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HYDROGEOCHEMICAL DESCRIPTION OF GROUNDWATER IN A COASTAL LOWLAND PLAIN NEAR THE ARIAKE SEA OF JAPAN

N. Cao Don[1,*], Mohan S. Kumar[2], H. Araki[1] and H. Yamanishi[1]

ABSTRACT: In the management of water resources, quality of water is just as important as its quantity. In this paper, an investigation was undertaken to better understand the hydrogeochemistry and hydrologic framework of the Shiroishi plain in Saga, Kyushu, Japan. A network of production boreholes and wells distributed over the studied region were sampled and the waters were analyzed for major ions. The results reveal that, in areas near the shore, salinization is more serious at deeper layers. Geochemical analyses showed that the Shiroishi aquifer has bicarbonate sodium water, with an increase of electrical conductivity, sodium and bicarbonates contents.

Keywords: Coastal lowland, groundwater pumping, groundwater chemistry, salinization

INTRODUCTION

In many countries, coastal lowlands are often convenient and attractive locations for human settlement, transportation, agriculture, industry and economic activities. The concentration of human activities in lowland areas intensifies local competition for all types of resources, such as for food, energy and natural resources with water amongst the most vital. These areas therefore become more and more important to the growth of human civilization and the development of their activities. However, under natural process of the water cycle and human interferences such as mining of natural resources and land reclamation, water environment problems in these areas have become causes for social concern.

Located in the Saga plain (in Kyushu island of Japan), Shiroishi region is one of the productive and intensely farmed agriculture areas in the plain. Water supplied to agriculture has traditionally been a high priority for water managers in this region. Under the climate of the monsoon Asian, about 1,900 mm of precipitation falls in the area. However, this rainfall water is run off quickly because rivers are rapid and short. Groundwater is therefore regarded as an important water resource of drinking water and the primary source of irrigation water for agriculture. Since 1960s, the use of ground water for irrigation in this district has increased rapidly. Withdrawal totals had been increased from 0.7 x 10^3 m^3/day in 1980 to 0.23 x 10^6 m^3/day in 1994. When the pumping is excessive, management of groundwater resources in the basin presents numerous problems of various degrees of complexity in each area, such as seawater intrusion, inter-aquifer flow, land subsidence,

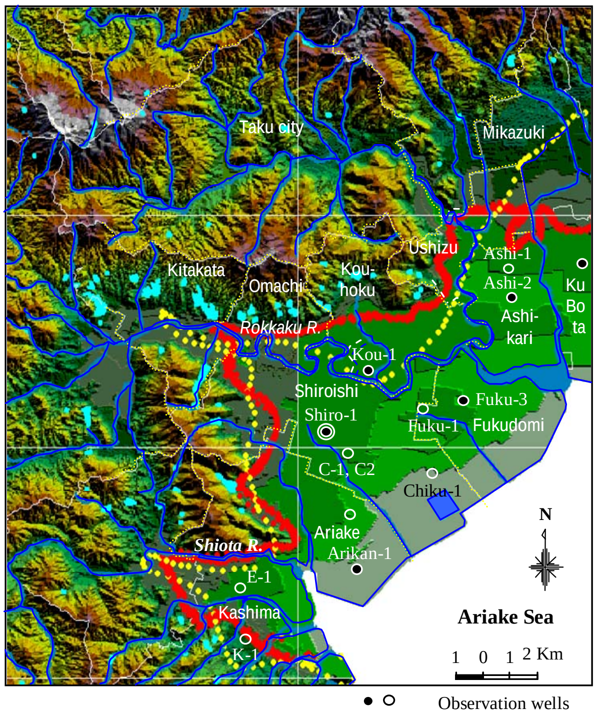

Fig. 1 Digital map showing Shiroishi plain in Saga, Kyushu, Japan (after Don et al. 2005)

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[1] IALT life Member, Institute of Lowland Technology, Saga University, Saga 840-8502, JAPAN

[*] *Corresponding author,* Email: don@ilt.saga-u.ac.jp; Tel. & Fax: +81 952 28 8571

[2] IALT life Member, Department of Civil Engineering, Indian Institute of Science, Bangalore, INDIA

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and ground-water contamination over the alluvial plain Don et al. (2005).

Understanding groundwater chemistry requires knowledge of the hydrology and hydrochemistry evolution as water travels through various pathways in an aquifer reservoir. Basic geochemical reactions, such as freshwater-seawater interactions and minerals dissolution, change solute composition of the aquifer system. A network of production boreholes and wells distributed over the studied region were sampled and the waters were analyzed. However, so far, there has been no interpretation on groundwater quality data to provide the understanding of hydrochemical processes happening in the region. This paper sets out to identify and explain the main geochemical processes controlling the local groundwater chemistry.

