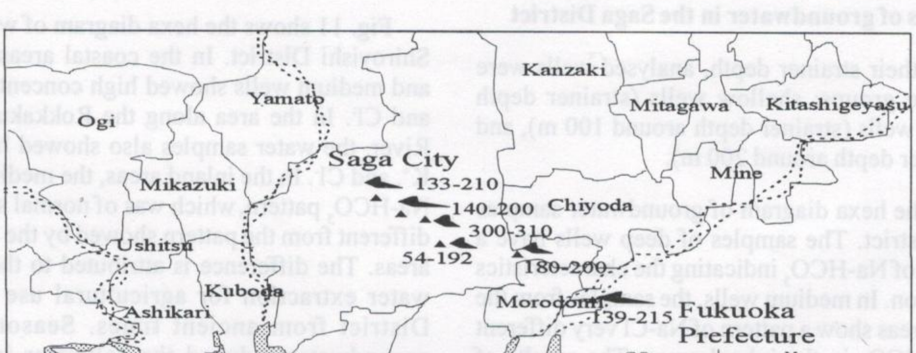

Fig. 8c: Hexa diagram of water samples from deep wells in the Saga District

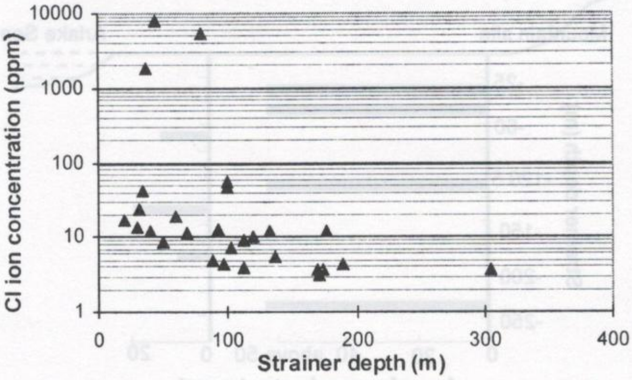

Fig. 9: Concentration of Cl at various depths in the groundwater of the Saga District

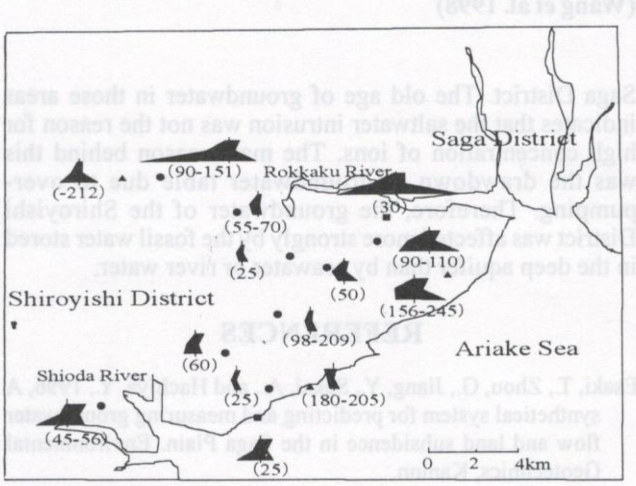

Fig. 11: Hexa diagram of water samples from the Shiroyishi District

Fig. 12 shows the distribution characteristics of Cl⁻ concentration by strainer and, Fig. 13 shows E_{Ca} value by Cl⁻ concentration in Shiroyishi District. The degree of saltwater intrusion in shallow and medium wells was serious, especially in the area near the Ariake Sea.

Tritium concentration analysis

Tritium, with the half-life of 12.33 years, is the isotope of hydrogen. It could be applied as a tracer to determine the groundwater age, its flow direction, and recharge source. There are two sources of tritium. One is from the natural resource such as sun or the nuclear reaction in the atmosphere, and it falls on the ground with rainfall. Another source is the artificial tritium produced by hydrogen bomb tests from 1953 and it spreads over the whole earth by rainfall and wind. Following equation was used to calculate the age of groundwater.

$$N = N_0 \exp(-\ln\frac{2t}{t_h})$$

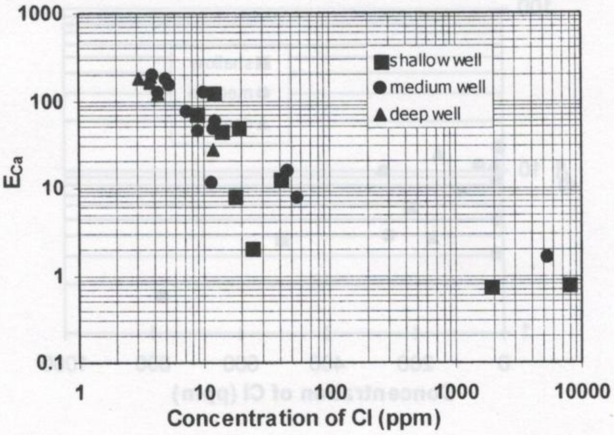

Fig. 10: Plot of E_{Ca} versus Cl concentration in the groundwater of the Saga District

