IMAGING OF AQUIFERS BENEATH WATERCOURSES

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ABSTRACT: Imaging of groundwater that interacts with surface watercourses is essential for providing detail needed to accurately manage both resources. It is particularly important where one resource is saline or otherwise polluted, where spatial quantification of the interacting resources is critical to water use planning and where losses from surface waterways need to be minimized in order to transport water long distances. Geo-electric arrays or transient electromagnetic devices can be towed along watercourses to image electrical conductivity (EC) at multiple depths within and beneath those watercourses. It has been found that in such environments, EC is typically related primarily to groundwater salinity and secondarily to clay content. Submerged geo-electric arrays can detect detailed canal-bottom variations if correctly designed. Floating arrays pass obstacles easily and are good for surveying constricted rivers and canals. Transient electromagnetic devices detect saline features clearly but have inferior ability to detect fine changes just below beds of watercourses. All require that water depth be measured by sonar or pressure sensors for successful elimination of effects of the water layer on the data. Presentation of the data using a 3D presentation technique where EC is imaged along vertical ribbons drawn along the watercourses is almost essential for handling the data produced because the meandering paths of rivers and canals combined with the shear volume of data typically acquired results in a geo-referencing dilemma that cannot be accommodated using traditional presentation techniques.

An extensive set of EC Imaging case studies, distributed across canals and rivers of the Australian Murray-Darling Basin, has been collected. They reveal the interaction of various rivers and canals with the underlying groundwater resources. At some sites, watercourses cross prior iver channel sands that are being recharged and are suitable for use as water storages with low evaporation losses. Canals and reservoirs that cross such prior river channel sands can be sealed but, with geophysical assistance in mapping aquifers, development of underground water storages with controlled recharge may be more lucrative. At some other sites, little connection between aquifers and surface watercourses is evident. Finally, at downstream ends of geological basins, sites where saline groundwater flows into, or is on the verge of flowing into rivers are evident.

KEYWORDS

Electrical Conductivity, Resistivity, Salinity, Hydrogeophysics, Rivers

INTRODUCTION

This paper is intended to be a guide for those who are attempting to select procedures for imaging aquifers connected to surface waterbodies.

Electrical conductivity (EC) imaging is useful for identifying salinity and clay content distribution, within unconsolidated and partially consolidated sediments, and salinity and porosity distribution within consolidated sediments. It is also affected by saturation but this usually is constant under watercourses. Geo-electric and electromagnetic devices have been used for many years for electrical conductivity imaging on land; however it is only with the advent of GPS positioning and high volume memory storage that continuous multi-depth electrical conductivity imaging of aquifers from watercourses has become possible. With this new possibility have come many new challenges due to the unusual nature of the great volumes of data that get produced. A great deal more automation of processing and quality control are essential. Because multi-depth data is collected along irregular paths, visualization and interpretation require new techniques. The effect of watercourse depth must be eliminated from the data if aquifers beneath the watercourses are to be clearly resolved.

Figure 1 presents a sample of data collected along the Murrumbidgee River and connecting canals. It reveals permeable buried prior stream channels that could be seepage sites. The blue end of the color scale represents low EC and the red, high EC. The colour scale is presented in figure 4. Data is projected up from the watercourses, like a vertical ribbon, on a logarithmic depth scale. Depth ticks are provided at some locations along the canal for reference. The depth of the watercourse beds are marked by an aqua line. The bottom of the 'ribbon' is jagged because data integrity at depth is marginal and requires clipping. The image is divided into discrete layers of variable thickness so that real discrete layer boundaries such as the watercourse beds can be accurately resolved. A distinct geological zone, not evident on the airphoto, is evident from EC contrast to be surrounding the river. In this zone, deep aquifer recharge, with water sourced from surface watercourses, is evident from low EC that extends right to the bottom of the ribbon. Localized seepage of about 140mm/day has been detected by the author at one low EC anomaly near the river. Later we will contrast this site with others by use of a common color scale.

Figure 1 EC data from a 144m long floating geo-electric array and of the Murrumbidgee River and adjacent canals in the vicinity of the Murrumbidgee Irrigation Area, NSW, Australia.

