Journal of Hydrology (NZ) 45 (2): 69-82 2006

Measuring and monitoring saltwater intrusion in shallow unconfined coastal aquifers using direct current resistivity traverses

M. Ingham[1], J. A. McConchie[2], S. R. Wilson[2] and N. Cozens[2]

[1] *School of Chemical and Physical Sciences, Victoria University, P.O. Box 600, Wellington, New Zealand. Corresponding author: Malcolm.Ingham@vuw.ac.nz*

[2] *School of Geography, Environment and Earth Sciences, Victoria University, P.O. Box 600, Wellington, New Zealand.*

Abstract

Saltwater intrusion into coastal aquifers is potentially a major problem in New Zealand, as in other areas around the world. Saline intrusion is usually investigated using point samples, e.g., discrete borehole measurements, and their analysis involves considerable extrapolation. Resistivity traverses, however, produce a two- or three-dimensional image of the saline interface. The technique has considerable potential for monitoring the interface, thereby facilitating management of coastal aquifers.

This study, using three examples from different field settings, shows that bulk electrical resistivity changes by two orders of magnitude across the fresh-saline boundary. The exact values depend on the interaction of the pore fluid with the aquifer media, i.e., the formation factor of the aquifer. At all sites a change in resistivity occurs at approximately the mean high tide mark, with significant mixing of fresh and saline water occurring inland of this position. There was no evidence of either the sharp boundary, or concave shape, to the interface predicted by simple models. Rather, the interface is a distributed zone through which saline and fresh waters mix. The shape of the interface depends on the thickness and stratigraphy of the aquifer, and its topographic profile and hydraulic gradient. Resistivity traverses from sites at Te Horo and Rarangi, which have significant groundwater abstraction, show that the mixing zone at the interface extends further inland, causing a significant reduction in resistivity. Monitoring changes in resistivity can therefore provide an early indication of saltwater intrusion.

Resistivity traverses are relatively cheap and non-intrusive, and offer considerable potential for both locating the position of the saline interface and monitoring any saltwater intrusion.

Introduction

Coastal aquifers are important sources of water throughout the world (International Association of Hydrologists, 2003). In New Zealand they supply over 50% of all groundwater (White, 2001). Because of New Zealand's population pattern and heavy reliance on agriculture and horticulture, most groundwater users tap into coastal aquifers (Lincoln Environmental, 2000). In the lower North Island over 12,000 bores tap this water resource to support communities, commerce, and agriculture. Many other countries are similarly dependent on coastal groundwater (International Association of Hydrologists, 2003). These water resources are extremely vulnerable to salinisation from saltwater intrusion, which is arguably the most common and widespread contamination problem in aquifers. The nature and dynamics of the saline interface; and its sensitivity to groundwater extraction, climate, and sea level fluctuations (both contemporary and historic) are poorly understood, even though coastal aquifers are vital sources of water throughout the world.

Saltwater intrusion is an existing and potential problem in many of New Zealand's aquifers. Its occurrence has been recognised by groundwater quality measurements, e.g., at Christchurch and Motueka (White *et al.*, 2001). Locating the saline/freshwater interface, and monitoring it to identify any changes are essential for managing coastal groundwater systems. Avoiding saline intrusion is particularly important, because once contamination has occurred it is often very difficult and expensive to remediate (Domenico and Schwartz, 1998).

Saline intrusion is commonly monitored using discrete measurements. These include direct measurements from boreholes (Rushton, 1980; Gimenez and Morell, 1997; Shearer, 1991; Schnoebelen *et al.*, 1995), groundwater geochemistry (Gimenez and Morell, 1997; Ebraheem *et al.*, 1997), and geophysical techniques (Shearer, 1991; Schnoebelen *et al.*, 1995; Ebraheem *et al.*, 1997; Albouy *et al.*, 2001; Choudhury *et al.*, 2001). Such data, based on small numbers of samples, yield at best only an imprecise assessment of the extent or existence of intrusion, and the location of the saline interface. The position of the saline interface may not be fixed over time, and it may be a transitional zone of changing salinity rather than a distinct boundary between saline and fresh water. This adds to the difficulty of using discrete measurements to resolve even basic questions relating to the saline interface.

Sea water is one of the least electrically resistive substances found naturally at the surface of the Earth. Its electrical resistivity (~ 0.3 Ωm) is over a 100 times less than that of fresh water. In the first few hundreds of metres below the ground surface, the bulk electrical resistivity of the subsurface is largely determined by the fluid content (e.g., salinity and amount). Therefore, the large contrast in resistivity between saline and fresh water makes measurement of the resistivity of the ground a useful technique for detecting and delineating the saline interface. Since changes in the nature of the pore fluid affect the resistivity, the technique can also be used to monitor saltwater intrusion.

Direct current (DC) resistivity is a geophysical technique commonly used to measure the bulk resistivity of the subsurface (e.g., Kearey and Brooks, 1991; Keller and Frischknecht, 1966). Measurements using DC techniques are increasingly being employed in hydrological studies (e.g., Aaltonen and Olofsson, 2002; Albouy *et al.*, 2001; Broadbent and Callander, 1991; Devi *et al.*, 2001; Ebraheem *et al.*, 1997; Karlik and Kaya, 2001; Lenkey *et al.*, 2005; Sandberg *et al.*, 2002; Sharma and Baranwal, 2005; Whittecar *et al.*, 2005).

