THE COMBINED USE OF AIR, GROUND AND 'IN RIVER' ELECTROMAGNETICS IN DEFINING SPATIAL PROCESSES OF SALINISATION ACROSS ECOLOGICALLY IMPORTANT FLOODPLAIN AREAS - LOWER RIVER MURRAY, SA

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BACKGROUND

In the southeast of Australia, the floodplains of the Lower River Murray have become extensively salinised. This is, in large part, related to an increase in recharge to the naturally saline groundwater system that flows into the River Murray from the irrigation that flanks the river, the regulation of river flow by weirs, increased water extraction from the river, and a marked reduction in flood events along its course. The result has been the accumulation and concentration of salt within the floodplains along the river and an increase in salt loads to it. The floodplains of the lower Murray represent a zone in which groundwater is shallow, and groundwater - atmosphere interactions through evapotranspiration (ET) are most pronounced. Spatial variations in evapotranspiration develop due to the variable distribution and type of floodplain sediments, patterns of vegetation type, floodplain elevation and geometry, and in places where the groundwater system is particularly close to the surface, evapotranspiration concentrates salt resulting in extensive salinisation, vegetation dieback or health decline. In many floodplain areas, ecologically important *Eucalyptus* woodlands and forests that inhabit the floodplain are dying from soil water salt concentrations that often exceed those of seawater (Overton & Jolly, 2004).

In order to manage the problem and to protect the ecology and biodiversity along the river, a range of management strategies are being employed including the development of salt interception schemes (SIS), targeted spear point pumping to lower groundwater under vulnerable tree communities, injection of fresh water in the same regions, and artificial flooding or environmental irrigation. Modelling tools are key to the development of effective and appropriate management strategies, particularly to assist the prediction of their effects on floodplain salinisation. However, there is an accompanying need to acquire biophysical data that permit resultant models to be calibrated and validated. Geophysical, particularly electrical, methods have the potential to provide detailed spatio-temporal information on the distribution of salinity in soils and groundwater, thereby indicating spatial patterns of groundwater evapotranspiration and baseflow across salinising floodplains that characterise the lower River Murray. In this paper we review this potential at varying scales and comment on the role of these methods in the validation of groundwater models. Specifically, a combination of technologies including airborne, ground and "in river" electrical methods are considered and we provide some preliminary observations on the information content of frequency domain helicopter EM data. High resolution RESOLVE frequency domain helicopter EM data are examined along with 'in river' NanoTEM and ground EM31 data.

STUDY AREA LOCATION AND HYDROGEOLOGY

This area for this study was the Bookpurnong floodplain is located adjacent to the Bookpurnong Irrigation District on the River Murray in the Riverland region of South Australia (Figure 1). It has a hydrogeology typical of the eastern part of the lower River Murray (see Figure 2). On the floodplain, the Coonambidgal Clay ranges from 3 to 7 m thick, while the Monoman Formation is approximately 7 m thick in this area. The cliffs adjacent the floodplains consist of a layer of Woorinen Sands over Blanchtown Clay, each approximately 2 m thick, overlying the Loxton Sands which can be up to 35 m thick.

The whole area is underlain by the Bookpurnong Beds, which act as an acquitard basement to the shallow aquifer that encompasses the Monoman Formation and Loxton Sands. Groundwater salinity in the Loxton Sands and Monoman Formation exceeds 30 000 mg/L, while irrigation recharge salinity is typically 5 000 mg/L (Figure 1). Excess recharge from the Bookpurnong Irrigation District has led to the formation of a groundwater mound, which displaces saline groundwater towards the floodplain and has led to increased waterlogging and salinisation on the floodplain, and groundwater seepage at the break of slope adjacent to the cliffs (Figure 2 and 3).

