GAMMA-RAY REMOTE SENSING OF SALT SOURCE MATERIALS IN THE MURRAY-DARLING BASIN

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Abstract

Previous studies by the author indicated that dry-land salinity outbreaks in NSW appeared to be associated with a particular gamma-ray emission signature. This study draws on new data to explain the phenomenon and to develop a model that can assist salinity management on a regional scale. The work involved compiling a mosaic of airborne gamma-radiometrics across the Murray-Darling Basin (MDB) and analysing this together with existing airborne geophysics and drilling data. A significant correlation was found between aeolian (wind-blown) materials, upland salts and the geophysical signatures of both airborne gamma-radiometrics and airborne electromagnetic (AEM) data. This is consistent with the conceptual model that much of the salt in the upland areas of the MDB is sourced from deposited aeolian materials that are derived from salt-bearing landscapes in the western arid part of the basin. Analysis of borehole data provided a characteristic gamma-radiometric signature for aeolian salt-sources. This signature was used to derive a continuous classification of upland salt-source from the airborne data mosaic. The major area of modelled aeolian salt-source materials forms a fragmented arcuate body stretching from northern Victoria to north-central NSW that is consistent with aeolian deposition from a dominant westerly dust path. The combined modelling and analysis of AEM and gamma-ray data provides a better understanding of salinity in relation to geological materials in the landscape. The new model offers an inexpensive management tool utilising existing data, although it may require further validation and refinement.

Introduction

Dryland salinity is recognised as a major problem in the Australian landscape affecting both economic productivity and biodiversity. Although surface salinisation has been readily identified in numerous catchments, the scope of the problem, future risk and management options are less clear. Much recent work has focussed on identifying the location of salt stores and mobility pathways using geophysical data, particularly Airborne Electromagnetic (AEM) surveys (Dent, 2003) although AEM does not differentiate between mobilised salt and salt-sources. Identifying and mapping sources of salt is fundamental

for salinity management yet has not been achieved at the regional or catchment scale.

In the south-eastern uplands of the Murray-Darling Basin (MDB), a common conception has been that salt is sourced from the whole landscape, being present in the overall geology or groundwater systems. This includes connate salts coincident with deposition (as in marine sediments) or salts derived from subsequent weathering processes. More recently, it has become accepted that salts have been introduced to the landscape rather than being derived insitu from bedrock. This can be by rainfall accessions with evapotranspiration causing accumulation of oceanic cyclic salts in the soil profile. Salts can also be associated with silty clay deposits derived from wind-blown sources (Bowler,1983; Acworth *et al*, 1997 and Evans, 1998) and this mechanism of aeolian deposition of salts is the focus of this paper. A new mapping technique, utilising airborne gamma-radiometrics, for locating aeolian salt sources is presented and validated by comparisons with other datasets in specific catchments. This work is covered in detail in the BRS report (Bierwirth and Brodie, 2006), which includes a comprehensive review of Aeolian deposits and their occurrence in the Murray-Darling Basin, and summarised in Bierwirth and Brodie (2008).

Evidence for aeolian deposit salt sources in the MDB

Although it is often difficult to identify the aeolian component of soils, aeolian dust deposits have commonly been observed in the MDB (Butler; 1956, Beattie, 1972; Bowler, 1976; Chartres *et al*, 1988; Chen, 2001). These are often red silty clays that form a continuous mantle, particularly in high plains (Chen, 2001). Another characteristic is a bi-modal particle size distribution with peaks in the clay and coarse silt fractions

The arid interior of Australia consists of desert landforms such as dune fields and playa lakes which are a vast reservoir of dust material and salt. Episodic dust storms originating from inland areas are vectors for sediment transport. In south-eastern Australia, the major wind systems are to the east, enabling aeolian deposition on the eastern flanks of the Murray-Darling Basin and beyond (Greene *et al*, 2001) (see Figure 1). Paleo-environmental studies of Quaternary landforms and sequences suggest that such processes and dust paths have persisted over the past 500,000 years (Bowler, 1976; McTainsh, 1989). For example, Lake Bungunnia was formed in the Murray Geological Basin during the Late Pliocene (~2.4 Ma) and covers an area of 33,000 km^2 (Stephenson, 1986) The onset of arid conditions is reflected in overlying gypsiferous evaporitic sediments indicating hypersaline conditions as well as aeolian sands. These deposits and their modern equivalents represent a major reservoir of clays and salt that was made available for aeolian transport eastwards by prevailing winds (Stephenson, 1986). The extent of the dune fields of the Mallee region provides testament to the dominance of aeolian processes since the demise of Lake Bungunnia. These dune fields can also be viewed as the proximal coarser equivalents of the distal finer aeolian deposits found in the upland areas to the east.

