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COMBINING GEOLOGY AND GEOPHYSICS TO DEVELOP A HYDROGEOLOGIC FRAMEWORK FOR SALT INTERCEPTION IN THE LOXTON SANDS AQUIFER, CENTRAL MURRAY BASIN, AUSTRALIA

T.J. Munday, A.J. Hill, T. Wilson, B. Hopkins, A.L. Telfer, G.J. White and A.A. Green

CRC LEME OPEN FILE REPORT 180 /
CSIRO Exploration and Mining Report P2004/86

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Headquarters: CRC LEME c/o CSIRO Exploration and Mining, PO Box 1130, Bentley WA 6102, Australia

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Address and Affiliation of Authors

T.J. Munday
CRCLEME/CSIRO Exploration and Mining,
ARRC, 26 Dick Perry Av. Kensington,
WA 6151
Tim.Munday@csiro.au

B. Hopkins, A.L. Telfer and G.J. White
Australian Water Environments P/L,
1/68 The Parade,
Norwood, SA 5067

A.J. Hill and T. Wilson
Department for Land, Water and Biodiversity Conservation,
GPO Box 2834, Adelaide, SA 5001

Andy Green
OTBC Pty. Ltd.,
8 Lawley Cres., Pymble,
NSW 207

EXECUTIVE SUMMARY

Salt interception schemes (SIS) have been developed to manage high salt loads and to improve the health of the River Murray, both in the Riverland (South Australia) and Sunraysia (Victoria/NSW) areas. Currently SIS at Loxton and Bookpurnong are being developed, both incorporating borefields in the Loxton Sands aquifer to intercept saline groundwater flux from groundwater mounds that have formed beneath irrigated areas. At Bookpurnong a sedimentological model that defines lateral and vertical changes in facies associated with the main aquifer systems relevant to the SIS, has been refined from a detailed interpretation of borehole geology, ground and airborne geophysics, combined with the analysis of sediments for the Loxton Sands and underlying Bookpurnong This is an important precursor in the development of a predictive model of groundwater hydraulic properties using available hydrogeological and geophysical data. Definition of the sedimentological characteristics and depositional setting of the principal aquifer system – the Loxton Sands, has been critical. Relatively narrow zones of high transmissivity, characterized by slightly reduced electrical conductivity response at the watertable, are the target for ground TEM geophysical traverses. These zones have been identified as elements of a Basin-wide beach-barrier strandline sequence that developed in the Pliocene. Results from the constrained inversion of helicopter EM data have helped to better define the geometry of this sedimentary system and together with a hydrogeological interpretation have contributed to a more informed approach to the design, development and potential performance of the Loxton Sands SIS borefields.

Keywords: Salt Interception Scheme, geophysics, Loxton Parilla Sands, aquifers, groundwater

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1. INTRODUCTION

The construction of salt interception schemes (SIS) in the Riverland region of South Australia (between Morgan and Renmark) forms an integral part of a broader engineering-based strategy to manage saline groundwater discharge into the River Murray. Several schemes are already in place, with others at the planning and implementation stage. Along the Bookpurnong reach of the River Murray, in-stream salinity measurements indicate that around 70 tonnes of salt is currently added to the river each day from groundwater discharge, with modelling suggesting that this will increase significantly as a consequence of irrigation development in the Bookpurnong area adjacent to the river (AWE 2002, Hill et al. 2004) (Figure 1). To manage this problem, the Bookpurnong SIS is being implemented, with a series of bores and pipelines to the Noora Disposal Basin.

The design of this SIS scheme predicated on a sound understanding of the hydrogeology of this region, and provides for direct River Murray salinity benefits as well as significant floodplain and wetland health benefits. Initial production bores in the Loxton Sands aquifer close to Lock 4 at Bookpurnong (Figure 2) indicated a variable yield in the target aquifer (0.5 - >3.0 l/s). Transmissivities varied from $110m^2/d$ to very low (AWE 2003a). An observed correspondence between the higher yields measured in bores BHP2 and BHP3 with the position of beach barrier strandline determined from an analysis of helicopter EM data covering the area (see Green et al. 2003) suggested that facies variations in the Loxton Sands aquifer, which are not well understood, could have a significant bearing on the different yields noted in the production bores. We therefore set out to develop an improved geological framework and a more informed hydrogeological model for the Loxton-Bookpurnong Project area.

2. OBJECTIVES

The principal objective of this project was to develop an improved hydrogeological framework to assist salt interception bore field design in the Loxton-Bookpurnong reach of the Murray River, through a combined interpretation of geological and geophysical data available for the area. Particular attention was given to understanding the geological information content of the helicopter EM data covering the Bookpurnong area it's relevance from a hydrogeological perspective.

Specific project objectives were to:

1. Refine existing (GIS) coverage of the Loxton Sands strand-plain depositional system using the inverted HEM data, with particular attention given to the Loxton-Bookpurnong area.
2. Determine factors that influence the observed conductivity variation in the HEM data, with particular attention to facies models, depositional environments and associated materials of the Loxton-Parilla Sands and Bookpurnong Beds.
3. Determine the relationship between facies variation, transmissivity and the electrical conductivity observed in the inverted HEM data, with specific attention given to their predictive capacity.
4. Define the scale of geological variability resolved by the HEM data (horizontal and vertical) and its relevance to the definition of a robust hydrogeological model for the SIS.
5. Refine the inversion of HEM data using a constrained inversion approach, with detailed geological and petrophysical information from the Loxton-Bookpurnong region.
6. Examine the role and value of the ground-based geophysical techniques (Ground EM) when used with the airborne EM data to develop an improved model for facies variability and associated hydraulic properties in the Loxton Sands.

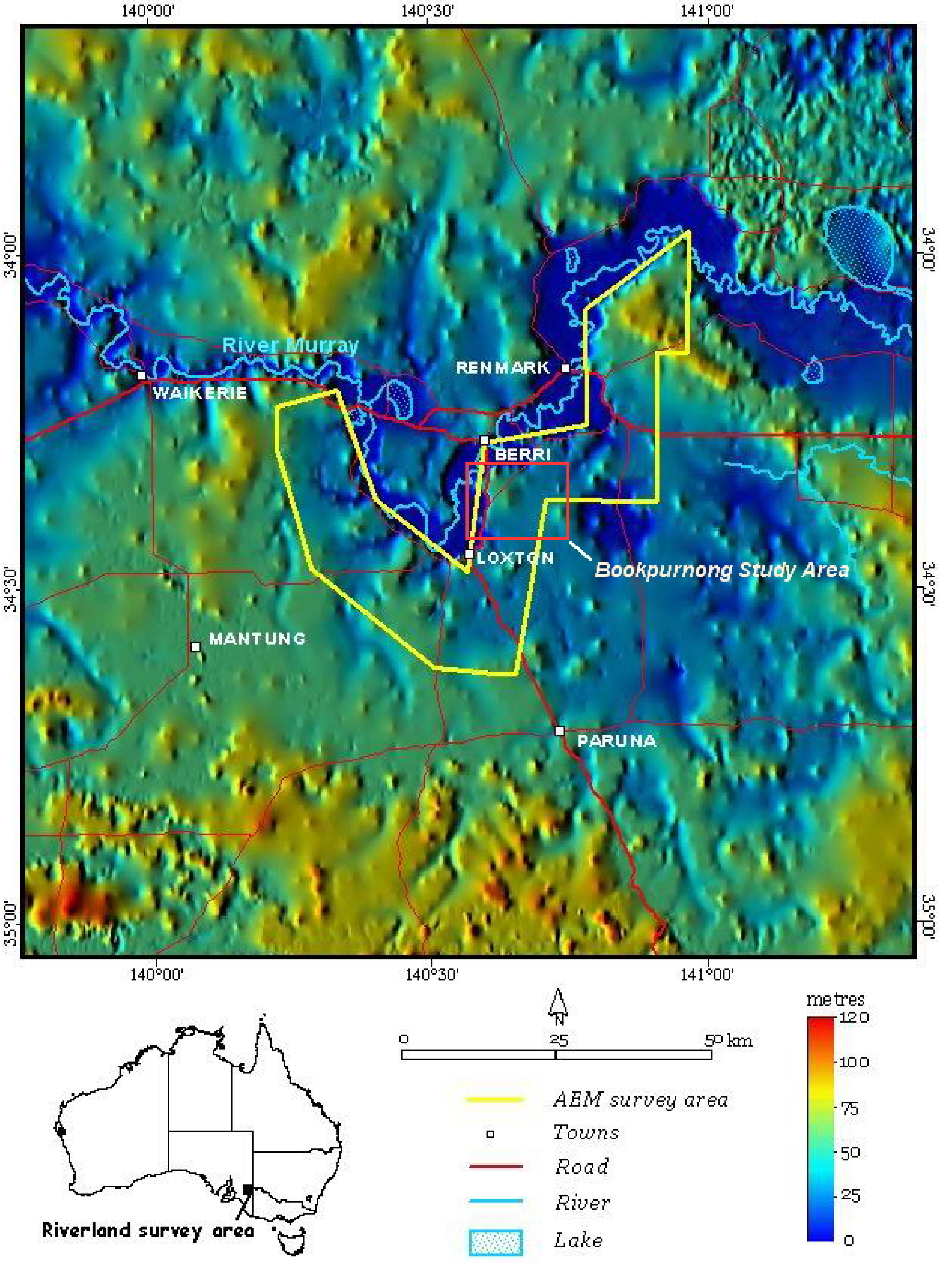

Figure 1. DEM of the Riverland region of South Australia, with study area centred on the Bookpurnong area indicated by the red polygon. The boundary of the helicopter EM survey is also indicated.