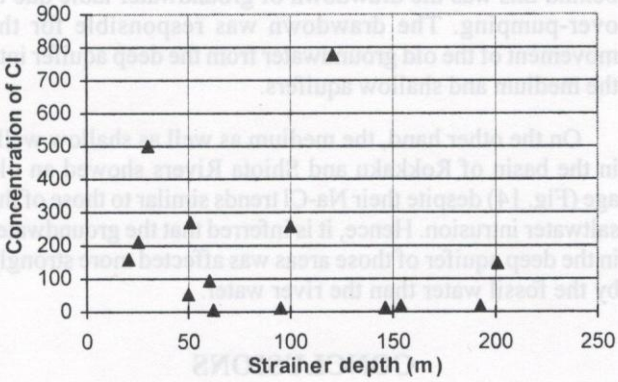

Fig. 12: Concentration of Cl at various depths in the groundwater of the Shiroyishi District

where, N is the present tritium concentration; N_0 is the tritium concentration of past rainfall; t_h is the half-life of tritium; and t is the duration of rainfall (The Research Group of Water Balance 1973).

In the Saga District, the tritium concentrations showed a young age of groundwater in shallow wells. In the inland areas, it was related to the effect of recharge from the northern mountain areas. In the coastal areas, it could be the effect of saltwater intrusion from the Ariake Sea. In medium and deep wells, while the samples from the inland areas showed an old age (normal stagnation), the samples from the coastal areas depicted a young age. This phenomenon might be attributed to the effect of saltwater intrusion.

In the coastal areas of the Shiroyishi District, even the samples of deep wells showed a young age. It is ascribed to the effect of saltwater intrusion from the Ariake Sea. In the inland areas, the samples from all types of well (i.e. shallow, medium, and deep) showed an old age. The main reason

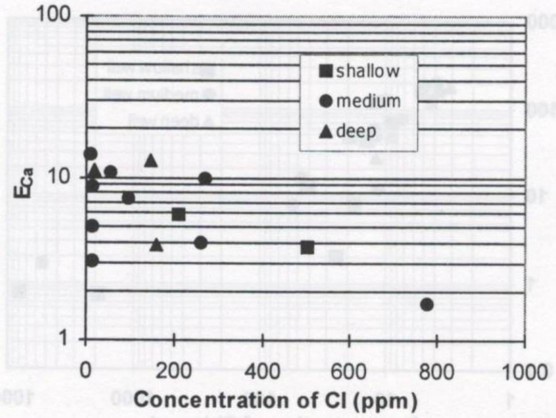

Fig. 13: Plot of E_{ca} versus Cl concentration in the groundwater of the Shiroyishi District Shiroyishi District

behind this was the drawdown of groundwater table due to over-pumping. The drawdown was responsible for the movement of the old groundwater from the deep aquifer into the medium and shallow aquifers.

On the other hand, the medium as well as shallow wells in the basin of Rokkaku and Shiota Rivers showed an old age (Fig. 14) despite their Na-Cl trends similar to those of the saltwater intrusion. Hence, it is inferred that the groundwater in the deep aquifer of those areas was affected more strongly by the fossil water than the river water.

CONCLUSIONS

The overdraft of groundwater has seriously affected the Saga Plain. The groundwater head varies seasonally with the variation of pumping amount and precipitation. In the Saga District, the foothills of the northern mountains are the main recharge zones, whereas in the Shiroyishi District, the recharge zone lies in the foothills of the northern and western mountains.

One-layer, two-dimensional plane model matches well with the actual groundwater head fluctuations in the wells of the Saga Plain.

In the Saga Plain, the groundwater of shallow and medium aquifers is polluted by saltwater intrusion due to over-pumping. The pollution in the coastal areas of the Saga District (near the Ariake Sea) is more serious than that in the inland areas. Even though a similar trend is observed in the Shiroyishi District by chemical component analyses, the reason of groundwater pollution is different from that of the Saga District. The old age of groundwater in those areas indicates that the saltwater intrusion was not the reason for high concentration of ions. The main reason behind this was the drawdown of groundwater table due to over-pumping. Therefore, the groundwater of the Shiroyishi District was affected more strongly by the fossil water stored in the deep aquifer than by seawater or river water.

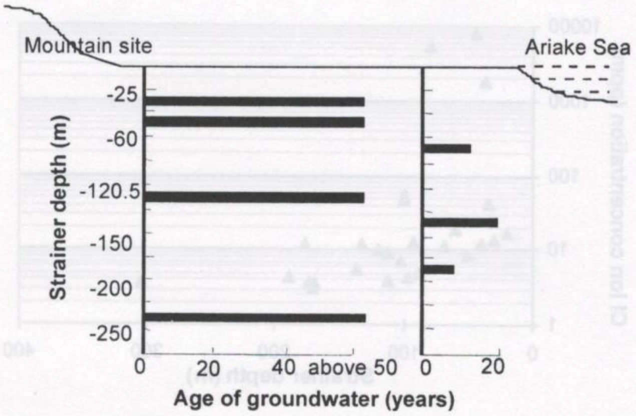

Fig. 14: Groundwater ages from the Shiroyishi District (Wang et al. 1998)

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