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Accurate quasi 3D versus practical full 3D inversion of AEM data – the Bookpurnong case study

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Introduction

The debate regarding the need for full 3D inversion in semi-layered environments is intensifying, and the issue is the subject of ongoing research (e.g., Ley-Cooper et al., 2010). Along these lines, the May 2010 issue of *Preview* (Issue 146) featured a paper by Wilson et al. entitled 'Practical 3D inversion of entire airborne electromagnetic surveys'. The article describes a novel, innovative approach to 3D inversion of AEM surveys, which the authors argue makes the routine inversion of large datasets a realistic proposition. Their approach uses a moving footprint methodology, which they describe in detail. As an example of the applicability of their inversion method to field data, they present results from the inversion of helicopter time domain (SkyTEM) and frequency domain (RESOLVE) EM data from the Bookpurnong floodplain in South Australia. Specifically they directly compare the results from the 3D inversion of data from these two systems with results from a 1D inversion they produced with *AirBeo* (Raiche et al., 2007). They also make reference to results from the quasi 3D spatially constrained inversion of SkyTEM data described by Viezzoli et al. (2009), and claim that their implementation of a 3D inversion procedure produces results that '…more accurately reflect the known geology of the Bookpurnong area than the results obtained from a variety of 1D interpretations'.

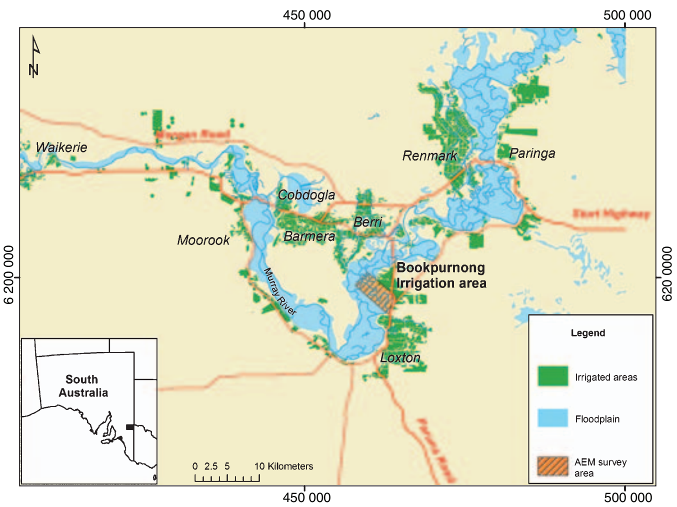

Fig. 1. *Bookpurnong Floodplain in the Lower Murray Region of South Australia.*

We accept that full 3D inversion has an important although, as yet, largely unproven role in the interpretation of AEM data in complex geological settings, and that the moving footprint approach represents a significant step forward towards making it practical. However, we contend that their observation does not adequately reflect the capabilities of accurate 1D inversion methods. We believe that methods based on 1D forward responses have a valuable and continuing role in extracting useful hydrogeological information from the types of AEM data acquired over Bookpurnong, and over other comparable settings, particularly if they use the expected spatial variability as prior information in the inversion. In the interests of encouraging debate and discussion, we take this opportunity to demonstrate the potential of some of these methods with the same data sets, in what is, arguably, as good a 1D environment as you could ask for – a conductive, flat-lying, layered geology which is laterally contiguous and extensive.

Prior to reviewing our results, it's appropriate to summarise the hydrogeology of the Bookpurnong area, not least to provide the reader with an appropriate context for the discussion that follows.

Bookpurnong floodplain hydrogeology

The Bookpurnong floodplain, located approximately 12 km upstream from the township of Loxton in the lower Murray region of South Australia (Figure 1), has been the focus of trials to manage a marked decline in tree health that has been observed along the River Murray in South Australia and elsewhere. The primary cause for this decline is recognised as a combination of floodplain salinisation from saline groundwater discharge, the decrease in flooding frequency, and the recent drought (Jolly et al., 2006; White et al., 2006; Berens et al., 2007). The study area has a hydrogeology characteristic of the eastern part of the lower Murray River and is represented schematically in Figure 2. Floodplain sediments consist of a clay (the Coonambidgal Clay) ranging from 3 to 7 m thick, overlying a sand (the Monoman Formation) which is approximately 7–10 m thick in this area. These sediments occupy the Murray Trench which cuts into a sequence of Pliocene sands (the Loxton-Parilla Sands) up to 35 m thick. These sands outcrop in the adjacent cliffs, and are covered by a layer of Woorinen Sands over Blanchetown Clay, each approximately 2 m thick (Figure 2). The whole area is underlain by the Bookpurnong Beds, which act as an aquitard basement to the shallow aquifer that encompasses the Monoman Formation and Loxton Sands.

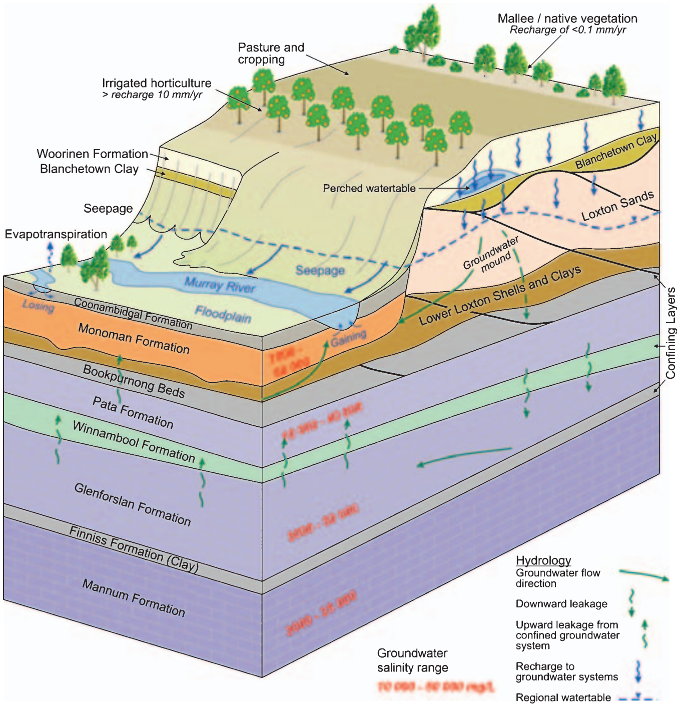

Fig. 2. *Schematic representation of the hydrogeology of the Bookpurnong Floodplain and adjacent highland areas.*

