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Assessment of seawater intrusion using geophysical well logging and electrical soundings in a coastal aquifer, Youngkwang-gun, Korea

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Key Words: seawater intrusion, well logging, equivalent NaCl concentration

ABSTRACT

A combination of drilling, geophysical well logging, and electrical soundings was performed to evaluate seawater intrusion in Baeksu-eup, Youngkwang-gun, Korea. The survey area extends for over 24 km^2. To delineate the extent of seawater intrusion, 60 vertical electrical soundings (VES) have been carried out. Twelve wells were also drilled for the collection of hydrogeological, geochemical, and geophysical well logging data, to delineate the degree and vertical extent of seawater intrusion. To map the spatial distribution of seawater in this coastal aquifer, geophysical data and hydrogeochemical results were used, and the relation between the resistivity of groundwater and equivalent NaCl concentration was found. Layer parameters derived from VES data, various in-situ physical properties from geophysical well logging, and the estimated equivalent NaCl concentration were very useful for quantitative evaluation of seawater intrusion. Our approach for evaluating seawater intrusion can be considered a valuable attempt at enhancing the use of geophysical data.

INTRODUCTION

Seawater intrusion, leading to deterioration in water quality in coastal aquifers, occurs commonly along the western and southern coasts of Korea. Hwang et al. (2003) reported that about 47% of groundwater wells within 10 km of the western and southern coasts are affected by seawater intrusion. Seawater intrusion is an inevitable problem in countries adjacent to the sea. In order to develop a technique for assessing seawater intrusion, a detailed survey area was selected, and various geophysical well logging and surface electrical soundings were carried out to see how these could be used to characterize seawater intrusion. Fitterman et al. (1999), Morin and Urish (1995), Nowroozi et al. (1999), Paillet et al. (1999), and Schnoebelen et al. (1995) have reported the applicability of geophysical well logging and surface geophysical surveys for the evaluation of the seawater intrusion characteristics. The main purpose of this study is to develop a relationship between electrical conductivity and equivalent NaCl concentration in groundwater from hydrogeochemical analysis results, to use this to map the salinity in a coastal aquifer, and thus to find the seawater/freshwater interface using geophysical well logging and vertical electrical soundings in a more quantitative analysis.

GEOLOGIC SETTING OF SURVEY AREA

The survey area is located in Baeksu-eup, Youngkwang-gun, on the western coast of Korea. The topography is generally flat, as shown in Figure 1. The central area mainly consists of paddy and dry fields. The western side is adjacent to the sea, while the northeastern side is hilly, with Gaji-san reaching an altitude of 50 m. The survey area is about 24 km^2. Figure 2 shows the geological logs resulting from 12 boreholes, which indicate that the geological structure of the survey area comprises mud (from the surface to a depth of 5~20 m), sand (to a depth of about 25 m), and granite bedrock (below an approximate depth of 25 m).

VERTICAL ELECTRICAL SOUNDINGS

Vertical electrical soundings (VES) were carried out at 60 stations to understand the geological structure of the survey area (see Figure 1). The Schlumberger electrode array was used, and the maximum current electrode spacing was 150 m. Figure 3 is one of the results of inversion of VES data for a station located near boreholes YK-2 and YK-4. From the surface to a depth of about 4 m, where there is an alluvial layer, the lowest resistivity indicates mud, the depth interval between about 14 and 27 m corresponds to sand, and we can see highly resistive bedrock granite below about 27 m. The thickness of the sand layer estimated from the VES data shown in Figure 3 was slightly more than that confirmed by drilling. This discrepancy is due to saturated pore water, with high electrical conductivity, in the weathered zone on the granite, below the sand layer. A three-dimensional view of layer boundaries interpreted by compiling the inversion results of VES data is shown in Figure 4, in which the vertical exaggeration is 50x. The left side of Figure 1 and that of Figure 4 are the same.

GEOPHYSICAL LOG ANALYSIS

Various geophysical well logs, including temperature, fluid conductivity, electromagnetic induction, caliper, natural gamma, gamma-gamma, and thermal neutron logging were obtained in 12 boreholes for analysing the hydrogeological characteristics and for calibrating the surface geophysical data. The slim-hole logging system, Pro-logger II manufactured by Robertson Geologging Ltd., was used for logging the holes. Figure 5 shows the results of geophysical well logs in boreholes YK-4 and YK-8, which are located near the centre of the survey area as shown in Figure 1. In the sand layer, the resistivity is less than 10 Ω.m, and the electrical conductivity of the borehole fluid is seen to be more than 5000 μS/cm (Figure 5a).