DESCRIPTION OF THE STUDY AREA

The Rokkaku river basin consists of the Shiroishi plain with the towns of Shiroishi, Omachi, Fukutomi, and Ariake (Fig. 1). The Rokkaku basin is the largest river basin in Saga lowland, with the total catchment area of 341 km2. Upstream, the river originates from the mountainous area and the lower reach is subject to tidal fluctuations and may be described as estuarine. The Rokkaku River flows to Ariake Bay and is an important river in the area. The river supplies water for water use, power generation, irrigation, navigation and waste disposal. However, it is subject to salinity intrusion from the bay.

Hydrologic Setting

In general, the whole area of Shiroishi plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea (Fig. 2). The subsurface strata of Shiroishi Plain are underlain by lowland quaternary soft deposits around the inland Ariake Sea. According to conventional classification, the sediments can be separately divided into several layers based on their geologic and hydrogeologic characteristics. The layer below the ground surface is a soft marine clay layer, which is known as the Ariake clay. It is a confining bed with thickness varying from 10 to 20m. Below this Ariake clay are dilluvial deposits dominated by sands, gravels, and pumices of various sizes, and are of 5m or less in thickness, in both vertical and lateral directions. The underlain are volcanic ash soils deposited in two gravel layers. The Aso-4 volcanic ash appears at about elevation of -20m. The Aso-3 volcanic ash sediment is very thick development. Both diluvium and volcanic ash layers form an excellent aquifer in this region.

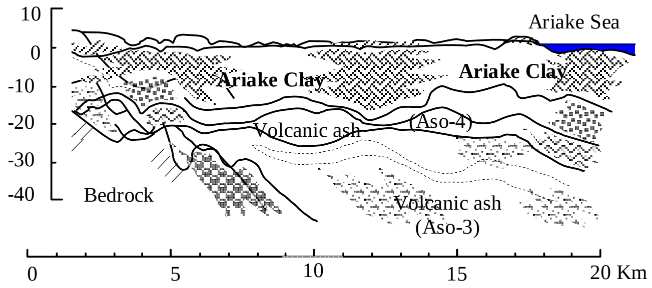

Fig. 2 A typical geological profile along a section near the Rokkaku River

METHODS

The chemical compositions of groundwater data were used to determine factors affecting the hydrogeochemistry of groundwater. Groundwater samples were collected from local wells in Shiroishi, Fukudomi, Ariake an Omachi town (see Fig. 1). Water parameters including depth, temperature, pH, electrical conductivity (EC), dissolved oxygen (DO) concentration, and turbidity were measured in the field. The waters were analyzed for major ions.

RESULTS AND DISCUSSION

The data of groundwater analyses for year 1995-1996 are presented in Table 1 and the average, minimum and maximum values of major ions of groundwater in the study area are presented in Table 2. The analytical data show considerable variation in the concentrations of components. The chemical composition of groundwater changes from area to area in the plain.

Physico-chemical properties (temperature, pH, and DO) of the groundwater bodies of all four areas contrast slightly between their upper and lower parts. Temperature gradually increases toward the surface. Measured pH values were approximately neutral to alkaline, ranging from 7.1 to 8.0, and meet the USEPA criteria (6.5 – 9.0) for freshwater aquatic life (USEPA 1998). The pH values in all areas are higher in the upper layers. This is related to active photosynthesis in the upper layers, making water under-saturated in CO_2 (HCO_3^- in water). Dissolved O_2 concentrations in the deeper parts are lower than those in overlying water layers. The reduction in pH and DO values seem to confirm increased respiration rates and reducing