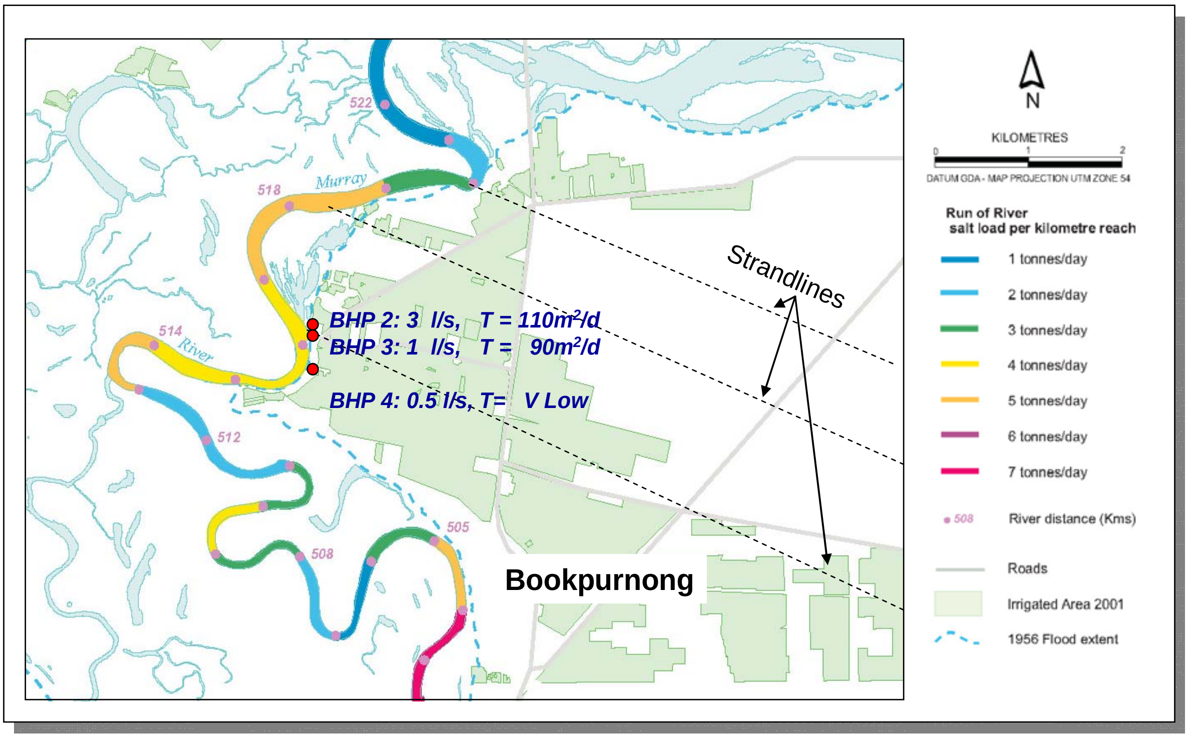

Figure 2. The Bookpurnong SIS Project area (source AWE 2002). The position of pilot production bores (BHP2, 3 &4) for the Bookpurnong SIS are also plotted. They show a varying yield. The higher yielding bores appear to have a spatial link with the position of beach strandline associated with the Loxton-Parilla Sands aquifer. The strandlines were mapped from low frequency apparent conductivity images generated from a helicopter EM survey over the area

3. METHODS

Our approach involved linking observations made from borehole, ground and airborne geophysics with an understanding of sedimentary systems and a detailed interpretation of borehole geology to improve our capacity to predict lateral and vertical changes in facies, and then to link facies changes to changes in the transmissivity of the Loxton Sands aquifer.

Besides looking at the RESOLVE frequency domain HEM data, which were inverted using a four-layer 1-D parameterisation of the earth using local constraint, neutron, natural gamma and inductive conductivity borehole logs were acquired for a number of holes across the Bookpurnong Project area. For a limited number of bores, the observed response was related to stratigraphy. Seven ground TEM traverses were also acquired using the NanoTEM system to better resolve subtleties in the deeper conductivity structure observed at the watertable. The NanoTEM data were acquired on the expectation that variations in ground conductivity could be related, at least in part, to facies changes in the aquifer.

4. GEOLOGY AND HYDROGEOLOGY OF THE RIVERLAND REGION

4.1 Geological setting

The Riverland region is located in the lower part of the Murray Basin, a roughly circular basin consisting of up to 600m of flat-lying Cainozoic sediments, which overlie various Palaeozoic and Mesozoic rocks (Brown and Stephenson, 1991). The basin is flanked by a series of subdued mountain ranges and hills. The Cainozoic history of the basin has been characterised by slow relative subsidence, minimal compaction, and low rates of sedimentation, with the sedimentary succession forming an extensive, but relatively thin sequence over a tectonically active platform which was subject to partial inundation by epicontinental seas (Brown 1985). These marine transgressions, correlated with global sea level changes at various times during the Tertiary, and related environments of deposition, resulted in a range of sedimentary units including limestones, shelf muds, marine and beach sands, estuarine clays, alluvial sands and aeolian dunes. The final depositional cycle in the Basin was initiated by a rapid marine transgression at the end of the Miocene. High stand deposition followed throughout the Pliocene leading to the progradation of the Loxton-Parilla sands – a composite assembly of (regressive) shoreface, beach, estuarine, dune, back-barrier lagoonal facies sediments that extend across a substantial part of the basin ((Stephenson, 1986, Roy et al, 2000) (Figure 3).

Three distinct depositional sequences are recognised within the Tertiary succession: Palaeocene to Early Oligocene Renmark Group, Late-Early Oligocene to Middle Miocene Murray Group and the Late Miocene to Pleistocene succession which includes the Loxton-Parilla sands. In this report we concentrate on aquifers associated with the latter two events, giving particular attention to the Loxton-Parilla Sands of Late Miocene to Late Pliocene age. This aquifer represents the prime target for production bores associated with both the Loxton and Bookpurnong SIS schemes.

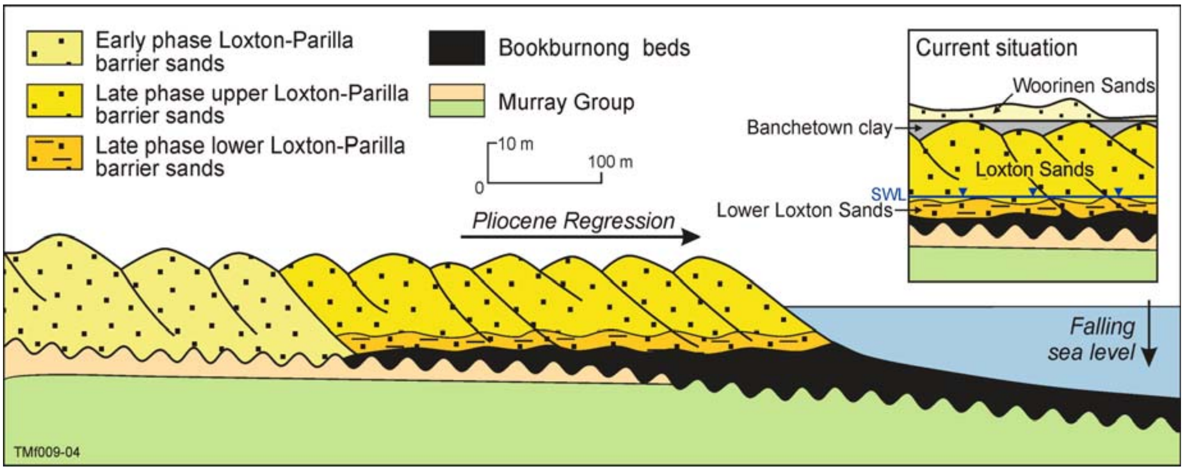

Figure 3. Simplified northeast-southwest stratigraphic cross-section through the southern part of the Murray Basin showing early-phase Loxton-Parilla barriers resulting from a reworking of the underlying Renmark Group of sediments, and later phase, younger Loxton-Parilla sands and Bookpurnong beds representative of those found in the study area. The inset figure presents a schematic of the contemporary sedimentary system found at Bookpurnong.

Early Oligocene to Mid-Miocene sedimentation

During the Late Oligocene to Mid-Miocene, the Murray basin experienced a major marine incursion, resulting in a change from predominantly fluvial environments of the Renmark Group to alternating lagoonal and marginal-marine muddy facies (shallow shelf environments) followed by deeper marine and shelf facies resulting in deposition of marl (Ettrick, Finniss and Winambool formations) aquitards and limestone (Upper and Lower Mannum, Glenforslan and Pata formations) aquifers of the Murray Group. In the late Miocene, sedimentation across the Murray Basin was interrupted by a global fall in sea level. The onset of drier climatic conditions with increased seasonality resulted in the local weathering and erosion and reworking of exposed sediments (Fabris, 2002).

Late Miocene to Pleistocene sedimentation

A rapid marine transgression at the end of the Miocene saw the development of shallow marine depositional environments with water depths up to 30 m (Hill *et al.* 2003) in the Bookpurnong-

Loxton region. High stand deposition followed throughout the Pliocene leading to the progradation of the Loxton-Parilla sands – a composite assembly of (regressive) lower and upper shoreface, beach, estuarine, dune and back-barrier lagoonal facies sediments that extend across a substantial part of the basin (Stephenson, 1986; Roy *et al.*, 2000). Parts of the Loxton-Parilla Sands are underlain by marine shelf muds, the Bookpurnong beds, that may be contemporaneous with the development of the regressive sand barrier sequences. If this were the case, this unit would represent a low energy, offshore component of the prograding barrier system. The Loxton-Parilla sands represent a relatively thin (10-20m), but very extensive sequence deposited over a 400km wide strand plain (Figure 4). Occasional transgressive phases resulted in the formation of stacked barrier islands (Roy et al., 2000, Fabris 2000).

