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Spatial analysis of small-loop electromagnetic survey data in a seawater intrusion region

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Key Words: spatial analysis, semivariogram,
small-loop electromagnetic survey, seawater intrusion, vertical electrical sounding, electrical conductivity logging

ABSTRACT

The main purpose of this study is to apply spatial analysis using semivariograms to small-loop electromagnetic survey data to assess the extent of seawater intrusion in an experimental watershed. To indicate the extent of seawater intrusion over the study area, vertical electrical soundings at 33 points and electrical conductivity logging in two wells were conducted. From the correlation between resistivities obtained by inversion and the depth of the aquifer at the two wells, the region of seawater intrusion was identified and demonstrated by electrical conductivity logging results obtained over two years. To measure the variation of apparent conductivity with depth, an electromagnetic survey in six frequency bands was adopted. Apparent conductivity mapping with spatial analysis using semivariograms is an effective technique for identifying the region of seawater intrusion at shallow depth.

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INTRODUCTION

Seawater is one of the most common pollutants of fresh groundwater in coastal area. Pollution of groundwater by seawater occurs when saline water displaces or mixes with freshwater in an aquifer. These phenomena are commonly called seawater intrusion.

To avoid indiscriminate and excessive drilling to find the seawater wedge, surface geophysics such as electrical or electromagnetic (EM) methods can be used to assess seawater intrusion. Electrical surveys generally measure the resistivity of subsurface constituents to indicate the electrical conductivity (EC), which is an intrinsic property of the formation and the groundwater. Since ECs of freshwater and seawater are differ by several orders of magnitude, electrical surveys are well suited for studying the relationship