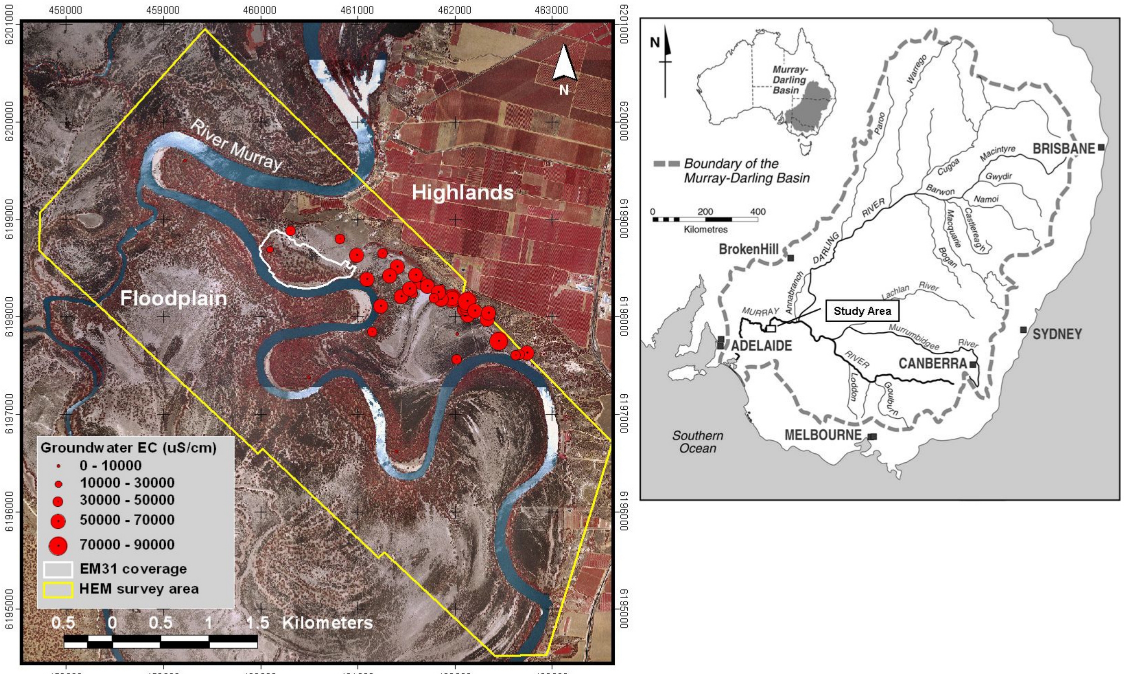

Figure 1: Bookpurnong study area in the Lower Murray and location of HEM and ground geophysical survey areas.