Table 1 The physio-chemical properties and major ions of groundwater

Name	Depth *(m)*	Temp ^oC	pH -	EC *μS/cm*	DO *mg/l*	Na$^+$ *mg/l*	K$^+$ *mg/l*	Ca^{2+} *mg/l*	Mg^{2+} *mg/l*	Cl$^-$ *mg/l*	HCO$_3$$^-$ *mg/l*	SO$_4$$^{2-}$ *mg/l*
Ariake	117-150	19.1	7.5	523.0	7.57	33.70	8.44	28.80	20.00	69.80	104.00	5.30
-	82-131	19.7	7.8	148.0	8.59	9.94	3.96	9.36	5.65	5.10	75.70	1.71
-	79-150	18.9	7.7	138.0	7.77	11.00	3.54	7.84	5.90	3.88	76.30	2.46
-	64-131	21.5	7.4	242.0	4.57	22.40	5.15	10.80	7.29	21.50	84.20	1.98
-	103-210	21.4	7.6	156.0	1.70	14.50	4.20	7.11	5.79	4.35	87.30	1.87
-	53-85	20.0	7.8	755.0	5.12	102.00	11.20	13.40	9.49	80.20	222.00	0.04
-	180-205	21.4	7.8	205.0	3.04	28.70	4.59	4.86	3.80	5.95	113.00	0.00
Fukudomi	100-130	22.6	7.5	1070.0	4.40	138.00	16.40	18.30	13.70	108.00	332.00	0.02
-	84-180	23.0	7.8	337.0	3.08	45.90	7.18	1.97	1.80	11.40	172.00	0.00
-	75-150	18.0	7.1	3830.0	2.57	557.00	20.00	63.60	40.50	617.00	416.00	0.62
-	70-160	19.3	7.3	1311.0	3.22	148.00	17.40	31.50	25.20	162.00	309.00	0.04
-	98-175	23.0	7.4	850.0	1.56	134.00	14.10	11.00	9.82	64.00	347.00	0.00
-	130-180	20.8	7.4	1078.0	5.98	115.00	19.20	30.10	26.30	113.00	339.00	0.00
-	100-180	23.3	7.4	820.0	2.35	119.00	17.10	20.70	17.50	52.10	372.00	0.02
Kitakata	30-40	19.5	7.8	184.0	7.72	15.20	3.60	11.20	5.93	11.40	78.10	4.13
-	39-80	19.6	7.6	222.0	6.58	29.20	4.21	7.28	3.95	18.10	80.50	3.66
-	73-159	20.1	7.6	569.0	3.41	73.90	7.23	5.78	3.95	52.10	170.00	0.17
Omachi	112-190	21.6	7.6	121.0	7.61	10.40	4.51	6.86	3.40	3.66	62.90	2.23
-	37-43	19.4	7.7	143.0	2.99	15.20	3.03	7.88	3.89	3.91	75.10	1.78
-	62-171	20.3	7.9	213.0	2.80	28.20	2.53	6.16	2.48	4.26	124.00	1.42
-	91-151		8.0	1992.0	3.20	279.00	3.03	23.60	14.20	268.00	395.00	4.63
-	32	22.5	7.9	567.0	4.56	70.80	8.40	10.20	5.71	74.80	122.00	3.54
Shiroishi	39-115	18.6	7.6	134.0	7.10	12.30	3.81	8.26	5.13	4.36	70.80	3.69
-	57-136	19.7	7.4	184.0	3.37	14.60	7.33	7.20	5.83	5.14	105.00	0.00
-	134-153	17.9	7.4	310.0	5.09	46.00	8.90	7.41	1.22	27.70	105.00	0.03
-	180	20.9	7.5	160.0	4.47	15.50	6.31	6.86	4.24	6.75	77.50	2.90
-	48-149	21.5	7.8	145.0	5.45	16.70	5.99	5.35	3.34	5.06	73.20	3.03
-	64-160	18.3	7.3	710.0	0.75	70.10	14.10	25.30	16.80	85.20	164.00	0.02
-	60-106	19.3	7.7	214.0	2.19	29.80	6.04	5.70	3.98	11.00	108.00	0.02
-	117-127	20.8	7.8	194.0	2.00	30.10	3.95	1.15	0.76	4.92	108.00	0.03

Table 2   Statistic samples, concentrations in *mg/l*

	Min	Max	Average	St. Dev.	Dev. Coeff	Var %
Na$^+$	9.94	557.0	69.465	108.85	156.698	98.0
K$^+$	1.15	63.6	12.219	12.292	100.595	98.0
Mg^{2+}	0.76	40.5	8.105	8.34	102.901	98.0
Cl$^-$	3.66	617.0	59.805	120.028	200.699	99.0
HCO$_3$$^-$	0.0	142.0	6.314	25.679	406.706	100.0
pH	7.1	8.0	7.609	0.234	3.077	11.0