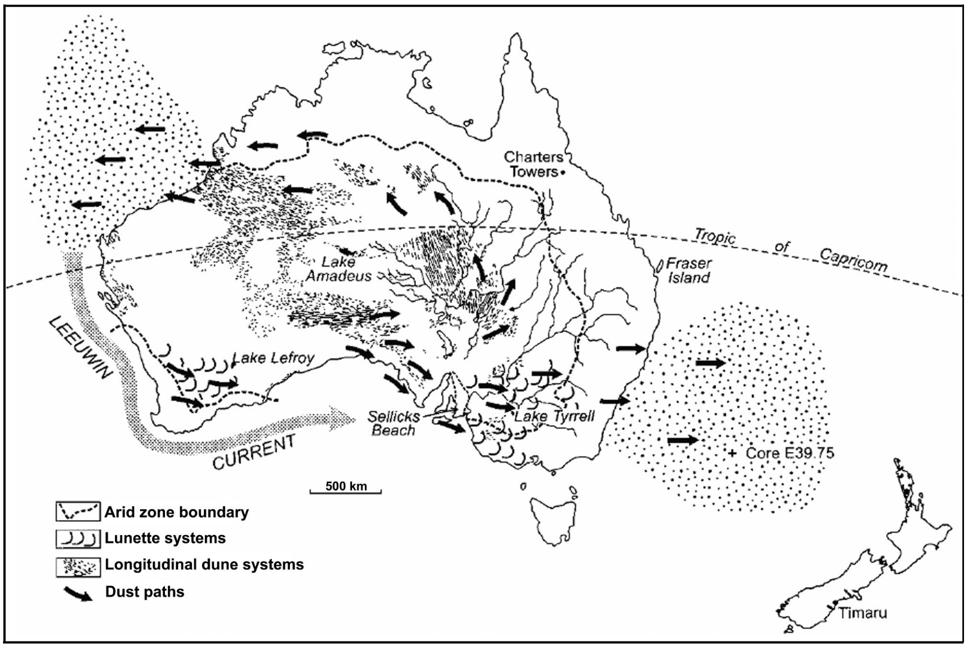

Figure 1. Arid-zone boundary, lunette zones, dune systems and dust paths after Bowler (1976) and McTainsh (1989). Figure from Pillans and Bourman, 2001.

It has been postulated that salt accompanying dust derived from the Murray Geological Basin is the principal source of salts found in the uplands region of the Murray-Darling Basin (Bowler, 1983). Investigations in some of the south-eastern upland catchments of the Murray-Darling Basin provide evidence for the linkage between aeolian deposits and salt (Evans, 1998; English *et al*, 2002).

Application of gamma radiometrics to mapping aeolian salt-source materials

Airborne gamma-spectrometry (AGS) is a profiling system, flown along lines and collecting point measurements, at low altitude, of gamma-ray emission in multiple wavelengths. It is comparable to other spectral remote sensing techniques in that it collects hyperspectral information in the gamma-ray range of the EM spectrum (very short wavelengths). Gamma-ray emissions are mostly derived from three radioactive elements that are present in rocks and soils - potassium (K), thorium (Th) and uranium (U). Data processing provides spatial images of these elements and reflects the geochemistry of the upper rock/soil layer to a depth of about 30-45cm. Although lacking in depth of penetration, the distribution of these element concentrations at the surface can often be interpreted and, to some extent, classified to show soil types and subsurface properties (Bierwirth, 1996). Gamma elements concentrations are generally related to bedrock, weathering and sediment transport processes so that mapping models can often be derived by combining AGS data with geology and terrain.

A relationship between AGS data and salinity was initially observed near Wagga Wagga (Bierwirth, 1996) where salt scalds fell within low K areas (Figure 7a). This area is contained within Ordovician metasediments where high K relates to bedrock signatures of the shallow lithosols. Although an inverse relationship was observed between EC and K, it was thought that the

low K was associated with areas of clay linked with increased weathering and salt accumulation.