The most frequently used types of measurement are vertical electric sounding and resistivity profiling. Vertical electrical soundings produce models of the variation of resistivity with depth beneath the centre of an electrode spread, assuming a uniform horizontal layering of the resistivity structure. Close to the saline/fresh water interface, however, significant lateral changes in the bulk resistivity occur within tens of metres perpendicular to the coast. Not only does this violate the assumption of horizontal uniformity, but it also means that tracking the degree of saline intrusion requires extrapolation of the results of several soundings made at different distances from the coast. A more accurate profile of the saline/fresh water boundary may be obtained using resistivity traverses. Resistivity traverses produce 2- or

3-dimensional images that show a continuous transition from low to high resistivity associated with the transition from saline to fresh groundwater. Resistivity traverses are also sensitive enough to track changes in aquifer resistivity within the mixing zone, further inland from the interface (Loke and Barker, 1996; Loke, 2000). The technique is relatively cheap and non-intrusive.

The aim of this paper is to illustrate the use of DC resistivity traverses for identifying saline intrusion in coastal aquifers. Examples are presented from three studies that demonstrate the use of the technique to locate, and monitor changes in, the saline interface. The limitations of the technique are also discussed.

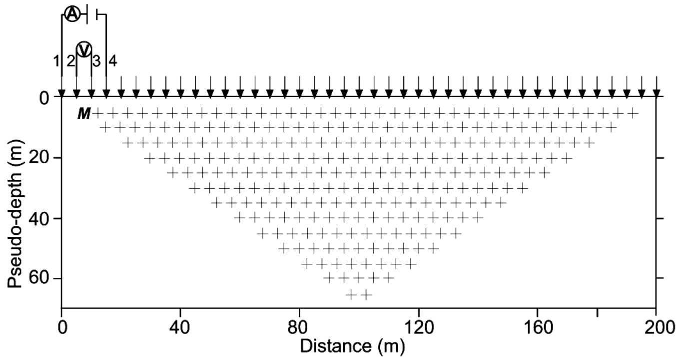

Figure 1 – Geometry of a DC resistivity traverse using 41 electrodes at 5 m separations. Electrode locations are marked by the arrows. Apparent resistivity measurements are assigned to depths to calculate a pseudo-section. For example, the resistivity measurement provided using electrodes 1, 2, 3 and 4 is assigned to location 'M' at 5 m pseudo-depth. Note that this is not 5 m below the ground surface.

Methods

Resistivity traverses typically use a large number of electrodes arranged in a straight line with a common basic spacing. In Figure 1, an electric current (I) is injected into, and taken from, the ground through two electrodes (e.g., 1 and 4) and the potential difference (ΔV), or voltage drop, is measured between two other electrodes (e.g., 2 and 3). Electrodes have a common spacing 'a', giving an apparent resistivity (ρ_a) according to the Wenner method from current, potential difference, and electrode spacing as:

$$\rho_a = 2\pi a \frac{\Delta V}{I} \qquad (1)$$

The depth to which the current penetrates the ground is proportional to the separation of the current electrodes, and the apparent resistivity value (approximately equal to the bulk resistivity) is assigned to the midpoint of the four electrodes used (M in Fig. 1) at a pseudo-depth equal to 'a'. By selecting different combinations of electrodes, and using multiples of the base electrode separation (i.e., increasing the separation of the current electrodes), a cone of measurements can be obtained. Measurements are presented as a pseudo-section that shows both the lateral and vertical variation in bulk resistivity (Fig. 2).

A complete set of traverse data may be numerically modelled in two-dimensions (Loke, 2000). This gives an image of the lateral and vertical variations in bulk resistivity beneath the traverse. If necessary, additional lateral coverage can be obtained by moving the entire electrode array in a manner similar to that used in seismic surveys. The variation of resistivity in three dimensions may, similarly, be obtained either by performing multiple two-dimensional surveys, each offset from the other, or by using a two-dimensional array of surface electrodes.

Interpretation of the results of DC resistivity traverses in terms of hydrological parameters is generally based on the empirical result first proposed by Archie (1942).

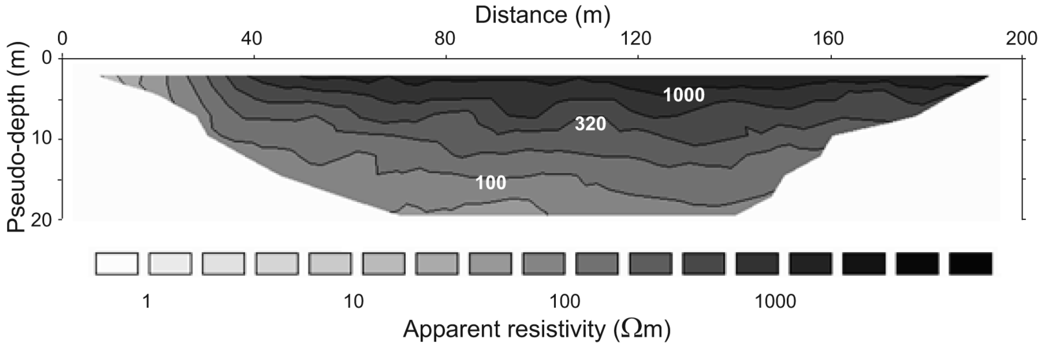

Figure 2 – A typical pseudo-section showing the variation in apparent resistivity with electrode spacing (pseudo-depth).

Within an aquifer, the bulk resistivity ρ may be regarded as obeying Archie's Law:

$$\rho = C\rho_w \varphi^{-m} S^{-n} \quad (2)$$

where ρ_w is the resistivity of the water in the aquifer and the other parameters (porosity φ, degree of saturation S, assumed to be 1 below the water table, and constants C, m and n with typical values of $0.5 \le C \le 2.5$, $1.3 \le m \le 2.5$, and n~2) collectively define the formation factor (F).

$$F = C\varphi^{-m} S^{-n} \quad (3)$$

It can be seen from equation 2 that the bulk resistivity of a fully saturated water-bearing formation depends primarily on the resistivity of the fluid, as the other parameters are relatively constant. The resistivity of a fluid, ρ_w, decreases with an increased concentration of dissolved ionic solid. Therefore, a large change in aquifer bulk resistivity results from the resistivity contrast between saline and fresh water. Further, since the formation factor is the ratio of the resistivity of a rock filled with fluid to the resistivity of that fluid, F can be a determined if the actual fluid resistivity is known. This then allows measurements of bulk resistivity to be interpreted directly in terms of fluid resistivity.