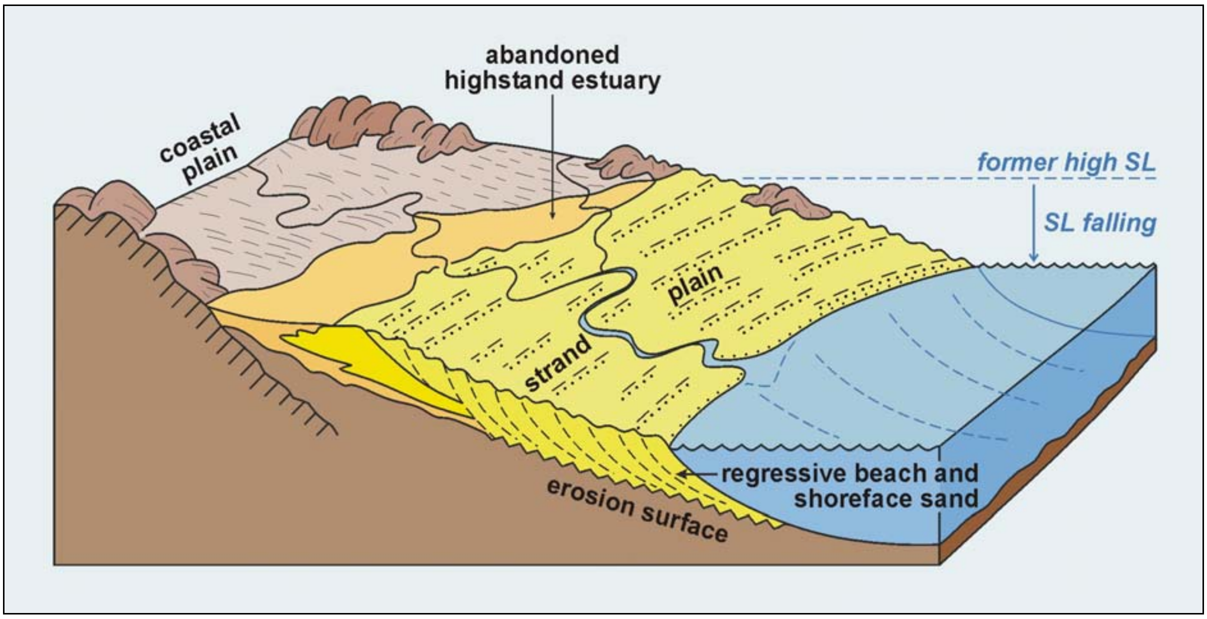

Figure 4. Schematic bock model describing illustrating a regressive barrier sequence prograding under falling sea levels to produce a tabular, gently seaward-inclined sand deposit some 10-20m thick (Adapted from Roy *et al.*, 1994). This describes the depositional model for the Loxton-Parilla Sands found in the Riverland region of the Murray Basin.

In the mid-Pliocene, barrier progradation stalled with the uplift of the Pinnaroo Block and Padthaway ridge (Roy *et al*., 2000; Sandiford, 2003) to the south of the study area. Drainage was impounded leading to the development of a large lake known as Lake Bungunnia (Stephenson, 1986) some 33,000km2 in area. Deposition of fine-grained lacustrine and fluvio-lacustrine sediments followed, referred to collectively as the Blanchetown Clay. Stephenson (1986) described this unit as "a greenish-grey, red-brown or variegated sandy clay with many local variations in lithology" and it has been reported as blanketing the swales between Loxton-Parilla sand barriers (Colwell, 1977). The Blanchetown Clay unit is commonly only a few metres thick but can reach 20m in isolated instances. In the study area the Blanchetown Clay has been mapped in drill holes and is known to occur on current topographic highs, suggesting some post depositional reworking and/or the possibility of mild tectonism in the area.

Quaternary

Increased aridity during the Quaternary precipitated the demise of Lake Bungunnia. This was accompanied by aeolian reworking of the clays and associated surficial sediments into mobile, east-west oriented sand sheets that form the Woorinen Formation and the Molineaux-Lowan Sands. These younger sediments are commonly up to 5m thick, though they may exceed 20m in some dunes. Fluvial activity in the region was limited to the main rivers (the ancestral Murray) and their margins. Both aeolian and fluvial processes have affected present-day topography. Besides influencing the development of an East-West dune system, aeolian processes have deflated the Blanchetown Clay in places, resulting in localised topographic lows with only the Loxton-Parilla sands remaining. In the central part of the basin, including the Riverland region, the maximum elevation of the Blanchetown Clay is at 60mAHD (Kotsonis, 1999; Stephenson, 1986). As a consequence, it is thought that, aside from landforms associated with recent aeolian activity, the current topography reflects that of the late Pliocene quite accurately.

4.2 Sedimentology of Loxton Parilla Sands (Loxton-Bookpurnong area)

Stratigraphically, the terms Loxton and Parilla have been used in the description of separate Pliocene sand units in various parts of the Murray Basin. As the distinction between the two is not always readily apparent, a combined term – the Loxton-Parilla Sands, was used by Brown and Stephenson (1991) to describe the sequence. In simple terms, the sequence observed in the Loxton-Bookpurnong area has the characteristics described in Figure 5.

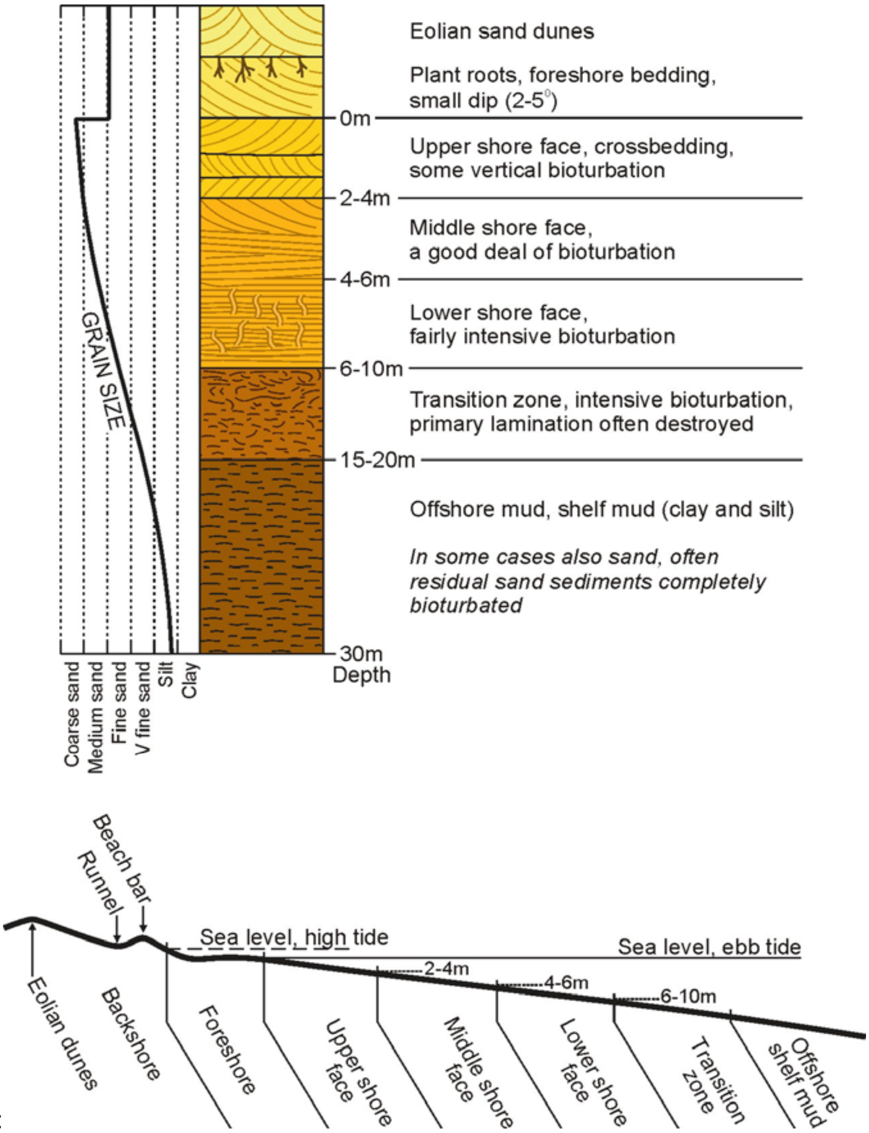

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Figure 5. Schematic representation of the stratigraphic and sedimentological relationships (top) associated with a regressive beach barrier system (bottom). These relationships are observed in the Loxton-Parilla Sands sequence.

Overall we are dealing with a generally coarsening upwards depositional system (Figure 5), overlain by the Blanchetown Clay unit, and Woorinen Sands.