DEVICES FOR IMAGING OF AQUIFERS CONNECTED TO WATERCOURSES.

Rapid aquifer imaging can only be achieved using non-invasive continuously moving devices. Electrical, electromagnetic, magnetic and seismic devices are therefore the only possibilities. Magnetic and seismic devices are typically useless for aquifer definition in unconsolidated environments and are not sensitive to salinity variations. Seismic streamers can be used to detect depth to consolidated rock beneath unconsolidated sediment beneath watercourses (http://water.usgs.gov/ogw/bgas/profiles/Feb2004-NE.html). This paper focuses on the use of electrical and electromagnetic devices (Barret et. al. 2003, Volmer et. al. 2004) which primarily measure EC. They also measure other properties relevant to aquifer definition such as induced polarization (Viezolli and Cull 2005) which is affected by clay content however EC is the only property that currently is being routinely measured in a clear and comprehensive way.

There should now be little reason for failure of EC imaging surveys because theoretical modeling of anticipated scenarios can quickly be carried out for any device that may be chosen. Various software tools are available for such modeling (eg HydroGeoImager - Allen 2005d and EMMA – Auken et.al. 2001,2) Geo-electric arrays measure EC by directly injecting electric current into the ground/water and measuring electric field perturbations, related to subsurface heterogeneity, along a towed array of electrodes. Electromagnetic devices induce electric current into the ground using loops of wire and then detect the change in the magnetic field at sensor coils that results from decay and migration of the electrical current 'smoke ring' that has been induced in the water/ground. Control of, and interpretation of signals from electromagnetic exploration devices is therefore more complicated than that of geo-electric devices.

Figure 2 presents various waterborne, multi-depth EC imaging devices. It can be observed that a lot of logistical decisions have to be made in order to select an appropriate device for a job. Navigability of the devices is very variable as are spatial and EC resolution and depth of investigation ranges.

Figure 2 Devices for imaging aquifers beneath waterways: a 144 m long floating Allen exponential bipole geo-electric array, a similar 20 m long submerged array and pressure depth sensor, an Iris Instruments Syscal Pro (courtesy of Geoforce) set up for surveying constricted waterways and a floating transient electromagnetic loop prototype (courtesy of Zonge Engineering and Research Organization – Australia). Similar configurations can be used for survey across land.

Towed array surveys are requested at sites where canal seepage is problematic, where transmission losses from rivers need to be studied, and where saline inflow, acid inflow (from acid sulfate soils) or other pollution inflow into rivers or drains is occurring. These sites rarely offer ideal navigation and innovative array towing solutions usually need to be implemented. Equipment used, including the geo-electric arrays, typically need to be light, rugged and streamlined. Field logistics, rather than geophysical limitations, is usually the primary factor that determines the viability ofvarious devices. Across land, geo-electric devices suffer from contact resistance problems whereas TEM such as NanoTEM (Allen 2005b), TerraTEM and SkyTEM (Sorensen and Auken 2004) and frequency domain EM devices such as the Geonics EM31 do not. Some geo-electric devices such as the Geometrics ohm-mapper can be effectively used in continuous towing mode on land because they use capacitive electrodes.

Geo-electric array configuration is critical for obtaining low noise data, good depth resolution, and good signal strength. An Allen Exponential Bipole array configuration (Allen 2005a) normally is optimal for towed array surveys. In order to detect very fine detail just below watercourse beds, the array needs to be submerged, towed along the bed. Arrays need to be about 5 times as long as their maximum exploration depth so, for navigation purposes, deep penetrating arrays must float instead.

PRESENTATION

Tens of megabytes of data can easily be collected by GPS tracked towed geo-electric arrays or electromagnetic devices in a day. Presentation of that data is only feasible once it is in a form in which it can be efficiently georeferenced by the viewer. Because of this, interactive 3D ribbon imaging in an OpenGL interface has been developed (Allen 2005b).