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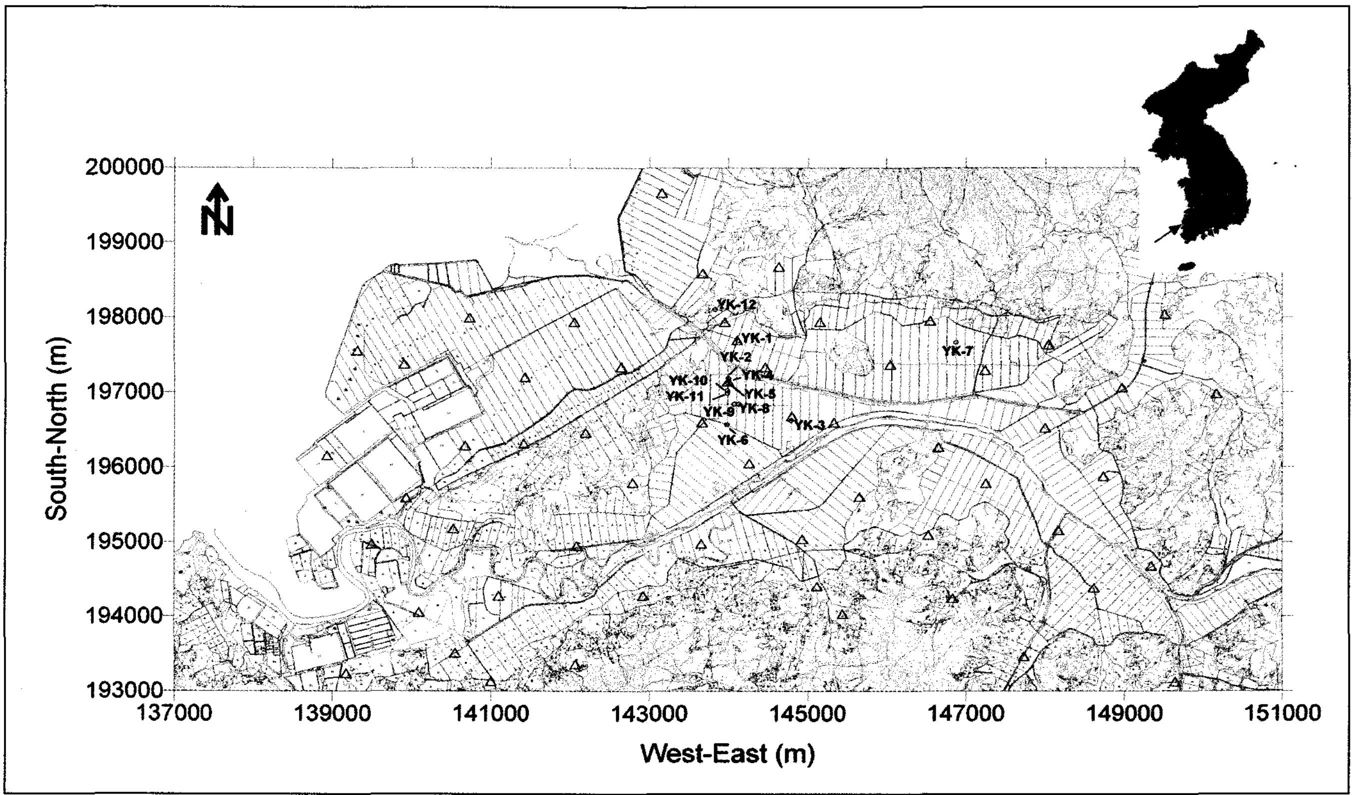


Fig. 1. Location map showing boreholes (open circles) and VES stations (solid triangles), superimposed on the topographic map of the survey area, Baeksu-eup, Youngkwang-gun, Korea.

Thermal neutron logs were run in boreholes YK-4 and YK-8 to estimate the formation porosity and the electrical conductivity of pore water of the sand layer. The distance between these two boreholes was about 200 m. The average porosity of the sand layer was about 38% (see Figure 5b). The electrical resistivity of pore water in the sand layer, R_W (Ω.m), was then obtained by Archie's law (Archie, 1942):

$$R_w = \frac{\phi^m R_o}{a}, \tag{1}$$

where R_O is the saturated formation resistivity (Ω.m), ϕ is the formation porosity, m is the cementation factor, and a the pore geometry coefficient. R_O and ϕ are obtained from the induction resistivity and thermal neutron porosity logs, respectively. For unconsolidated sands, gravels, and most granular systems, m and a are assumed to be 1.4 and 1, respectively (Kwader, 1985; 1986).

