GROUND-TRUTHING OF A TEMPEST AIRBORNE ELECTROMAGNETIC SURVEY IN THE SALINISED KAMAROOKA CATCHMENT, NEAR BENDIGO IN CENTRAL VICTORIA.

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INTRODUCTION

The Kamarooka catchment near Bendigo in central Victoria is badly affected by dryland salinity. Since the 1940s the area of saline discharge has rapidly expanded from small patches of failed crop to a large southwest–northeast trending strip approximately one kilometre wide and eight kilometres long, incorporating 900 hectares of previously productive agricultural land (Figure 1). The Kamarooka area has been the subject of a high-resolution Airborne Electromagnetic (AEM) survey (TEMPEST) (Fugro Airborne Surveys 2000), because it represents a relatively well-studied salinised catchment from which background hydrogeological data was available (e.g., Dyson & Jenkin 1981).

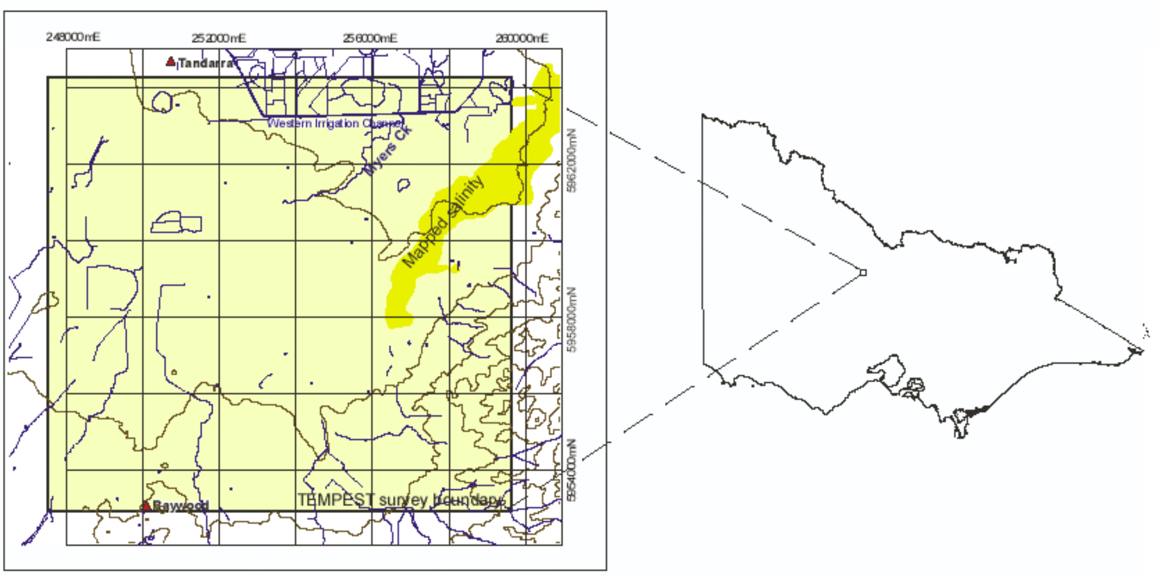

Figure 1: locality map showing the TEMPEST survey area and extent of mapped salinity.

The TEMPEST system produces accurate three-dimensional sub-surface conductivity images (Lane *et al.* 2000), which can be displayed as conductivity depth slices, iso-conductivity surfaces and cross-sections. TEMPEST was flown at Kamarooka in an attempt to use the sub-surface conductivity to map the three-dimensional distribution of saline groundwater.

Most rock and soil materials are electrical insulators of high resistivity, with electrical current being carried by the passage of ions in pore waters (Kearey & Brooks 1991). Earth resistivity (ρ) is described by Archie's equation:

$$\rho = a\phi^{-b} f^{-c} \rho_w$$

where ϕ is porosity, f is the fraction of pore space filled with water of resistivity ρ_w, and a, b and c are empirical constants. It follows that earth conductivity (the inverse of resistivity) is a function of both porosity and pore water salinity.