The simplest model of a saline interface is that predicted by the Ghyben-Herzberg approximation (Fig. 3). This assumes that the saline interface is a sharp boundary between fresh water of density D_f and salt water of density D_s. At the coast there is zero head (h) of fresh water. Equating hydrostatic pressures below sea level leads to the relation between the saline interface below sea level as a function of the fresh water head (h) as:

$$z_s = \frac{D_f}{D_s - D_f} h \quad (4)$$

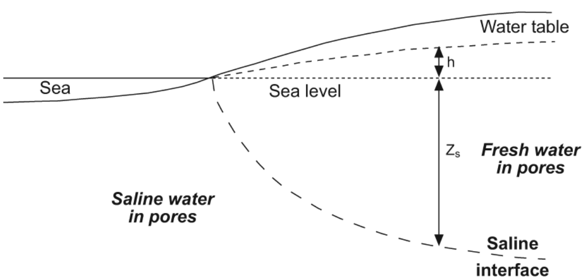

Figure 3 – The simplest model of a saline interface predicted by the Ghyben-Herzberg approximation. This assumes a sharp boundary between the fresh and saline waters, and zero head of fresh water at the coast.

Taking standard values for the densities of salt and fresh water, this relation reduces to $z_s \approx 40h$. In reality, groundwater flow towards the coast will generally lead to the existence of a seepage face where fresh water enters the sea (Glover, 1959). In addition, tidal movement leads to diffusive mixing of salt and fresh water. The saline interface may therefore not be a sharp boundary. Nevertheless, the strong contrast between the resistivity of salt and fresh water means that the bulk resistivity of aquifers containing saline water will be less than that of aquifers containing fresh water. The exact values of bulk resistivity in a given situation will depend on the formation factor. In most cases it is likely that the bulk resistivity will rise from only a few ohm metres (saline water) to approximately 100 Ωm (fresh water) over tens of metres across the interface.

Exactly how saline intrusion occurs in response to fresh water abstraction is not clear, and in fact may not be uniform. But a reduction in the depth to the saline interface below the ground in response to a lowered fresh water head is one response. Perhaps more important locally, will be a widening of the mixing zone in the vicinity of where the fresh water is removed. This will lead to local horizontal penetration of sea water into the aquifer. It is in detecting the resulting reduction in bulk resistivity in such a situation that resistivity measurements are of particular value.

Field examples

Since 2003 a number of studies (Cozens, 2003; Wilson, 2003; Ingham, 2004; Wilson *et al.*, 2006) have been conducted in which DC resistivity traverses have been used to investigate the saline interface in unconfined aquifers subject to differing degrees of fresh water abstraction. Taken together, the results of these studies reveal some common features in the resistivity structure of the saline interface in different environments, and indicate the manner in which the interface migrates in response to groundwater abstraction.

Example 1 – Waikanae Beach

As an extension of a study of the interaction between the Waikanae River and the shallow aquifer at Waikanae on the Kapiti Coast (Cozens, 2003), DC resistivity was measured along a traverse (S1) just south of the river mouth (Fig. 4). The traverse ran perpendicular to the coast from below the mean high tide mark, across an area of salt flats, to some 200 m further inland. The distance between the mean low and high tide marks is approximately 100 m. The Kapiti coastal plain consists of inter-fingered alluvial and marine sediments, overlain by a sequence of sand dunes. The dunes become lower and less extensive towards the coast. The shallow unconfined aquifer is within a wedge of unconsolidated gravels and sands that thicken towards the coast. Bore logs show the aquifer near the coast is composed of homogeneous water-bearing sands to a depth of over 20 m (Wilson, 2003).

A two-dimensional resistivity model derived from the traverse is shown in Figure 5. Wilson (2003) estimated the formation factor as approximately 3 for the unconfined aquifer along the Kapiti/Horowhenua coast. A fluid resistivity of 0.3 Ωm (corresponding to sea water) will therefore result in a bulk resistivity of about 1 Ωm. This in turn implies that the saline interface, near the ground surface, is located about 35 m along the traverse. There is a sharp gradient in resistivity between depths of about 3 and 15 m. This occurs nearly coincident with the mean high tide mark, and shows that at these depths the saline interface is near vertical. A broad area of resistivity between 10 Ωm and 32 Ωm immediately to the east of this suggests diffusive mixing of saline and fresh water. This may be the result of tidal action.

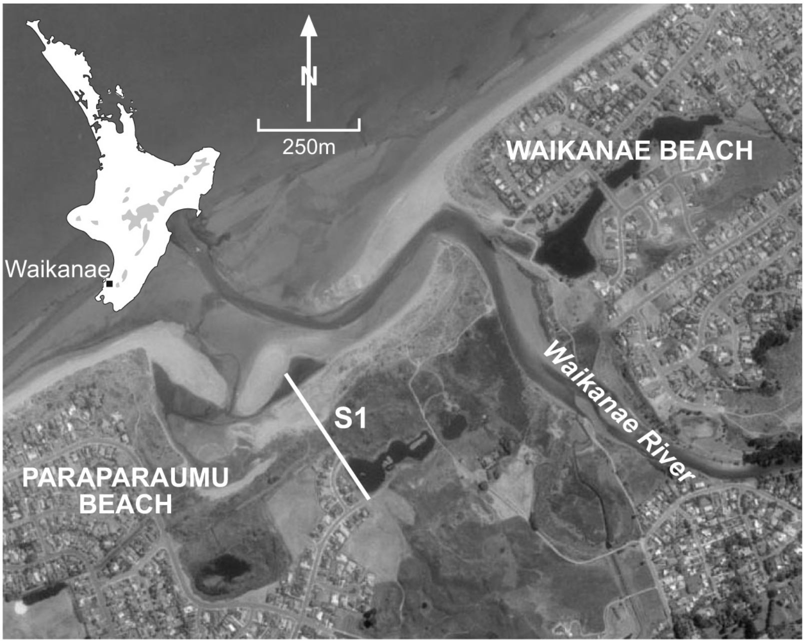

Figure 4 – Location of the Waikanae traverse. The traverse ran from below mean high tide, across a salt flat, and then approximately 200 m inland. Mean high tide is essentially marked by the inland limit of the pale sand at the beach and around the estuary.