Any data can be imaged using apparent EC equations that create blurred imagery; however floating array data is best processed using horizontal layer inversion, an iterative process of creating horizontal layer scenarios that may match the data, calculating the result and how it matches the data, and then creating a new model, repeating until an appropriate model is determined. Two dimensional inversion which models a grid of infinite length horizontal prisms that are perpendicular to the survey direction, instead of horizontal layers, is excessively time consuming and ill posed to towed array data. Horizontal ripple in the imagery usually results (Allen and Merrick 2005). Two dimensional modeling is appropriate for producing imagery that must resolve steeply dipping boundaries accurately for high cost engineering works (eg. Loke and Lane 2004). Initial models fed to inversion should be adjusted using the measured water depths. Inversion routines should not however be forced to honor the water depth especially where surface water stratification is anticipated or where water depth is laterally variable (i.e. most rivers and canals). Forcing inversion to honor the measured water depth in those situations would produce neater more impressive images but they would have geophysical artifacts in themthat could confuse interpreters (Allen 2005d). Inversion code for imaging aquifers below surface water bodies must be designed to resolve high EC contrast boundaries. This is best done by minimizing the number of layers in models so that layer boundaries can be allowed to move to match real geological boundaries. This approach has been adopted in HydroGeoImager (Allen 2005b) by centering layers over the focus depth of investigation of each configuration in an array and using a balance of layer stretch constraint and smoothness constrant. The minimum number of layers approach also has been adopted, with the additional benefits of laterally constrained inversion by the Aarhus HydroGeophysics Group (Auken and Christiansen 2004).

Low conductivity surface water overlying highly conductive groundwater results in signal to noise problems in many cases. Data must therefore be clipped to prevent artifacts; however the clipping itself can cause artifacts. Inversion must be able to accommodate the complications added by clipping (eg HydroGeoImager, Allen 2005b).

INTERPRETATION– ADDITIONAL CASE STUDIES

Sturt Canal – Seepage investigation using a submerged geo-electric array

A little local geological information usually resolves ambiguity in interpretation of the significance of electrical conductivity anomalies. Anomalies almost always correlate with groundwater salinity. Correlation with clay content is also common (Slavich and Petterson 1993). Correlation with sodicity, which is related to permeability, normally also occurs (Shaw 2002). Figure 6 presents a case where a submerged array has been used to suggest where water is seeping from a canal into buried river channels. Comparison with seepage under the river, which is connected to one end of the canal, is possible. Under the river, a much lower conductivity than under the canal is observed. In this environment, this suggests that seepage under the river is far more significant than seepage out of the canal.

Mildura – A Murray River Salt Interception Scheme in a fossil groundwater discharge region surveyed using both TEM and a floating geo-electric array.

About 120km of the Murray River in the vicinity of Mildura was surveyed using both TEM and a 144m long geo-electric array. Part of both datasets has been coloured using the same EC histogram (Figure 4) so that direct comparison is possible. The histogram used was developed by averaging histograms from all over the Murray Darling Basin, therefore, it was not optimized in such a way as to favour either dataset. Observe that the TEM dataset has poor and ambiguous resolution of details above about 6m. Conductive features below 6 metres deep are resolved well but erroneously extended up to the surface. This is because the assumptions used in mathematics for interpreting TEM loose validity above about this depth. The datasets are reasonably comparable below 6 metres deep. In the geo-electric dataset, features just below the riverbed are clearly visible. The interception scheme at this location has not been able to remove all saline water from below the river, however, it has removed saline water from immediately below the river. That water has been replaced with fresh water being drawn out of the river which has resulted in a low EC anomaly just below the river bed. On the images, purple spheres placed at every kilometre along the river are sized in proportion to salt load increase along the river. It can be observed that they correlate very well with EC just below the river bed a few kilometres upstream of their locations.