This investigation aims to provide a ground-truthing of the TEMPEST dataset, by comparing the groundwater Electrical Conductivity (EC) data obtained from bores during the present study, with the earth conductivities measured by TEMPEST.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Kamarooka area straddles Victoria's upland front and therefore incorporates both the basement Ordovician metasedimentary rocks of the Western Uplands and the overlying Quaternary alluvium of the southern Murray Basin, which has covered all but the most elevated areas of the Ordovician basement.

Topography is very subdued, with maximum relief across the study area of less the 60 m. Local groundwater flows to the northwest, from the rolling hills of the Ordovician uplands out into the alluvial Riverine Plain. Surface drainage is to the north as poorly defined ephemeral streams; swamps (currently dry) characterise the lowest parts of the study area.

SUB-SURFACE CONDUCTIVITY STRUCTURE

The TEMPEST images from Kamarooka show that at shallow depths of 0-14 m the conductivity structure has a broad northeast-southwest orientation (Figure 2), approximately parallel to the junction between the Ordovician metasediments and the Riverine Plain, with higher conductivities associated with the Riverine Plain sediments.

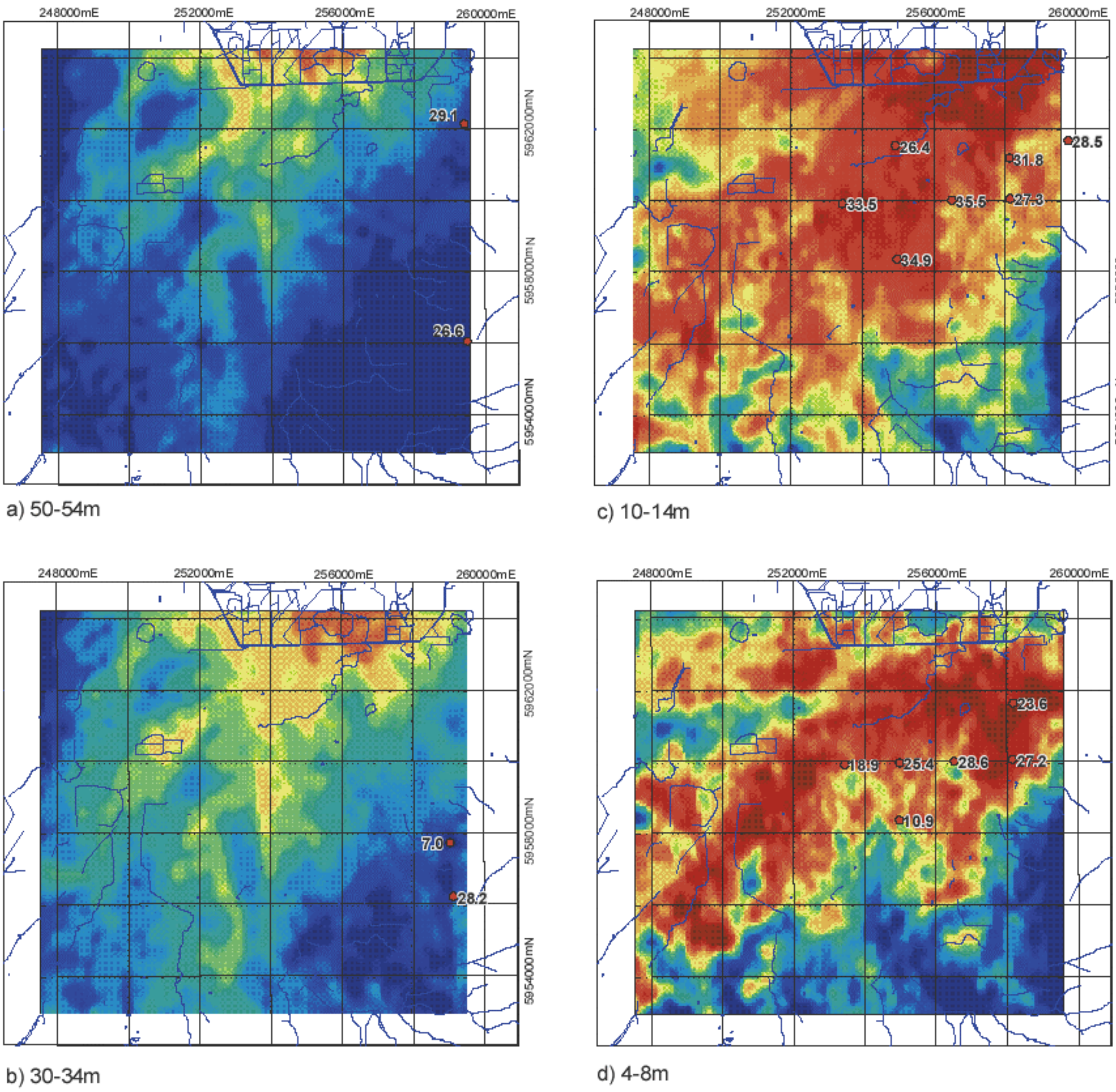

Figure 2: TEMPEST AEM survey imagery for the Kamarooka catchment, central Victoria. **Figures 2a - 2d** show the conductivity-depth intervals corresponding to the screened intervals of groundwater monitoring bores throughout the survey area. Bores are labelled with their respective groundwater. Electrical Conductivies (EC) in mS/cm.

At depths greater than 14 m, the conductivity structure begins to look markedly different, adopting a more north-south orientation. With increasing depth the pattern becomes distinctly dendritic, indicating the presence of a palaeo-drainage system, the orientation of which is closely analogous to, but more strongly defined than the present day surface drainage. Such features have also been readily discernible in other TEMPEST datasets (e.g., Lawrie *et al*. 2000, Dent *et al*. 2002).

The basement topography may also be detected by the onset of lower conductivities with depth, and below this, the depth where conductivities become their lowest may approximate the base of saturated zone, or where effective porosity becomes negligible.

The palaeo-drainage at Kamarooka becomes clearly evident at ~20 m depth and continues to depths exceeding 70 m, indicating progressive infill of topographic relief during Tertiary times. If groundwater at depth is moving preferentially through the palaeochannels, then it is flowing in a more northerly direction than the groundwater closer to the surface, which flows to the northwest in this area.