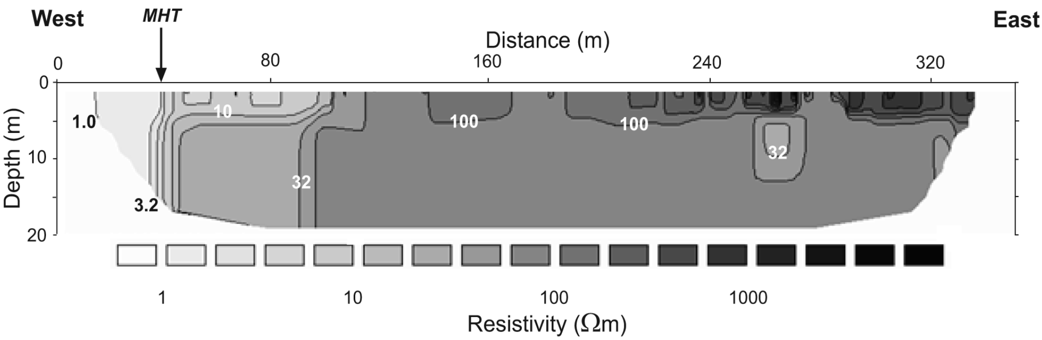

Figure 5 – The two-dimensional resistivity model derived from the data along traverse S1 shown in Figure 4.

Resistivities of around 100 Ωm further inland are typical of fresh water in the unconfined aquifers on the Kapiti Coast. A thin surficial layer of low resistivity at a distance of between 30 and 90 m correlates with the extent of salt flats above the mean high tide mark. There is no evidence in the profile of the concave shape to the saline interface shown in Figure 3, and predicted by the Ghyben-Herzberg and Glover (1959) models. This may be because there is little variation in the freshwater head along the traverse, and therefore the depth to the saline interface is constant. The interface may also be deeper than the 15-20 m modelled along the traverse.

These results show the utility of DC resistivity traverses for locating the saline interface in the near surface. The results also indicate that the standard model of the saline interface as a sharp boundary may not be correct. The mixing of saline and fresh water may lead to a transitional zone of gradually increasing resistivity rather than a distinct boundary.

Example 2 – Rarangi

The coastal settlement of Rarangi (Fig. 6) is on the north-eastern edge of the Wairau Plains, 20 km north of Blenheim. A small number of properties draw potable water from the Rarangi Shallow Aquifer. The Rarangi Shallow Aquifer is an unconfined, mixed sand and gravel aquifer, underlain by a thick sequence of passive marine silt and fine sand. Ongoing development of residential properties to the south of Rarangi, as well as viticulture, has led to concern that the aquifer may become subject to saltwater intrusion. Resistivity measurements were therefore made to determine the location of the saline/fresh water interface, and to provide a baseline for future monitoring of any saline intrusion (Ingham, 2004).

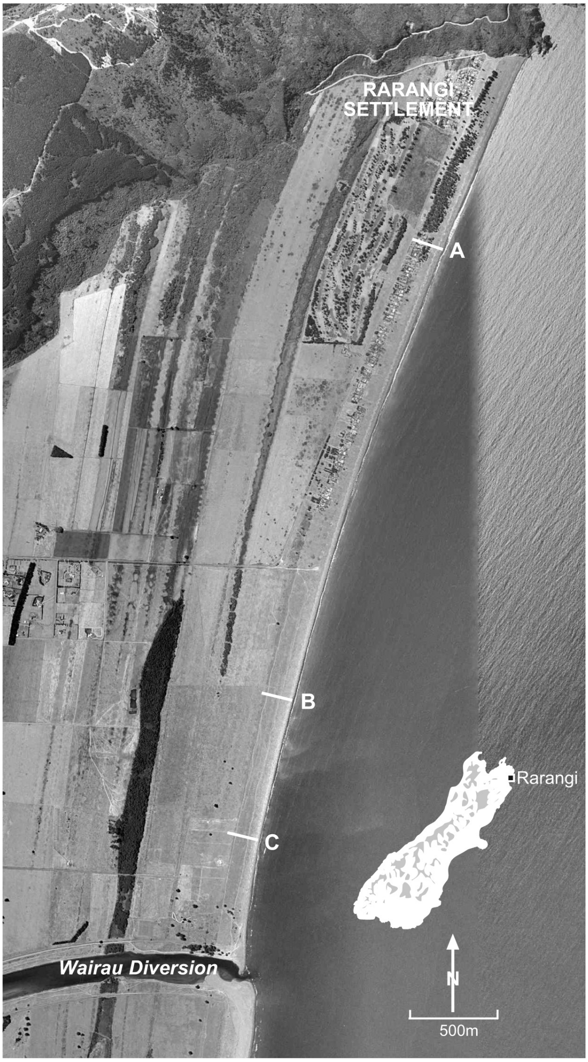

Figure 6 – Location of the three traverses from Rarangi. Traverse ‘A’ is located in an area of significant groundwater abstraction, while traverses ‘B’ and ‘C’ are across areas where the groundwater is ‘undisturbed’.