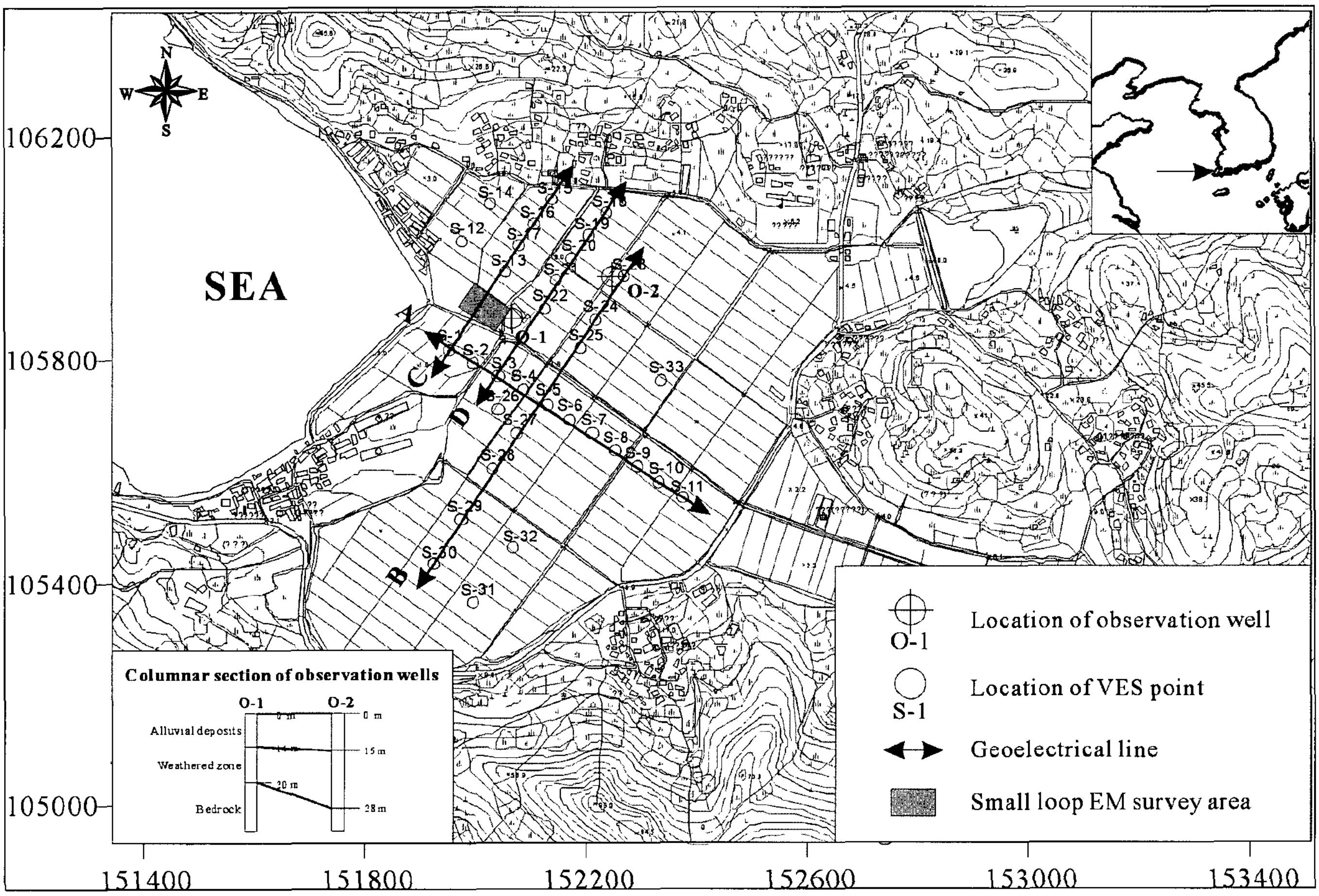

Fig. 1. Location map of the study area with a columnar section of observation wells O-1 and O-2. Transverse Mercator (TM) projection. Coordinates in metres.

between freshwater and seawater in coastal aquifers. Among electrical surveys, vertical electrical sounding (VES) is especially useful for the finding vertical extent of a saline water layer. EM surveys measure the impedance of subsurface constituents, which can be converted to the resistivity of subsurface formations. The small-loop EM survey adopted in this study utilises broadband bi-static EM sensors, which can be used to detect landfill, unexploded ordnances, buried drums, trench boundaries, contaminant plumes, and so on (Keiswetter and Won, 1997).

The purpose of this study is to apply the spatial analysis of small-loop EM survey data to assessing the extent of seawater intrusion in an experimental watershed. To indicate the extent of seawater intrusion over the experimental site, VES and groundwater logging were used.

HYDROGEOLOGICAL SETTING

The study area is located in Haenam-gun, on the southwestern coastal area of Korea (Figure 1). The topography is generally flat in the central part, where agricultural activities are concentrated. Several pumping wells exist for agricultural use, and two observation wells (O-1 and O-2) have been installed to monitor the level and EC of groundwater over time. The stratigraphic units