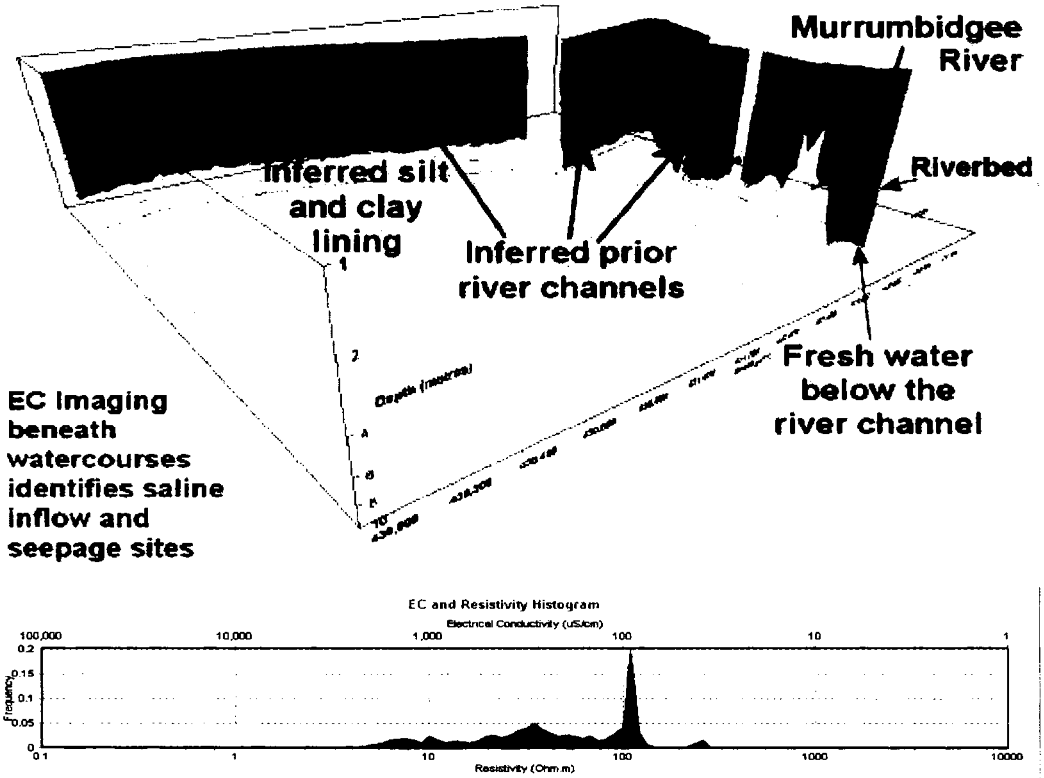

Figure 3.: Sturt Canal - Murrumbidgee Irrigaiton Area – NSW – Australia. An example of submerged geo-electric array data with intense detail right at the riverbed. Data was collected using an Iris Instruments Syscal Pro provided by Geoforce Pty Ltd. This data has been imaged simply by using an apparent resistivity formula for a submerged array in a half space along with sonar depth information, surface water resistivity and half space effective depths. The imaging procedure used is far from optimal however the level of detail produced is still impressive. Fast submerged array inversion is not yet available.

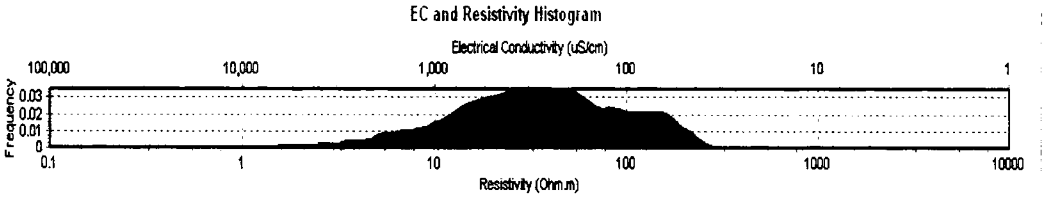

Figure 4 A composite EC histogram created from numerous datasets from the Murray Darling Basin. This histogram has been used to colour figures 1, 6, 7 and 8 so that they can be directly compared.