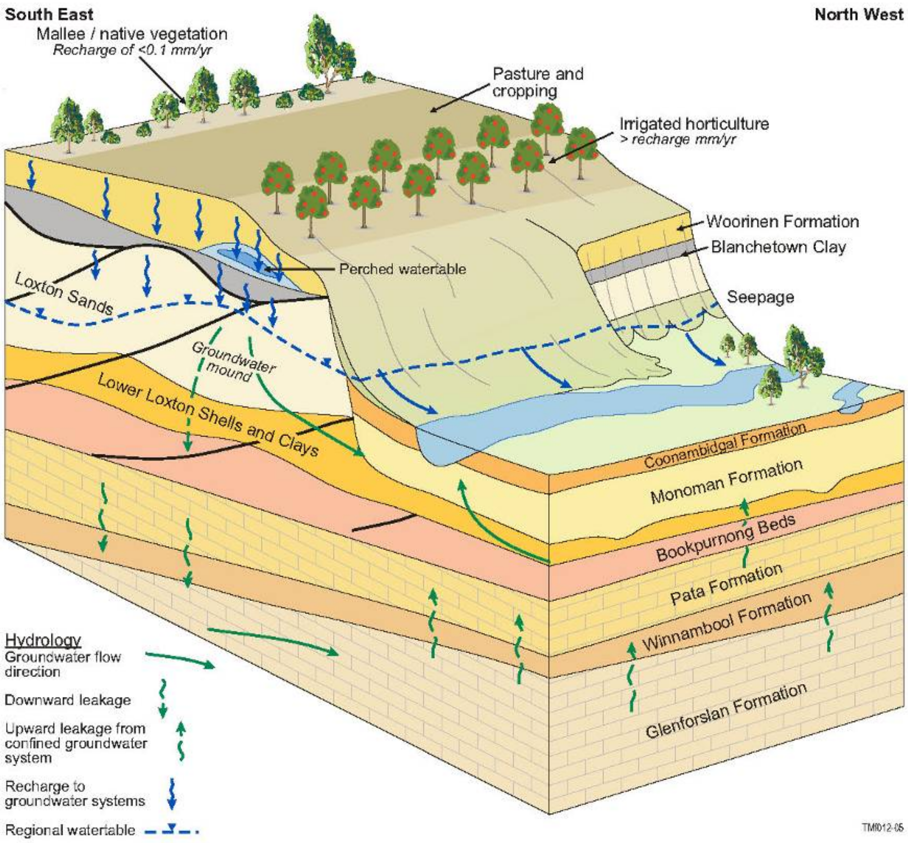

Figure 2: Schematic hydrogeological model of the Bookpurnong floodplain and adjacent highlands. High recharge from irrigation on the highlands adjacent to the floodplain results in the development of a groundwater mound and an increase in the hydraulic gradient towards the floodplain. A rise in water levels across the floodplain results. Increased evapotranspiration results in the concentration of salt in the near surface soils. These changes also promote the discharge of higher salt loads into the river.

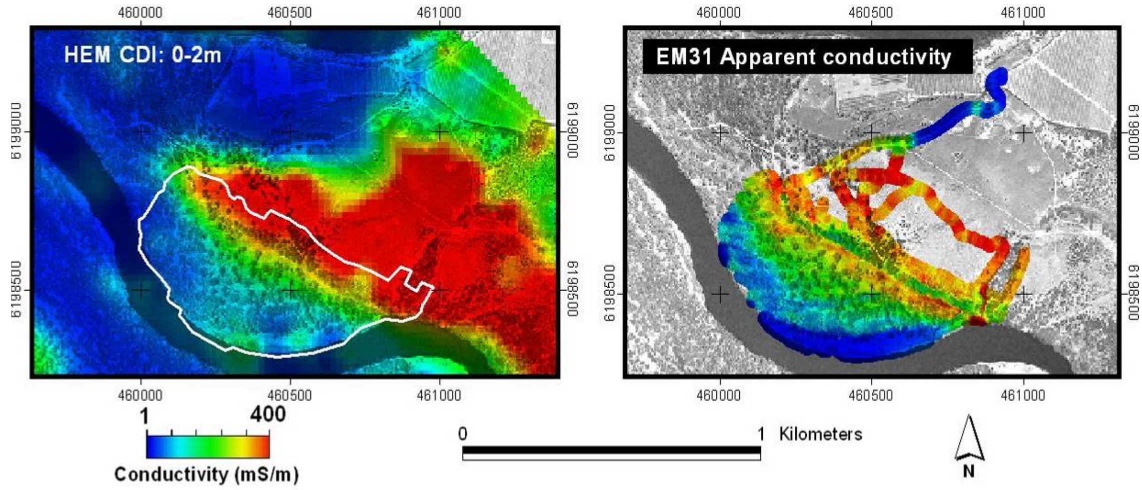

Figure 3: Scaled interval conductivity slice from the RESOLVE HEM data for the top 2 m of the ground surface (left) shows similar spatial patterns of conductivity to those measured with an EM31 (right). The densest and healthiest vegetation communities are found adjacent to the river in areas of low conductivity

GEOPHYSICAL METHODS

Ground and "in river" EM acquisition and processing

Ground EM data were acquired over a small part of Bookpurnong floodplain (see Figure 1) using a Geonics EM 31. Data were processed to apparent conductivities. The "in river" EM data acquired for the Bookpurnong reach of the River Murray, were collected using a floating version of Zonge Engineering's land-based NanoTEM system (Telfer *et al*. 2004). A single-turn transmitting antenna (7.5 m x 7.5 m) and receiving antenna (2.5 m x 2.5 m) were mounted on a stiff PVC framework of four floating pontoons, towed behind a boat. Data were acquired in a nearly continuous mode every 4 seconds using 64 cycles at a repetition rate of 32 hertz and a sampling rate of 1.2 or 1.6 microseconds. An average boat speed of 5 km/h resulted in a TEM reading approximately every 5 to 8 metres along the river. Progress along the river was determined with a GPS/sounder, which logged position and water depth approximately every 10 metres. All three data sets were time stamped and synchronised, resulting in an accurately located TEM sounding and associated water depth (Berens *et al*. 2004). These data were inverted to a model resistivity vs. depth using STEMINV (MacInnes & Raymond, 2001).