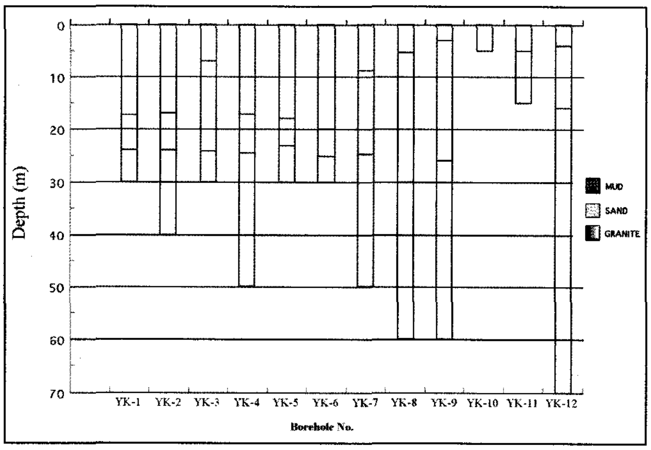


Fig. 2. Drilling logs from the survey area.

The vertical distribution of pore water resistivity can be estimated in this way from the porosity and induction logs.

A pore water conductivity log estimated in this way for borehole YK-4 is shown in Figure 6, and is compared with the electrical conductivity of borehole fluid measured directly, using electrical conductivity logging. The discrepancies between the two logs at shallow depth are partly due to errors in porosity

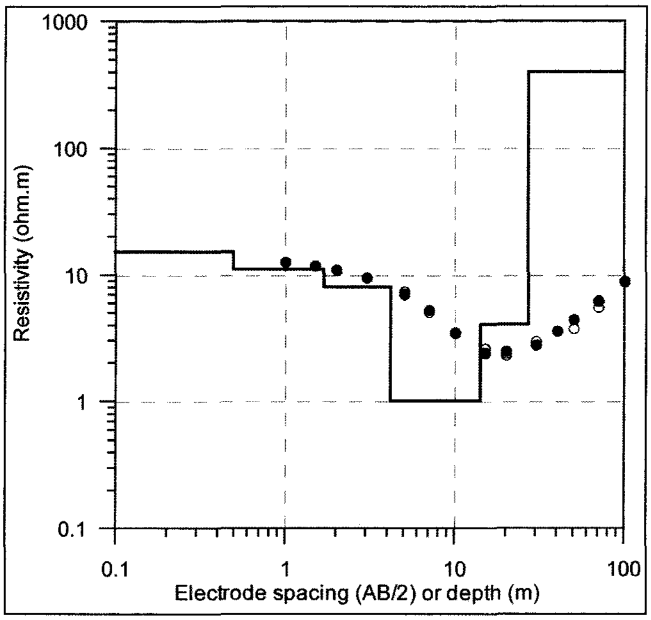


Fig. 3. An example of inversion of VES data, measured near the boreholes YK-2 and YK-4. Solid and open circles are the measured and calculated VES data, respectively. The solid line is the estimated subsurface model.

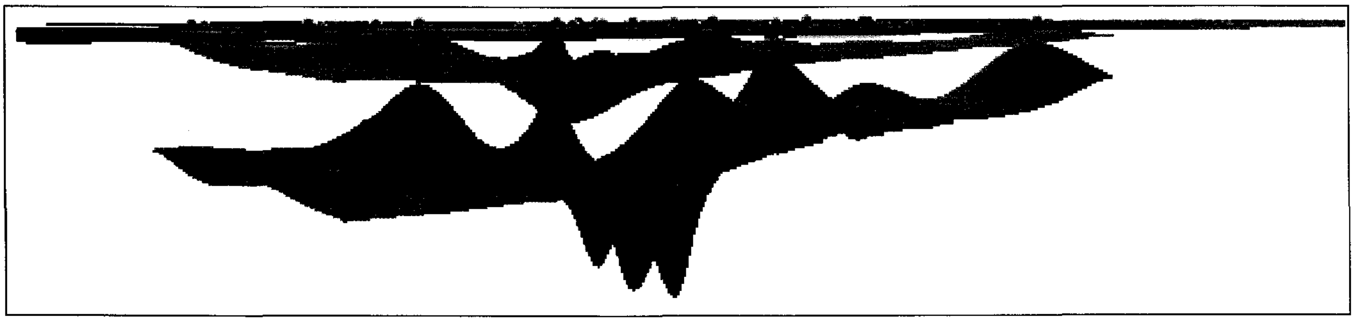


Fig. 4. A three-dimensional view of the layer boundaries interpreted from VES data (1:50 vertical exaggeration).

measurement using thermal neutron logging. In the mud layer, there will be a high proportion of hydrogen chemically bonded in clay minerals. This increase in hydrogen concentration will generally cause an anomalously low count rate in the neutron sonde detectors. In the sand interval, the estimated pore water conductivity and the measured fluid conductivity show similar values. This similarity indicates that the saline borehole fluid originates from the sand layer. We can, therefore, conclude that the sand layer is the main aquifer of seawater intrusion, and transform the saturated formation resistivity of the sand layer to pore water resistivity using Archie's law.