Regional groundwater salinity in the Loxton Sands and Monoman Formation ranges between 30 and 40 000 mg/L, with the high salinities commonly found on the floodplain resulting from evaporative concentration. Irrigation recharge salinity is typically 1000–3000 mg/L (Figure 2). Beneath the Bookpurnong Beds lie limestones and clays of the Murray Group. The regional groundwater salinities in these sediments lie between 15 000 and 30 000 mg/L, that is they are very saline. The above mentioned sedimentary package is sub-horizontal with a very gradual dip in a westerly direction.

High recharge from irrigation on the highlands adjacent to the floodplain results in the development of localised perching and the formation of a groundwater mound in the Loxton-Parilla sands. The mound increases the hydraulic gradient towards the floodplain causing a rise in water levels in the floodplain sediments. Groundwater seepage at the break of slope adjacent to the cliffs may also occur (Figure 2). High water levels coupled with high rates of evapotranspiration, concentrates salt in the near surface across the floodplain. Elevated groundwater levels in the floodplain also promote the discharge of saline groundwater into the Murray River, along what are termed ‘gaining’ stretches of the river system. Elsewhere along the river, river water discharges into the adjacent banks and we have extensive reaches that are referred to as ‘losing’ stretches.

AEM over the floodplain

Data from two helicopter EM systems have been acquired on several occasions across the Bookpurnong floodplain. In July 2005, and in August 2008 the Bookpurnong area was flown with the Fugro RESOLVE frequency domain helicopter EM system. In August/September 2006, the area was also flown with the SkyTEM time domain EM system. The repeat survey across Bookpurnong provided a rare opportunity to investigate the relative merits of these systems for surveying the Murray River corridor (Munday et al., 2007). In this paper we examine results from the 2006 SkyTEM and 2008 RESOLVE surveys. The next two sections describe the technical specifications of the two AEM systems employed at the time of the surveys. The SkyTEM system currently in operation has been updated significantly on many of these key parameters when it comes to resolution capabilities.

RESOLVE FDHEM system

RESOLVE is a six fixed-frequency EM system mounted in a 9 m long ‘bird’ towed beneath a helicopter at a nominal survey altitude of 30 m above the ground, although for the Bookpurnong survey, the nominal altitude was ~50 m because of the presence of tall trees along the river. The bird contains five rigidly mounted horizontal coplanar coils, and in the Bookpurnong survey measured an EM response at nominal frequencies of ~400 Hz, 1800 Hz, 8200 Hz, 39 500 Hz and 133 000 Hz. It also has one coaxial coil pair which measured a response at ~3200 Hz.

SkyTEM TDHEM system

The SkyTEM time domain EM system is carried as a sling load towed beneath the helicopter. Here we describe the SkyTEM system at the time of the survey. Survey altitude of the transmitter in the Bookpurnong survey was ~60 m. The transmitter, mounted on a lightweight wooden lattice frame, was a four-turn, 256 m^2 eight sided loop, transmitting a low moment in one turn and a high moment in all four turns. SkyTEM is capable of operating in a dual transmitter mode (Sørensen and Auken, 2004). In the Low Moment mode, a low current, high base frequency and fast switch off provides early time data for shallow imaging. In contrast when in High Moment mode, a higher current and a lower base frequency provide late time data for deeper imaging. The two modes can be run sequentially during a survey, as was the Bookpurnong survey. In Low moment mode the transmitter base frequency is 222.50 Hz and in High Moment mode base frequency is 25 Hz, which can be lowered to 12.5 Hz. Peak current in the low moment was about 40 A with a typical turn-off time of about 4 µs; while the high moment transmitted approximately 90 A and had a typical turn-off time of about 29 µs. The receiver loop is rigidly mounted at the rear and slightly above the transmitter loop in a near-null position relative to the primary field, thereby minimising distortions from the transmitter. In this survey, the first gate used was at 18 µs after beginning of turn off.

Data acquisition

Twenty-six lines (and 7 tie lines) of RESOLVE data orientated NW–SE were acquired over the floodplain with a line spacing of 100 m (Figure 3). A single calibration line orientated NE-SW over the adjacent highland area was also acquired. Twenty nine lines of SkyTEM data were surveyed on the floodplain in a similar orientation to the RESOLVE data, with 100 m spacing between lines. One line was collected perpendicular to the primary flight line orientation.

