Instream nanoTEM: providing increased resolution to stream salinisation and floodplain processes along the river Murray, southeast Australia *

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SUMMARY: *Increasing salinity in the River Murray is well documented and is of concern environmentally, economically and socially. The Murray Darling Basin Commission and the Mallee Catchment Management Authority engaged the authors to collect base-line in-stream NanoTEM data within the River Murray from Lock 1 to Mallee Cliffs (675 km). This is a new application of a high resolution fast sampling Transient Electro-Magnetic (TEM) system, towed behind a boat, taking soundings every seven to ten metres along the river. The observed NanoTEM response was interpreted against the current understanding of the regional hydrogeology and groundwater processes in and around the river. This paper summarises some of the results from this investigation. The observed response correlates strongly with previously mapped major changes in underlying lithostratigraphy along the Murray River, and with gaining and losing reaches of the river. The extensive length of the survey provides an insight into potential interactions between the river, floodplain and groundwater, but does not replace the need for focussed ground-truthing programs to examine specific correlations. This rapid, portable technique should be applicable outside the Murray-Darling Basin as well as at additional locations within the Basin.*

1 INTRODUCTION

1.1 Background

Increasing salinity in the River Murray is well documented and is of concern environmentally, economically and socially.

To mitigate the increasing salinity of the River Murray within a suitable time frame, Salt Interception Schemes (SIS's) have been established in areas where groundwater entering the River Murray is identified as carrying high salt loads. These areas have historically been identified through surface water salinity monitoring, based on continuous instream EC monitoring, and Run of River (ROR) surveys, which quantify the in-stream salt loads. Continuous EC recording measurement stations are located 10's of kilometres apart. They provide a record of salinity at a point in space but no details on where the salt comes from between stations. The ROR surveys measure near-surface river water electrical conductivity at 1 km intervals, suitable for assessing broad zones of high salt loads. However they are effective only during low, stable river flow periods. While these techniques have provided valuable information, they do not provide sub-kilometre resolution to target isolated remnant salt load inputs within existing SIS's or elsewhere along the river. The NanoTEM methodology was identified as having the potential to do so.

The Waikerie SIS has been operational for over 10 years. Telfer et al [2000] reviewed its performance, and recommended river bed pore water salinity measurements to identify where the SIS borefield was pulling fresh river water into the sediments (ie overpumping) and where riverbed sediments were saturated with saline groundwater (ie underpumping). In 2001 and 2002 [Barrett 2003] the use of a very early time Time domain ElectroMagnetic (NanoTEM) array towed behind a boat was trialled to remotely measure the river bed pore water salinity variations. The NanoTEM technique responds to variations in the electrical

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conductivity of the sediments within the top 5 to 25 m of sediments below the River Murray. Barrett [2003] tested Zonge Engineering's NanoTEM system and compared it to data analysed and reported by AWE. Results of the pilot study indicated that the NanoTEM data correlated with expected pore-water salinity patterns. The river-bed NanoTEM resistivity identified halos of higher resistivity that correlated with SIS bore locations, and appear to represent cones of substantially altered sediment water salinities around extraction bores. The trends in resistivity at depth also appeared to correlate to the salinity of water contained in the underlying Murray Group aquifer.

1.2 Survey aims and proposed outcomes

The successful trial at Waikerie, and subsequent additional trials at Loxton (SA), Mallee Cliffs (NSW) and Wentworth (NSW) confirmed the technique's potential. In 2004, Australian Water Environments (AWE), Zonge Engineering and Research Organisation Pty Ltd (Zonge) and the Department of Water, Land and Biodiversity Conservation (DWLBC) were engaged by the Murray Darling Basin Commission (MDBC) and the Mallee Catchment Management Authority (Mallee CMA) to collect base-line in-stream NanoTEM data within the River Murray from Blanchetown to Mallee Cliffs (river kilometres 275 to 950 - Figure 1). The primary intent of the study was to identify correlations between the NanoTEM results and the locations of gaining and losing reaches of the river; the location of major hydrogeological boundaries beneath the river; and the salinity of river-bed sediments.

Results from this survey will be presented in an "Atlas of Instream NanoTEM 2004" (Telfer et al, 2004a), illustrating the vertical resistivity profiles, maps of the resistivity values, and the relationships between the resistivity patterns and potential causes. Analysis is presented in Telfer et al (2004b).