RELATION BETWEEN GROUNDWATER RESISTIVITY AND EQUIVALENT NaCl CONCENTRATION

The VES results were used to map the salinity and to find the seawater/freshwater interface in the sand layer, the main aquifer in the survey area. The salinity, and the location of the seawater/freshwater interface, in the sand layer could be estimated more quantitatively if we expressed the resistivity of groundwater in terms of the concentration of dissolved salts in the aquifer. We therefore transformed the groundwater resistivity in the main aquifer to an equivalent NaCl concentration in the following way. The equivalent NaCl concentration for the pore water in a sand layer was estimated by using the results of chemical analyses for cations and anions of the ground water within the survey area, because the equations proposed by Schlumberger Ltd (1972) and Hilchie (1984) only work in NaCl solutions. Figure 7 shows the resulting relation between the equivalent NaCl concentration and the electrical resistivity of groundwater in the survey area. A linear least-squares fit (in log-log space) using 22 borehole data gives

$$ppm_{eq} = 4612 \times R_o^{-0.98}, \quad R^2 = 0.98 \quad , \tag{2}$$

where ppm_{eq} is the equivalent NaCl concentration (ppm), R_W the pore water resistivity (Ω.m) at 25°C, and R^2 the correlation coefficient in the least-squares fit.

Figure 8 is a contour map of the estimated equivalent NaCl concentration in the sand layer of the survey area. The seawater/freshwater interface is along a north-south to slightly east direction at the centre of the survey area when the electrical conductivity of brackish water is assumed to be 2000–8000 μS/cm (i.e., 1.25–5 Ω.m in Figure 7). The distribution of equivalent NaCl concentrations in Figure 8 can now be used as input data (for example, for groundwater density distribution) for numerical fluid flow modelling of seawater intrusion.

We also tried to verify the reliability of the estimated equivalent NaCl concentration in the sand layer using the borehole data. Comparing the fluid electrical conductivity in boreholes YK-1,

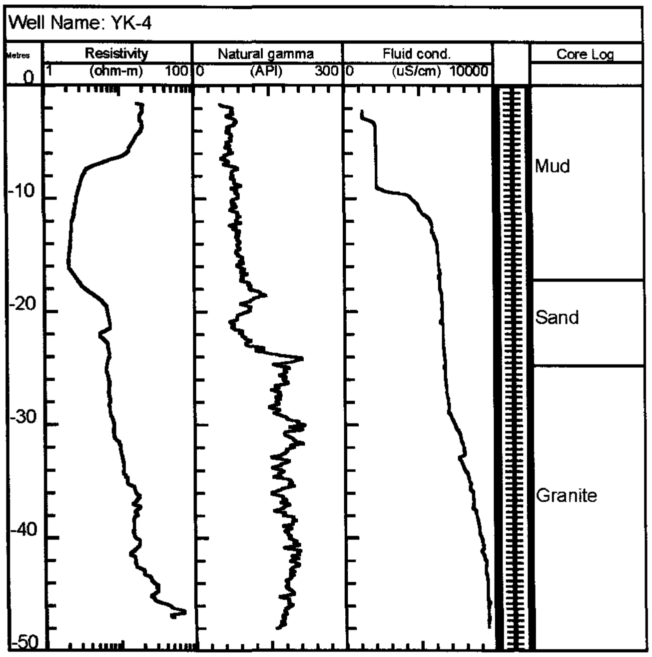


Fig. 5(a). Resistivity, fluid conductivity, and natural gamma logs from borehole YK-4.