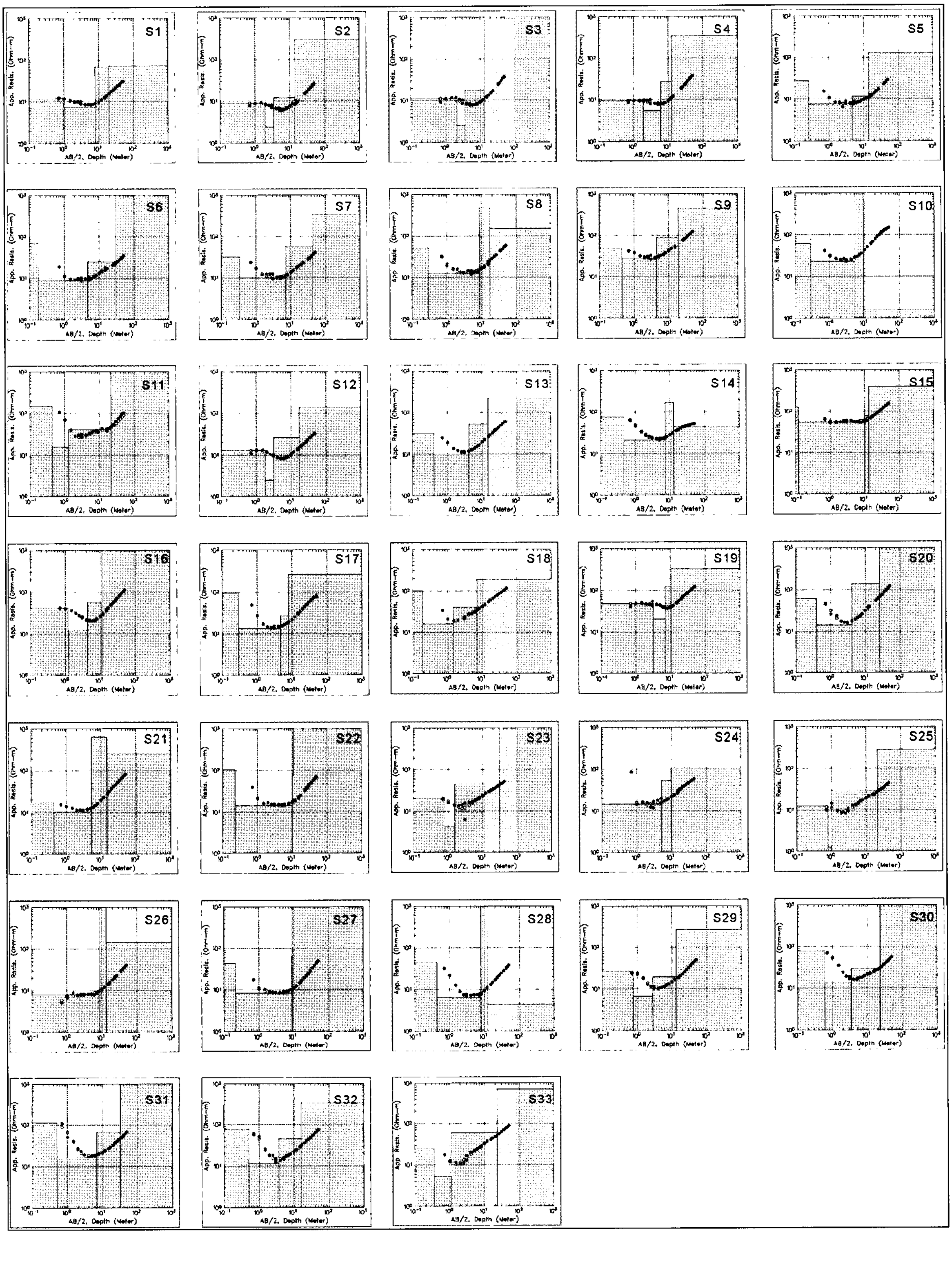

Fig. 2. Inversion results from VES data at 33 points (○: field data, •: theoretical data, and ▒: inverted model layers).

in the study area are alluvial deposits, with topsoil, weathered zone, and bedrock. Of these hydrostratigraphic units, the upper two layers are water-bearing units. Vertical electric soundings were conducted at 33 points, distributed over the flat area, and small-loop EM surveys were performed in a small area of 4500 m^2 near the coast, indicated by the grey rectangle in Figure 1.

GEOPHYSICAL PROPERTIES

The electrical current flow in a saturated subsurface formation depends primarily on three factors: porosity, connectivity of pores, and EC of the water in the pores (Lowrie, 1997). Water and the chemicals dissolved in it are the dominant factors influencing the flow of the electric current, because formation materials are in general resistant to electrical flow. The EC of a formation may also be expressed as resistivity, its inverse, and resistivity decreases as porosity, hydraulic conductivity, and water salinity increase. Apparent resistivities are obtained by VES, from which a depth profile of the subsurface materials at that point can be obtained by numerical analysis. The geophysical measurements applied for delineating the seawater intrusion region are VES, small-loop EM survey and EC logging for groundwater at the two wells.

Vertical electrical sounding

Data obtained by VES reflect the variations of resistivity with depth. In VES using the Schlumberger array, the potential electrodes remain fixed while the current electrode spacing is expanded symmetrically about the centre of the electrode spread. VES surveys were carried out at 33 points with the maximum half-length of the current electrode (AB/2) being 50 m. From the 33 VES measurements, four resistivity profiles have been constructed to disclose the spatial extent of seawater intrusion (lines A, B, C and D in Figure 1).

Figure 2 shows the apparent resistivity data, plotted versus array size (AB/2), and interpreted resistivity profiles, plotted versus depth assuming a layered earth, at the 33 points. The apparent resistivity curves correspond to a curve type H, which implies that the middle layer of a three-layered structure is conductive compared to the overlying topsoil and underlying layers (Telford et al., 1990). This resistivity structure coincided with the hydrogeological sequence in the study area, composed of alluvial deposits with topsoil, a weathered zone, and bedrock. Because the interpretation of VES over a horizontally layered formation is nonlinear in the unknown parameters such as resistivity and thickness of each layer, we adopt a one-dimensional inversion method using a non-linear least-squares technique. Figure 2 shows that inversion results in which the middle layer has resistivity lower than 10 Ω.m are concentrated in the central part of the study area, at soundings S-1, S-2, S-3, S-4, S-5, S-6, S-7, S-12, S-13, S-25, S-26, S-27, S-28, and S-29. Therefore, considering that high conductivity is closely related with seawater intrusion, intrusion is progressing mainly in the central part of the area.

Four resistivity cross-section profiles were constructed from the inversion results: along line A away from the coastline and along lines B, C, and D perpendicular to line A (Figure 1). The resistivity profile along line A shows that a zone with resistivity lower than 25 Ω.m is developed near the coastal zone while a zone with resistivity higher than 200 Ω.m occurs inland, far from the coastline (Figure 3(a)). The resistivity profile along line B shows that the zone with resistivity lower than 25 Ω.m is developed in the central part (Figure 3(b)). Both profiles along lines C and D show resistivities that are less than 25 Ω.m on the southern end, although sounding points further south are absent (Figures 3(c) and (d)).