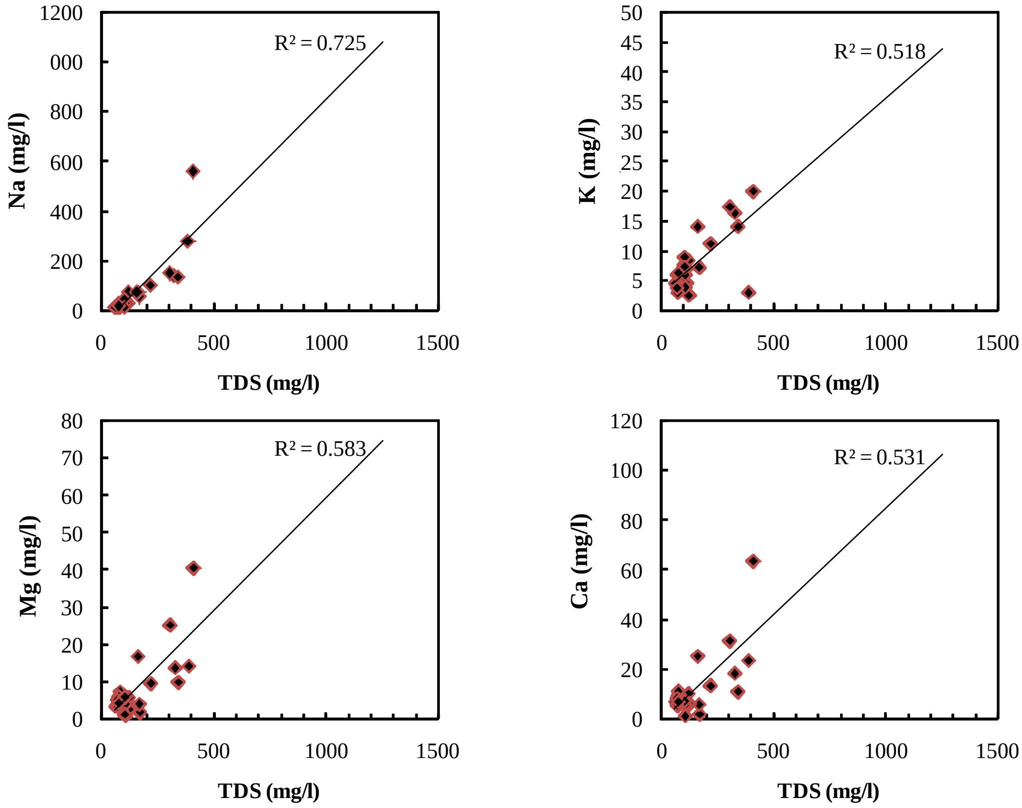

Fig. 3 The diagrams of variations between TDS (total dissolved solid) and cations (K, Na, Mg, Ca) in the groundwater

conditions in deeper water strata. The value of EC ranges from 121.0 (Omachi) to 3,830 µS/cm (Fukudomi). The average EC is 309.6 µS/cm in Ariake; 256.4 µS/cm in Shiroishi; 501.4 µS/cm in Omachi and 1328.0 µS/cm in Fukudomi. High EC values in all areas suggest higher ionic concentrations.

A classification on chloride concentrations into three main types of fresh, brackish or saline groundwater is as follows: fresh $Cl \leq 300$ mg/L, brackish $300 < Cl < 10{,}000$ mg/L and saline $Cl \geq 10{,}000$ mg/L. The drinking water standard in the European Community has been 150 mg Cl/L (Stuyfzand 1986), while a convenient chloride concentration limit is 250 mg Cl/L (Bakker 2000). The chloride concentrations of the groundwater samples range from 3.66 in Omachi to 617 mg/l in Fukudomi. The groundwater over Fukudomi area is not suitable for drinking or irrigation water, based on the 250 mg Cl/l guideline for potable water.

The lowest sodium value is 9.94 and the highest value is 557 mg/l. The lowest calcium content is 1.15 and the highest value is 63.6 mg/l. Magnesium concentrations generally have a similar trend to calcium. Because magnesium is the second most abundant cation in seawater, the main source of magnesium might be seawater. The highest value of the study area is 40.5 mg/l and the lowest value is 0.76 mg/l.

The relationship between total dissolved solids (TDS) and major ions are plotted in Figs. 3 and 4, which show the major components influencing groundwater quality. From these two graphs, it can be seen that most ions have a positively good correlation with TDS. In particular, Na, Cl, and Mg show a good correlation with TDS with $R^2 = 0.73$ for Na, 0.62 for Cl, and 0.58 for Mg, indicating that such ions are derived from the same source of saline waters. Because these components, Na, Cl and Mg, are dominant in seawater, this implies that salinization of this area is closely connected with seawater.