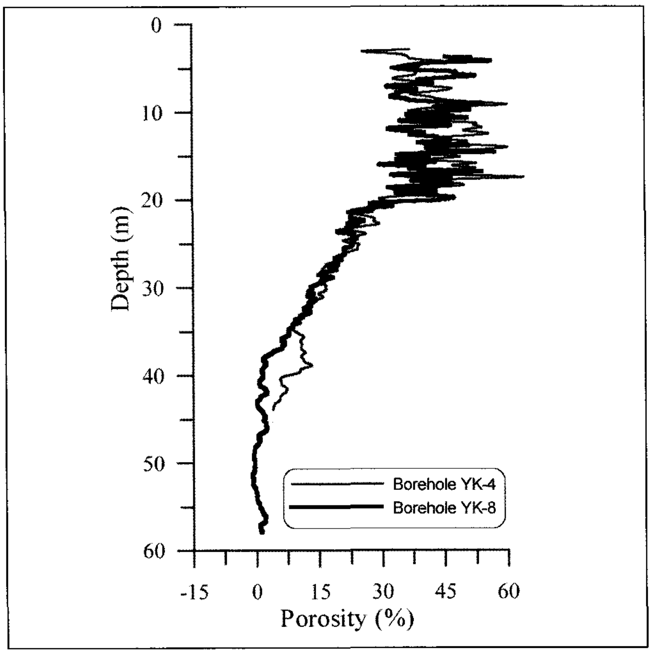


Fig. 5(b). Porosity logs obtained from the thermal neutron logs in boreholes YK-4 and YK-8.

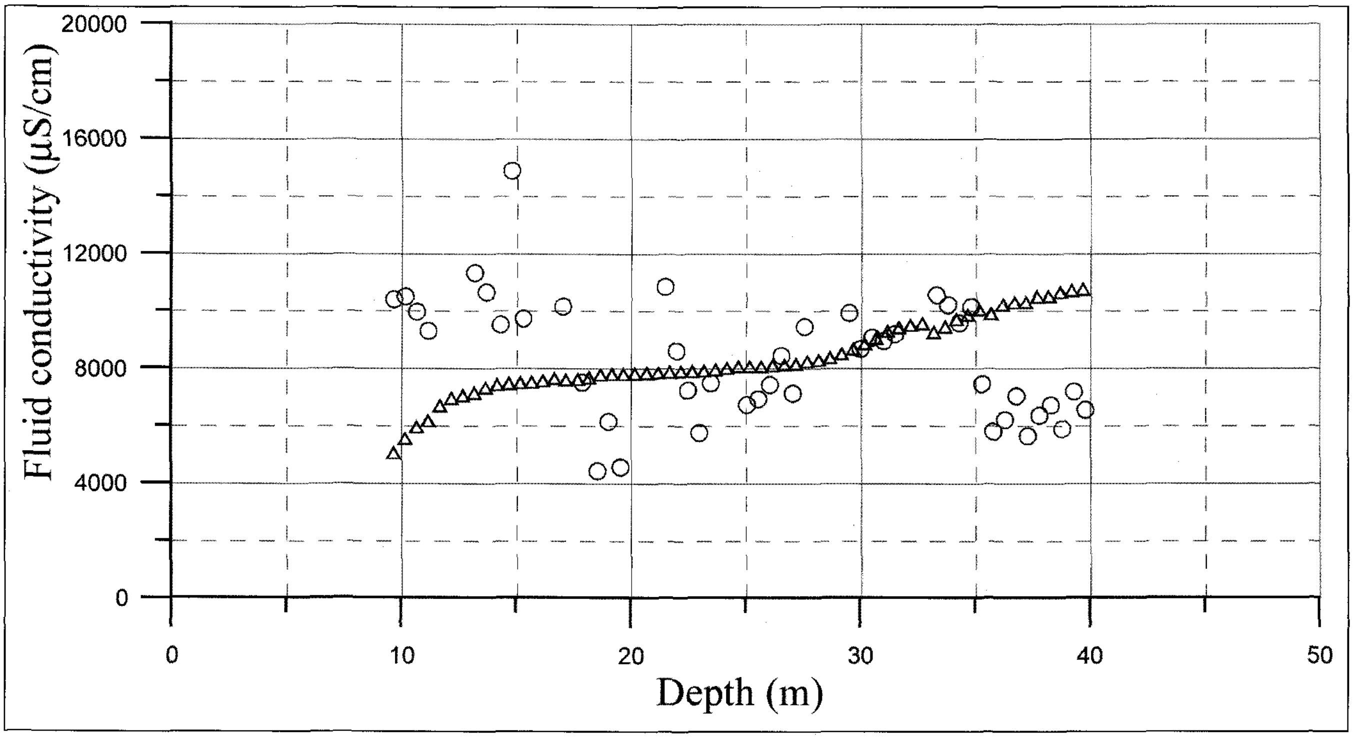


Fig. 6. Estimated electrical conductivity of pore water (circles), and measured electrical conductivity of fluid (triangles) in borehole YK-4.

YK-7, and YK-4 (see Figures 5a and 9), we can find that boreholes YK-7, YK-1, and YK-4 are located in fresh, brackish, and saline water zones, respectively.