Electrical conductivity logging

EC loggings were performed in wells O-1 and O-2 at different times to see the progress of seawater intrusion. The distance between the wells is 235 m and casing depths in the wells are 20 m and 28 m from surface, respectively. As neither well has a screen installed below the casing, it is possible to confirm the depth to the interface between fresh water and saline water. Figure 4(a) shows that EC values at observation well O-1 shift gradually from about 3200 μS/cm in October, 2003 to about 8300 μS/cm in May, 2005. This variation indicates that the seawater wedge moves inland from the coastline; EC also increases with time within the casing. However, the EC profiles in well O-2 do not show notable variation from the average value of 650 μS/cm, which means that the seawater did not reach to this well (Figure 4(b)).

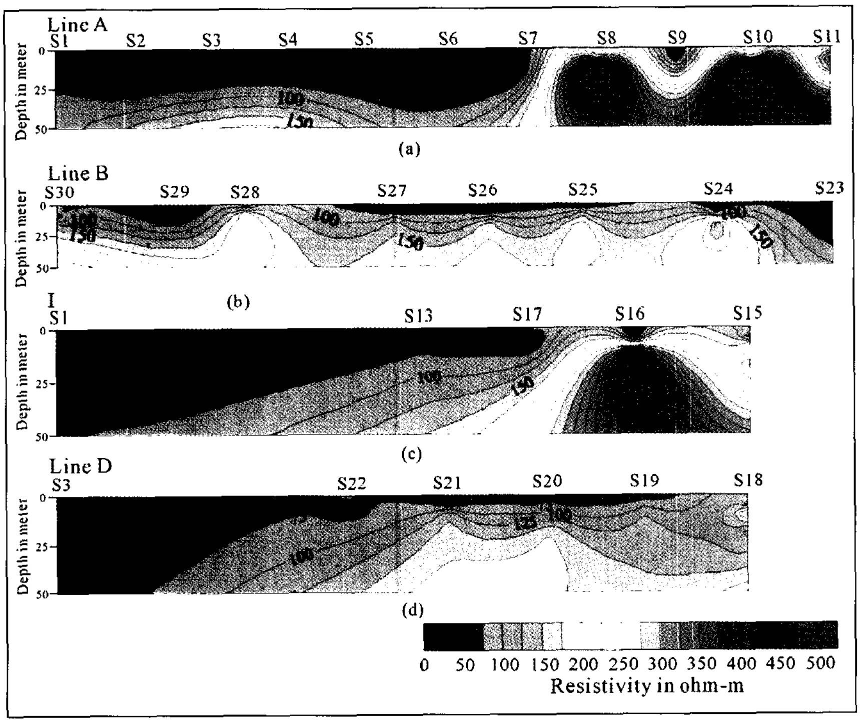

Fig. 3. Four resistivity profiles showing the low resistivity zones due to the intrusion of seawater.

Small-loop EM survey

Among many geophysical survey techniques, a small-loop EM survey provides valuable information about the shallow subsurface, and a hand-held sensor is very convenient for measuring EM data although the target depth is limited to about 10 m. Depth of investigation, related to skin depth, is inversely proportional to frequency; a low-frequency signal travels further through a conductive earth than does a high-frequency signal. Won et al. (1996) developed a broadband, multi-frequency EM sensor, GEM-2, for mapping such targets as formation boundaries, landfills, and contaminant plumes. Interpretation of the survey results is based on analysis of in-phase and quadrature components of the EM response, measured in parts per million (ppm), and mapping of apparent conductivity, which is derived from the quadrature component of the EM response. Apparent conductivity is defined