The palaeo-drainage may be visible in the AEM dataset either because it hosts anomalously saline groundwater, or because it has greater porosity (and therefore contains larger volumes of groundwater) than the surrounding sediments. However, closer to the surface porosity might be expected to be more uniform, so the shallow AEM pattern may reflect the presence of anomalously saline groundwater.

Whether TEMPEST is detecting variations in groundwater salinity or aquifer porosity is precisely the issue that requires resolution. If porosity variations are dominant, then TEMPEST may be of little use in mapping the distribution of saline groundwater. If however, groundwater conductivity variations are visible in the data, TEMPEST may prove invaluable in mapping current and future occurences of dryland salinity.

GROUND-TRUTHING

The groundwater salinity distribution at Kamarooka, as measured from bore water samples, was compared with the earth conductivity determined by TEMPEST, using four conductivity depth slices, chosen to correspond with the screened intervals of available groundwater monitoring bores. The depth slices produced by TEMPEST were calibrated using a down-hole electromagnetic technique (EM-39; Fugro Airborne Surveys 2000), applied to 11 bores throughout the survey area. Thus the depths of the conductivity slices are assumed to be accurate.

At a depth interval of 50-54 m (Figure 2a), the groundwater salinity has little in common with the distribution of TEMPEST conductivity, with localities shown as having low earth conductivies corresponding to areas where pore water salinities are high (~ 28 mS/cm). Both bores at this depth screen the Ordovician metasedimentary basement, which has low inter-granular porosity (Dyson & Jenkin 1981), matching the low TEMPEST response. The component of earth conductivity due to pore water salinity at this depth is clearly undetectable.

At 30-34 m below the surface (Figure 2b), groundwater electrical conductivities are separated by an order of magnitude, but fail to induce a detectable earth conductivity response. Pore water salinities of 7.0 and 28.2 mS/cm correspond to regions of equally low earth conductivity. Again, the earth conductivity distribution is dominated by porosity.

Between 10 and 14 m (Figure 2c), saline bore waters (26.4 – 35.5 mS/cm) correspond to high earth conductivities. However, this correlation should be viewed with caution. These bores screen the Quaternary sediments of the Riverine plain, a sequence of considerably higher inter-granular porosity (Hekmeijer *et al*. 2000). Thus the TEMPEST response may merely reflect the fact that sediments of higher porosity now host the saline groundwater body.