In the Billabong Creek area, McKenzie and Gallant (2005) used airborne gamma K and topographic indices to map aeolian soils that English et al (2002) suggested were salt-source materials. Dickson and Scott (1998) found that red aeolian soils in the Blayney district, NSW, had a characteristic gamma-radiometrics signature of 0.7% K, 2 ppm U and 11 ppm Th.

Based on previous work, there does appear to be a case for both aeolian sources of salt and the potential for gamma-radiometrics to identify these regionally. This is particularly the case in south-eastern Australia where there is substantial evidence for westerly aeolian transport from a large inland reservoir of salt for at least the last 350,000 years.

To investigate this concept, it was necessary to acquire AGS data and analyse these in relation to available borehole data with the intent of constructing a model for spatially characterising salt sources. Airborne radiometrics data for the Murray-Darling Basin were downloaded from the Geophysical Archive Data Delivery (GADDS) system at Geoscience Australia. This included image data of the three gamma emitting elements (K, Th and U) for 94 individual airborne surveys. A mosaic, with a pixel size of 100m, was created for each of the three elements over the spatial extent of the basin.

Comparison of AGS and borehole salinity data

As part of the MDBC airborne geophysics project (Dent *et al*, 2003) a series of bores were drilled with the aim of verifying and calibrating airborne EM (AEM) data-sets. Samples from these bores, often drilled through to basement rocks, were analysed for geophysical and chemical properties including salt (EC 1:5 soil extracts). This data were then used to assess landscape relationships between salt distribution and the airborne gamma-radiometrics data.

For this analysis it was decided to analyse only upland areas since the gamma-ray signatures of transported alluvial materials may intersect salt accumulations associated with sediments that do not relate to the original salt source. In upland areas there is more likely to be a correlation between the gamma-radiometrics and salt, where salt-bearing sources and relatively salt-free areas are present. Selection of upland boreholes for further analysis was based on the Multi-Resolution Valley Bottom Flatness (MRVBF) index (Gallant and Dowling, 2003) which is derived from topographic modelling of a digital elevation model (DEM). An index of MRVBF < 2.7 was used to define erosional uplands (McKenzie and Gallant, 2005). Those boreholes defined as upland were from only two AEM survey areas at Billabong Creek and Billabung Creek, both in NSW (see Figure 2).

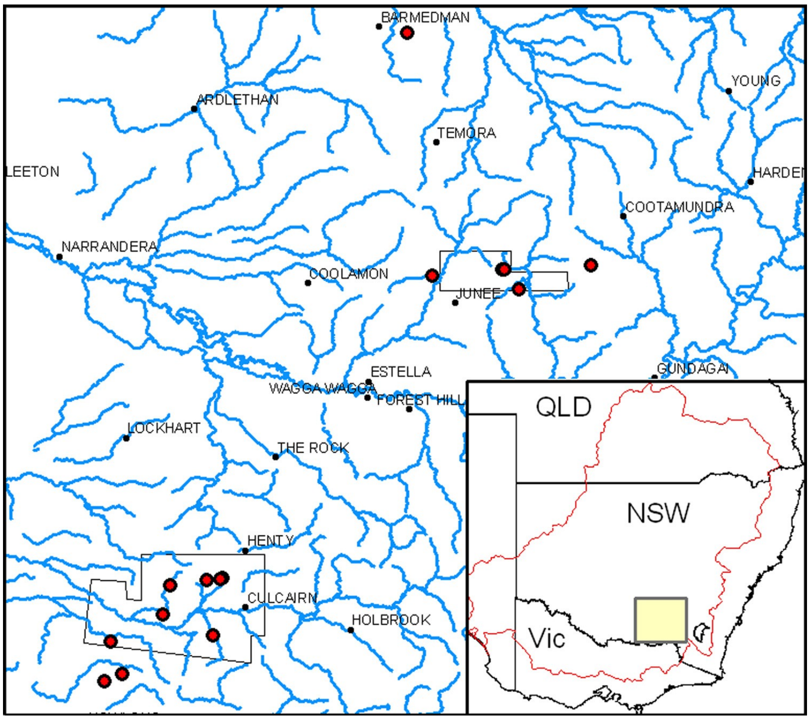

Figure 2. Location of upland boreholes produced from the MDBC airborne geophysics project. Outlined are AEM surveys at Billabong Ck (bottom-left) and Billabung Ck.