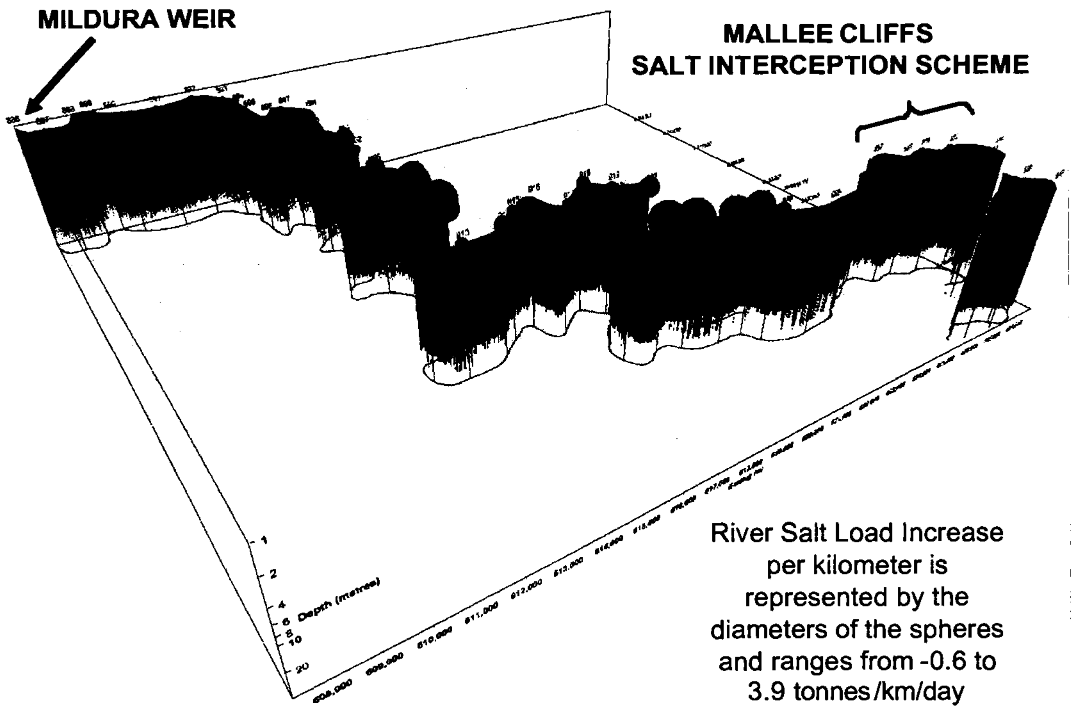

Figure 5 EC below the Murray River as imaged using Zonge NanoTEM with an 8 x 8m loop.