DISCUSSION

In order to evaluate accurately the extent of seawater intrusion, it is necessary to perform various surveys including geological mapping, drilling, geophysical surveys, as well as hydrogeochemical analyses and numerical modelling of the flow and transport of groundwater. In numerical modelling, reliable input parameters are indispensable. Geophysical results could be used as valuable input parameters of numerical groundwater modelling. For example, subsurface geological information produced by VES, various in-situ physical properties derived from geophysical well logs, and salinity in the sand layer is typical of the inputs used in numerical modelling.

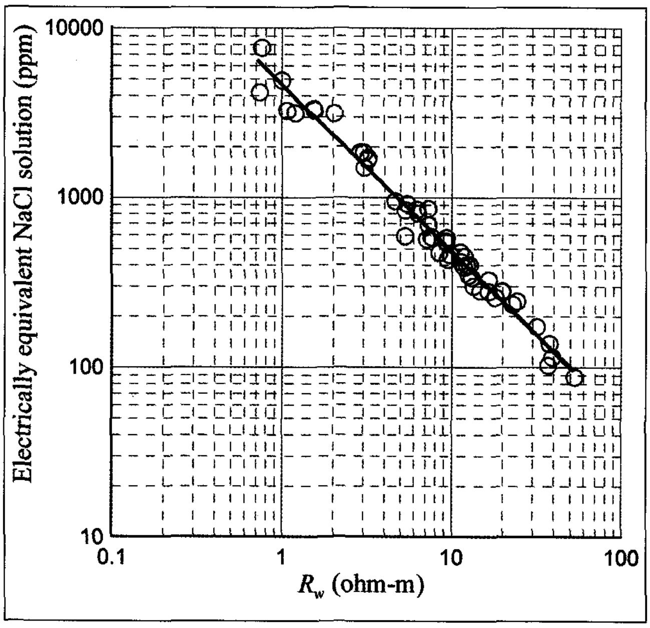


Fig. 7. Relation between the groundwater resistivity, derived from induction and thermal neutron logs, and equivalent NaCl concentration estimated from chemical analyses. The solid line shows a least-squares fit.

One of the important results of this study is the spatial distribution of equivalent NaCl concentration in the sand layer. From Figure 8, we can find the seawater/freshwater interface. However, the *estimated* NaCl concentration in pore water in the sand layer is derived from geophysical surveys by indirect methods. Therefore, it is necessary to verify the reliability of Figure 8 using a direct method such as hydrogeochemical analysis of groundwater in the survey area. Therefore, we have compared the NaCl concentration in Figure 8, estimated from geophysical surveys, with Figure 10, which shows the chloride concentration obtained by hydrogeochemical analyses.

Before we discuss the reliability of Figure 8, it is necessary to understand the difference between the direct and indirect methods. The most important difference is the sampled depth and volume, i.e., the measurement scale. Almost all the groundwater wells within the survey area are shallow, because of highly salty water in the sand layer. Comparing the estimated equivalent NaCl concentration in Figure 8 with the chloride concentration in Figure 10, a similar distribution can be seen in the central area where the brackish/fresh water boundary in Figure 10 compares with the green colour (representing approximately 1000 ppm chloride concentration) in Figure 8. The discrepancy between the lower parts of Figures 8 and 10 could be explained by the difference of sampling depth between the geophysical and hydrogeochemical data. Although much still remains to be studied, the similarity of trends in each set of results is quite encouraging, because the geophysical data can be obtained more quickly and cheaply than hydrological sampling and geochemical analysis.