1D inversion results and interpretation

The two data sets were inverted using the Spatially Constrained Inversion (SCI) methodology (Viezzoli et al., 2008). The SCI is a

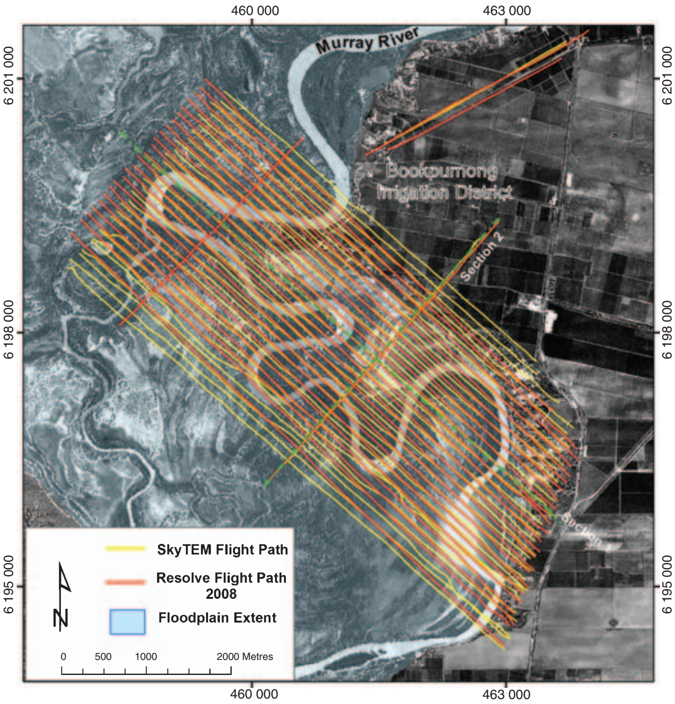

Fig. 3. *Flight line diagram for the RESOLVE and SkyTEM Systems over the Bookpurnong Floodplain. The location of Section Lines 1 and 2, which are discussed in the text, are also shown.*

quasi 3D inversion methodology, based on a 1D forward response, with 3D spatial constraints. The spatial constraints allow prior information (e.g., the expected geological variability of the area, or the downhole conductivity) to migrate across the entire dataset. The output models balance the information present locally within the individual TEM soundings with the ones carried by the constraints. The SCI has a demonstrated applicability in semi-layered environments (e.g. Viezzoli et al., 2009, 2010). We applied the SCI to both the SkyTEM and the RESOLVE 2008 datasets.

The SkyTEM data were fitted within noise levels which were ranging from 3% at early times (nominal) to roughly 20% at late times, based on the stacked data. Data were first inverted with a smooth model with 19 layers, then with blocky discretisation (3 layers for RESOLVE and 4 layers for SkyTEM). The SkyTEM data had both Low and High moment converging locally to the same models. This approach yields the maximum possible resolution of model parameters, as the Low moment contains most information in the near surface, and the High moment on the deeper part of the models. For the RESOLVE dataset, the 2 highest frequencies had a noise level of 15%, whereas for the others it was set to 5%. The data were fitted within noise level over majority of the conductive areas, with exceptions in the more resistive areas, which may be linked to some minor, presently undefined calibration problems.

Figure 4 shows the RESOLVE and SkyTEM SCI results, for conductivity-depth interval of 4–5 and 8–9 m below the ground surface, obtained from the smooth models (19 layers). These images are overlain on a map of the Bookpurnong area, and can be compared directly with the results for the 3D inversion presented by Wilson et al. (2010, figures 3 and 4, p. 31).

The quasi 3D SCI results for both the RESOLVE and SkyTEM data sets show a large degree of medium scale variability, whilst preserving very small scale spatial coherency. For a thorough analysis of absolute conductivity values we refer the reader to the few layer cross sections presented below. However, the near surface conductivity models for both data sets presented in Figure 4 are similar and consistent with the prior knowledge on the soil and groundwater salinities of the area, both in terms of absolute values and spatial variability. A shallow, highly saline aquifer in the floodplains (TDS in excess of 35 000 mg/L, yielding formation conductivities in the order of 1 S/m), is recharged with fresher water in the proximity of the irrigated highlands (see Figure 2). Along the Murray River alternating losing and gaining stretches occur, which are also clearly visible in the SCI results. In-river NanoTEM measurements gave comparable results (cfr Tan et al., 2007 and Viezzoli et al., 2009). The groundwater salinity obtained from shallow boreholes show similar patterns of recharging and discharging areas, and correlate with RESOLVE and SkyTEM results, as shown in Munday et al. (2006) and Viezzoli et al. (2009).

Let us now examine how the SCI recovers the vertical conductivity structure and informs the hydrogeology of the study area. We present the SCI results from both the RESOLVE and SkyTEM data sets (Figure 5 and 6), as vertical sections of conductivity for Section Line 1 (see Figure 3 for location), which corresponds to the profile presented by Wilson et al. (2010) in the Preview article (see Figures 7 and 8). Results from a blocky and smooth model discretisation are presented. In order to assess the absolute values of conductivities, we refer to the blocky model, which, as opposed to the smooth one, has all the degrees of freedom necessary to recover the model parameters correctly, without vertical smoothing or a dependence on the thickness of the starting model. The consistency between the absolute values of modeled conductivity for the 3 layer RESOLVE and the 4 layer SkyTEM data sets is evident, perhaps more so than in the average conductivity maps based on smooth models presented earlier (Figure 4). Flushed (resistive) zones beneath and adjacent to the Murray River are well defined in the near surface for both data sets. Their extent is determined by the proximity to the highland areas, with reaches of the river close to the floodplain-highland boundary more likely to experience the ingress, or discharge of saline groundwater directly into the river, i.e. where the river is gaining. Reaches further away from this boundary show more extensive flushed zones and imply the vertical flux of fresher river water into the adjacent or underlying sediments, referred to as ‘losing reaches’, although it may be more appropriate to describe them as hyporheic zones. Hyporheic zones are zones along a river or stream where there is mixing of shallow groundwater and river water beneath and next to the river bed, through a process of hyporheic, or through-flow.