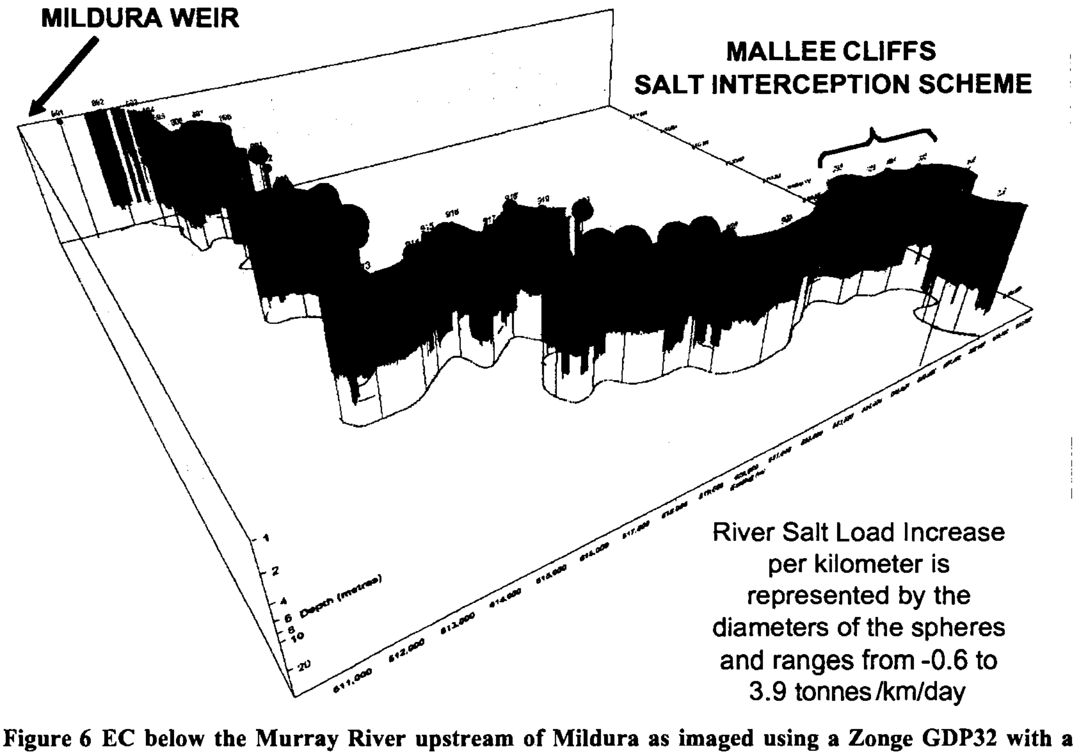

Figure 6 EC below the Murray River upstream of Mildura as imaged using a Zonge GDP32 with a 144m long, exponential, bipole geo-electric array.

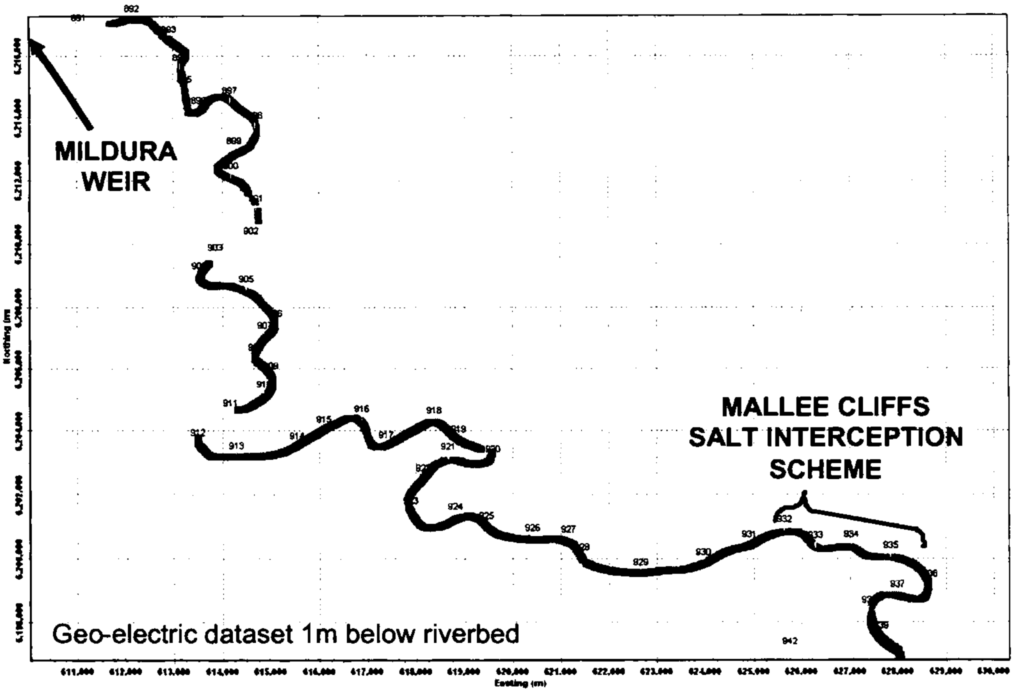

Figure 7 Saline inflow hotspots inferred using geo-electric EC data 1 metre below the riverbed - a simplified way of presenting important data from figure 7.

Figure 7 presents EC one metre below the riverbed as observed by the geo-electric array. This simple form of presentation is good for showing audiences exactly where salt is entering a river but lacks the fullness of detail of the 3D imagery.

Contrast the Murrumbidgee near Griffith (Figure 1) with the Murray near Mildura (Figure 6) which both have been coloured using the colour scale of figure 4. Figure 1 is of an aquifer recharge area while figure 6 is of a fossil aquifer discharge area. These two images show how, once a regional database of sub-river EC imagery has been established, that imagery can be used to clearly identify gaining and losing parts of rivers.

Waikerie – A Murray River salt interception scheme and prior channel surveyed by a geo-electric array.