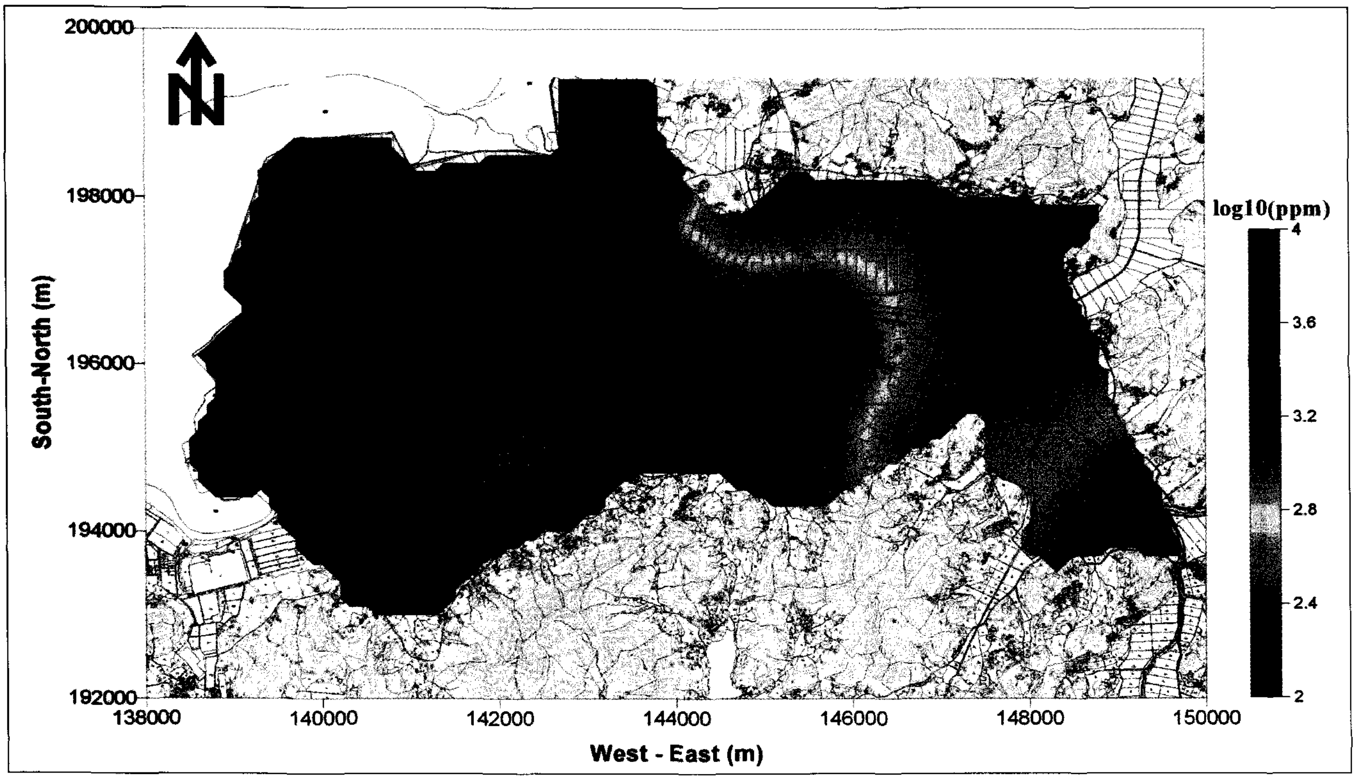
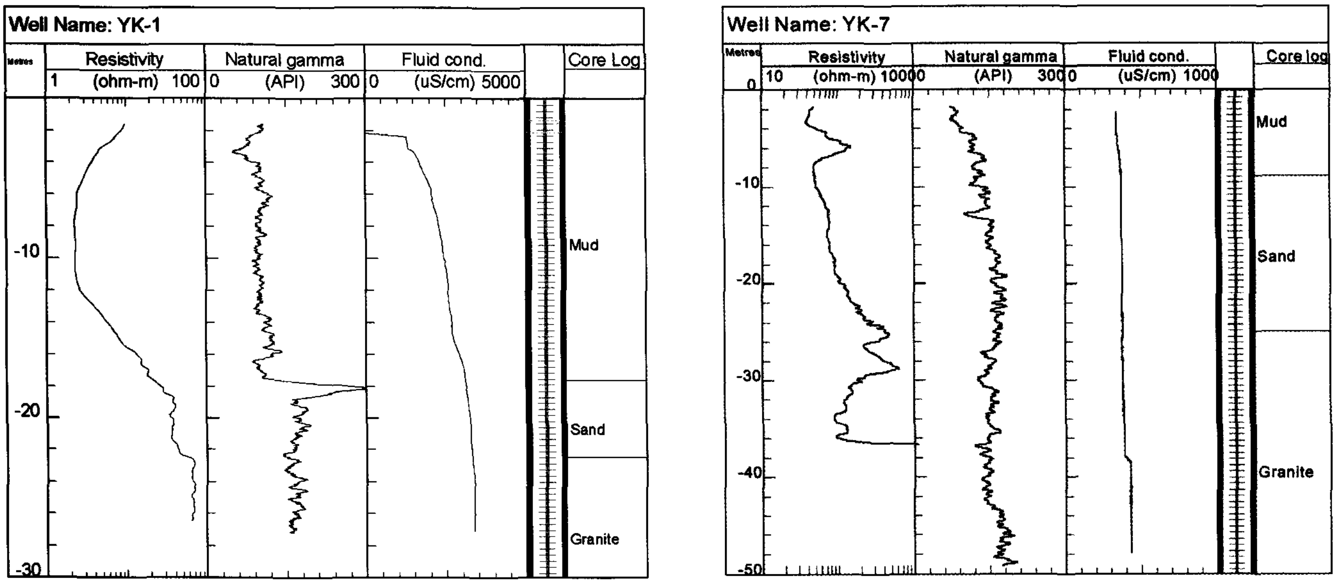


Fig. 8. Contour map of estimated equivalent NaCl concentration, in ppm, in the sand layer. Note that the image is coloured on a logarithmic scale.