To help determine whether the observed variations in measured conductivity reflect changing ground conditions (i.e. the data) rather than model driven changes arising from the inversion process, we also plot an estimate of the depth of investigation (DOI) for both the RESOLVE and SkyTEM systems on cross sections (Figures 5 and 6). The DOI determination is based on the cumulative sensitivity of the actual model output from the inversion (which includes the full system response and geometry) and is described in Christiansen and Auken (2010). It also accounts for the data noise and the number of data points that are integrated into the calculation.

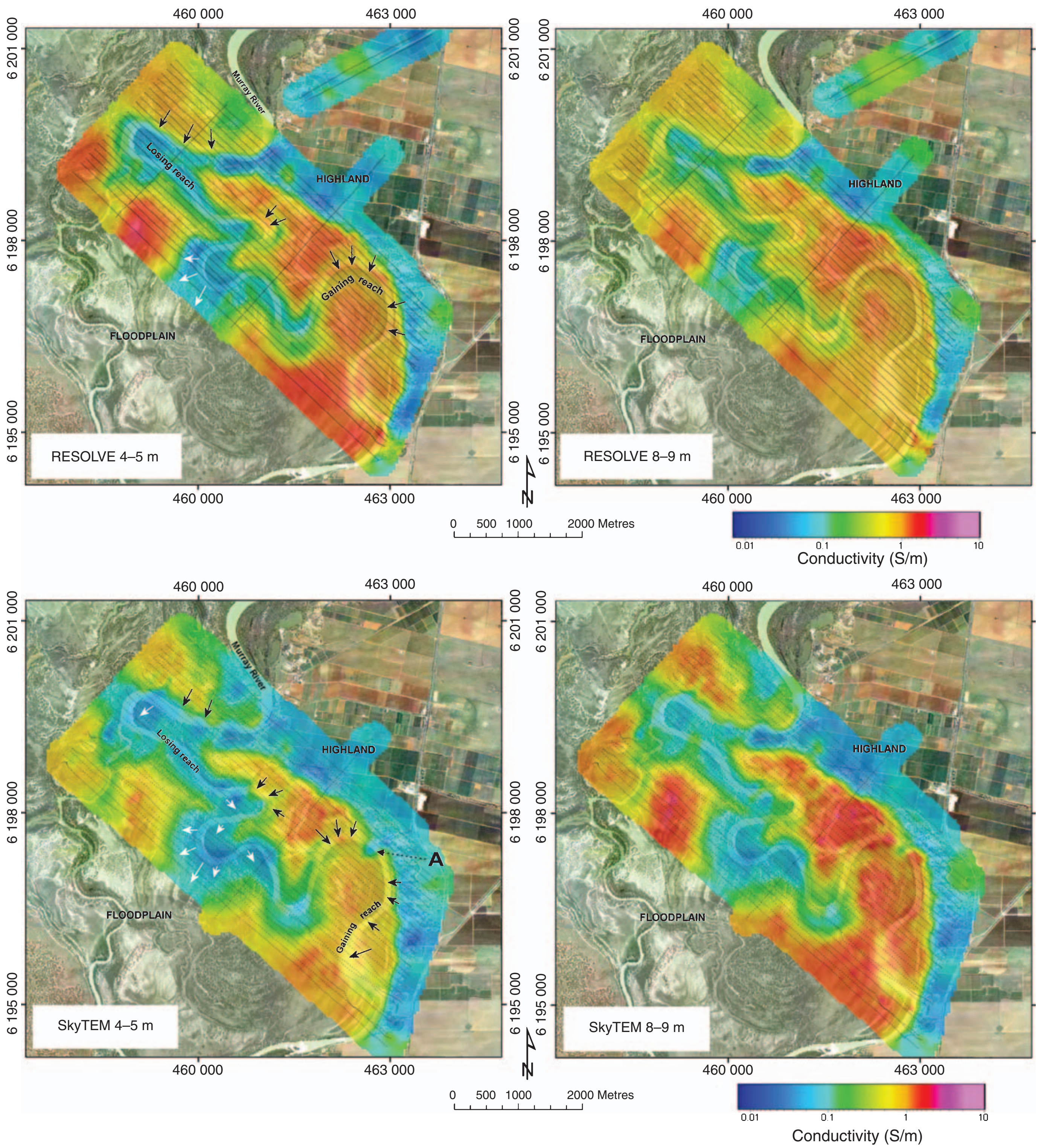

Fig. 4. *Interval conductivity images for the depth intervals 4–5 (left) and 8–9 m derived from 19 layer smooth model quasi 3D SCI inversions of the RESOLVE (top) and SkyTEM (bottom) data sets covering the Bookpurnong floodplain. Black arrows indicate stretches of the river which gain salinity from discharging groundwater, white arrows indicate stretches which lose fresh water from the river into the adjacent floodplain. A wide flushed (resistive) zone is apparent along significant stretches of the river through this area. The resistive zone at locality 'A' (indicated by the dashed arrow on the SkyTEM 4–5 m interval conductivity) may represent a drawdown of fresh river water into the substrate through over-pumping of Salt Interception bores on the adjacent floodplain.*

The DOI suggest an average investigation depth of ~15 m for the RESOLVE system across the highly conductive floodplains at Bookpurnong (Figure 5). Both the smooth and blocky models indicate well defined flushed (resistive) zones in the vicinity of the river, where fresher river water discharges into the adjacent river banks and into the sediments beneath the river. Results from the SkyTEM system (shown in Figure 6) indicate a significantly greater depth of investigation (generally in excess of 60 m) reflecting the High moment capability of that system. A comparison of the modelled conductivity structure for both