5. GEOPHYSICAL DATA PROCESSING AND INTERPRETATION

5.1 Survey area and HEM system description

RESOLVE helicopter electromagnetic data were acquired over 13,145 line kilometres in the Riverland region at line spacings of 150 or 300 m. RESOLVE is six frequency, frequency domain, EM system mounted in a "bird" towed beneath a helicopter. The bird contains horizontal coplanar coils, and in the Riverland survey measured an EM response at 385Hz, 1518Hz, 6135Hz, 25380Hz and 106140 Hz. It also has one coaxial coil pair which measured a response at 3323Hz. The primary objective of the original survey was to map the depth, thickness and conductivity of the Blanchetown Clay, an important constraint on the drainage of surface water to the underlying saline groundwater (Cook et al., 2003).

One output from the processing of those data for mapping the Blanchetown Clay, was a map detailing the elevation of the top of the Loxton-Parilla Sands – the target aquifer for the Loxton & Bookpurnong SIS (Green et al. 2003). This elevation model shows the distribution of beach strandlines traversing the region in a NW-SE orientation (Figure 6). It was their orientation and coincidence with observed variations in production bore yield that suggested targeted processing of the HEM data may yield more information about the sedimentary system and facies variability in particular.

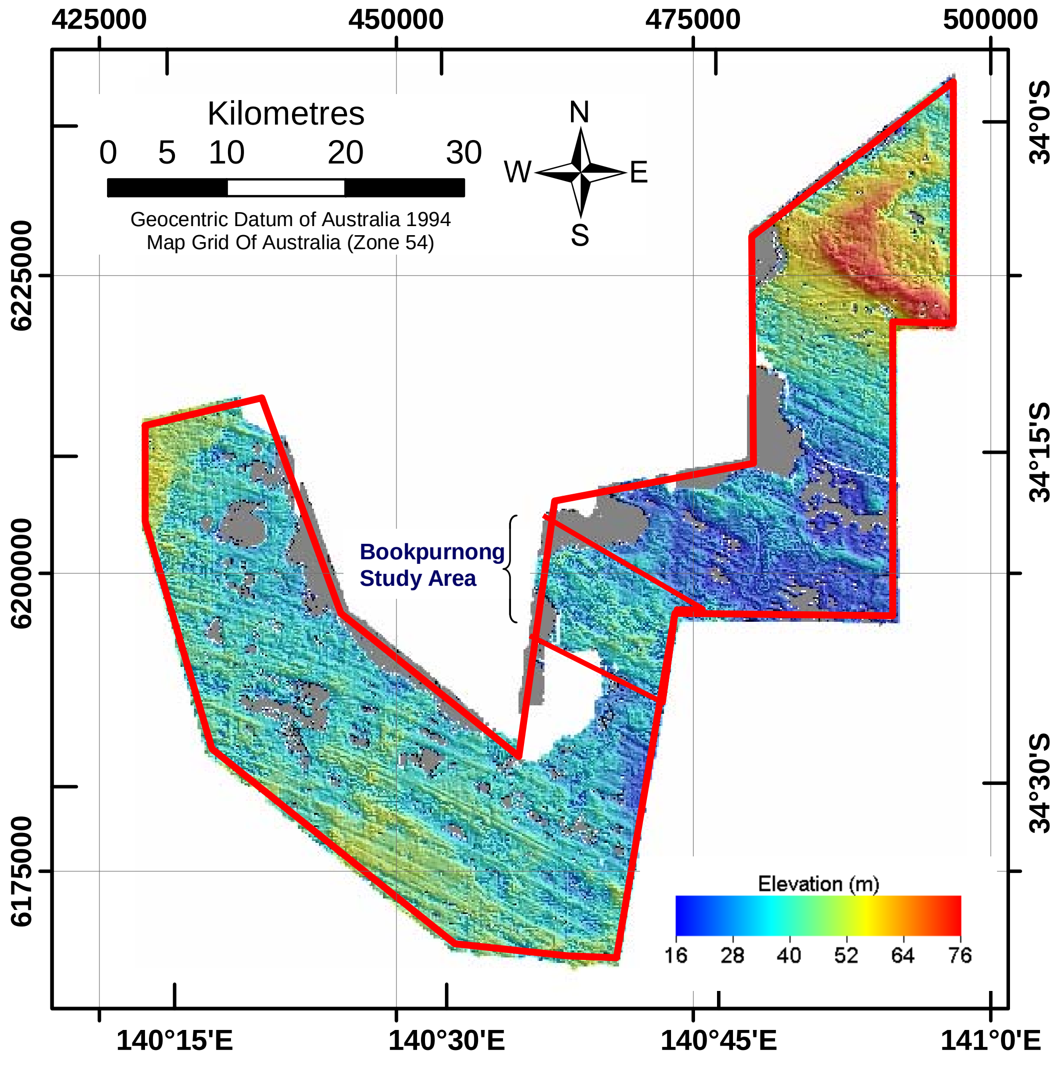

Figure 6. Elevation of the top of the Loxton_Parilla Sands in the Riverland HEM survey area.

For the purposes of this study, a subset of the full Riverland HEM survey data set was extracted. This subset of data covered the Bookpurnong area, extending from an area just north of the Loxton to the River Murray Floodplain just to the north of Bookpurnong (see Figure 6). The area studies represents a 15 km by 5km region.

5.2 HEM data processing

In a previous study of the Riverland HEM data set reported by Green et al (2003), it was established that a constrained Layered Earth inversion of the HEM data worked effectively in resolving elements of the sedimentary sequence and variability at or below the watertable that may have significance from a hydrogeological perspective. We believed that further refinement of this approch was warranted for the bookpurnong study, only with site-specific constraints being used in the inversion.

5.2.1 *Constrained Inversion Formulation*

Based upon stratigraphic drilling in the Bookpurnong district, we adopted a simple four-layer geophysical model comprising resistive sands over the more conductive Blanchetown Clay overlying the Loxton-Parilla Sands, which are resistive when dry and conductive below the saline watertable, to adequately fit the data. Examination of down-hole induction logs and preliminary data products, confirmed this model, as summarised in Figure 7. The earth was thus parameterised by seven quantities– five conductivity $(\sigma_{us}, \sigma_c, \sigma_{ls}, \sigma_{slls})$ and four thickness (t_{us}, t_c, t_{ls}) parameters. The inversion scheme employed was an iterative, non-linear least squares, gradient based approach (see Menke 1989) which seeks to minimise an objective function of the form $\Phi = \Phi_d + \Phi_m$ (Brodie et al. 2004). Here Φ_d is an error normalised measure of misfit between observed and predicted data and Φ_m is a normalised measure of discrepancy between the *a-priori* reference model and estimated model parameters. The inversion scheme capitalised on extensive *a-priori* information about watertable elevation and groundwater conductivity from the study area. Watertable elevation data, derived from both point samples and a contour map, were considered to be accurate to ±0.1m (Steve Barnett *pers. comms.*, 2003). These were gridded to a cell size of 1 km to form a smooth elevation surface. A watertable elevation value was then interpolated at each airborne observation, from which a watertable depth-below-surface value $d_{gw}(x,y)$ was calculated using the airborne survey's digital elevation model. The sum of the thickness values of the three layers above the standing water level was constrained to be equal to the standing water depth by including the equation $t_{us} + t_c + t_{ls} = d_{gw}(x,y)$ in the formulation and assigning the datum a small uncertainty (0.1m standard deviation).

In the original inversion of the Riverland HEM data set, a reference model was constructed by observation and statistical analysis (of lithological thickness data from drill holes, groundwater information and downhole conductivity logs) and our knowledge about the geomorphic history of the area. A similar approach was taken with the Bookpurnong data set, only in this instance we assigned an uncertainty, that reflected our level of confidence in and/or belief about the variability to each of the parameters in the reference model based on locally derived groundwater information and drillhole petrophysical logs. The smaller the uncertainty the more confident we were in the value assigned to the parameter. In this manner the reference model imposed constraints in the form of prior probability information.

A simple empirical linear relationship between the conductivity of available groundwater samples and the bulk conductivity below the standing water level was derived. A value of the bulk conductivity could then be inferred for each of the samples where groundwater conductivity data were available. Similarly to the watertable elevation data, a smooth surface for the bulk conductivity of the zone below the standing water level was defined. This surface served as a reference model value for the bottom layer. The conductivity of the bottom layer was tightly constrained to this value.