In order to avoid errors in calibration between AGS data-sets at this stage, only the boreholes from a single radiometrics data-set (at Billabong Creek) were analysed. Pixel values for gamma-element concentrations and upslope averages relating to the representative Billabong Creek boreholes and for all elements, are shown in Figure 3. These values are compared with the average EC 1:5 (soil extract) for the cover combined with the top 15m of saprolite. This zone of saprolite was included due to the general observations of higher EC 1:5 values at this depth, interpreted to be due to salt infiltration into the weathered bedrock. A broad negative relationship is observed for both K and Th and this had been expected (particularly for K) based on earlier observations. The U data is less clear due to low-count noise and were not presented. Given the broad footprint of airborne measurements, the relationships are likely to improve by the collection of ground-based or in-hole gamma-ray measurements.

Given that salt in deep boreholes is likely to be sourced from materials that are upslope from the site, regions of interest were drawn to include up-slope colluvial sediments with a maximum distance of 1km. The upslope values of K corresponding to each hole can be compared with insitu values (Figure 3). The upslope relationship is generally improved and these results indicate that upland salt storages can broadly be estimated using the airborne K and Th data. Some variation can be explained by geological influence on AGS signatures. For example, borehole BC 1 is in a foot-slope area of quartz-sandstone hills and has a correspondingly low K value (similar to saline aeolian soils), particularly for the upslope area that relates to low K sandstone outcrops. The same site has a low Th value relating to the quartz sand content, and this is much lower than the aeolian saline soils. Conversely one site with

low salinity in metasediments (BC 11) has a similar Th signature to aeolian soils but a contrasting K signature. With the data trends in Figure 3, it appears possible to derive an index from both K and Th that might differentiate saline aeolian soils.

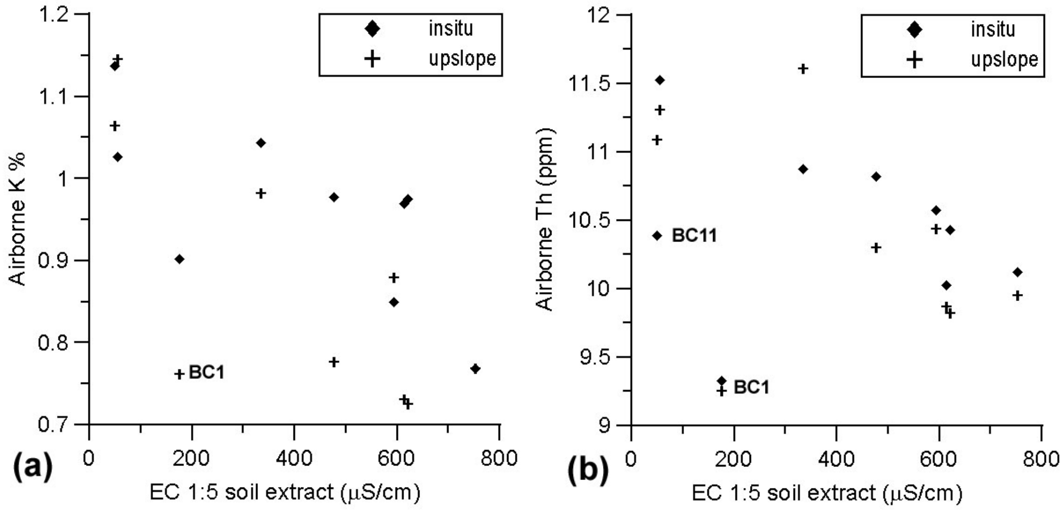

Figure 3. (a) Upland airborne K pixel values for boreholes versus the average EC 1:5 for the cover including the top 15m of saprolite for nearest value and averaged upslope from the borehole (b) same for airborne Th.

Generating a salt source model

A simple model is achieved by calculating the Euclidean distance (E_D):

$$E_D = \sqrt{((K_i - K_t)^2 + (Th_i - Th_t)^2)} \quad (1)$$

where (K_i Th_i) are the radiometric data values for i^{th} pixel and (K_t Th_t) is the target value for the saline aeolian soils end-member. Prior to this calculation, the K data was transformed so that the mean and standard deviation equalled those for the Th data. A target value of 0.7% K and 10ppm Th for saline aeolian soils were obtained from Figure 3. Using equation 1 above, E_D was calculated and pixel values extracted for upland boreholes for both the Billabong Creek and Billabung Creek areas (see Figure 2 for location). These were plotted against EC 1:5 (soil extract) data which were averaged for the cover material including the top of the saprolite (Figure 4). In general there is a much better correlation between E_D and upland salinity than for the individual elements K and Th, as depicted in Figure 3. Apart from the borehole BC1, whose distance appears to be still influenced by the gamma-ray signature of sandstone soils, pixels with a Euclidean distance (to the target signature) of less than 1 generally have an EC 1:5 (soil extract) > 400 uS/cm, a value that, although not quite a saline soil, represents a substantial salt-source. A soil with EC 1: 5 of 700 uS/cm is considered saline with respect to the viability of crops (Baskaran Sundaratnam pers. com.), although lower values could potentially indicate salt source materials.