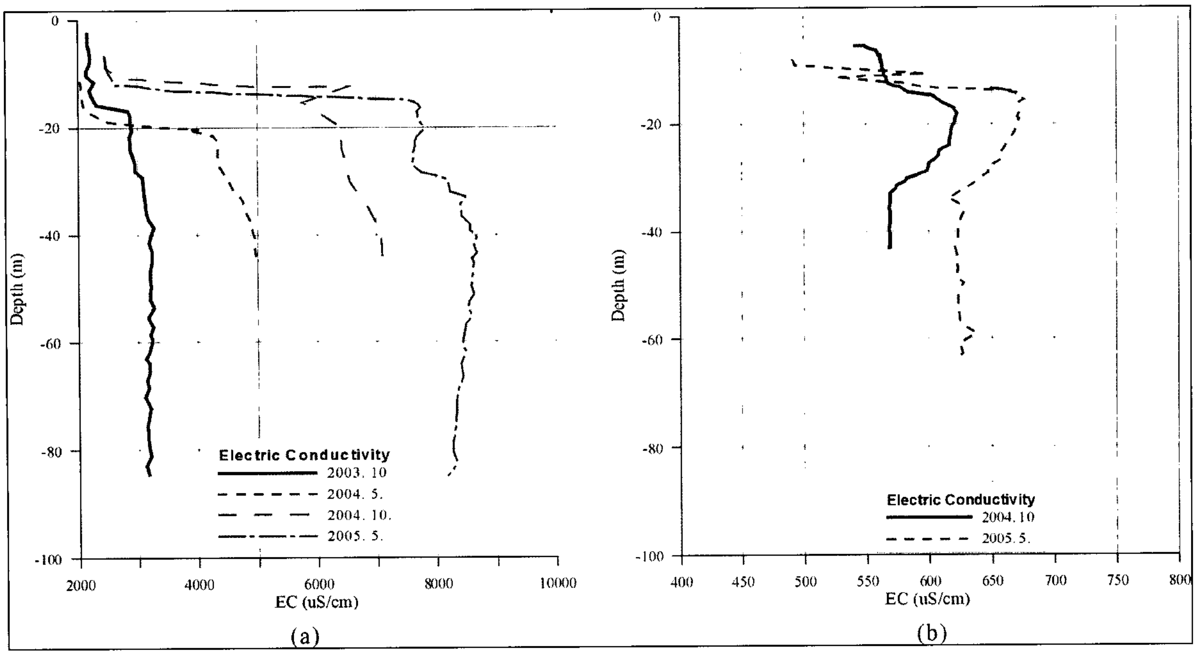

Fig. 4. EC logging results showing the effect of seawater intrusion at wells O-1 (a) and O-2 (b).

as the conductivity of a homogeneous half-space that produces the same response as that measured over the real ground with the same sensor, and is a parameter that is related to the electrical properties of subsurface constituents.

The EM survey area was located between stations S1 and S13 in line C and between S3 and S22 in line D, and its size was 45 m by 100 m. This area is also located near well O-1 in which seawater intrusion was confirmed by EC logging over two years (Figure 4(a)). From Figures 3(c) and (d), resistivities from surface to 10 m depth were less than 25 Ω.m, corresponding to conductivities greater than 400 μS/cm. The EM system used was the GEM-2, made by Geophex Ltd., USA. EM data were acquired at 2 m intervals along 10 lines with 5 m spacing between lines, using six frequencies at each location: 3150 Hz, 4650 Hz, 6810 Hz, 10 350 Hz, 14 610 Hz, and 20 010 Hz. Geological logging of wells O-1 and O-2 suggested that layering was uniform in the study area. Therefore, the apparent conductivities from GEM-2 can be applied to analyse the extent of seawater intrusion using spatial analysis.

SPATIAL ANALYSIS OF EM DATA USING VARIOGRAM

Semivariogram (or more simply variogram) analysis is a typical tool used to analyse how data are spatially interconnected (Isaaks and Srivastava, 1989). By definition, as the lag class interval h between pairs increases, the corresponding semivariogram value will also generally increase. However, the semivariogram will no longer increase beyond a maximum distance over which the pair of values maintain interconnection, called the *range*. The maximum value that the semivariogram reaches at the *range* distance is called the *sill* and is an estimate of the variance of the data. Although the value of the semivariogram for $h = 0$ should strictly be zero, the semivariogram value very close to the origin may not zero because of several factors such as sampling error and short scale variability. This vertical jump is called the *nugget* effect (Isaaks and Srivastava, 1989).

The theoretical semivariograms in this study are calculated using a spherical model for which, beyond some distance, pairs of data will no longer be autocorrelated and the semivariogram reaches an asymptote. The formula used for this model is a modified quadratic function:

$$\begin{aligned} \gamma(h) &= C_0 + C\left[1.5\frac{h}{a} - 0.5\frac{h^3}{a^3}\right], \quad (h \le a) \\ \gamma(h) &= C_0 + C, \quad (h > a) \end{aligned} \quad (1)$$

where $\gamma(h)$ is the semivariogram, C_0 the *nugget* variance, C the structural variance, and a the *range* (Journel and Huijbregts, 1978).

In order to determine the suitability of this model in the study area, we calculated the coefficient of determination, R^2, as a measure of goodness of fit. The semivariogram model may be considered excellent as this value is nearly unity (Robertson, 1998). Table 1 shows that the spherical model turned out to be well-suited at all the frequency bands in the EM survey because the values of R^2 are nearly 1 for all. The results of semivariogram analysis show only small differences in *range*, but more noticable variation in *nugget* and *sill* values, with frequency (Figure 5).