The two-dimensional resistivity sections, and their interpretations, derived from three traverses are shown in Figure 7. On each traverse ‘MHT’ shows the position of the mean high tide mark. Locations of Marlborough District Council monitoring bores 3711 and 3668 or private bore 3683 are also shown. Measurements from these

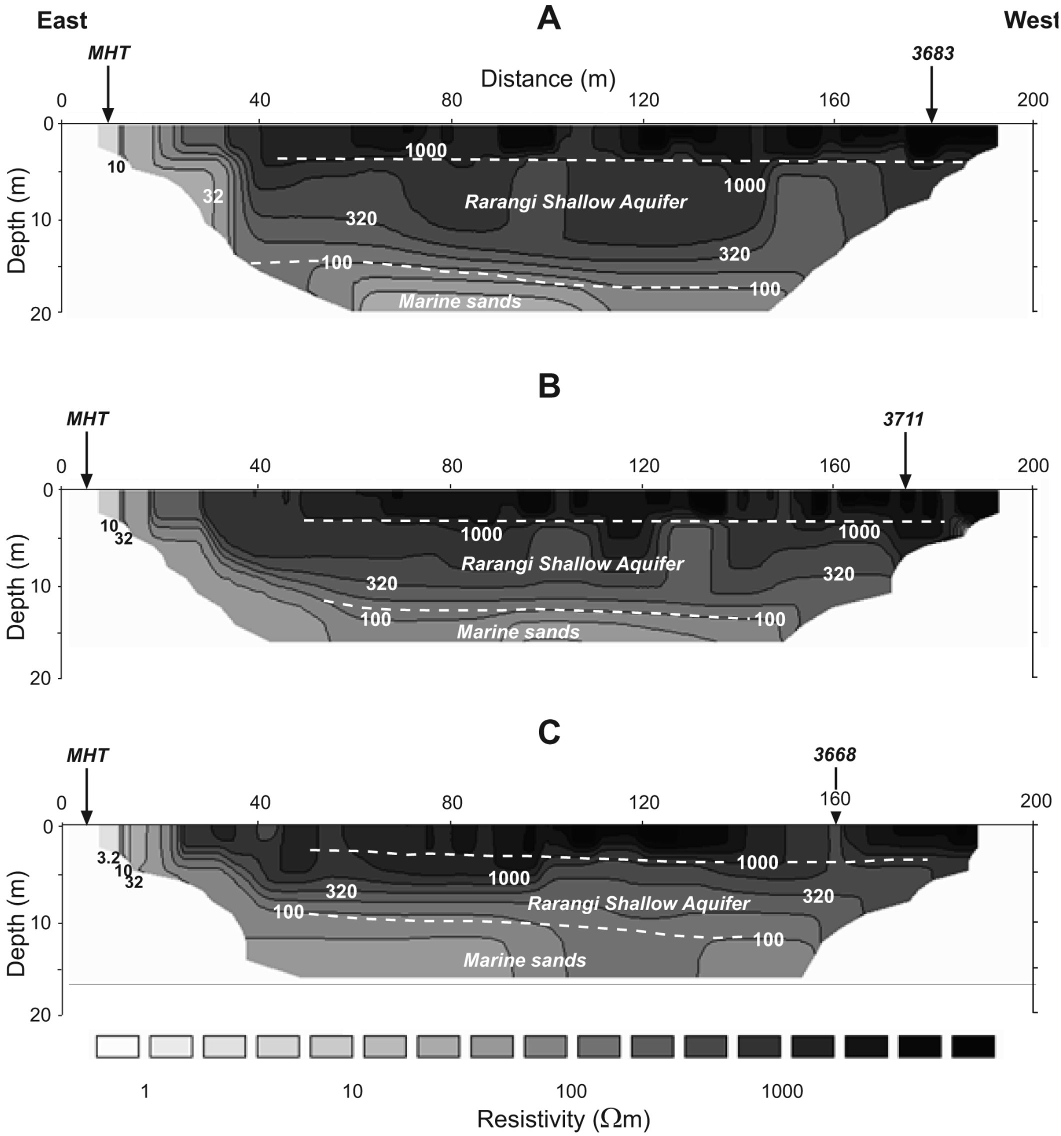

Figure 7 – Two-dimensional resistivity sections for the three traverses at Rarangi. MHT is the position of mean high tide, the numbered arrows are monitoring bores, while the dashed lines represent the water table (upper line) and aquifer boundary with the underlying marine sands (lower line).

bores show that the water table is approximately 3.5 m below the surface of the beach ridge. The water table is marked by the upper dashed line on each traverse. The depth to the underlying marine sands is less than 15 m (lower dashed line). The formation factor for the Rarangi Shallow Aquifer must be approximately 11, because the resistivity of fresh water is about 30 Ωm and the bulk resistivity of the aquifer is about 320 Ωm. The near-surface part of the saline interface therefore lies in the east of each traverse, near or just inland of the mean high tide mark. Relatively extensive regions of lower resistivity (in this case around 10-100 Ωm) some tens of metres inland of mean high tide, suggest that a mixing zone between salt and fresh water exists.

Bulk resistivity is resolved down to 15 m, which is deeper than the thickness of the unconfined aquifer. The substantial decrease in bulk resistivity at the base of the traverse is caused by the lower resistivity of the underlying marine silts. However, the semi-concave nature of the resistivity contours between mean high tide and 40 m inland, evident particularly on traverse B, may also reflect the shape predicted for the saline interface by simple models (e.g., Ghyben-Herzberg) in situations where there is an increase in fresh water head inland over this distance. This interpretation is reinforced by the fact that the two-dimensional sections are presented in terms of the depth beneath the ground surface, not depth relative to mean sea level or some other datum. The beach at Rarangi is very steep, and so there is a strong topographic component in the near-shore profiles. When this topographic effect is removed, the interface assumes the predicted parabolic shape.