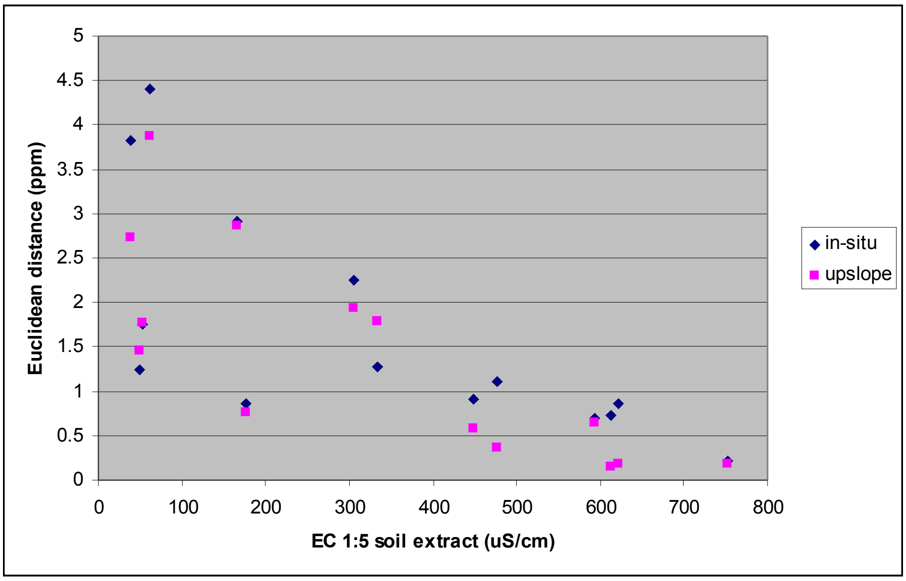

Figure 4. Correlation between EC 1:5 of the soils in upland boreholes to the Euclidean distance from pixel values to a specified target value of K and Th for saline aeolian soils.

Using the linear relationship between E_D and EC 1:5 from Figure 4, the available radiometrics E_D data for the basin were converted to EC 1:5 of the soil for upland areas. The model was then run and a threshold applied at EC 1:5 (soil extract) > 430 uS/cm with the results overlain in red on a shaded DEM (Figure 5). The major area of saline aeolian materials derived from the AGS analysis forms a fragmented arcuate body stretching from northern Victoria to north-central NSW (Figure 5). This fits with dominant westerly wind paths sourcing material from the inland arid parts of the Murray Geological Basin (Figure 1). Figure 5 also shows the distribution of the AGS-modelled aeolian deposits downwind of the ancient Lake Bungunnnia and the dune fields and playa lakes that make up the landscape in this area today. Aeolian deposition occurs when the dust plume encounters decreasing wind velocity or turbulence due to changes in land surface roughness (such as vegetation or hilly terrain) or wash out due to rainfall (Pye, 1984). The arcuate distribution along the eastern flank of the basin corresponds to where the topography becomes more undulating, vegetation more significant and rainfall higher, when compared with the flat arid landscape to the west.

Comparison with AEM study areas

As shown in Figure 4, borehole data suggests that aeolian deposits and soils with close-to-target gamma-ray signatures have elevated salt contents. As discussed earlier, the borehole data were associated with airborne EM surveys conducted as part of the MDBC airborne geophysics project (Dent *et al*, 2003).