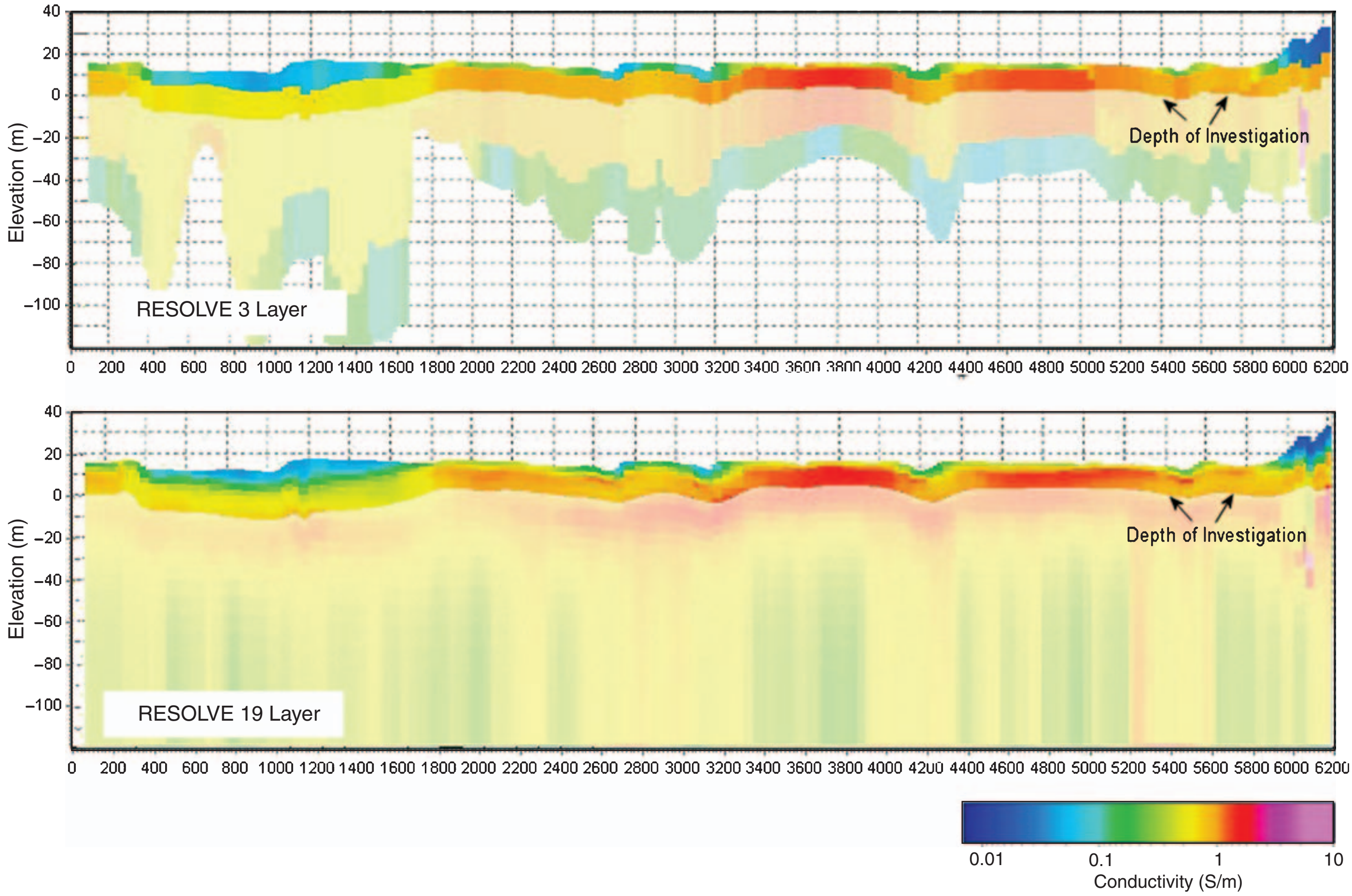

Fig. 5. *2D conductivity depth sections for Section Line 1 from the RESOLVE SCI. Results from a 3-Layer blocky model and a 19 layer smooth model are presented, with the depth of investigation (DOI) marked as a pale-shaded overlay on the 3 layer and 19 layer models are also shown. The cross section has been fitted to topography.*

systems shows that they define similar vertical structure, although RESOLVE, thanks to its higher frequencies, appears to recover finer detail in lateral conductivity variations over resistive areas compared to the SkyTEM system. That said, the extent and depths of flushed zones around the river are comparable for the two systems, and both define the presence of a highly conductive groundwater system at depth. SkyTEM, with its greater depth of investigation, indicates the presence of a fresher aquifer associated with the Limestones of the Mannum Formation at 60–70 m (Figure 6), information which cannot be reliably interpreted from the RESOLVE data set.

We would argue that, in a simple comparison of the SCI results reported here versus those presented by Wilson et al. (2010, figures 7 and 8, p. 32), accurate 1D inversions appear to do as well, if not better, than their 3D inversion procedure in defining finer detail associated with the hydrogeology of the Bookpurnong area. We also contend that the inclusion of an estimate of the system DOI provides further confidence in interpreting the results from the inversions presented here.

The absolute values of conductivity recovered by Wilson et al. (2010) for the SkyTEM dataset (both with 1D code Airbeo and with the 3D moving footprint inversion) are one order of magnitude lower than in the SCI results presented here, and also from what has been determined from bore data in the area. Part of the discrepancy possibly results from their use of the High moment data alone in the inversion. In this and other studies of the Bookpurnong SkyTEM data set, we have included both Low and High moments in the SCI, allowing them to enter the inversion and converge to the same model. The Low moment data is crucial for resolving the shallow parts of the model. However, Wilson's results also differ from the known ground conductivity structure for the area, and from our results. For example the reader is referred to the left hand side of their conductivity cross section reproduced in Figure 8 (p. 32 in Wilson et al., 2010) where resistive areas appear to extend to depth from the surface. Figure 7 shows the effect in the data space (late time apparent resistivity) of changing the conductivity of a half space from 1 to 10 Ohm m. The forward response was calculated modeling the full system transfer function for the SkyTEM system used in Bookpurnong Survey. As expected, the effect on the data of such change in the resistivity (or conductivity) is very large, extending over the entire transient. This means that the results obtained by Wilson et al. (2010), assuming they are fitting the measured High moment data within noise level, are not simply explained by the lack of Low moment data. Another reason for this discrepancy might be linked to the inaccurate modeling of other parameters of the system transfer function, which, as shown by Christiansen et al. (2011), could account for an underestimation of the ground conductivities. We believe that the one parameter that can be ruled out as the cause of the discrepancies in the modeled conductivity structure is the dimensionality of the forward response.