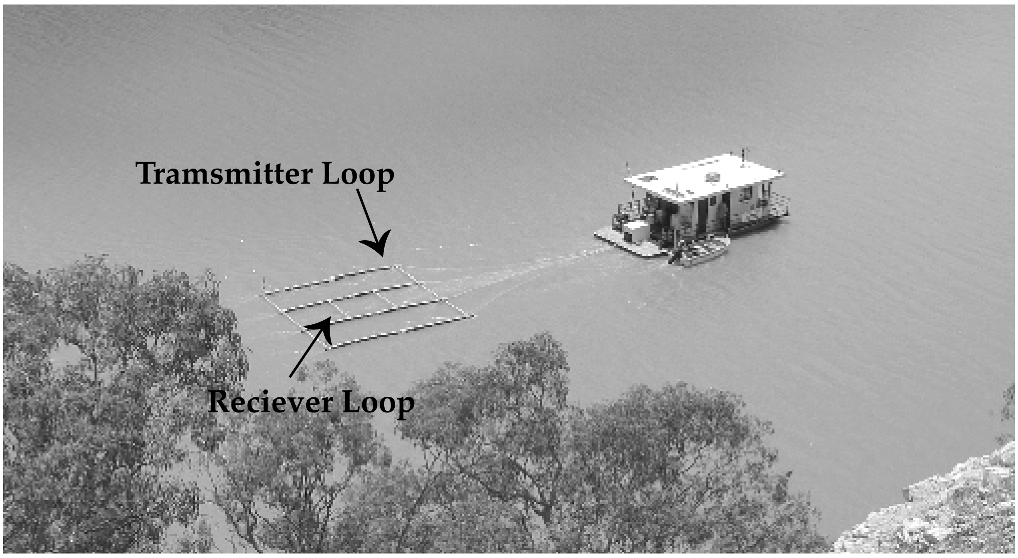
2 DATA COLLECTION & PROCESSING

On the 28th January 2004, Zonge Engineering and Research Organization (Zonge) mobilised a one person geophysical field crew and fast sampling transient electromagnetic (NanoTEM) equipment to the Murray River at Blanchetown, South Australia. The NanoTEM array was attached to a mobile platform (Figure 2) with two crew. Approximately 951 kilometres of NanoTEM data were collected over 18 production days. There was no significant down time and data quality was good. Demobilisation back to Adelaide was completed on the 16th of February 2004.

A Zonge multipurpose microprocessor-controlled GDP-32 II receiver was used to collect the data. Source fields were generated with a Zonge NT-20 NanoTEM geophysical transmitter set to transmit at 3.0 amps, powered by a 12-volt battery pack. The receiver provided control of the square-wave transmitter waveform. A 7.5 by 7.5 m NanoTEM transmitter loop was constructed of a single turn of 2.5 mm^2 copper wire, mounted on four floating pontoons with a stiff PVC frame. The 2.5 by 2.5 m receiving antenna was made up of a single turn of 2.5 mm^2 copper wire, and was mounted in the centre of the transmitter loop frame (Figure 2).

Data were acquired using a repetition rate of 32 hertz and a sampling period of 1.6 microseconds. The data were collected every four seconds, stacking 64 readings. With a boat speed of 6 km/hour, readings were taken every 6.7 metres along the river. Nearly 2 million data points were collected. DWLBC's Garmin 186 Plotter Sounder logged a non-differential position (WGS-84 geodetic datum) and water depth at approximately 10 metre intervals along the river. Both the NanoTEM and positional data sets were stored with a time stamp.

Unlocated, time-stamped data from the NanoTEM receiver were combined with time-stamped GPS location information, and then inverted using



STEMINV v3.01b (MacInnes & Raymond 2001) which transforms time vs. signal magnitude data (ie TEM field decays) into model resistivity as a function of depth assuming 1-D earth.

The TEM and bathymetry data were inspected using a Geographical Information System (GIS). Incorrect GPS easting and northing values were recorded almost every day and were removed from further processing. The data was gridded using a 40m by 1m grid, and contoured using kriging. For presentation, data is plotted as 30 km long by 20 m deep vertical strips, annotated with cultural features. The resistivity values closest to the river sediment interface were selected and plotted on 1:200,000 ale Landsat images.

3 ANALYSIS & INTERPRETATION

This paper presents only a small selection of the correlation analysis that has been undertaken. The results presented herein illustrate the overall consistency of the correlations between the NanoTEM response and key regional factors.