AEM data acquisition and processing

Following a review of available AEM systems against the desired objective of resolving very near surface (<5m) combined with deeper (10-20m) conductivity variations in a floodplain setting, the Bookpurnong area (Figure 1) was surveyed in July 2005 with the Fugro RESOLVE frequency domain helicopter EM system. RESOLVE is a six frequency EM system mounted in a bird towed beneath a helicopter at a nominal altitude of 30m. The bird contains horizontal coplanar coils, and in the Bookpurnong survey measured an EM response at 390Hz, 1798Hz, 8177Hz, 39470Hz and 132700Hz. It also has one coaxial coil pair which measured a response at 3242Hz. RESOLVE is a digital frequency domain EM system with internal calibration coils for automatic phase and gain calibration in the air. Twenty six lines of data orientated NW-SE were acquired over the study area with a line spacing of 100m. Conductivity depth images (CDI's) of the RESOLVE data were produced using EMFlow (Macnae *et al*. 1998). The data were also inverted using a holistic inversion algorithm (Brodie & Sambridge, 2006). Interval conductivity slices were then calculated for various depth intervals from the surface and these slices were gridded and imaged.

RESULTS

Ground EM interpretation

In a pilot project established on the Bookpurnong floodplain, under the auspices of the "The Living Murray Program", several trials have started with the intent to observe the responses of fringing vegetation to watering, and at some sites observe the lateral spread of fresh water, within the groundwater system, from the flooded creeks. Ground EM data are now being collected (Figure 3 - right) to gain a more detailed understanding of consequential spatio-temporal soil zone responses linked to these flooding trials. Variations in near surface conductivity are expected to correlate with changes in the salinity and saturation of the unsaturated zone, and changes in the salinity of the saturated zone. Verification of these processes is currently underway. Initial observations indicate a close correspondence between vegetation type, density, health and the observed conductivity (Figure 3).

Interpretation of 'in river" NanoTEM and HEM conductivity responses

The interval conductivity slices shown in Figure 4, show a variably conductive floodplain with patterns of conductivity varying horizontally and vertically. The most conductive responses are observed near surface, particularly on the NE floodplain (Clarkes Floodplain) adjacent to highlands. While the transformation to conductivity using a conductivity depth transform such as from EMFlow tends to accentuate the conductor closest to the surface (Hunter & Macnae, 2001), its existence is well supported by available borehole data on the bulk salt content of the near surface sediments (Figure 5). The HEM data identify a well defined flushed (resistive) zone which parallels the main channel. This is particularly well developed between km 507 and Lock 4 (Figure 4) and extends up to 0.5km from the river bank. The interval conductivities also suggest that the extent of flushed zone varies with depth.