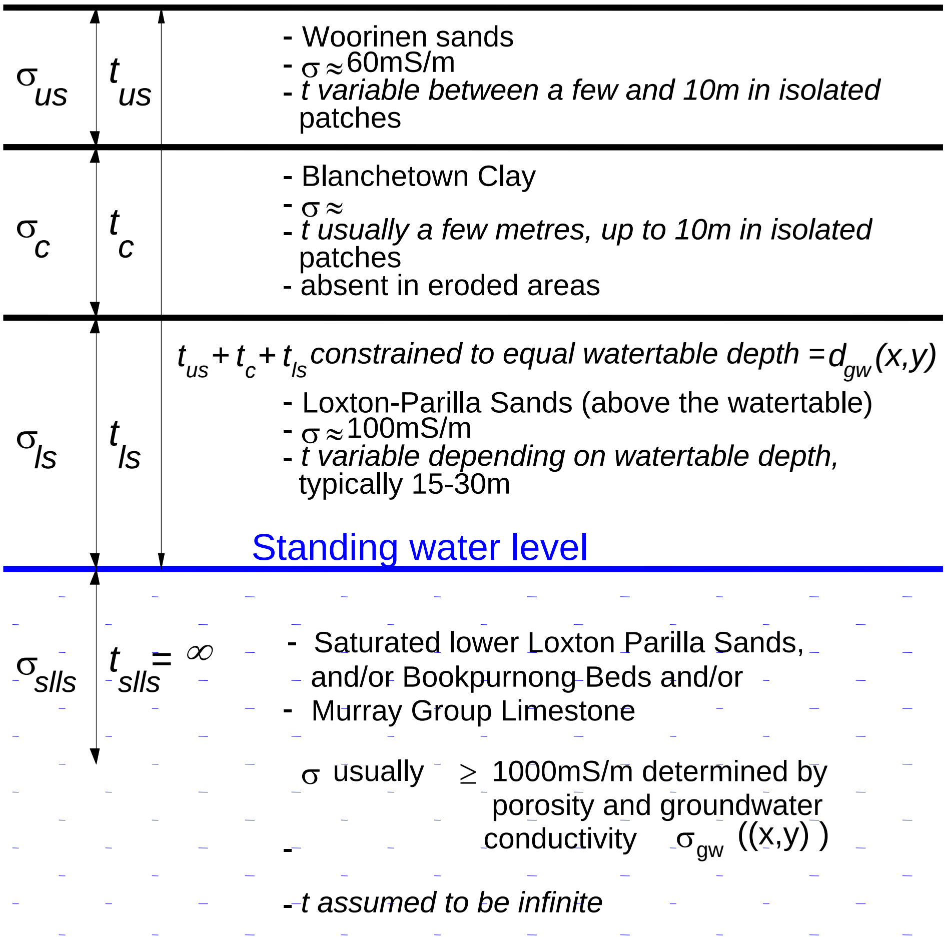

Figure 7. A schematic representation of the 4 layer 1D parameterisation of the earth used in the constrained inversion of the HEM data

We used the base-10 logarithms for all parameters in the formulation to enforce positivity constraints on conductivity and thickness values. However, for the clay conductivity σ_c, the inverted quantity was $log_{10}(\sigma_c - 0.1)$ to constrain it to be greater than 0.1 Siemens. In this particular formulation the quantity Φ_d is given by $\Phi_d = \left(\dfrac{d_{gw} - \sum_{k=6}^{8} 10^{m_k}}{0.1} \right)^2 + \sum_{i=1}^{12} \left(\dfrac{d_i - g_i(m_1 ... m_9)}{e_i} \right)^2$ The first term implements the constraint $t_{us} + t_c + t_{ls} = d_{gw}(x,y)$ described earlier (noting that $10^{m6} = t_{us}, 10^{m7} = t_c \text{ and } 10^{m8} = t_{ls}$ and 0.1 was the error assigned to standing water depth data). The second term is the summation of the squared misfits between the 12 (6 inphase and 6 quadrature) observed (d_i) and predicted (g_i) airborne data channels. The function $g_i(m_1,...,m_9)$ is the forward model for the RESOLVE system at the measured bird height for the current parameter estimates. Forward models were computed by the formulation of Wait (1982) using the digital filtering coefficients of Guptasarma and Singh (1997) to evaluate the Hankel transforms. The error values (e_i) for each observed airborne datum were standard deviations calculated from the results of Green and Lane (2003). The quantity $\Phi_m = \sum_{j=1}^{9} \left(\dfrac{\hat{m}_j - m_j}{s_j} \right)^2$ was the summation of the squared misfits between the reference model parameters ($\hat{m}_j$) and the parameter estimates (m_j), normalised by the assigned reference model uncertainty (s_j). The reference model was used as the initial estimate of the model parameters. The inversion was iterated until either $\Phi \leq 6.25$, Φ changed by less than 0.5% between iterations or, the 30th iteration had been completed. A summary of the inversion parameters that were used are provided in Table 2. Every fifth data point (~15 m) was inverted. After inversion, all conductivity and thickness estimates were filtered with a 5-point median filter (length ~75 m) to produce the final parameter set.

5.3 Inversion results

As mentioned earlier, our approach to better understanding the Loxton Sands aquifer system involved the linking of observations made from borehole, ground and airborne geophysics with an understanding of sedimentary systems and a detailed interpretation of borehole geology. The intent was to improve our capacity to predict lateral and vertical changes in facies associated with the main aquifers relevant to the SIS. The four layer inversion of the HEM data as summarised in a stitched section for one flight line (Figure 8) revealed regular, though broken, NW-SE trending linear patterns in the conductivity of Layer 4 – the saturated basement (Figure 9), defined as the water table and below, which has also been observed elsewhere by Green *et al.* (2004).

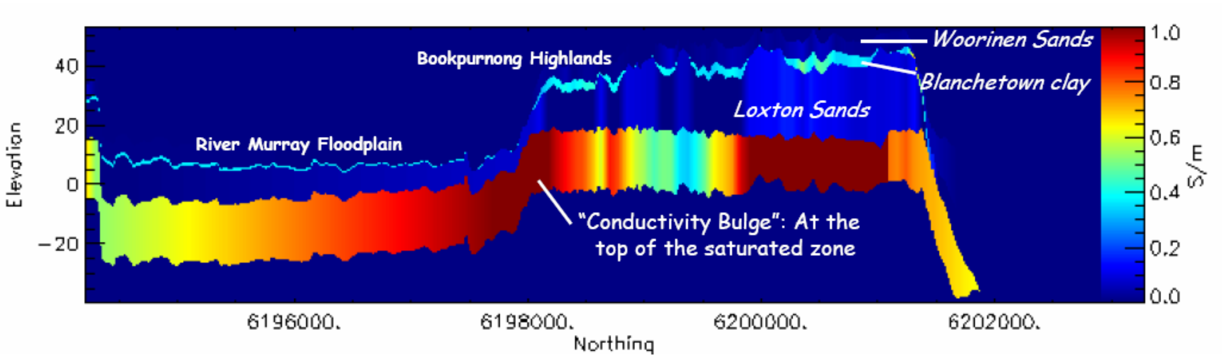

Figure 8. Stitched section from constrained inversion of HEM data for flight line shown Figure 10 below.

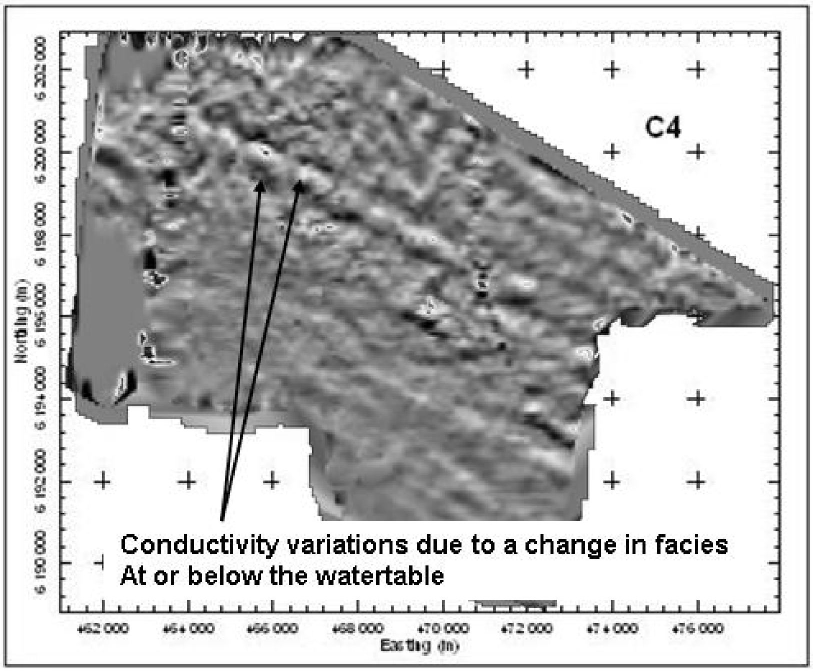

Figure 9. Greyscale rendition of layer 4 conductivity from a four-layered 1D parameterisation of the earth for the Bookpurnong data set. The image is illuminated from the NNE. Note the strong NW-SE linear trends in conductivity.

5.4 Borehole geophysics and sedimentology

Geophysical logs were acquired for ~90 drillholes in the Boopurnong-Loxton area to assist with aquifer characterisation and sedimentological analysis Neutron, natural gamma and inductive conductivity logs were recorded, although only a limited number of bores were measured for inductive conductivity. Where possible, the observed response was related to stratigraphy, and in the case of the natural gamma logs could be linked to facies variation. Representative borehole conductivity and natural gamma data for several bores studied in the Bookpurnong area are shown in Figure 10. The location of these bores is indicated in Figure 11.