3.1 Theoretical considerations

Losing river reaches will be adding relatively fresh water to the groundwater system, and will appear as relatively resistive zones in the NanoTEM data. **Gaining** reaches will appear more conductive where more saline water is added to the river from the groundwater system. Subsurface clays are usually less resistive than sands. These broad patterns were expected in the NanoTEM results.

3.2 Influence of regional factors

Three regional factors are believed to have a strong influence on the pattern of instream NanoTEM resistivity values: direction and magnitude of groundwater flux relative to the floodplain; regional geology; and floodplain processes. These are discussed below. The implications for the observed NanoTEM response are discussed in Section REF _Ref81045266 \r\h 3.3.

3.2.1 Regional groundwater flux

The gaining/losing stream conditions are fundamentally controlled by regional groundwater gradients and flux. The regional groundwater gradients (both natural and irrigation induced) dictate whether the regional aquifers deliver water to the floodplain (gaining floodplain) or carry water away from the floodplain (losing floodplain). In gaining floodplain reaches, the magnitude of the groundwater flux to the floodplain influences whether the river exhibits gaining or losing stream conditions (see Section REF_Ref80675249\r\h 3.2.3).

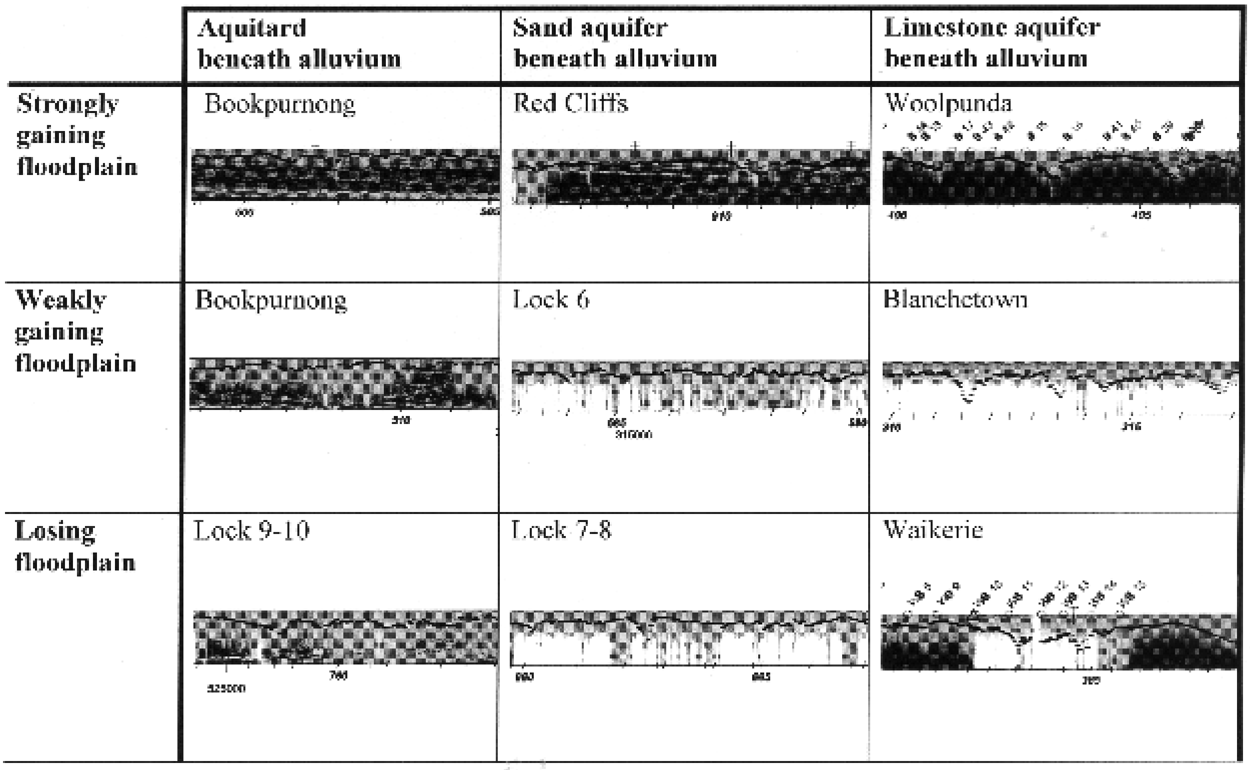


Figure 3: Stitched typical NanoTEM section (each strip is 20m deep and 7000m long), showing responses in relation to geology and groundwater flux. See Figure 4 for NanoTEM greyscale. Black line represents bed of river. Salt Interception Scheme bores are annotated.