The groundwater quality data are also plotted in a Piper diagram in Fig. 5. To construct the piper diagram, the relative abundance of cations of Na, K, Ca, and Mg is first plotted on the cation triangle. The relative abundance of Cl, SO_4, and HCO_3 is then plotted on the anion triangle. The two data points on the cation and anion triangles are then combined into the quadrilateral field that shows the overall chemical property of the water sample.

It shows different ranges in chemical components, such as sodium, calcium, magnesium and chloride. Using the pattern on the figure, the groundwater was classified into three types, namely the Na-HCO_3, Na-Cl-HCO_3 and Na+Mg+Ca-HCO_3. The major ion trends of the Na–HCO_3 type are Na > K > Ca > Mg and HCO_3 > Cl > SO4. In contrast, those of Na-CL-HCO_3 type are Na > Ca > Mg > K and Cl > HCO_3 > SO4. For the type of Na+Mg+Ca-HCO_3, the major ion trends are Na > Ca > K > Mg and HCO_3 > Cl > SO4.

Calcium and bicarbonate are the predominant ions in fresh waters near the recharge zones of the aquifer system. This type of water occurs along the areas near mountains in the studied area. The dominance of HCO_3 in solution reflects the importance of exchange of CO_2 in soils and the dissolution of calcite in some aquifer materials. It is certain that the Na-CL-HCO_3 type is mainly a result of mixing with seawater. Na-HCO_3 and Na+Mg+Ca-HCO_3 types may result from two possibilities, one of which is the effect of cultivation. K+, Ca^{2+} and Mg^{2+}, NO_3^- likely comes from anthropogenic sources such as chemical fertilizers. Another possible reaction is cation exchange reaction with aquifer minerals. Moreover, groundwater quality concentrations and EC values in Fukudomi and Ariake measured from a depth ranging from 80 to 210 m were found higher than those measured at depths from 30 to 80 m. It means that near the shore, the salinization is more serious at deeper layers. The Piper diagram (Fig. 5) illustrates the clustering of anion compositions compared with the cations. It also shows that groundwater in Fukudomi and Ariake tends to have higher concentrations of Cl than groundwater in other areas, which is dominated by HCO_3. This phenomenon can be understood using models.

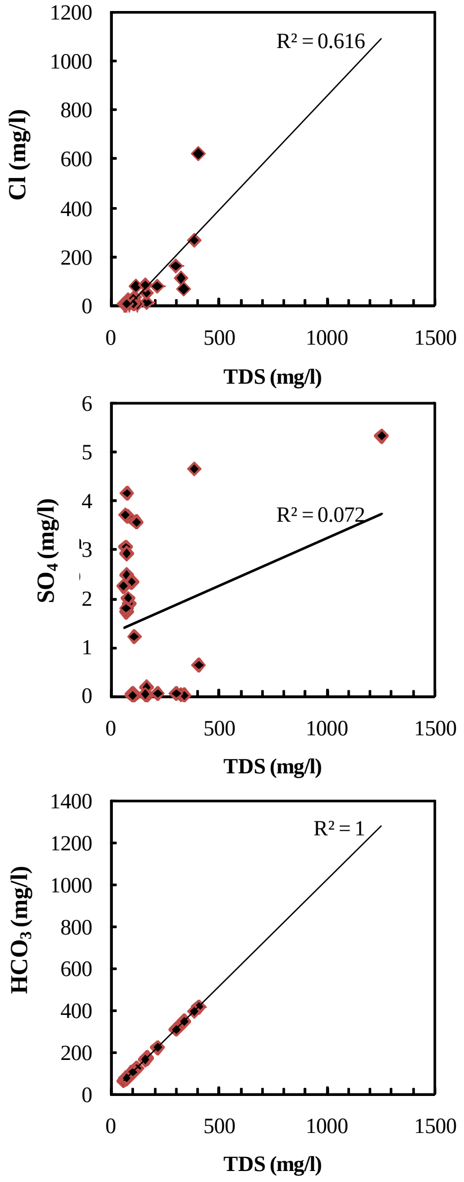

Fig. 4 Diagrams of variations between TDS (total dissolved oxygen) and anions (Cl, SO_4, HCO_3) in the groundwater of the study area