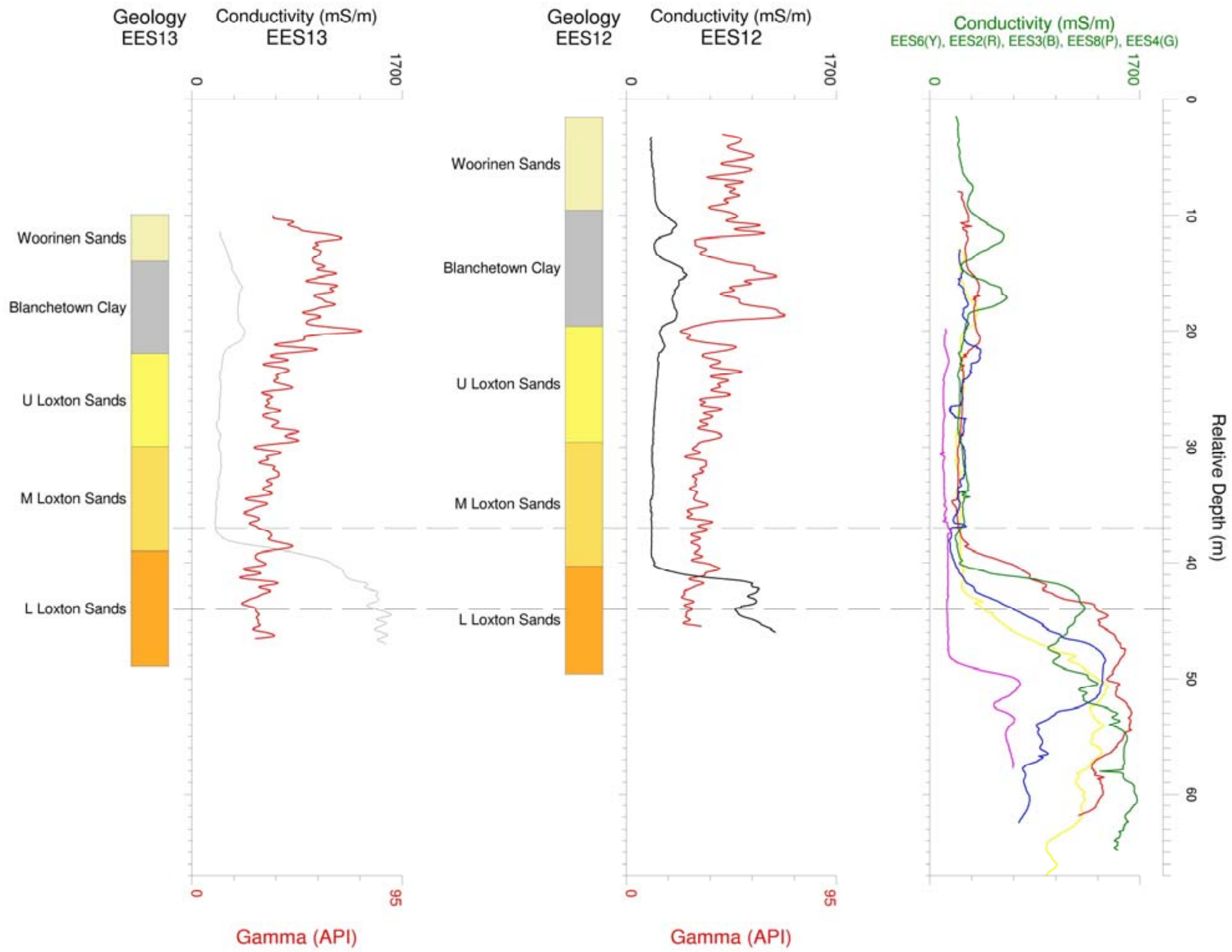

Figure 10. Representative borehole geophysical logs for the Bookpurnong area. Locations are shown in Figure 11. Logs are adjusted to topography. The inductive conductivity logs are dominated by the elevated response recorded at or near the water table. The variability observed in Layer 4 conductivity of the constrained inversion of the RESOLVE HEM data (Figure 9) corresponds primarily to differences in the region between the two dashed horizontal lines centered at about 40mAHD.

Sediments of the Loxton Sands within the area of the Loxton-Bookpurnong SIS drilling program were analysed for grain size distribution, sorting, roundness and colour.. An analysis of gamma and neutron borehole logs along with the sedimentological information has led to the identification of three distinct sequences within the generally coarsening upwards Loxton Sands succession with varying depositional environments. These informal sequences build on the existing AWE stratigraphy and comprise:

Lower Loxton: consisting of three distinct units grading from grey clay at the base to fine shells and silt overlain by grey, very fine to medium-grained, unimodal and moderately well sorted, highly micaceous , polished quartz sand. It is thought to represent a shallow marine (lower shoreface) dominantly fine grained clay rich sequence with local (storm related?) coarser sandy units.

Middle Loxton: predominantly fine grained sand, mustard to cream coloured, highly micaceous at the base becoming bimodal towards the top of the sequence with mixing of coarse, variably sorted sand and reducing clay content. This sequence, interpreted as being associated with a transition from lower to upper shoreface with local reworking of estuarine sands at the shoreface. This sequence most likely equates with upper shoreface deposits of northwestern Murray Basin as identified by Fabris (2002). A coarsening upwards sequence with diminishing mica content is evident at Habel's Landing, 2 km south of Loxton. Coarse grained tidal channel deposits (often with shell hash at the base of the sequence) appear to occur within discrete zones parallel to strandlines and have been mapped over several kilometres in the Bookpurnong region. These sediments were most probably transported along the shoreline as a result of longshore drift and rapidly grade to fine sand basinward, tangential to the shoreline. The sequence reaches a maximum thickness of 10m in the study area.

Upper Loxton*:* medium to very coarse- grained quartz sand with minor fossiliferous material (reworked shell fragments), white, yellow, occasionally red, variably sorted. This sequence represents upper shoreface deposits to beach-barrier bar sequences with fluvial input, and comprises higher permeability sands. Whilst it represents a target aquifer at Bookpurnong, it is largely confined to the unsaturated zone in the Loxton area project area where it reaches a maximum thickness of 20m. This sequence is usually overlain by Blanchetown Clay unless it has been removed by erosion.

In the Loxton and Bookpurnong areas, the observed inductive conductivity response is dominated by the elevated response which occurs at or near the water table. This is attributed to the saline groundwater. Minor kicks in conductivity occur near surface where the Blanchetown Clay is encountered (Figure 10). Commonly, higher conductivities are encountered where finer textured units are present.

5.5 Ground EM data

Seven ground TEM traverses were also acquired in the Bookpurnong area, in the vicinity of proposed sites for the SIS highland borefield. The intent was to use the ground EM data to confirm the variability noted in the HEM data and to use them to better resolve subtleties in the deeper conductivity structure observed at the watertable.

All of the time domain EM data were recorded using a Zonge Engineering and Research Organization NanoTEM system.. The NanoTEM transmitter is characterized by a quick turn off time and low current compared with other ground TEM systems. Its receiver sampling rate is much faster, resulting in far less depth penetration, but much better resolution of the top 20 to 50 metres. The transmitter loop was a square 20 metres by 20 metres, with a centrally placed horizontal receiver loop 5 metres square. The transmitter turn-off time was approximately 2 microseconds and the sampling rate was set to either 1.2 or 1.6 microseconds (depending on the depth and resolution desired). In typical conductive ground the first data window is collected within 4 microseconds of the beginning of transmitter turn-off; the first sample is typically taken within the top four metres.

Acquisition parameters were similar to those reported by Hatch et al. (2003). The data were inverted using a smooth model 1D inversion. Three stitched sections are shown in Figure 12. The NanoTEM data were acquired on the expectation that variations in ground conductivity could be related, at least in part, to facies changes in the aquifer.

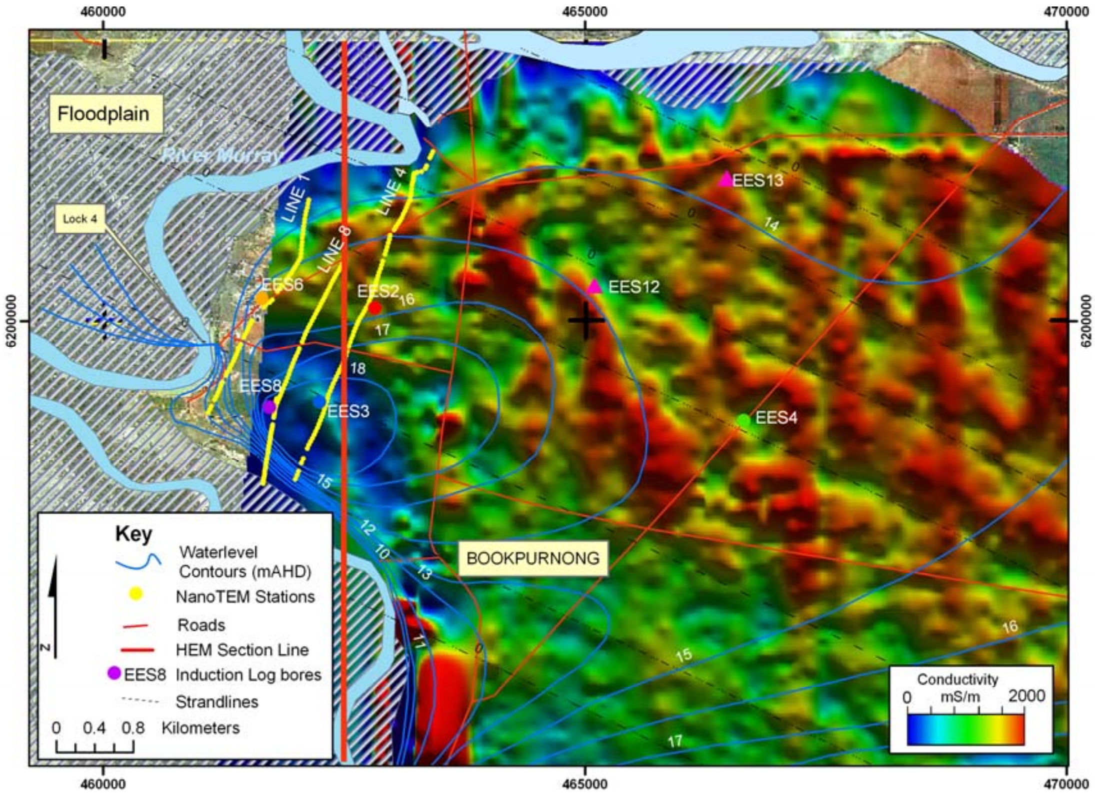

Figure 11. Bookpurnong Study area with pseudocoloured image of the conductivity of the 4th layer from constrained layered earth inversion of RESOLVE HEM data. These data are overlain by water level contours. The location of stitched section from the HEM data (See Figure 8), boreholes which were measured using a suite of logging tools (see Figure 10) and NanoTEM lines (Figure 12) are indicated.