3.2.2 Regional geology

The regional geology directly influences the NanoTEM response, with clays exhibiting very low resistivity and sands/limestones exhibiting moderate to high resistivities. Additionally, the presence or absence of regional aquitards influences where major gaining and losing floodplain reaches occur. Also, the presence of clay beneath the floodplain can isolate the floodplain from regional groundwater processes. As a consequence, local floodplain processes dominate the NanoTEM response (see REF_Ref80675249\r \h 3.2.3).

3.2.3 Floodplain processes

The floodplain is largely a net loser of water, via: evaporation from open water; evaporation through the soil, and; through evapotranspiration by vegetation. Where groundwater inputs are greater than the floodplain losses, gaining stream conditions and hence low sediment resistivities will occur. Where groundwater inputs are less than the floodplain losses (eg losing floodplain), losing stream conditions and hence higher resistivities will occur. Where losses roughly balance inputs (which is likely to occur above clays in gaining floodplain environments), the NanoTEM responses suggest both gaining and losing stream conditions in close proximity.

3.2.3 Discussion of NanoTEM response

The instream resistivity patterns reflect the interplay between these three regional factors. Samples of the observed patterns and their relationship with variations in groundwater flux and regional geology are illustrated in Figure 3, correlated to the regional groundwater flux and regional geology patterns.

3.2.4 Strongly gaining floodplains

Strongly gaining floodplains have gaining streams. Where groundwater salinities are high, resistivities are typically <3 Ωm. Where groundwater salinities are low (eg. in areas of irrigation drainage returns) the resistivities are ~20Ωm.

3.2.5 Weakly gaining floodplain over aquitard

Weakly gaining floodplains (ie characterised by low hydraulic gradients) underlain by aquitards are typified by high frequency oscillations in resistivity caused by local flow patterns. The rapid variation of the resistivity is attributed to the clay aquitard isolating the alluvium from the regional aquifer. Where the alluvium is isolated from the regional aquifer, the direction of regional flux may be retained (ie into or out of the alluvium) but the magnitude of the flux will be considerably diminished. In a diminished regional flux, local flow systems within the alluvium will predominate. These local flow systems can be induced by: flow through alluvium short-circuiting across meander loops; evaporation through the soil surface and evapotranspiration through floodplain vegetation, and; lateral flow through the floodplain alluvial sediments, with discharge to an adjacent wetland/lagoon complex.

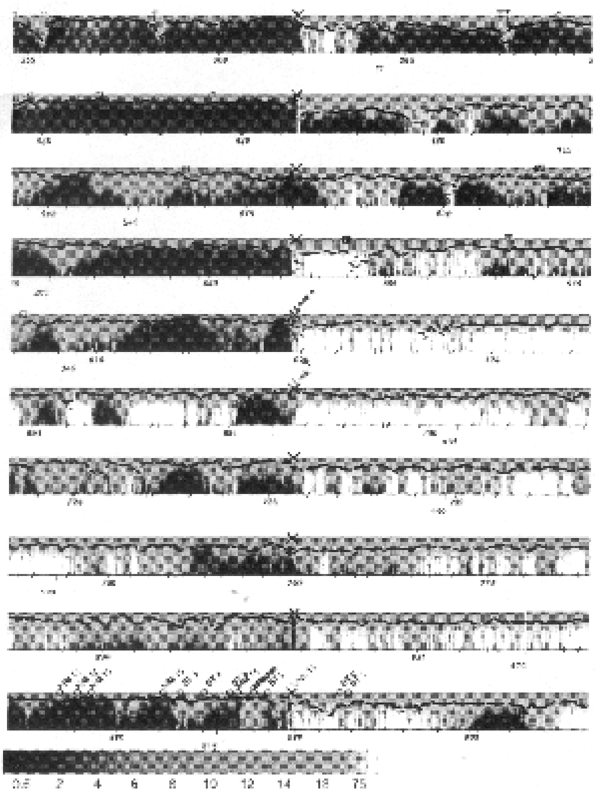


Figure 4: NanoTEM responses at Locks. NanoTEM resistibity value in Ω.m, scale at bottom.

3.2.6 Weakly gaining floodplains over aquifers

Weakly gaining floodplains tend to contain losing streams, indicating that the evaporative and evapotranspirative fluxes through the floodplain soils and water bodies exceed the regional groundwater flux. The additional water requirement to the floodplain is derived from stream losses. High resistivities are typical.