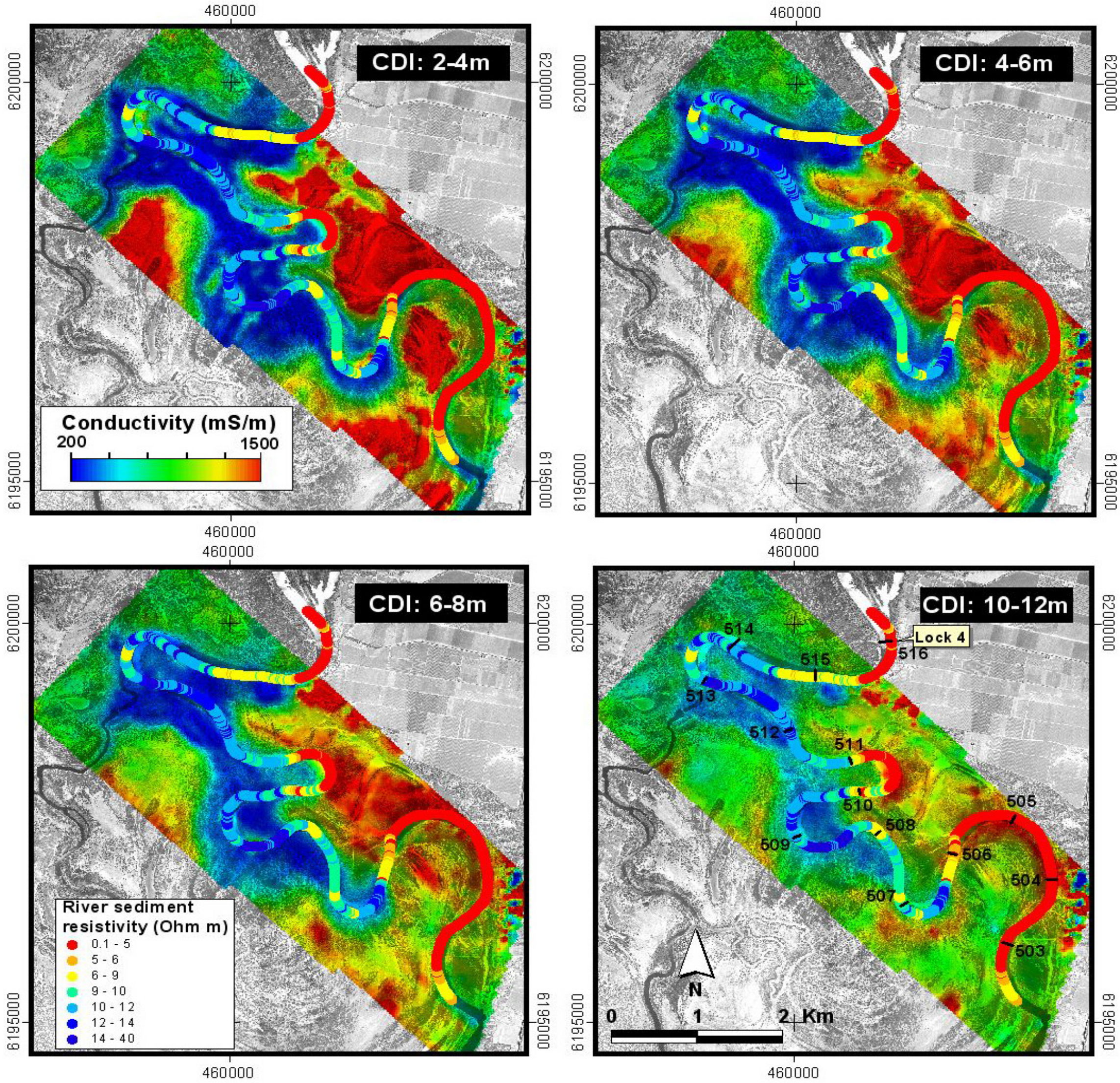

Figure 4: RESOLVE HEM interval conductivity slices for the Bookpurnong floodplain survey are shown draped on an air photo. The slices are for 2m intervals covering a 2 - 12m depth interval. "In river" NanoTEM responses from the river-bed sediments are plotted on the images.

There is a close spatial relationship between areas of the floodplain with high conductivity (i.e. areas of high chloride content) and reaches of the river with a high sediment conductivity (e.g. between km 503 and 506) as defined by the 'in river" NanoTEM. These correspond to 'gaining' reaches where baseflow from the regional groundwater system discharges salt into the river and has been confirmed by run of river surveys that support the accession of salt to the River Murray in these reaches (Berens *et al*. 2004). Interestingly, the HEM data also suggest that the connectivity between the regional groundwater system and the river may vary with depth. Modeled baseflow from a steady state groundwater model (Doble *et al*. 2004) showed higher groundwater discharge in areas where the river is close to the highland, and negative baseflow in the sandy areas at the ends of the meanders. These observations correlate strongly with the observed conductivities in both the NanoTEM and RESOLVE data (Figures 4 & 6). Where the modelled flow budget returns high total salt flux to the river (km 516, 511 and between 506 and 504 - Figure 4) the NanoTEM and RESOLVE data display high conductivity responses (Figure 6). Conversely, where it returns negative flux away from the river (between km 506 - 510, and 512 – 514), both the NanoTEM and HEM data are characterised by resistive responses. These correlations lend credence to the notion that deeper EM responses are related to variations in groundwater salinity.

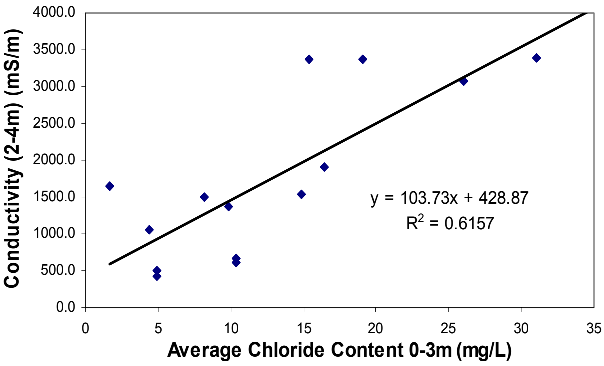

Figure 5: Relationship between RESOLVE conductivity (2-4m) and bulk chloride content in floodplain sediments