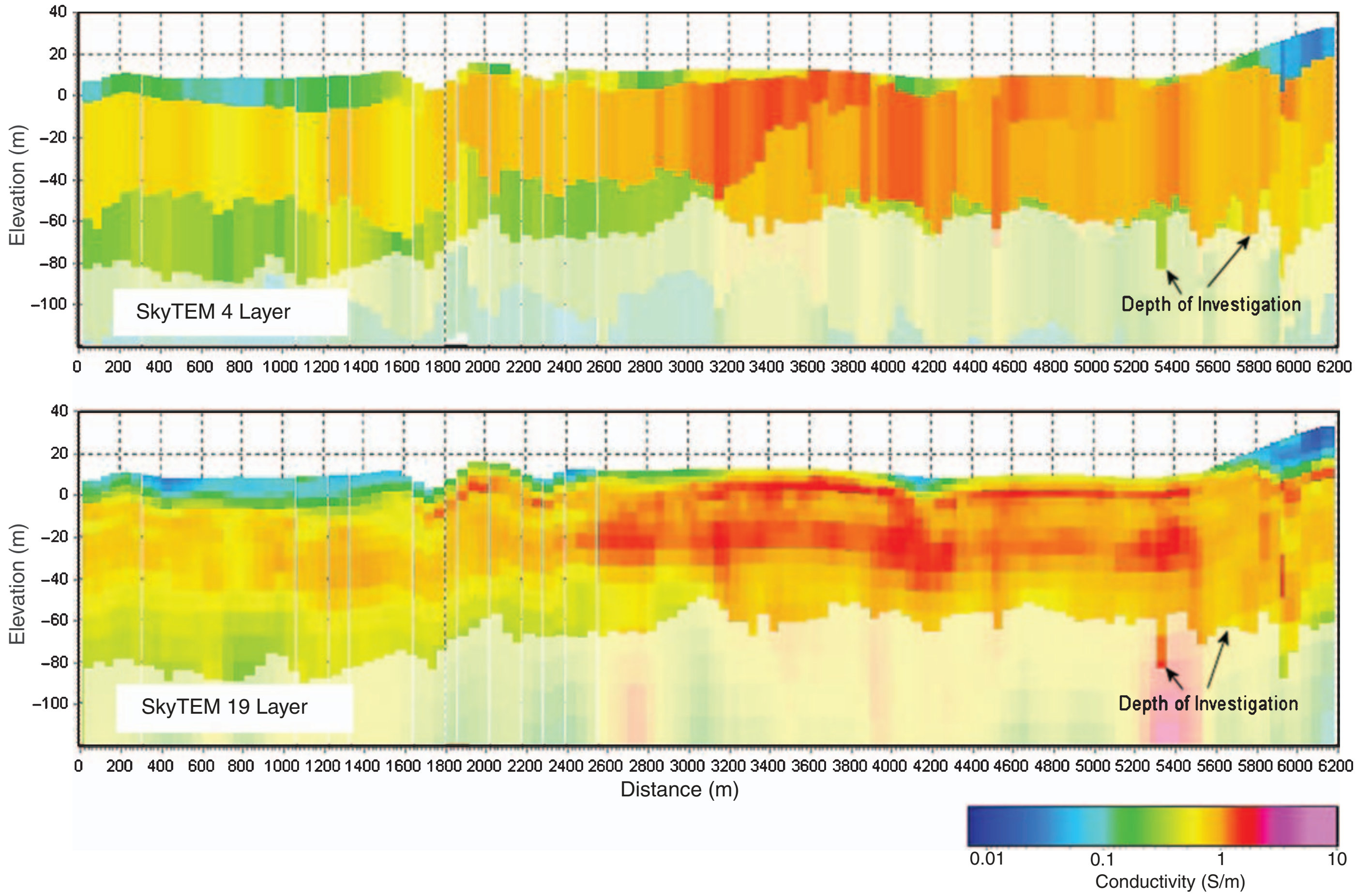

Fig. 6. *2D conductivity depth sections for Section Line 1 from the SkyTEM SCI. Results from a 4 layer blocky model and a 19 layer smooth model are presented, with the depth of investigation (DOI) marked as a pale-shaded overlay on the 4 layer and 19 layer models are also shown. The cross section has been fitted to topography.*