The small variations of *range* indicate that the interconnection between pairs of apparent conductivities is quite high at all frequencies. However, *nugget* and *sill* values increase as frequency decreases, which means that the variance of apparent conductivities is greater at lower frequencies than at higher frequencies.

Semivariogram calculations with lag distances greater than 70 m are possibly less reliable because fewer sample pairs are available (Figure 5). However, the results show that the semivariogram using small-loop EM data is well bounded for the seawater intrusion area.

Frequency (Hz)	*nugget*	*sill*	*range*	R^2
3 150	17 160	42 230	24.6	0.988
4 650	10 500	33 840	23.8	0.858
6 810	4 810	25 700	22.9	0.941
10 350	10	21 340	23.2	0.907
14 610	10	20 590	23.2	0.897
20 010	10	19 740	23.5	0.896

Table 1. Parameters of the semivariogram analysis using a spherical model.

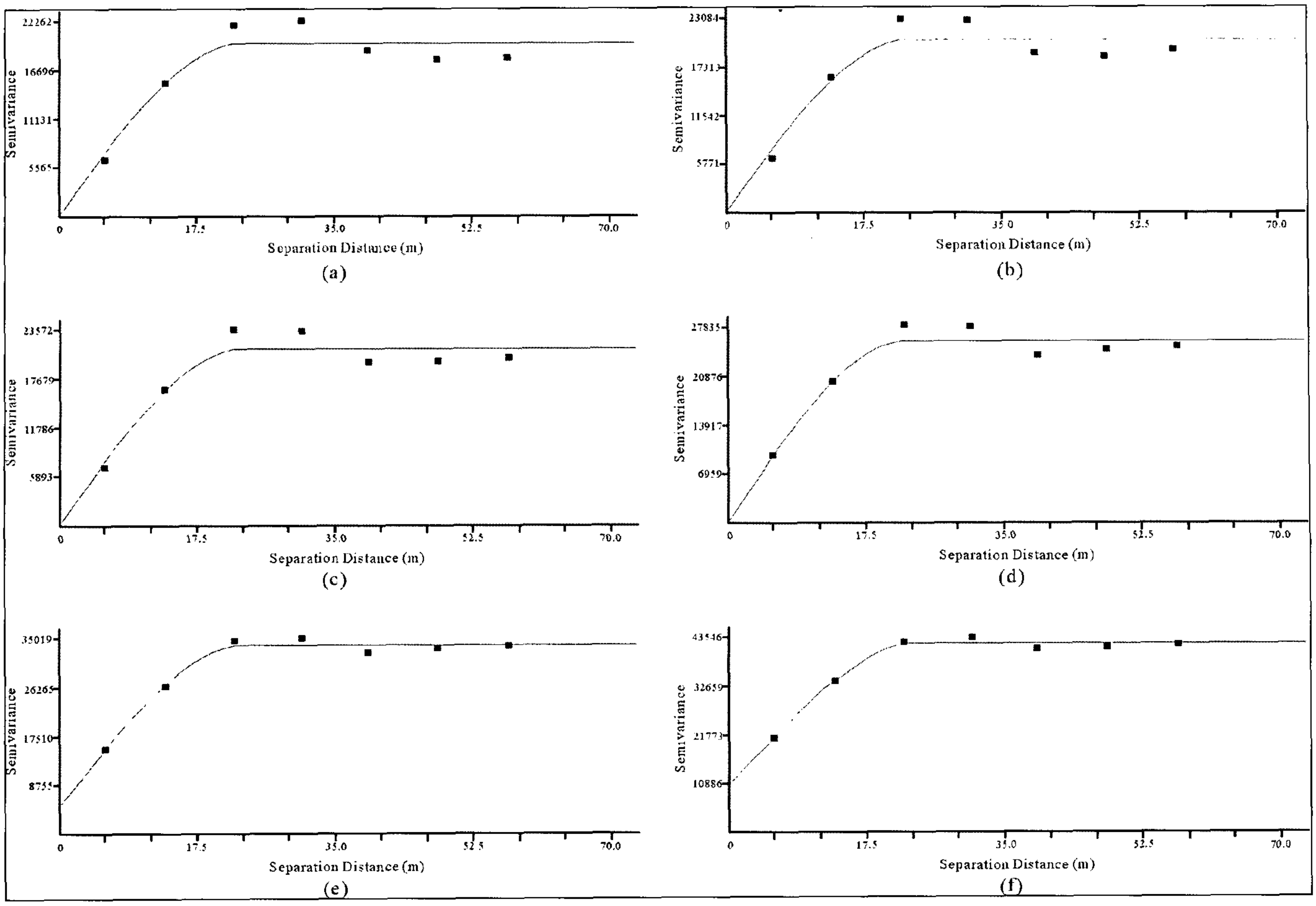

Fig. 5. Semivariograms at six frequencies using a spherical model. a) 20 010 Hz; b) 14 610 Hz; c) 10 350 Hz; d) 6 810 Hz; e) 4 650 Hz; and f) 3 150 Hz.