The resistivities in the inferred mixing zone are somewhat lower on traverse A than on the other two traverses. Traverse A lies within the settlement of Rarangi, where households and a golf course up-gradient of the traverse have used the Rarangi Shallow Aquifer for water supply for many years. There were no bores, and there had been no groundwater extraction, near traverses B and C at the time of the study. The difference in observed resistivity between A, and B and C, may therefore be an indication of movement of the saline interface in response to water abstraction. Confirmation of this would require improved resolution of the saline interface by extending the traverse using additional electrodes further to the east of mean high tide.

Example 3 – Te Horo

The saline interface at Te Horo appears to have moved significantly in response to groundwater abstraction, as discussed by Wilson (2003) and Wilson *et al.* (2006). Figure 8 shows the location of two traverses relative to the settlement. T1 lies 700 m to the north of Te Horo settlement in an area where there are few bores and there has been comparatively little groundwater extraction. In contrast, traverse T3 is in the centre of the Te Horo beach settlement. Because of the number of bores and permanent residents within the community, groundwater usage is significantly higher here than to the north or south. Figure 9 shows the two-dimensional resistivity models derived for these two traverses. On both models 0 m on the horizontal scale marks the mean high tide mark. Note that to better illustrate the reduction in bulk resistivity below T3, a different contouring interval has been used from that in Figures 5 and 7.

A near vertical saline interface to some 5 m depth on the model of traverse T1 is observed just inland (south-east) of the mean high tide, with a deeper zone of diffusive mixing extending further inland. Resistivities of approximately 100 Ωm typify the unconfined aquifer. These resistivities are similar to those of fresh-water saturated sediments at

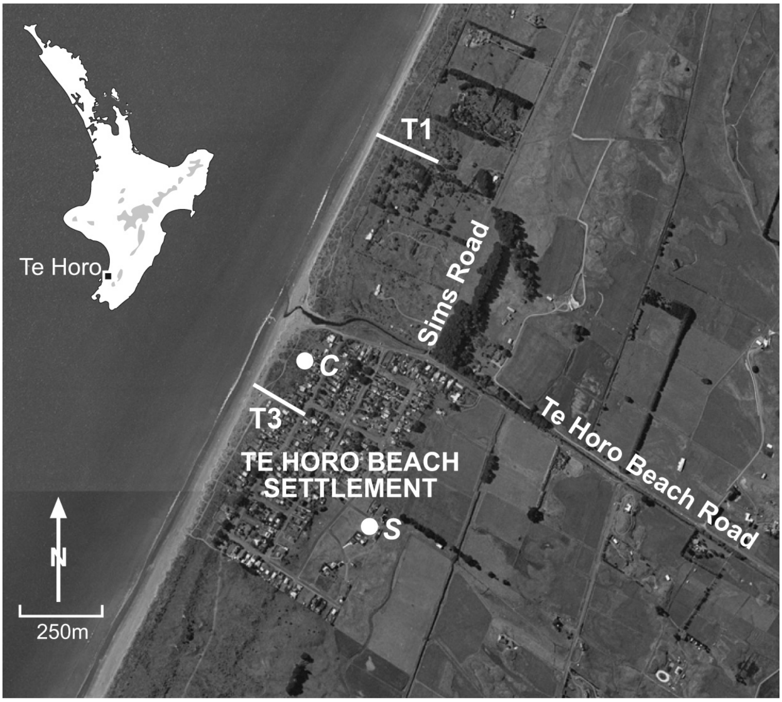

Figure 8 – Locations of the two resistivity traverses, and bores used for water chemistry analysis, at Te Horo.

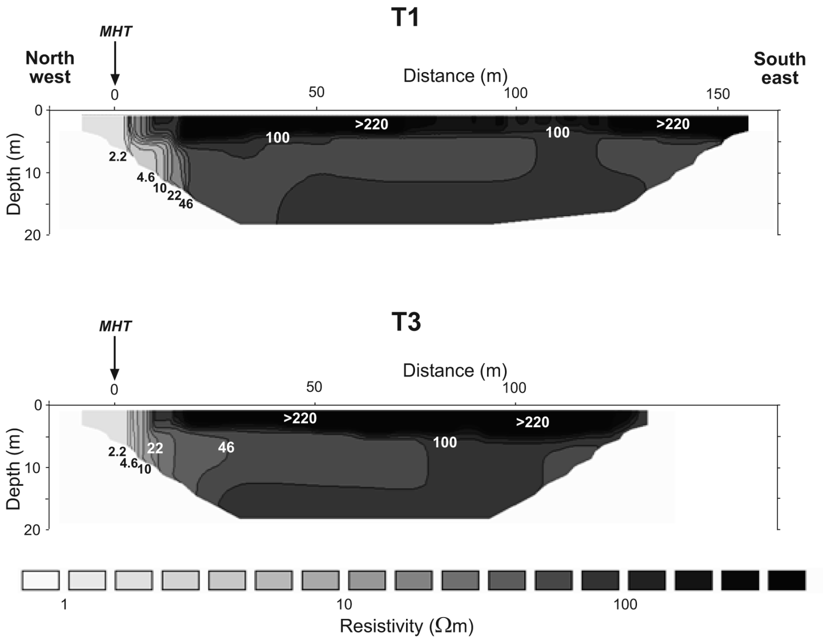

Figure 9 – Two-dimensional resistivity sections for the two traverses at Te Horo. The position of mean high tide (MHT) is at ‘0’ distance.

Waikanae (Fig. 5). Higher resistivity in the near-surface is typical of the unsaturated zone. Between a depth of 5 and 15 m, resistivity increases markedly from 4.6 to 46 Ωm over a horizontal distance of 10 m.