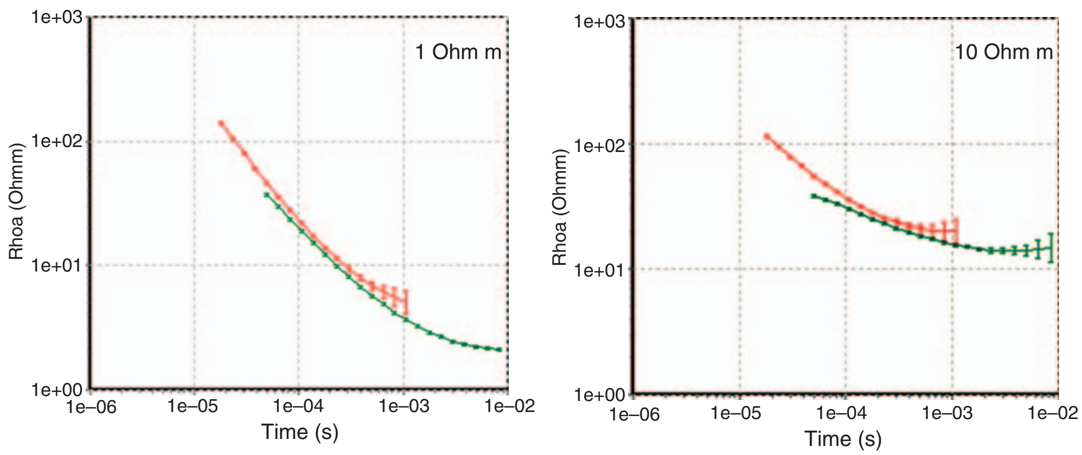

Fig. 7. *The effect on forward responses for the SkyTEM system on changing the conductivity of an half space from 1 S/m to 0.1 S/m.*

As a further test of the value of accurate 1D inversions in understanding the conductivity structure associated with the Murray River trench, we have also examined the applicability of the SCI technique in modelling conductivity structure across the floodplain – highland boundary, a setting where 2 and 3D effects might be more apparent. The interest in this boundary arises from a need to understand the links between irrigation practice occurring on the highlands along the Murray (see Figure 1) and floodplain salinity. AEM systems have the potential to provide a spatial picture of inter-aquifer mixing and surface water-groundwater interaction as it occurs across these physiographic settings (see Figure 8), which could assist conceptual hydrogeological model development and refinement (Munday et al., 2009).

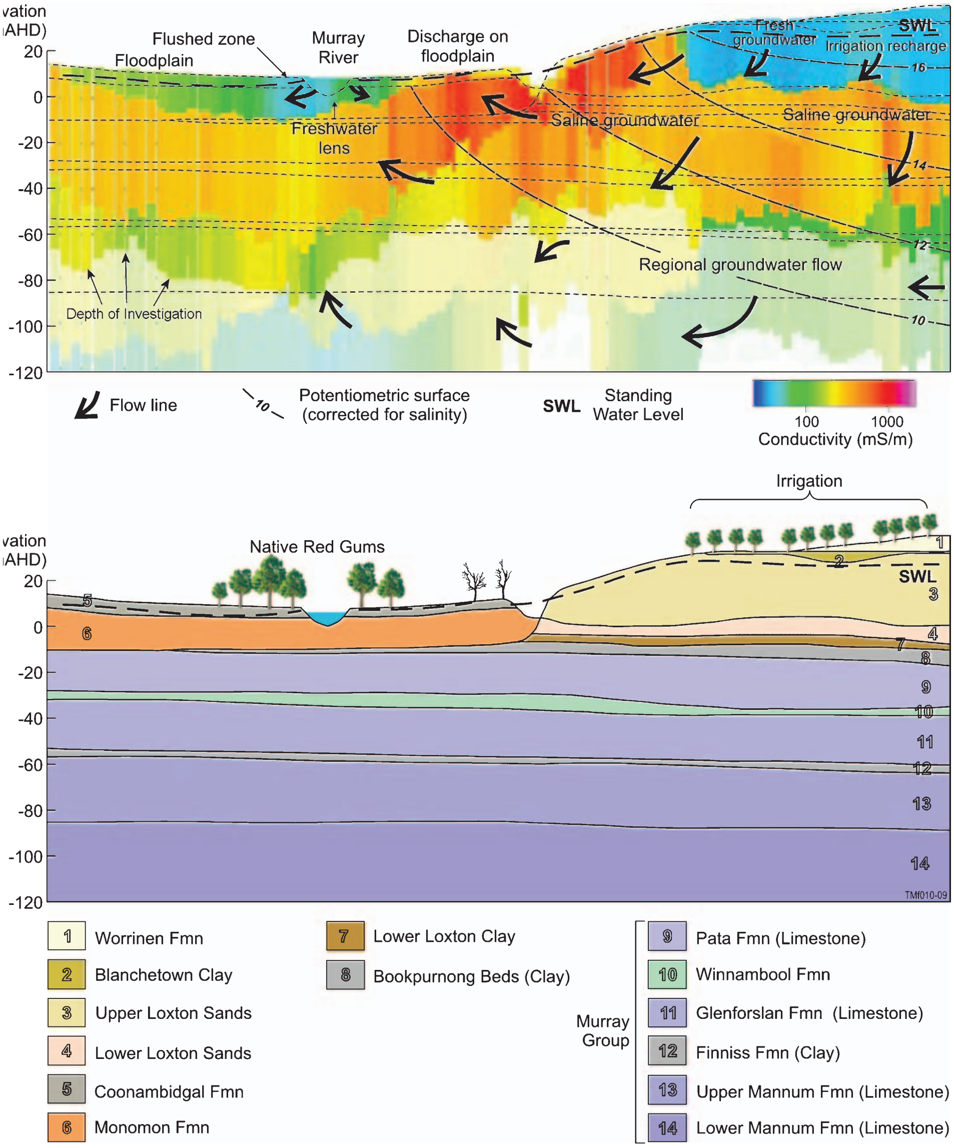

Fig. 8. *Vertical conductivity depth section derived from a 4 layer SCI of SkyTEM data for the floodplain – highland transect shown as Section 2 in Figure 3. The hydrogeology is illustrated in the lower section. Groundwater flow lines have been superimposed over the section and have been derived from an understanding of the potentiometric heads in the different aquifers. Groundwater quality is highly variable, with a fresh groundwater mound developed under the highlands adjacent to the floodplain as a consequence of excess irrigation drainage. The mound sits over a saline groundwater system and the elevated hydraulic gradient to the floodplain encourages an upward flux of saline groundwater across the Bookpurnong Clay aquitard. Groundwater conductivity values from bores in the vicinity of the section line 2 are projected onto the section for reference. The section length represents a distance of ~3.5 km.*