Figure 8 presents a site where saline inflow into the Murray River is being prevented by salt water interception scheme (SIS) bores. Because EC reflects groundwater salinity rather than rate of saline flow, in most cases, in the vicinity of SIS bores, EC anomalies are not expected unless the SIS bores have been pumping sufficient flows to have caused a reversal of vertical groundwater flux under the river so that river water is drawn into the SIS bores. As soon as that occurs, the strata under the river become flushed with fresh river water rather than up-welling saline groundwater and a distinct EC anomaly occurs. The EC anomaly then shows the extent of strong influence of the SIS bore which in many cases has been distorted by geological variations such as prior river channels. At Waikerie SIS – Murray River – South Australia, good examples of such anomalies do seem to exist. Figure 8 shows such anomalies as well as another good anomaly believed to be resulting from the only palaeo-river-channel under this part of the river due to its co-incidence with geomorphological features evident on airphotos.

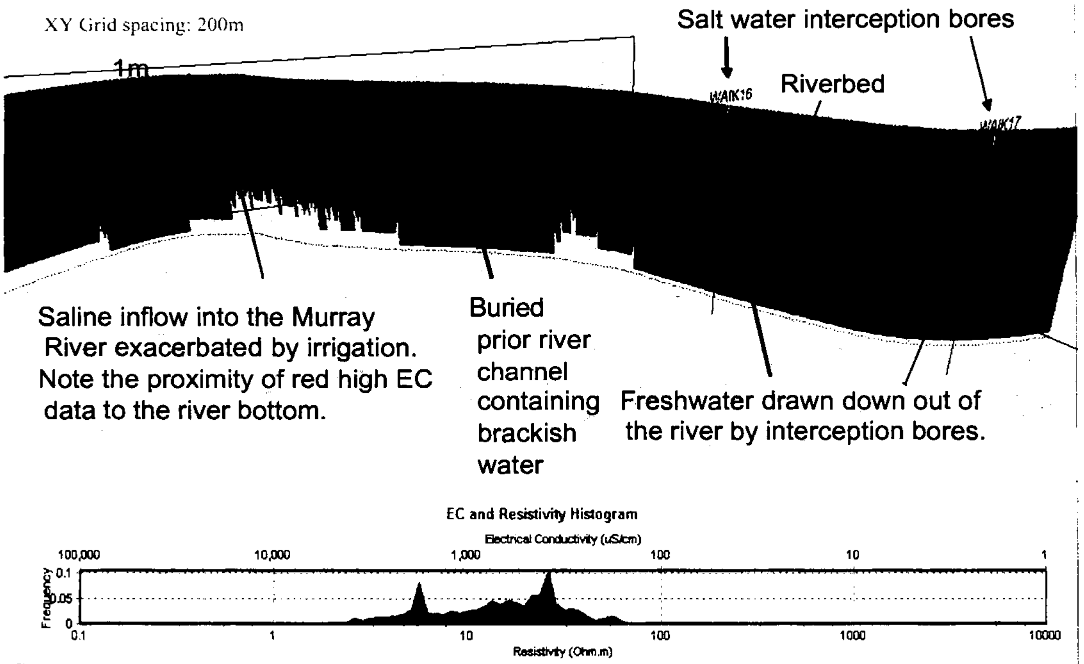

Figure 8 Part of Waikerie SIS scheme shown in Figure 7. A close-up of anomalies resulting from a palaeochannel, and Waikerie SIS bores 16 and 17 (shown as vertical black lines). This ribbon image was generated using 1D inversion. Note how the riverbed (aqua line) does not correspond with the base of the blue low EC anomaly near the SIS bores – the bores appear to have drawn freshwater downwards from the bottom of the river in the vicinity of the bores.

It is believed that because the bores shown in Figure 8 are very close to the river, and because the geological strata there, that the river has incised, are permeable, distinct 'drawdown cone' anomalies exist around the bores. Irrigation there has a localized impact on saline inflow into the river as is evident from localization of groundwater mounds around irrigated land. Figure 8 was created using the 1D inversion software written by the authors.

CONCLUSION

Transient electromagnetic (TEM) surveys conducted from water can identify salt stores in aquifers beneath watercourses but cannot effectively resolve depths of features near beds of typical watercourses. Continuous TEM surveys can, however, image aquifer variations across land if the TEM loop is towed behind a land vehicle or suspended from a helicopter.