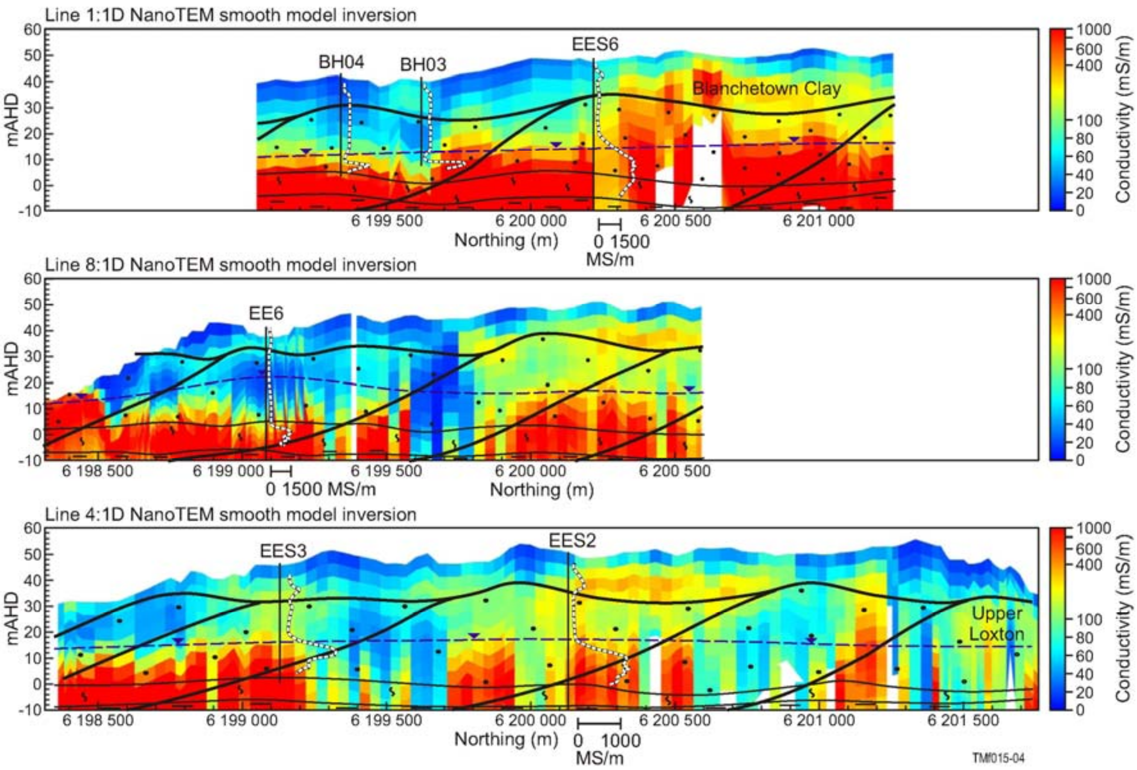

Figure 12. Stitched NanoTEM sections for three traverses at Bookpurnong. Their orientation is shown in Figure 11.

The three sections shown have been fitted to topography and projected onto an Easting grid. At depth, conductivity patterns relate to variations in groundwater salinity and facies. The orientation and interpreted position (from boreholes) of the Loxton-Parilla Sand sedimentary package has been superimposed onto these sections. Elevated conductivity responses at depth are generally associated with the saline groundwater. Locally, the high conductivity response linked to the groundwater is pushed deeper, due to the mounding of relatively fresh irrigation water. An example of this behaviour is noted on NanoTEM line 8, in the vicinity of bore EES6 (Figure 12).

6. DISCUSSION

Layer 4 in the inverted HEM data resolves a highly conductive groundwater system, which sits in the lower part of a generally coarsening upwards, though locally varying, Loxton-Parilla Sands succession (Figure 3). This sedimentary package represents a complex assembly of (regressive) lower and upper shoreface, beach, estuarine, dune and back-barrier lagoonal facies sediments (Figure 4) that extend across a substantial part of the Murray Basin (Fabris 2002, 2003, and Roy *et al.* 2000).

The Loxton sands can be divided into three sub-horizontal units, characterized by distinct facies (AWE 2003b, Hill et al. 2004). The lower unit grades from grey clay at the base, to fine shells and silt overlain by grey, fine to medium-grained, highly micaceous, polished quartz sand. It is interpreted to represent a shallow marine (lower shoreface) dominantly fine-grained sequence (Figure 5). This unit grades up into the middle Loxton sands unit which is dominantly fine- to medium-grained. The boundary between these two units can be described as an undulating surface, with thin, narrow (~200m wide), shore parallel coarser-gained sedimentary units developed by the reworking of finer-grained, shell and clay rich units at the wave base in periods of slow or near-stalled barrier progradation. A possible schematic model for this sedimentary system is shown in Figure 13. Petrophysical data indicates that the coarser sedimentary units, including the thin shell hash units are relatively porous (~38%), and more permeable than the underlying fine grained sediments from which they are derived. The latter have high apparent porosities (~58%) but low permeabilities. Apparent electrical conductivity measurements of saturated core for these two units indicates that the lower clay rich unit is up to 3 times more conductive than the overlying coarser materials. A geoelectrical model that incorporates these observations is illustrated in Figure 14. This section indicates that high conductivities are encountered at the water table, a contributory factor in the observed conductivity seen in the Layer 4 product from the inverted HEM data is facies variation. Where coarser grained units increase in relative thickness the bulk conductivity drops, whereas the reverse is true where the finer grained units thicken. The borehole conductivity data supports this with contrasts in the inductive response observed where bores sit in positions D1 or D2. Bore D2 has a higher observed response below the water table and would be the equivalent to Bore EES13 in Figures 10 and 11. Bore EES12 (Figures 10 and 11) would be equivalent to D1 in this section.

Analysis of samples from scout drilling conducted as part of the Bookpurnong SIS highland borefield program indicates that the linear zones (trending NW-SE) of lower observed conductivity in the inverted HEM data (Figures 9 & 11) coincide with the coarser grained sedimentary deposits in the lower Loxton. As mentioned above, these coarser facies are interpreted to be coincident with a reworking of the lower shoreface units, and the development of sandy shell hash layer. They may represent periods of stalled barrier progradation and/or a minor transgression, when the larger beach barriers systems started to develop. In these periods thicker sequences of clay developed offshore, while in the lower shore face, wave action reworked the Lower Loxton forming relatively narrow, thicker bands of shell hash and sand at the wave base. (location 2 in Figure 13. These bands of coarser sediment are a potential target aquifer for the SIS at Loxton and Bookpurnong.

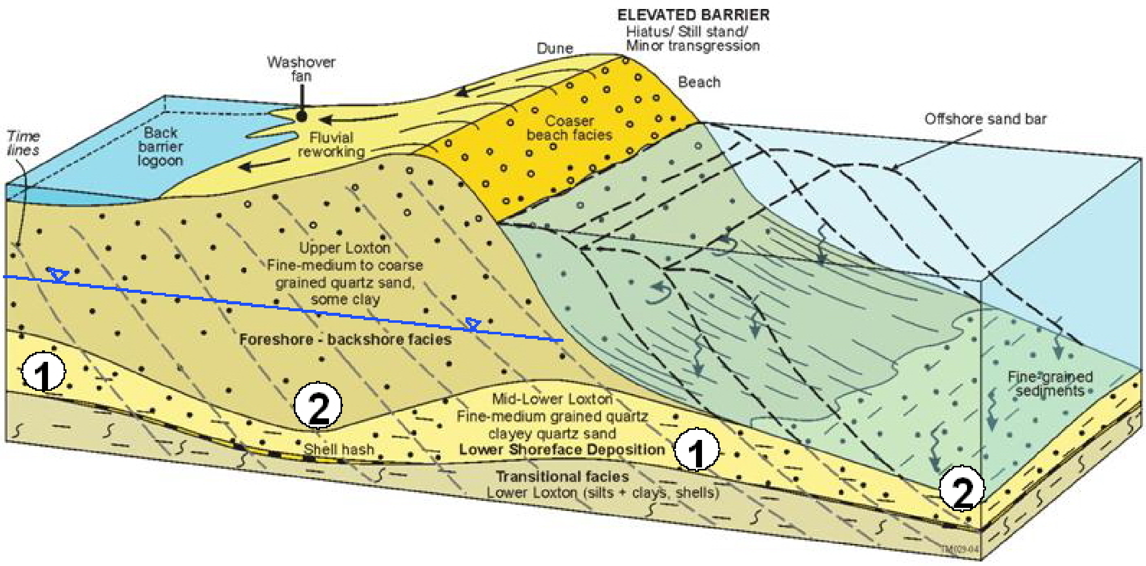

Figure 13. Schematic representation of a regressive (prograding) strandplain sequence that characterises the depositional environment of the Loxton-Parilla Sands. This model is developed from an interpretation of derived products from the HEM inversion and available borehole data. The HEM data suggest an undulating package of finer-grained sediments that alternatively thickens (1) and thins (2) in the lower part of the Loxton-Parilla Sands sequence. A thicker lower sequence is coincident with the development of a beach barrier system, which may correspond to a hiatus, or minor transgressive phase in the progradation of the sand package. Areas of higher transmissivity (see Figure 2) in the contemporary saturated zone (approximately below the blue horizontal line) correspond with coarser-grained sandier or shell hash facies developed just above fine grained lower shore face sediments at position 2.