CONCLUSIONS

The use of borehole and surface geophysical methods for evaluating seawater intrusion is very promising because of the ability to estimate water quality quickly and to obtain hydrogeological information. From vertical electric soundings and drilling, we have mapped the subsurface geology in the survey area, and we have provided this geological information as a simplified model for numerical modelling of flow and transport of groundwater. We have estimated various in-situ physical properties, such as resistivity and porosity, from geophysical well logs, and these were used to estimate the pore water resistivity in the sand aquifer. From the equivalent NaCl concentration in the sand aquifer, estimated from geophysical data and hydrogeochemical analysis, we could quantitatively map the salinity, and evaluate the location of the seawater/fresh water boundary in the sand layer. More accurate measurement of porosity, determination of bedrock depth, and verification and characterisation of the seawater/fresh water interface still remain for further study. However, our approach to the evaluation of seawater intrusion is considered a valuable attempt at enhancing the use of geophysical data and the reliability of numerical modelling for flow and transport of groundwater.



(a) (b)

Fig. 9. Electromagnetic induction resistivity, natural gamma, and fluid electrical conductivity logs in boreholes YK-1 (a), and YK-7 (b).

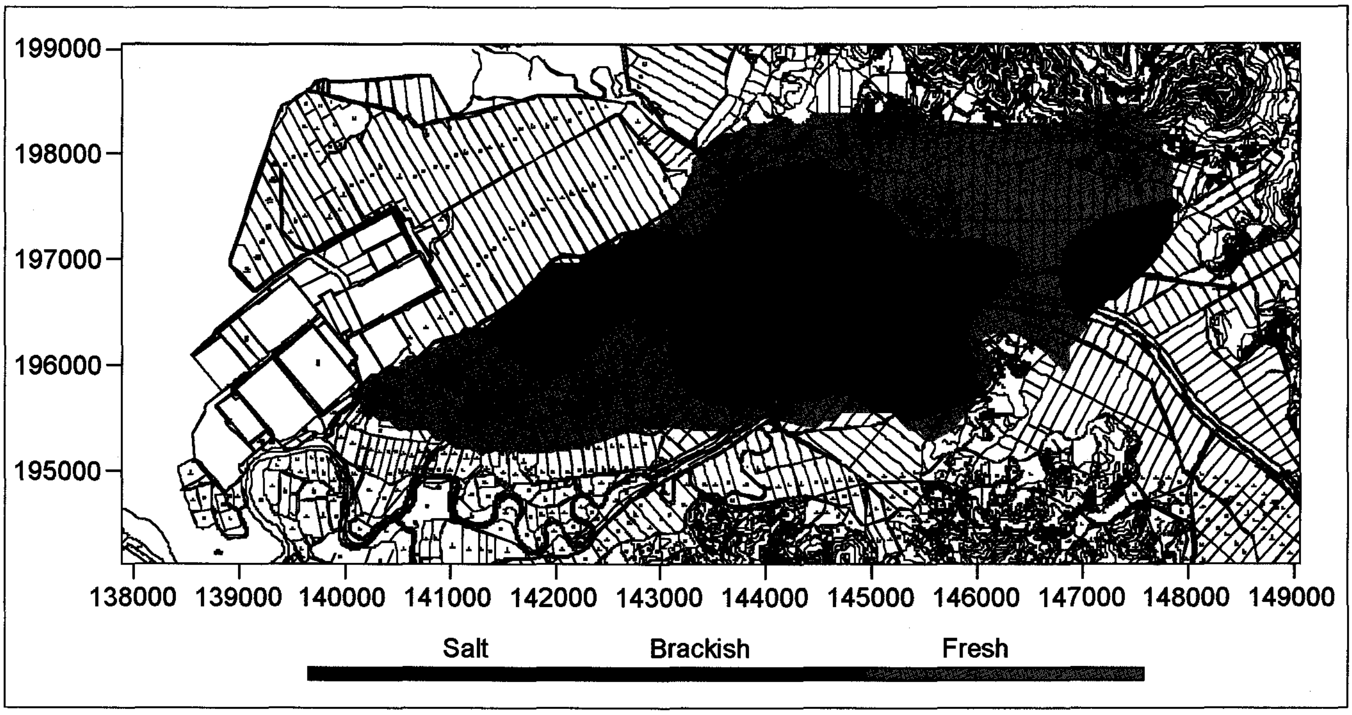


Fig. 10. Distribution of chloride concentration of groundwater, evaluated by hydrogeochemical analyses in the Youngkwang area.

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