Kriging, basically a form of generalised linear regression, is a well-known spatial estimation technique (Matheron, 1969). However, kriging results typically smooth out local details of the spatial variation between the data. Thus, a simulation approach that can generate multiple maps is more effective than a kriging approach that only generates one deterministic map.

Figure 6 shows contour maps of apparent conductivity, in units of μS/cm, drawn using simulation based on spherical model results. Apparent conductivity distributions over the whole area generally lie between 700 and 800 μS/cm, corresponding to 13 to 14 Ω.m, which nearly coincides with the results of Figures 3(c) and (d) that are higher than 400 μS/cm. However, prominent anomalies include large circular features in the same locations at all frequencies, with apparent conductivities of more than 1000 μS/cm, which may be affected by seawater intrusion. The right side of each frequency map may possibly show an old trench extending to deeper levels. The old trench may be filled with alluvial deposits composed of relatively conductive constituents, so that apparent conductivity becomes lower as frequency decreases.

DISCUSSION AND CONCLUSIONS

To comprehend the extent of seawater intrusion over the experimental site, both VESs at 33 points and EC logging in two wells have been carried out. The sounding data were analysed by a one-dimensional inversion method using non-linear least-squares technique, and the resulting models were compared with the depth of the aquifer displayed by the columnar section of the two observation wells.

The depth of the unconfined aquifer, ranging the from surface to 14 m, at well O-1 in Figure 1 corresponds to the depth of the region with resistivity lower than 25 Ω.m near point S3 in Figure 3(a) because the resistivity is affected by seawater intrusion through the unconfined aquifer. On the other hand, resistivity higher than 50 Ω.m near well O-2, between S23 and S24 in Figure 3(b), can be explained by concluding that this well has not been reached by the leading edge of seawater intrusion. These results were confirmed by the repeated logging results; the EC of groundwater in well O-1 increased continuously after the well was installed in October, 2003, but the conductivities in well O-2 did not show a noticable change.

To measure the variation of apparent conductivity in both space and depth, six frequency bands were used in an EM survey. In order to avoid smoothing out local spatial variation in the data, with small values being overestimated and large values being underestimated, a spatial analysis using a semivariogram with a spherical model was performed. From this simulation approach, apparent conductivity mapping is an effective technique for identifying the region of seawater intrusion at shallow depth. Although apparent conductivities determined by a multi-frequency EM survey have limited depth information, scanning across frequency windows is equivalent to depth sounding, so the apparent conductivities turned out to be applicable to delineating the region of seawater intrusion at shallow depth despite the absence of quantitative information.