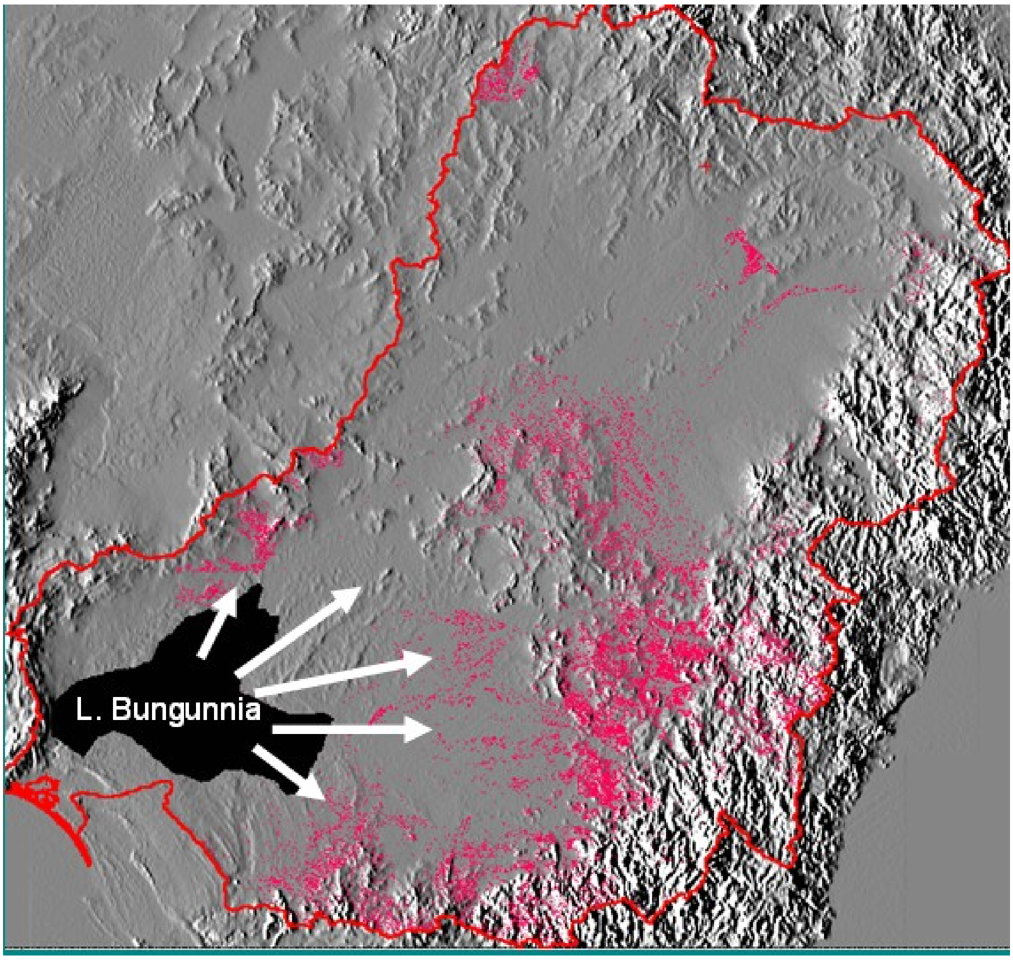

Figure 5. Aeolian salt-sources (red) in the MDB overlain on a hill-shaded DEM (Shuttle Radar Topography Mission – sourced from NASA) in relation to the ancient Lake Bungunnia.

The Billabong Creek AEM survey area, outlined in white, is overlain on the AGS derived upland salt-source model in Figure 6. The relationship between the E_D and EC shown in Figure 4 was then used to convert the gamma-ray data to an EC estimation for upland areas. Interpretation of both the gamma-radiometrics and AEM data is discussed in detail in Bierwirth (2006). Significant aeolian deposits are mapped by McKenzie and Gallant (2005) and correspond with red areas in Figure 6. These red areas represent low E_D to the target gamma-ray signature of aeolian soils associated with high-salinity boreholes. The areas of shallow salt storage defined by the AEM are also shown on Figure 6, defining a spatial relationship between upland salt sources indicated by the radiometrics and salt accumulations, shown by the AEM, that are lower in the landscape. The significant lowland saline areas are downslope from the upland accumulations of aeolian deposits. It is highly likely that yellow to red areas (EC 1:5 – 400 to > 700 uS/cm) in Figure 6, corresponding with aeolian soils, are major salt sources in the Billabong area. In upland areas, relationship also exists between the Gamma EC and the AEM upper-layer EC estimations (Bierwirth and Brodie, 2006) which is evidence for the validity of both methods.