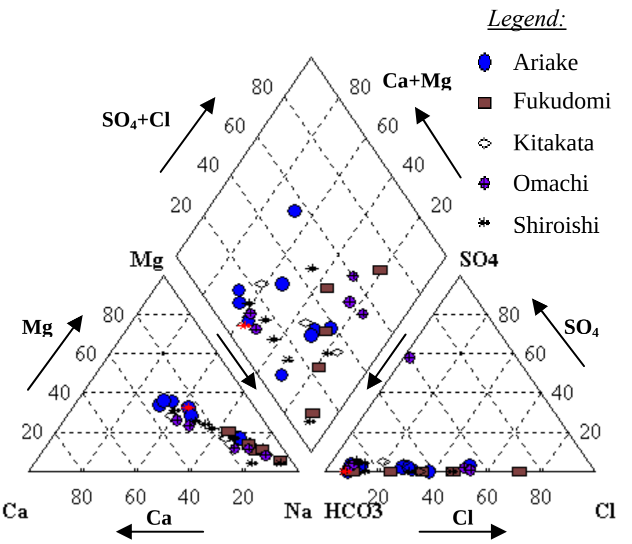

Fig. 5 Modified Piper diagram of the groundwater samples in the study area

A numerical model for simulating salinity intrusion into the Shiroishi aquifer was setup to the study area in term of chloride (Cl) concentration. As a result, a contour map of simulated chloride concentration in a deep aquifer was built and is plotted in Fig. 6 that illustrates the down-gradient migration of saltwater in a deep aquifer (-80m to -120m) after a 20-year simulation from 1979 to 1998. The saltwater, initially flowing from offshore and existing rivers, has mixed with fresh water and laterally leaked downward through the confining unit, and apparently across the aquifer unit toward pumping centers. It is apparent that the salinity plume appears to extend at least 1.2 km far inland from the coast. Moreover, the plume of liquid brine extended down-gradient to few wells located about 1.5 km from the coast (Don et al. 2005). Based on the above observation, it is apparent that seawater intrusion would worsen in the confined aquifer along the coast if the current scheme of groundwater pumping continues.

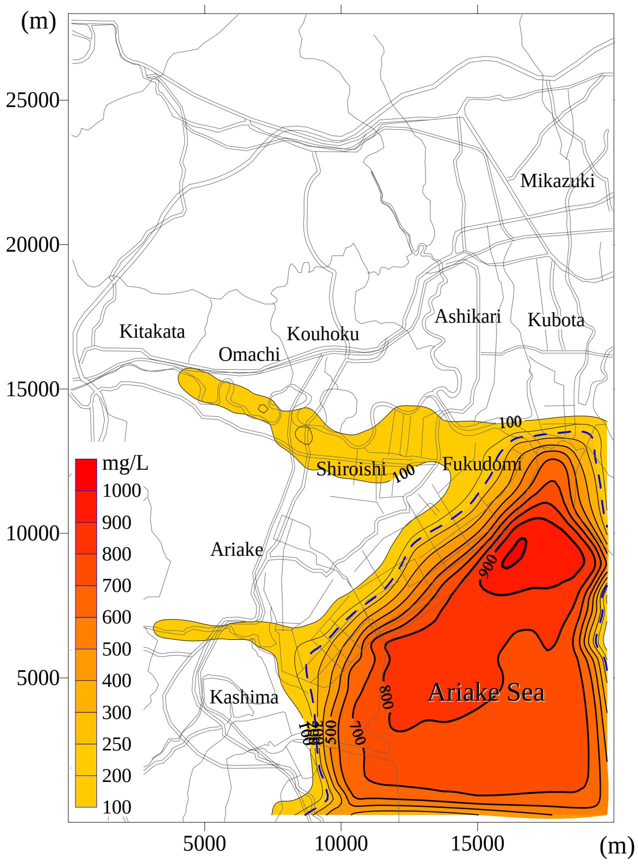

Fig. 6 Contour of simulated chloride (Cl) concentration (in mg/l) in a deep aquifer

Therefore, any groundwater development activity in the region needs to be carefully planned with remedial measures in order to minimize the further intrusion of seawater.

CONCLUSION

In this study, the hydrogeochemical and hydrological processes of groundwater in a coastal lowland plain are presented. Solution chemistry of groundwater in the local Shiroishi aquifer provides valuable information related to freshwater-salinity water interaction occurring during natural and human activities related process.

New finding shows that a Na-Cl-HCO_3 type of water, which is apparent downstream of the recharge zones, along the Ariake Sea coast, denotes excessive mixing and ion exchange processes and possible saline water intrusion.

Monitoring the present salinisation process is useful to participate in time possible threats to fresh groundwater supplies in the near future. Instead, a reduction in pumping rate can limit seawater intrusion significantly. This alternative is of practical value when considering the importance of the groundwater resources in the area.

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