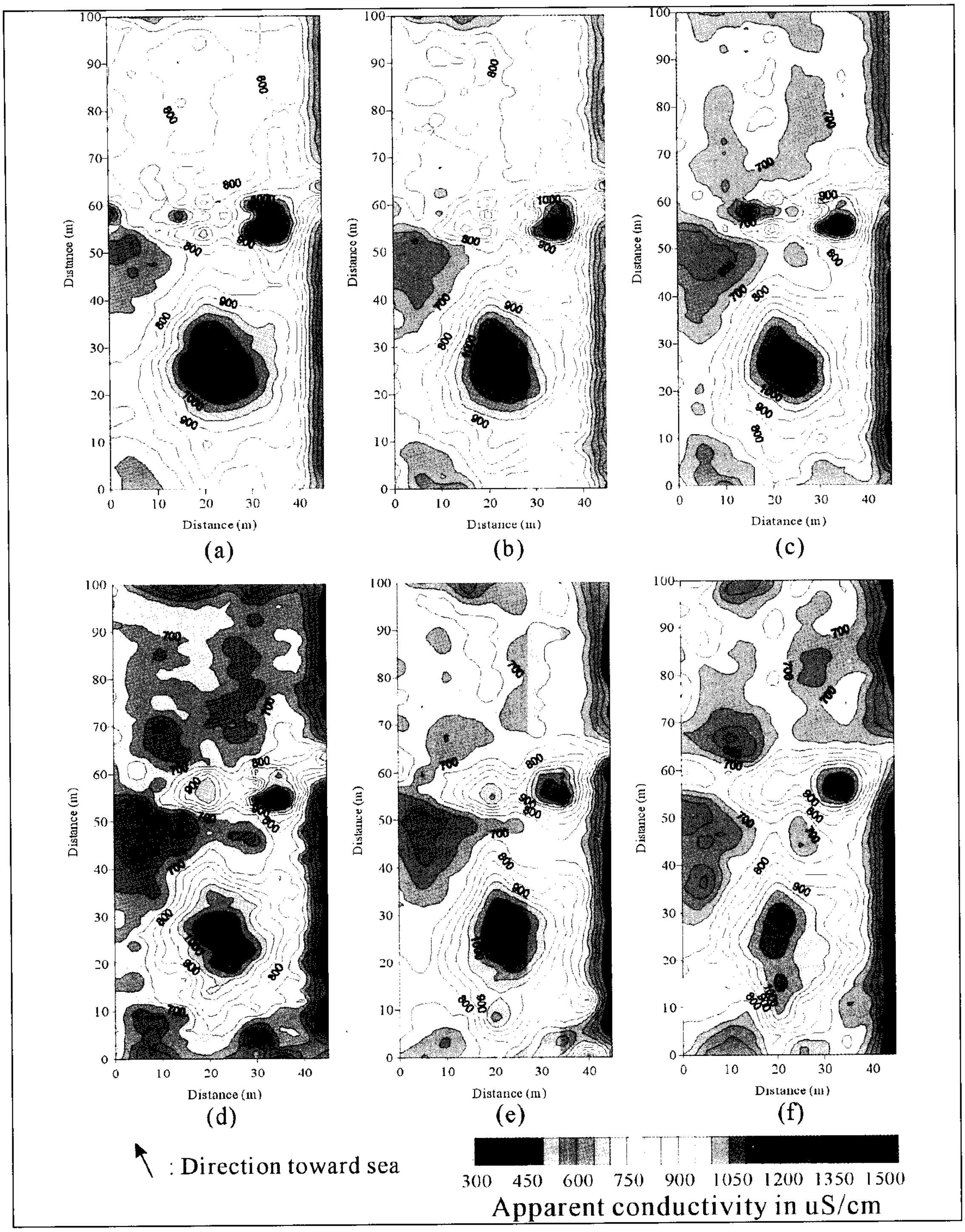

Fig. 6. Contour maps of apparent conductivity drawn by semivariogram analysis. a) 20 010 Hz; b) 14 610 Hz; c) 10 350 Hz; d) 6 810 Hz; e) 4 650 Hz; and f) 3 150 Hz.

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해수침투 지역에서 소형루프 전자탐사 자료의 공간 분석

송성호[1]

요 약: 이 연구의 목적은 해안지역의 소유역에 대한 해수침투 범위를 규명하기 위하여 소형루프 전자탐사 자료에 대하여 베리오그램을 이용한 공간분석 기법의 적용성을 파악하는 것이다. 이를 위하여 일차적으로 소유역 전체에 대하여 33 지점의 전기비저항 수직탐사와 두 곳의 관정에 대한 전기전도도 검층이 수행되었다. 수직탐사 역산에 의한 전기비저항과 관정들의 대수층 두께를 비교한 결과, 연구지역 소유역 전체에 대한 해수침투 범위가 파악되었으며, 이러한 결과는 2 년간 정기적으로 측정된 전기전도도 검층 결과로 확인되었다. 소유역 일부 지역에 대한 심도별 겉보기 전도도 변화를 확인하기 위하여 6 개 주파수 대역을 이용한 전자기 탐사를 수행하였다. 베리오그램을 이용한 공간분석 결과로 겉보기 전도도 분포도를 작성한 결과, 이 방법이 얕은 깊이에 대한 해수침투 범위를 효과적으로 규명할 수 있는 것으로 밝혀졌다.

주요어 : 공간분석, 베리오그램, 소형루프 전자탐사, 해수침투, 전기비저항 수직탐사, 전기전도도 검층

海水浸入地域での小規模ループ電磁探査データの空間領域解析

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要　旨: この研究の主な目的は、semivariogramsを使用する空間解析を小規模ループ電磁調査データに適用し、分水界実験現場で海水浸入の範囲を算定することである。この現場の海水浸入の範囲を示すために、33 点の垂直電気探査と、2 つの孔井での電気伝導率検層が実施された。インバージョンから得られた比抵抗と 2 つの井戸での帯水層の深さとの間の相関から海水浸入の範囲が認識され、2 年間以上にわたる電気伝導率検層においても確認された。深度変化に伴う見かけ導電率の変化を測定するために、6 周波数での電磁探査を実施した。semivariogramsを用いた空間解析結果である、見かけ導電率のマッピングは、浅部での海水浸入範囲を特定するために効果的な手法である。

キーワード : 空間解析、semivariograms、小規模ループ電磁調査、海水浸入、垂直電気探査、電気伝導率検層

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