The model for traverse T3 shows an inland indentation of the 46 Ω contour, which indicates saline intrusion. This suggests a landward migration of the saline/fresh water mixing zone of between 10 and 15 m. This is consistent with chemical data from boreholes C and S (Fig. 8). Bore C, 75 m from mean high tide, has a Cl^- concentration of ~ 140 g/m^3. This is three times higher than the Cl^- concentration at Bore S, ~ 45 g/m^3, which is 500 m inland. Use of the formation factor allows actual Cl^- concentrations to be estimated. Wilson *et al.* (2006) calculated that within the unconfined aquifer at Te Horo, a bulk resistivity of ~ 100 Ωm typifies zones of fresh water, and resistivities of less than 50 Ωm indicate saline intrusion. Fluid resistivities of ~ 35 Ωm (fresh) and 15 Ωm (saline) are implied, with a formation factor of approximately 3 (Wilson, 2003). Using standard data (e.g., Keller and Frischknecht, 1966) for NaCl solutions, the relationship between the resistivity of a fluid ρ_w and concentration (C) of dissolved ionic solids may be expressed as:

$$\log_{10}(\rho_w) \approx 0.672 - 1.047 \log_{10}(C) \qquad (5)$$

where C is measured in g/L. Using this expression, the interpreted values of fluid resistivity are consistent with a tripling of Cl^- concentration, as indicated by the chemical data. A bulk resistivity of approximately 45 Ωm corresponds to a Cl^- concentration of between 300 and 400 g/m^3.

Discussion and conclusions

These studies address saline intrusion in unconfined coastal aquifers occurring within sand and gravel formations. These aquifers are broadly typical of many aquifers in New Zealand. The estimated formation factors, ranging from 3 to 11, can therefore also be assumed to be representative of most unconfined coastal aquifers. A rise in bulk resistivity by a factor of up to a 100, moving from saline to fresh water across the saline interface, may also be regarded as typical. Resistivity traverses can therefore provide a sensitive means of locating the saline interface.

The shape and nature of the saline interface are somewhat harder to typify. While the ability of resistivity to resolve sharp boundaries depends on the electrode separation used, it is clear that the saline interface seldom has the form and characteristics presented in a simple conceptual and mathematical model. Typically it appears that resistivity changes gradually across a mixing zone tens of metres in horizontal extent. The existence of a mixing zone is not unexpected, and indeed has been observed at shallow depth on a beach-face using cross-borehole resistivity (Turner and Acworth, 2004). The measured shape of the saline interface in the examples discussed does not correspond to that predicted by a simple model, but it is difficult to determine whether this is a general characteristic. The shape of the interface in a given situation depends largely on the hydraulic gradient perpendicular to the coast, and it may be further constrained by the thickness of the aquifer. Where a conductive layer, such as the marine sands at Rarangi, underlies the aquifer, the interface shape may be masked by the vertical resistivity contrast.

Comparing a coastal aquifer where there has been little fresh water abstraction (e.g., Te Horo traverse T1 or Rarangi C) with situations where there has been significant groundwater use (e.g., Rarangi A and Te Horo traverse T3) provides a conceptual model of the onset of saline intrusion. In the 'undisturbed' area, the saline interface is marked by a relatively narrow mixing zone of saline and fresh water across which the resistivity rises by approximately 2 orders of magnitude. As water is removed from the aquifer at a faster rate than it recharges, the mixing zone widens over the depth from which water is taken. Further abstraction of fresh water results in a 'tongue-like' extension of the mixing zone inland. The large resistivity contrast between saline and fresh water, and the relationship between Cl^- ion concentration and fluid resistivity, ensures that even a small increase in Cl^- concentration is marked by a significant lowering in the bulk resistivity. This illustrates the ability of the traverse technique to detect the early onset of salt-water intrusion.

In summary, the studies outlined above show that the following features appear typical of the saline interface in unconfined coastal aquifers.

1. Across the interface, moving from saline to fresh water, there is a rise in bulk resistivity of up to 2 orders of magnitude. The actual values of bulk resistivity observed depend upon the formation factor for the aquifer.
2. Simple models predict the saline interface to be a sharp boundary. In this study the interface appears to be a transitional zone over which mixing of saline and fresh water occurs. This leads to a more gradual increase in bulk resistivity over tens of metres, both vertically and horizontally.
3. The existence of a mixing zone means that the characteristic shape of the saline interface predicted by simple models is not generally observed. This may be partly dependent upon the thickness of the aquifers, and their topographic slope and hydraulic gradient. It is possible that the traverses were not long enough to detect the interface at depth but this seems unlikely.
4. The response of the saline interface to abstraction exceeding recharge may start with the extension of the saline/fresh water mixing zone. This causes a significant reduction in bulk resistivities measured inland.

Notwithstanding the above, resistivity traverses have some limitations which restrict their applicability. Measurements are obtained in a cone, with deeper measurements requiring a much wider separation of current electrodes. Therefore, it is difficult to obtain data using electrodes positioned at significant distances on the seaward side of the saline interface (i.e., below low tide). This clearly restricts detailed study of the interface at depths below 10 m. Although in principle measurement of inland intrusion into deeper aquifers should be possible, the typical loss of resolution with depth makes the use of resistivity traverses difficult. Despite these limitations, resistivity traverses have much to offer in terms of measurement and monitoring of the saline interface in shallow unconfined coastal aquifers.

Acknowledgements

The authors gratefully acknowledge support from the Greater Wellington Regional Council, and the University and Science Faculty Research Funds of Victoria University of Wellington. They are also most grateful to the reviewers of this paper who made many valuable suggestions.