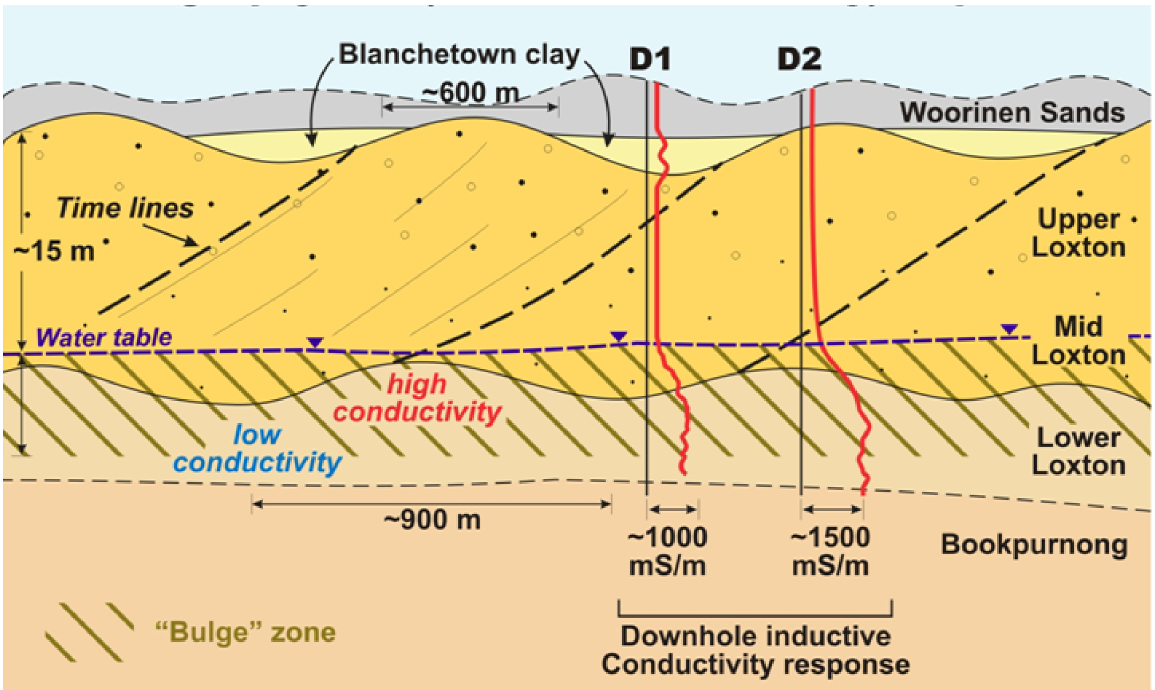

Figure14. Simplified geo-electrical model for the Loxton-Parilla Sands sequence at Bookpurnong. The variability in the Lower Loxton sequence beneath the water table drives the conductivity variation seen in Layer 4 conductivity product from the inverted HEM data.

Transmissivities calculated from grain size measurements of saturated zone samples returned from the scout drilling across the Bookpurnong highlands indicate that higher bore yields might be expected from these bands of coarser, less conductive sediments which appear to be mapped by the HEM data (Figure 15). Further work is required to resolve this. Interestingly, the modelled transmissivities appear to display an asymmetry about the strandlines predicted in the HEM data, with a suggestion that the thickest sequence of permeable sediments sits to the north of the predicted strandline position (Figure 15).

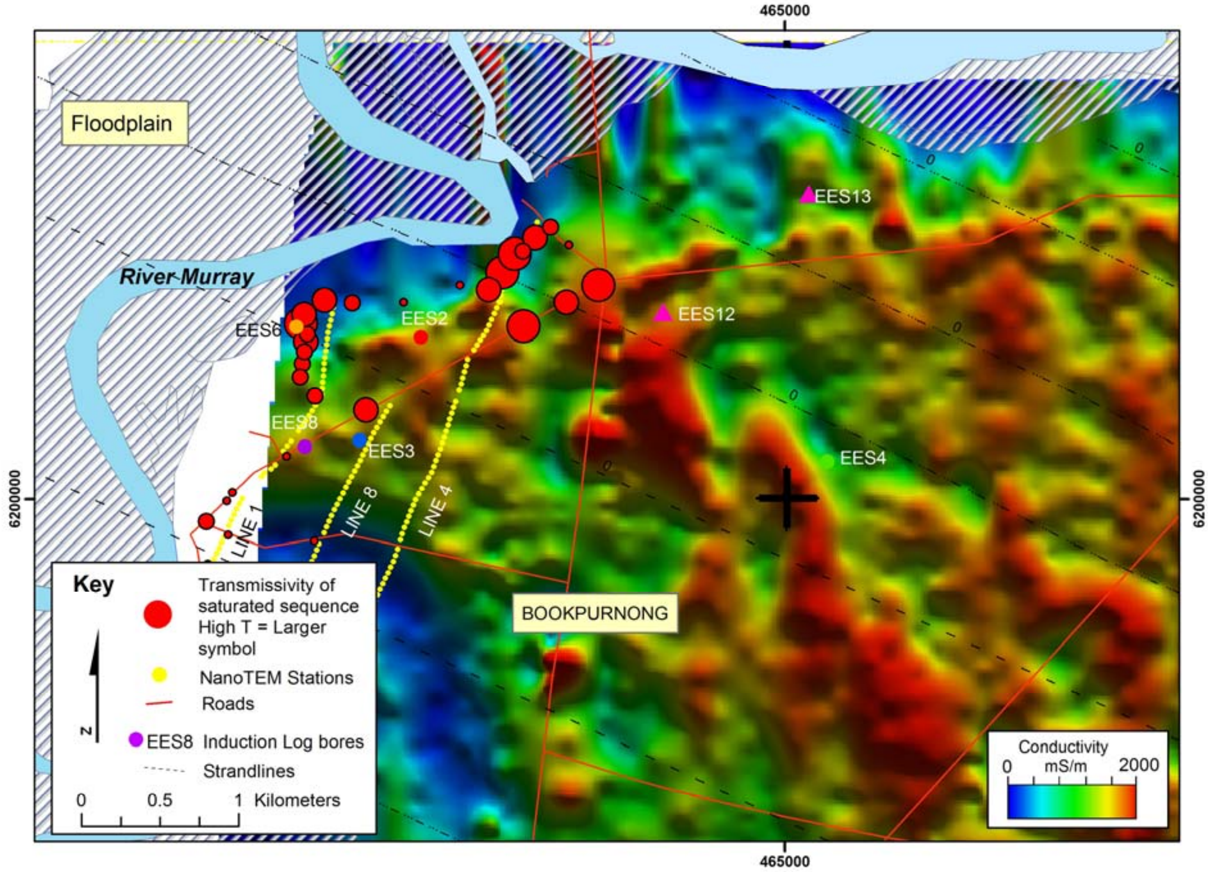

Figure 15. Transmissivities of saturated materials from select pilot bores are shown. Higher transmissivities have been recorded in holes straddling the HEM determined strandlines.

Downhole conductivity logs and the NanoTEM data support the trends in electrical conductivity seen in the HEM data. The borehole data confirmed the association between sedimentary facies and observed conductivity as discussed above. However, they also suggest that the identification of high yielding facies may be obscured by irrigation water mixing in the upper part of the saturated zone and suppressing subtle conductivity contrasts. This is observed around bore EES3, an area with a high SWL (Figure 2). Similar patterns are observed in the NanoTEM data (Figure 5, Line 1).

7. CONCLUSIONS

A combined analysis of geological and geophysical data for Bookpurnong has shown that:

- The constrained inversion of HEM data informs the orientation of strandlines linked with the Loxton Parilla Sands aquifer.
- Subtle variations in conductivity at the top of the main groundwater system (observed in Layer 4 of the HEM inversion) are interpreted to reflect undulations in the essentially flat-lying, saturated lower Loxton sedimentary sequence and facies variations above the lower Loxton clay and shell

unit which reflect changes in porosity and permeability (i.e. changes in their formation factor which influences electrical conductivity.). Linear zones of lower electrical conductivity coincide with zones of lower apparent porosity, though slightly coarser facies within the lower Loxton unit. They may represent periods when barrier progradation stalled and barrier islands may have developed.

- Similar relationships between facies and electrical conductivity are noted in borehole geophysical data.
- Higher aquifer transmissivities are noted straddling the orientation of the strandlines, with transmissivity decreasing away from the low conductivity zones.
- Higher aquifer yields are more likely from production bores that are sited on areas with lower conductivity as defined in the inverted HEM and NanoTEM data, as these appear to be coincident with more permeable sedimentary facies, including shell hash.
- Differential recharge from irrigation in the Bookpurnong area also contributes to changes in the observed HEM conductivity in the upper part of the saturated zone.
- A combined analysis of geophysics and geology has helped refine the sedimentological model for the Loxton Sands aquifer. This is an important precursor to linking transmissivity with variations in facies that might be mapped using geophysical techniques.
- Results from the Bookpurnong study provide a basis for using AEM and other ground geophysical technologies for informing SIS development in the central Murray Basin, particularly when dealing with the Loxton Sands aquifer system. However, further work is required to develop the predictive capacity of geophysics as an aid to SIS borefield design and development .

8. ACKNOWLEDGEMENTS

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