Towed geo-electric surveys conducted from water can be of tremendous value due to the high productivity rate attainable on water. They can focus directly on the principal sites of surface water groundwater interaction – right beneath the surface water bodies. Because electrical conductivity is very dependant on salinity, both freshwater flushing of saline aquifers and saline inflow into rivers and drains can be studied in exceptional spatial detail.

It is likely that, with the additional information that can be gained using aquifer imaging, much more precise, and economically viable use of connected surface and groundwater resources will occur in the future.

REFERENCES

Allen, D.A. & Merrick, N.P., 2003, A floating electrode array for continuous geo-electric imaging. Extended abstract – *proceedings of the Aust. Soc. of Exploration Geophysicists 16th Geophysical Conference and Exhibition.*

Allen, D.A. & Merrick N.P. 2003, Identifying fresh and saline water using hydro-geophysical imagery of strata beneath watercourses. *Paper and posters presented in the proceedings of the 9th Murray Darling Basin Groundwater Conference – Feb. - Bendigo.*

Allen, D.A. & Merrick N.P. 2005, Towed geo-electric arrays for analysis of surface water groundwater interaction. *Proceedings of the Sypos. on Applications of Geophy. to Engineering and Environmental Problems conference* – April – Atlanta, USA, ISSN 1554-8015.

Allen, D.A., 2005, Electrical conductivity imaging of aquifers connected to watercourses – A thesis focused in the Murray Darling Basin, Australia. PhD, University of Technology, Sydney. (under review)

Auken, E., Breiner, M., Nebel, L., Pellerin, L., Thomsen, P., and Sørensen, K. I., 2001, EMMA - Electromagnetic modelling and analysis. *EEGS Birmingham Proceedings.* Birmingham, U.K.:EEGS. 114-115, 2001. JED.

Aukin, E., and Christiansen, A.V., 2004, Layered and laterally constrained 2D inversion of resistivity data. *Geophysics*, Vol. 69, No. 3, (May-June), p. 752-761.

Auken, E., Nebel, L., Sørensen, K., Bre iner, M., Pellerin, L., and Christensen, N., The Hydrogeophysics Group, Dept. of Earth Sciences, University of Aarhus, Finlandsgade 8, DK-8200 Aarhus N, Denmark., 2002, EMMA – A Geophysical Training and Educational Tool for Electromagnetic Modeling and Analysis. *Journal of Engineering and Environmental Geophysics*, Vol. 7, Issue 2, pp. 57-68, (June).

Barret, B., Hatch, M., Heinson, G., and Telfer, A., 2003, Salinity monitoring of the Murray River using a towed TEM array: *Aust. Soc. of Explor. Geophysicists 16th Geophysical Conference and Exhibition.*

Loke, M.H. and Lane, J.W. 2004, Inversion of data from electrical imaging surveys in water-covered areas, Extended abstract (and paper submitted for publication in *Exploration Geophysics*), *Proceedings of the Australian Society of Exploration Geophysicists Conference* (August).

Shaw, C. 2002, *Infiltration on common rice soils within MIL.* chriss@murrayirrigation.com.au

Slavich, P.J. & Petterson, G.H., 1993, Estimating the Electrical Conductivity of Saturated Paste Extracts from 1:5 Soil:Water Suspensions and Texture, *Aust. J. Soil Res.*, 31, 73-81.

Sørensen, K.I. and Auken, E., 2004, SkyTEM, a new high-resolution helicopter transient electromagnetic system., *Exploration Geophysics* Vol 35, No. 3.

Viezzoli, A. & Cull, J.P., 2005, Induced Polarization measurements applied to irrigation canals freshwater seepage detection, Submitted to *Near Surface 2005* – Palermo, Italy, Sept.

Volmer, B., Hatch, M., Wilson, T. and Hill, T. 2004, River-borne NanoTEM survey for location of salt accession to the River Murray at Loxton, Extended Abstract, *Proceedings of the Australian Society of Exploration Geophysicists Conference* (August).

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