References

Aaltonen, J.; Olofsson, B. 2002: Direct current (DC) resistivity measurements in long-term groundwater monitoring programmes. *Environmental Geology 41:* 662-671.

Albouy, Y.; Andrieux, P.; Rakotondrasoa, G.; Ritz, M.; Descloitres, M.; Join, J-L.; Rasolomanana, E. 2001: Mapping coastal aquifers by joint inversion of DC and TEM soundings – three case histories. *Ground Water 39:* 87-97.

Archie, G.E. 1942: The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the American Institute of Mining & Metallurgical Engineers 146:* 54-62.

Broadbent, M.; Callander, P.F. 1991: A resistivity survey near Waimakariri River, Canterbury Plains, to improve understanding of local groundwater flow and of the capabilities of the survey method. *New Zealand Journal of Geology & Geophysics 34:* 441-453.

Choudhury, K.; Saha, D.K.; Chakraborty, P. 2001: Geophysical study for saline water intrusion in a coastal alluvial terrain. *Journal of Applied Geophysics 46:* 189-200.

Cozens, N. 2003: Resistivity investigations of groundwater in the vicinity of the Waikanae River mouth. Unpublished BSc(Hons) dissertation, School of Earth Sciences, Victoria University of Wellington, 103 p.

Devi, S.P.; Srinivasulu, S.; Raju, K.K. 2001: Delineation of groundwater potential zones and electrical resistivity studies for groundwater exploration. *Environmental Geology 40:* 1252-1264.

Domenico, P.A.; Schwartz, F.W. *(eds.)* 1998: *Physical and chemical hydrogeology* (2nd edition). John Wiley and Sons, Inc. New York, U.S.A.

Ebraheem, A-A.M.; Senosy, M.M.; Dahab, K.A. 1997: Geoelectrical and hydrogeochemical studies for delineating ground-water contamination due to salt-water intrusion in the northern part of the Nile delta, Egypt. *Ground Water 35:* 216-222.

Gimenez, E.; Morell, I. 1997: Hydrogeochemical analysis of salinization processes in the coastal aquifer of Oropesa (Castellon, Spain). *Environmental Geology 29 (1-2):* 118-131.

Glover, R.E. 1959: The pattern of fresh-water flow in a coastal aquifer. *Journal of Geophysical Research 64:* 457-459.

Ingham, M. 2004: Measurement of the saline/ fresh water interface at Rarangi using DC resistivity traversing. Report for Marlborough District Council, February 2004, 30 p.

International Association of Hydrologists 2003: Groundwater – from development to management. Briefing paper for 3rd World Water Forum, Kyoto, Japan, March 2003.

Karlik, G.; Kaya, M.A. 2001: Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey. *Environmental Geology 40:* 725-731.

Kearey, P.; Brooks, M. 1991: *An introduction to geophysical exploration.* Blackwell Scientific Publishing.

Keller, G.V.; Frischknecht, F.C. 1966: *Electrical methods in geophysical prospecting.* Pergamon Press.

Lenkey, L.; Hámori, Z.; Mihálffy, P. 2005: Investigating the hydrogeology of a water-supply area using direct-current vertical electrical soundings. *Geophysics 70 (4):* H11-H19.

Lincoln Environmental 2000: Information on water allocation in New Zealand. Report for Ministry for the Environment, Report No 4375/1, 107 p.

Loke, M.H. 2000: Electrical imaging surveys for environmental and engineering studies. Unpublished short training course lecture notes, Geotome Software, Penang, Malaysia, 65 p.

Loke, M.H.; Barker, R.D. 1996: Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting 44:* 499-523.

Rushton, K.R. 1980: Differing positions of saline interfaces in aquifers and observation boreholes. *Journal of Hydrology 48:* 185-189.

Sandberg, S.K.; Slater, L.D.; Versteeg, R. 2002: An integrated geophysical investigation of the hydrogeology of an anisotropic unconfined aquifer. *Journal of Hydrology 267:* 227-243.

Schnoebelen, D.J.; Bugliosi, E.F.; Krothe, W.C. 1995: Delineation of a saline ground water boundary from borehole geophysical data. *Ground Water 33:* 965-976.

Sharma, S.P.; Baranwal, V.C. 2005: Delineation of groundwater-bearing fracture zones in a hard rock area integrating very low frequency electromagnetic and resistivity data. *Journal of Applied Geophysics 57(2):* 155-166.

Shearer, T.R. 1991: Saline intrusion at Valle San Quintin, Mexico BC: Geophysical borehole logs, Report No. WD/91/45R, British Geological Survey, Wallingford.

Turner, I.L.; Acworth, R.I. 2004: Field measurements of beach-face salinity structure using cross-borehole resistivity imaging. *Journal of Coastal Research 20:* 753-760.

White, P.A. 2001: Groundwater resources in New Zealand. *In* Rosen, M. and White, P. (*eds.*) *Groundwaters of New Zealand*, 45-75.

White, P.; Clausen, B.; Hunt, B.; Cameron, S.; Weir, J. 2001: Ground water – surface water interaction. *In* Rosen, M. and White, P. (*eds.*) *Groundwaters of New Zealand*, 133-160.

Whittecar, G.R.; Nowroozi, A.A.; Hall, J.R. 2005: Delineation of saltwater intrusion through a coastal borrow pit by resistivity survey. *Environmental and Engineering Geoscience 11(3):* 209-219.

Wilson, S.R. 2003: The saltwater-freshwater interface, Te Horo Beach, Kapiti Coast. Unpublished MSc thesis, School of Earth Sciences, Victoria University of Wellington, 147 p.

Wilson, S.R.; Ingham, M.; McConchie, J.A. 2006: The applicability of earth resistivity methods for saline interface definition. *Journal of Hydrology 316:* 301-312.

Manuscript received 3 February 2006; accepted for publication 31 October 2006