At 4-8 m depth a similar situation exists, with a reasonable overall correlation between groundwater and earth conductivities (Figure 2d). However, some discrepancies are evident, with groundwater salinities of 10.9 mS/cm and 28.6 mS/cm both corresponding to areas of high earth conductivity. Thus at Kamarooka salinity variations of the order of 5-20 mS/cm are undetected by the TEMPEST data.

However, in the Billabung Creek catchment of southwest New South Wales, Braaten *et al*. (2002) found that differences in groundwater salinity of as little as 3 mS/cm (corrected after Braaten *et al*. 2002) can induce changes in earth conductivities detectable by TEMPEST. It may be that at Kamarooka porosities are altogether too low or too variable for changes in groundwater salinity to appreciably or systematically affect the measured earth conductivity.

Nevertheless, the saline discharge zone is identified quite effectively by shallow TEMPEST images (Figures 2d, 3), although at the same depth a large swath of similar conductivities does not correspond to areas of saline discharge. Lawrie *et al*. (2000) and Dent *et al*. (2002) have noted similar phenomena and concluded that these areas may correspond to high groundwater salinities. Whether these adjacent areas of high conductivity at Kamarooka correspond to anomalously saline groundwater is also uncertain, as there are no groundwater monitoring bores within them.

In cross-section (Figure 3) it is clear that the overall distribution of saline groundwater at Kamarooka does not correlate well with the distribution of earth conductivities measured by TEMPEST. In particular, TEMPEST data indicate a declining conductivity with depth. This is probably due to decreasing porosity, and not decreasing groundwater salinity, which remains fairly constant with depth (Figure 3).