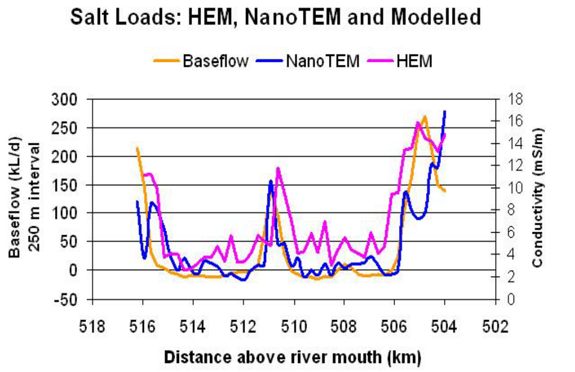

Figure 6: Salt load patterns from Clarks Floodplain showing modelled data and resistivity from the 'in river' NanoTEM data.

Patterns of groundwater salinity and their relationship with vegetation density and health are summarized in a series of conductivity parasections shown in Figure 7, for the section lines shown in Figure 8. The sections depict a saline groundwater system and also show the relationship between the flushed zone around the river and the presence of healthy Red Gums, Cooba and Black Box. Indicative groundwater conductivities are also shown.

CONCLUSIONS

A combination of ground, in river and airborne electrical techniques provide spatial data on the distribution of salt concentrations in floodplain and river sediments. The RESOLVE data indicated the presence of an extensive flushed zone adjacent to the River Murray, but that this zone is not always present. Both NanoTEM and RESOLVE data were useful in identifying fine scale variations in baseflow, showing alternation between losing and gaining groundwater in a river broadly understood to be a gaining system. While further detailed borehole and in river measurements are required to gain a more accurate interpolation of salt loads from the nanoTEM and RESOLVE data, the inferred groundwater baseflow patterns were found to correlate with the modelled data. These geophysical data are now being used to provide additional constraint to groundwater models, significantly improving our ability to predict the consequences of current and future salinity management practices.

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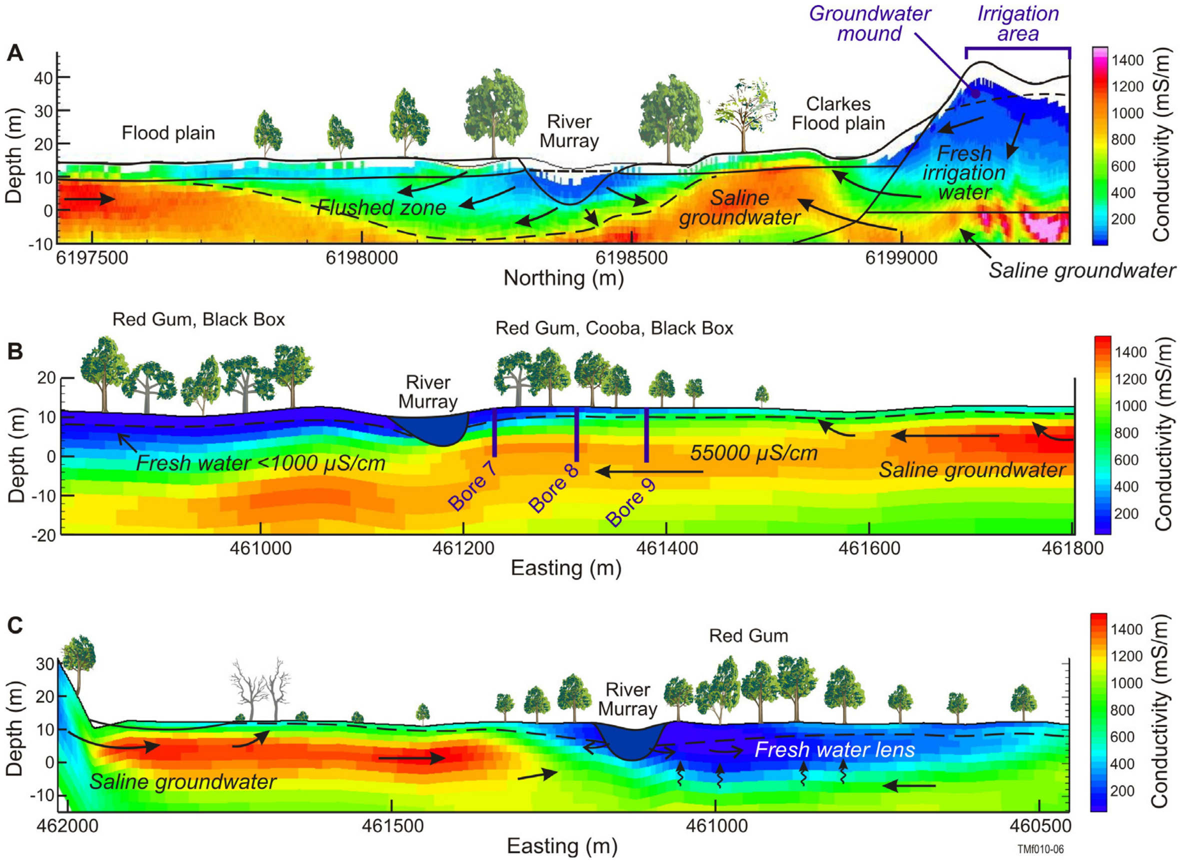