The fluid potential of a groundwater flow system can be determined from empirical observations of hydraulic head distributions. As vertical fluxes are particularly important, we present the distribution of heads (corrected for salinity) as defined by Harrington et al. (2005), in a cross sectional view (Figure 8). Equipotential lines are superimposed on the conductivity depth section derived from the SCI of the floodplain transect line (Section 2) shown in Figure 3. The vertical change in hydraulic heads indicates a potential for downward leakage of comparatively fresh irrigation water (TDS ~<6500 mg/L) from the Upper Loxton Sands aquifer (on the right of the section) into the Lower Loxton sediments. The groundwater mound developed beneath the highland area generates a significant head and flux of the saline groundwater system (that characterises the Pata Limestone at depth) towards the floodplain. On the floodplain-highland boundary groundwater flow is towards the floodplain, and there is an upward head and surface discharge of saline groundwater is observed at that boundary. The observed conductivity structure (Figure 7) indicates that the saline groundwater leaks through Lower Loxton Clays and Bookpurnong Beds and into the floodplain sediments of the Monoman Formation. At depth, in the Murray Group Limestones, lateral flow of the regional saline groundwater system (TDS between 15 000 and 30 000 mg/L) dominates. However, the conductivity structure suggests that under the floodplain, groundwater in the Mannum Formation freshens significantly. Whether this reflects an upward flux of relatively fresh groundwater from the deeper Renmark Group aquifer into the overlying Murray Group sediments remains to be determined.

In the floodplain aquifers, lateral flow of relatively fresh river water occurs in the sediments adjacent to the river. These flushed zones extend a considerable distance: up to a kilometre away from the river (Figures 4 and 8). The moderate conductivities of the Monoman and Coonambidgal Formations, where present, may reflect the presence of relatively freshwater from previous high flow events. The upward leakage the saline groundwater system is apparent in several places, particularly in the lower part of the Quaternary floodplain sequence, with discharge directly into the river noted in some reaches, particularly where the Murray approached the floodplain-highland boundary in the Bookpurnong area as mentioned previously (see Figure 4).

Recent studies by Harrington et al. (2005) in the region around Bookpurnong provide hydrochemical evidence for upward and downward leakage between aquifers, and given the highly saline nature of the lower groundwater system we believe AEM data, inverted with accurate 1D procedures have considerable potential to elucidate the nature of inter-aquifer leakage and the patterns of surface water and groundwater interaction. In the Bookpurnong and Loxton irrigation areas the high moment capability of SkyTEM permits us to investigate variations in the quality of groundwater at depth (>60 m), which in turn allows us to visualise how groundwater may be moving across aquitards and within particular aquifer systems. These data, when combined with bore data, including hydrochemical and environmental isotope data will permit the development of more robust conceptual models for the groundwater system and inter-aquifer leakage. They also provide for better understanding spatial patterns and processes that relate to surface water-groundwater interaction. However, accurate definition of inter-aquifer leakage arguably requires good constraint on aquifer/aquitard geometry and aquifer properties. Where possible information should be incorporated as constraints in the interpretation of the AEM data, if only to remove ambiguity in interpretation.

Conclusions

In the case study presented here, a 'quasi' 3D inversion methodology, the SCI, produces accurate results consistent with prior knowledge over the floodplain and across the floodplain–highland boundary at Bookpurnong. The results are also consistent across datasets acquired at different times, and with different systems.

Whilst recognizing the potential of the practical moving footprint full 3D inversion method described by Wilson et al. (2010) for large AEM datasets, we believe we have demonstrated the value of accurate and innovative quasi 3D inversion methods in landscapes such as those represented by the Bookpurnong case study. In this geological setting, we note that the assumption that each observation can be modeled with 1D forward responses and spatial constraints describing its relation to its neighbours, and that the subsurface is represented as a series of horizontal layers, holds well, particularly at the scale of the footprint of two AEM systems considered. It is worth noting that previous studies by Toft (2001), Auken et al. (2008) and Viezzoli et al. (2008, 2009) have also demonstrated that constrained inversion with 1D forward response can effectively recover the variability associated with a 3D geological structures in sedimentary environments.

Finally we contend that it is critical to ensure the forward responses are locally accurate, particularly for recovering accurate models from AEM data. We believe that, for hydrogeological applications in these and other sedimentary environments, the dimensionality of the forward responses is secondary to the accuracy of the modeling of the system transfer function used in the inversion.

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A brief reply

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We thank the authors for their comments regarding our paper, Wilson et al. (2010).

First of all, we would like to draw the reader's attention to a full paper on 3D AEM inversion with a moving footprint appearing in *Exploration Geophysics* (Cox et al., 2010). This paper independently addresses many of the questions posed by Viezolli et al. (2010) and further elaborates on the Bookpurnong case study. Cox et al. (2010) also provides a more detailed comparison between 3D and 1D inversions for AEM data.

Secondly, the main purpose of the Wilson et al. (2010) paper was to make *Preview* readers aware that 3D inversion of entire AEM surveys is both practical and now available.

Finally, real geological formations are 3D in nature and 3D inversion is required to produce accurate images of the subsurface. We chose to present the Bookpurnong case study in both our publications because it provided the best opportunity for a fair comparison of our 3D inversion results with a variety of 1D methods in the situations where the nearest representation of 1D geology was possible.

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