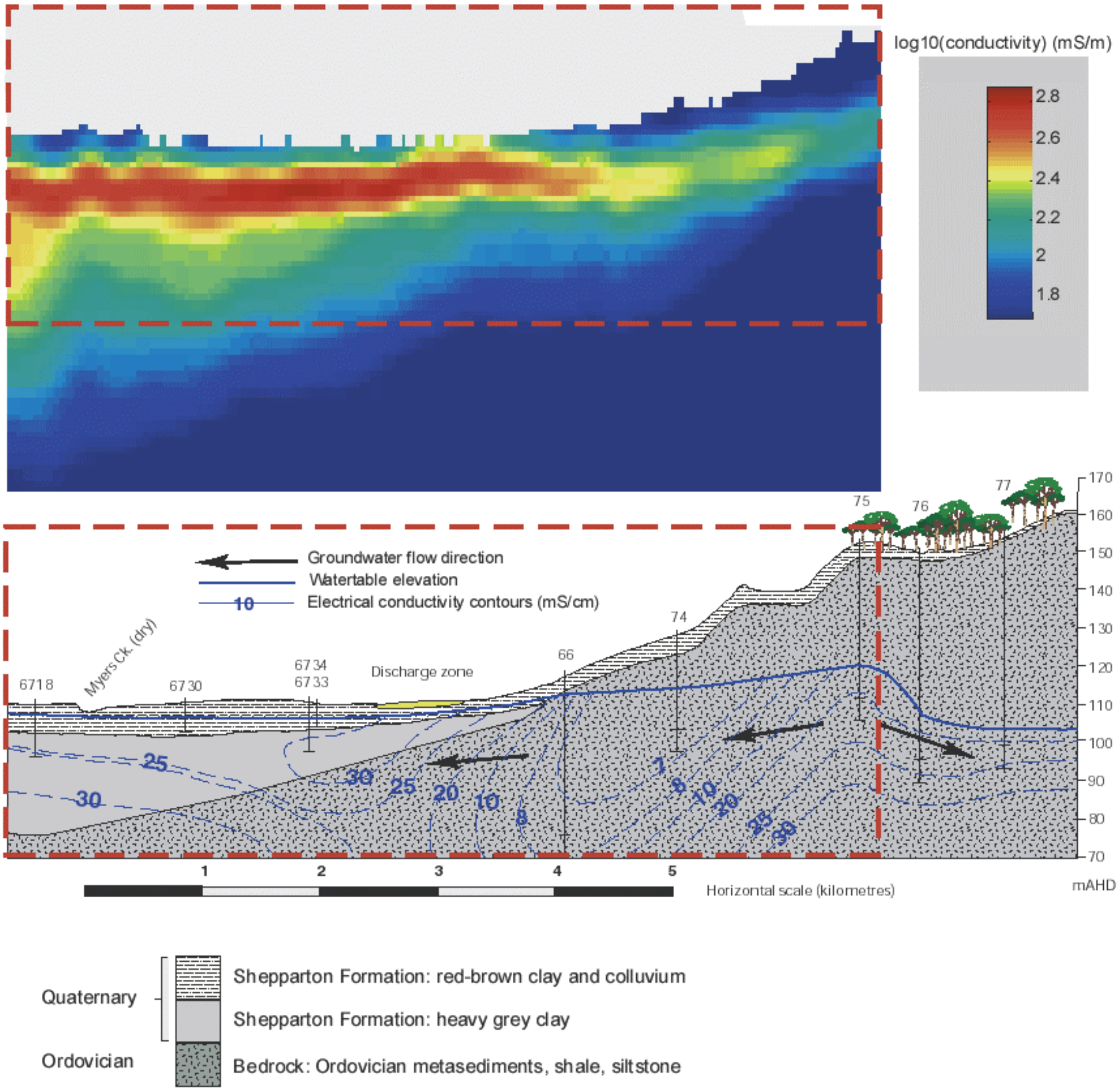

Figure 3: Cross-section comparison between TEMPEST conductivity and groundwater salinity. The distribution of TEMPEST conductivity does not resemble the distribution of groundwater salinities, however the discharge zone appears to be detected. Note: Cross-sections have slightly different orientations. The dashed line defines the directly comparable areas of the sections.

There is a strong near-surface conductor within the sediments of the Riverine Plain at depths of approximately 10-15 m (5-10 m below the watertable). Borehole EM39 conductivity logs (Fugro Airborne Surveys 2000) also indicate high conductivity at this depth. Bore water salinities are high throughout these sediments; there is no evidence that they are particularly high 10-15 m below the surface. Instead, this conductor may correspond to the top of a heavy textured grey clay unit, ~25 m thick, that is encountered in bore logs at about this depth (CLPR n.d.). Clays often have very low resistivities (high conductivities) compared to other sediment types (Kearey & Brooks 1991). However, the thickness of this conductor (~10 m) is much less than the thickness of the clay unit (Figure 3). This may be an artifact of the data processing, as thick and moderately conductive bodies can be spuriously transformed into thinner bodies of higher conductivity during the inversion process (R. Musgrave *pers. comm*. 2002).

DISCUSSION AND CONCLUSIONS

The current ground-truthing indicates that TEMPEST conductivities at Kamarooka have a strong porosity dependence, and that TEMPEST imagery is not a simple proxy for groundwater salinity. In terms of the relationship between groundwater salinity and TEMPEST conductivity, a simple and direct link does not exist at Kamarooka. In low porosity media, such as the Ordovician basement, it is apparent that TEMPEST data cannot detect the presence of high-salinity groundwater. Although there is a reasonable correlation between a strong near-surface conductor and high groundwater salinities within the sediments of the Riverine Plain, the high conductivity is most likely related to the presence of a clay layer.

Overall, the three-dimensional earth conductivities measured by TEMPEST show a far more heterogeneous distribution than that of the groundwater salinity. This is most evident in cross section, where a decline in TEMPEST conductivities with depth is unrelated to the groundwater salinity, which is reasonably constant, and most likely reflects the low porosity of the basement rocks at depth.

The porosity dependence of the earth conductivity data means, however, that TEMPEST can resolve the physical hydrogeology of the Kamarooka system. The palaeo-drainage system identified on the TEMPEST images almost certainly represents a network of preferential groundwater flow. The lower limit of effective groundwater transmission, possibly parallel to the basement topography, also appears to be shown by the onset of relatively low conductivities at depth (e.g., Figure 3). Thus, TEMPEST imagery may be of considerable use in general groundwater studies, although its interpretation is not straightforward.

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