Figure 7. Conductivity-depth sections across the Bokkpurnong floodplain illustrating the observed relationships between ground conductivity, inferred groundwater flow and vegetation health. Section A was derived from EMFlow. Sections B & C were derived from the Holistic inversion of the data. The location of the section lines is illustrated in Figure 8.

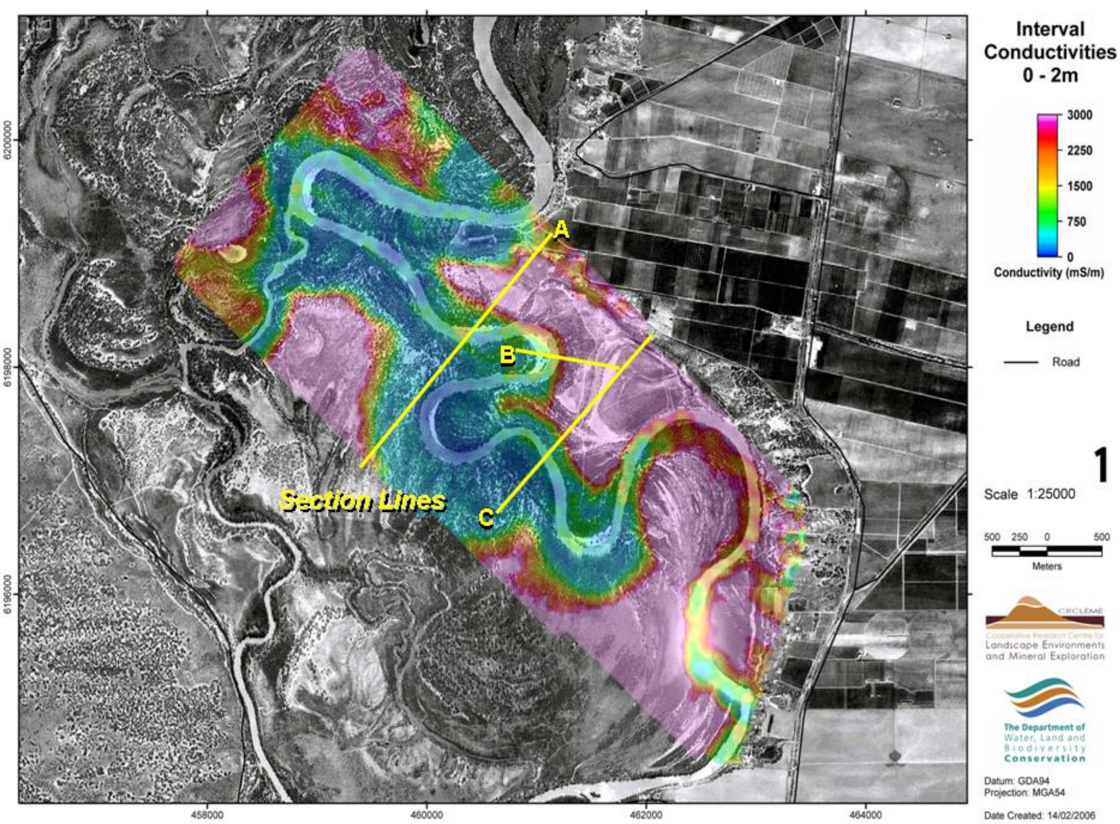

Figure 8. Location of Conductivity depth sections over the Bookpurnong floodplain. Section lines are overlain on an interval conductivity image for the top 2 metres of the land surface.