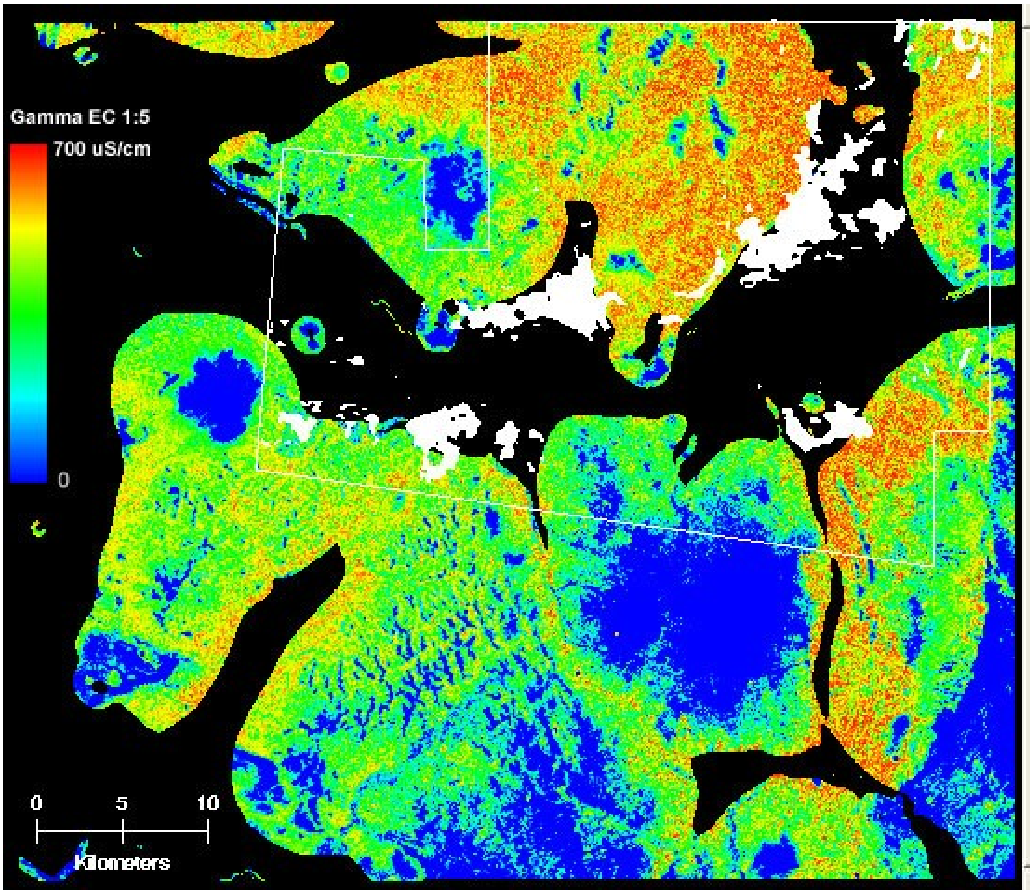

Figure 6. Upland salt model based on Euclidean distance and airborne K and Th converted to borehole EC 1:5 data for Billabong Creek. Black areas are alluvium defined by thresholding the MRVBF topographic index. White areas, indicating salt, are the highest values of uppermost AEM layer (20-25m).

The Billabung Ck AEM (see Figure 2 for location) was acquired due to high levels of salt found in Billabung Creek and the problem of this salt contribution to the Murrumbidgee River. (Braaten *et al*, 2003). Braaten *et al* (2003) found localised salt stores generally associated with thick clay soils and regolith.

The gamma-radiometrics salt source model (Figure 7a) shows a close visual correlation with the near-surface AEM data (Figure 7b), with red and orange colours in both images related to salt. These zones are transgressing the different lithologies (Bierwirth and Brodie, 2006) and often lying in low slope areas. The indicated aeolian soils (red in Figure 7a) are overlain on the AEM data in Figure 7(c) demonstrating a good spatial correlation. Only a broad correlation is expected given that the gamma model is expected to detect surficial salt-source materials while the AEM data maps deeper and often mobilised salts. However a proximal relatioship between patterns derived from the two geophysical methods would be expected and this has been observed at all sites assessed, e.g. at Billabong Creek, Billabung Creek and Honeysuckle Creek (Bierwirth and Brodie, 2006).