3.2.7 Losing floodplains

Losing floodplains contain losing streams. High resistivities are typical. Note that the only losing river section over limestone occurs within the Waikerie SIS where slight overpumping of the scheme has induced flow of river water down into the sediments (Figure 3).

3.2.8 Influence of locks

The difference in pool level across the Locks (up to 3.5m) establishes a hydraulic potential for flux out of the river upstream of the Lock, and flow into the river downstream of the Lock. This provides an opportunity to examine the influence of flux (direction and magnitude) without complication from changes in regional hydrogeology.

The patterns of resistivity are largely consistent from lock to lock, and with the observed patterns of resistivity strongly correlated with expected and known patterns of flow.

3.2.9 Responses Upstream of Locks

The observed NanoTEM response upstream of all Locks (except Lock 4) are resistive. The resistive response extends up to a kilometre upstream, suggesting that river water is lost into the floodplain over that distance. This is consistent with groundwater modelling results and flow net analyses.

Locks 2, 5, 6, 7, 10 and 11 show high resistivities, correlated with losing stream conditions, upstream of the Lock. The upstream extent of the losing stream conditions at Lock 2, where the floodplain is generally strongly gaining, is around 1.5 km.

Locks 8 and 9 show significant variation in resistivity values, suggesting occurrence of clay at depth. This conclusion is supported at Lock 8 by regional mapping results (Thorne *et al* 1990), however clay is not mapped beneath the alluvium at Lock 9. Lock 9 is located immediately downstream of the outfall from Walpolla River, and the low resistivity response may be caused by inflow from the Walpolla anabranch.

NanoTEM responses for Lock 4, located at Bookpurnong, are conductive both upstream and downstream of the Lock. It is suggested that the Bookpurnong groundwater mound overwhelms the usual upstream-of-Lock response. The very low resistivities upstream of the Lock correlate strongly with observed groundwater gradients on the flank of the Bookpurnong groundwater mound [Hopkins and others [2003]. Gaining stream conditions at Lock 4 correlate well with known and modelled patterns of groundwater discharge to the River.

Lock 3 is located immediately upstream of the Woolpunda SIS. The low resistivity values suggest either the presence of clay beneath the alluvium (the Winnambool Formation can be inferred to be present at this location) or of saline groundwater discharge into the river upstream of the Lock. The Run-of-River results do not indicate salt loads immediately upstream of the Lock, and it is >2 km from the closest irrigation. The most likely explanation is clay at depth, coupled with only weak fluxes out of the river.

3.2.10 Downstream of locks

Conductive features occur downstream of all Locks, suggesting that the fresh river water either does not return into the river channel, or it returns in relatively small quantities mixed with regional saline groundwater

All Locks have low resistivity values downstream of the Lock, which correlates well with groundwater inflow. Where Locks are located in losing stream reaches (eg Locks 6 to 9) there is a consistent length of gaining stream (0.5 to 1 km in length) downstream of the Lock. Lock 6 and Lock 9 show additional reaches of low resistivity, however this can be correlated with the focussing of regional groundwater flow to reaches of the river downstream of the Lock. The focussing of flow is caused by a head difference across the Lock, with the regional flow displaced downstream where the groundwater levels are not held up by the flow around the Lock. Lock 10 appears to have only minor inflow downstream of the Lock. The Buronga and Mildura-Merbein SIS's influence the observed resistivities below Lock 11.

4 CONCLUSIONS

The 2004 Instream NanoTEM survey has demonstrated a promising new application for time domain EM technology along the nation's most important waterway. Strong correlations are noted between the observed NanoTEM response and other available data sets (such as studies conducted at Bookpurnong, Waikerie and Sunraysia). The Instream NanoTEM survey clearly maps gaining and losing reaches of river, and subsurface hydrogeologic boundaries. Quantifying flux using NanoTEM is problematic, although preliminary results suggest that where the flux is well quantified a relationship can be determined with observed resistivity.

The 575 km of survey provides a surrogate for ground-based mapping methods (for example, drilling). It does not replace the need for focussed programs to examine specific patterns and processes. Suggested high priority follow-up activities include a scout hole program to confirm the presence / absence of aquitards beneath the river, and piezometer installation to measure heads and salinities at selected locations. Further NanoTEM surveys will be of use in the major anabranches (such as at Chowilla, Lindsey River, and Walpolla Creek).

The towed – time domain EM technique is rapid, portable and should be applicable outside the Murray-Darling Basin as well as at additional locations within the Basin.

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