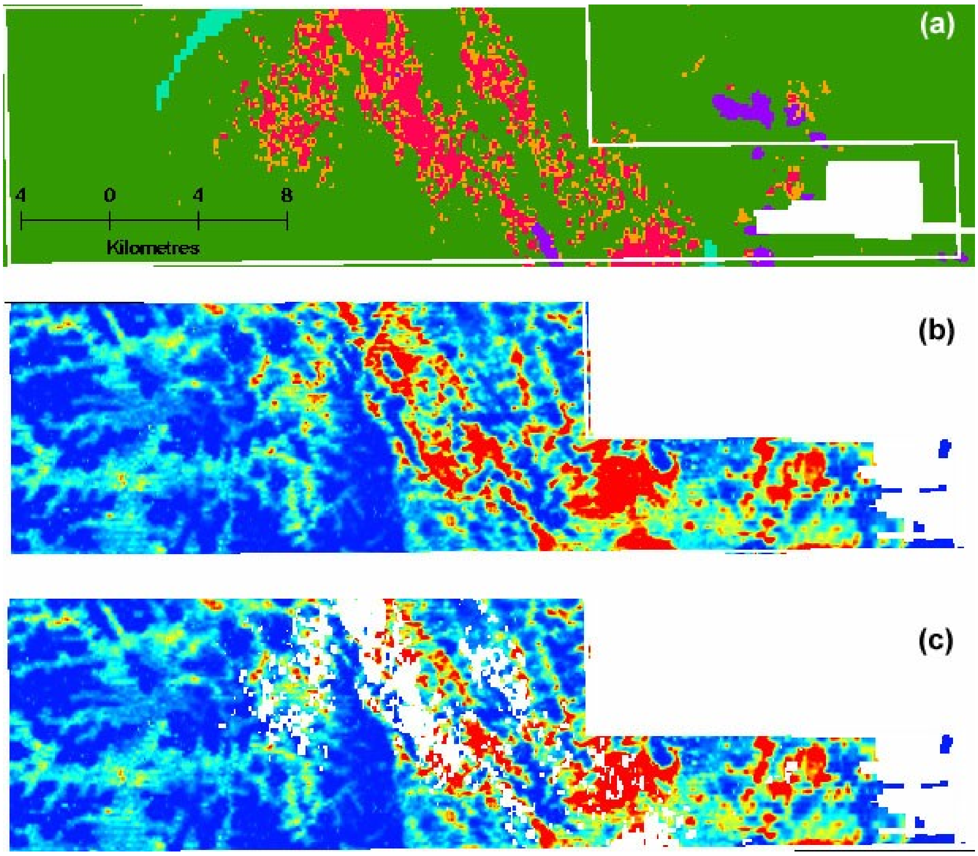

Figure 7. Billabung Creek AEM fly-zone. (a) gamma-ray salt source model (b) AEM conductivity layer 10-15m and (c) AEM layer 10-15m with high gamma model salt source (red from Figure 7a) overlain in white.

5. Discussion and Conclusions

The evidence presented suggests that it is possible to broadly map salt-sources across large parts of the Murray Darling Basin using airborne gamma-radiometrics. This is supported by both borehole data and correlation with airborne EM surveys, a technique that has been demonstrated to detect salt stores in the landscape. The developed mapping model is based on the concept that surficial aeolian materials are a significant landscape salt store..

The geographical relationship of the mapped aeolian deposits, forming an arcuate shaped pattern around and to the east of the ancient Lake Bungunnia and its arid hypersaline equivalents, is also evidence that these are salt source zones in the MDB.

The gamma-ray signature of the modelled saline aeolian deposits is explained by the nature of the source materials. Salt lake materials would generally be expected to have low potassium and thorium, but these materials mixed with weathered lake-interstitial iron-oxide-rich silts could produce the observed signature. These latter silts are likely to have a low potassium concentration due to weathering and a higher thorium value due to the complexing of thorium with Fe-oxides (Dickson and Scott, 1998). This would result in a general low K and mid-range Th that is the observed signature. Although uncommon, it is possible that in some areas this aeolian signature will overlap with bedrock signatures.

In terms of management, the new model adds an extra dimension to existing geophysical techniques. While the AEM data has proved valuable in understanding where the salt stores are in the landscape, the AGS model appears to show the component of the AEM that represents the major source of the salt. In this way the AEM can be further interpreted as to which part of these data represent mobilised salt. This is highly significant in terms of management.

As AGS data is widely available, the technique is a cost-effective addition to the current tools. AEM has proved a contentious tool largely because of the large costs involved and resulting low area coverage. The gamma model is a method that can be readily and synoptically applied over large areas.

7. References

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