Putting salt on the map: arresting salinity and finding new water resources

David Dent[1], Richard Cresswell[2], Scott Macaulay[3], Jim Kellett[3], Ian Mullen[3] and Grant Jones[3]

[1]ISRIC – World Soil Information, PO Box 353, 6700 AJ Wageningen, The Netherlands. Email: Yolanda.Karpes@wur.nl
[2]CSIRO Land and Water, 120 Meiers Road, Indooroopilly, QLD 4068, Australia
[3]Bureau of Rural Sciences, PO Box E11, Kingston ACT, Australia

Abstract

Salinity and fresh water are two sides of the same coin and most conveniently measured by electrical conductivity; therefore they can be mapped rapidly, in three dimensions, using airborne electromagnetics (AEM). Recent developments in AEM, in particular the calibration of airborne data against field measurements, lend new insights into salinity, groundwater flow systems and water resources. Mapping of soil and water resources is further supported by airborne radiometrics, magnetics and radar or laser altimetry. Salinity risk and the outcome of management interventions may now be forecast on the basis of system architecture, enabling cost-effective protection of farmland, infrastructure and development of water resources: it certainly beats water divining!

Keywords

Land degradation, Water quality, Enhanced soil mapping, Airborne geophysics

Context

Across the dry regions of the world the most precious resource, fresh water, is threatened by salinity: salt in the wrong place – in water for drinking, irrigation and industrial use, farmland, foundations of roads and buildings, and freshwater ecosystems.

In Australia, salinity is a fact of life - determined by a dry climate and sluggish drainage. It is argued that changes of land use since European settlement are forcing a rising water table, bringing salt to the surface and into the rivers: soil erosion, and replacement of native vegetation with crops and pastures that use less water, mean that more water is infiltrating to the groundwater; elsewhere, irrigation applies more water than comes naturally. It is further argued that the trend can be reversed only by equally massive reversion to perennial vegetation cover, especially tree planting (NLWRA 2001).

But it's not all the same out there! To protect water resources, we need to know: where the salt lies in the landscape and how much is there, how it is mobilised, what are the conduits carrying it to streams and the land surface, the rate of delivery now and under feasible management options, and if there are other freshwater resources to be exploited. Answers are emerging from the application of a combination of techniques: 1) airborne geophysics that can map the salt stores, conduits and groundwater resources in three dimensions; 2) drilling to investigate and calibrate the patterns revealed by airborne surveys and to establish the nature of the aquifers (structure, lithology, geochemistry, transmissivity and hydraulic head); 3) modelling water and salt movement, on the basis of the architecture of each groundwater flow system, to establish the risk of salinity and the outcomes of possible management interventions; 4) projection of this knowledge beyond the areas covered by geophysical survey, using landscape analogues that draw on existing soils, terrain and hydrogeological data. With this information, action on the ground can then be tailored to specific situations.

Here, we illustrate the approach with case studies from the mid-Broken catchment in Victoria and St George in southern Queensland). Magnetics and radiometrics were flown at 60m with line spacing of 100m (Mid-Broken) and 100 and 200m (St George).

Where's the salt?

The salt is stored as briny pore fluid, especially in thick clays. Recent advances in airborne geophysics enable rapid mapping of salt and fresh water to more than 100m below ground (Dent *et al*. 1999). The most potent tool is *airborne electromagnetics (AEM)* in which an on-board generator sends pulses of electric current through the aircraft's transmitter loop, inducing an electromagnetic (EM) field that penetrates the ground. This, in turn, induces a secondary current in any conductive material and the current induces a secondary EM field that is detected by a receiver towed behind the aircraft. Fugro

Airborne Surveys using the TEMPEST AEM system flew airborne surveys; the flying height was 120m, the line spacing 200m (Mid-Broken) and 200 and 400m (St George).

The signals are translated into a three-dimensional map by *conductivity depth imaging* (CDI) using *EMFLOW* software (McNae *et al.* 1998) and *layered earth inversion* (LEI). Typically these models are guided towards low conductivity values at the depth of investigation of the system, between 100 and 200m, but a constrained inversion procedure was used in the St George survey to take account of the conductive basement (Lane *et al.* 2003).

Calibration is essential: observed patterns are tested by induction conductivity (EM39) measurements in bores. The first conductivity model derived from the airborne data characteristically exaggerates the conductivity bulge close to the surface. However, Christiansen (2002) achieved a significant improvement in the fit of the *EMFLOW* model by: 1) iteration of the specified system geometry (transmitter terrain clearance, transmitter-receiver horizontal and vertical separation) and 2) governing the maximum conductivity within the range actually measured. Figure 1, showing the mid-Broken catchment abutting the Shepparton irrigation area in Victoria, contrasts the modelled conductivity before and after calibration; r^2 was improved to 0.33-0.47 for the 0-5m and 5-10m slices, rising to 0.87 for deeper layers. A perfect match is impossible because the 150m-radius footprint of the AEM system encompasses much more inherent variation than the 1m-radius footprint of the *EM39* instrument.

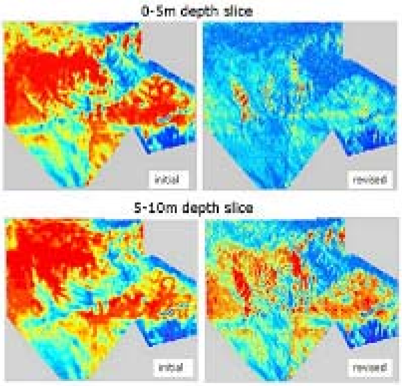

Figure 1. Mid-Broken catchment, Victoria: initial and calibrated CDIs. Blue indicates resistive materials and red, conductive.

Ground conductivity may be calibrated in terms of salt load, either using pore fluid expressed from undisturbed samples or a standard water extraction such as $EC_{1:5.}$ The direct relationship between salt load and ground conductivity enables calculation of a regional k_{salt} factor that translates maps of conductance into maps of salt load (Cresswell *et al*. 2004). Figure 2 depicts the summation of conductance of the whole conductive layer: in this example, there are some 175 000 tonnes of salt in a sump to the south and 700 000 tonnes in buried valleys draining northwards towards the irrigation area).

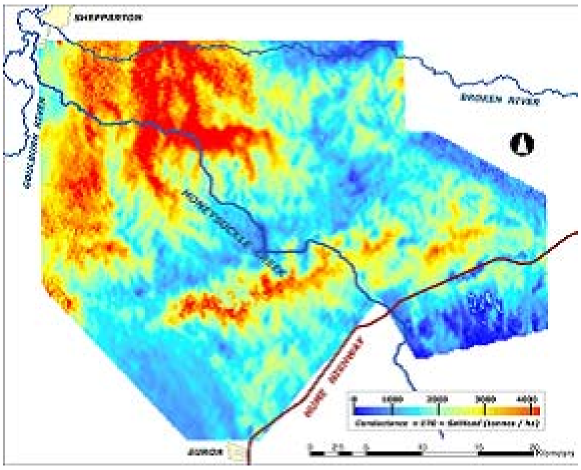

Figure 2. Mid-Broken catchment: salt load.

Only AEM maps salt directly but supporting information may be provided by *airborne radiometrics* which measures the natural gamma radiation from K, Th and U in the top 30cm of the soil - reflecting the composition of the bedrock, weathering, erosion and transport of surface materials and, so, the pattern of soil parent materials. Figure3, from the Southern Tablelands of New South Wales, is a ternary radiometric image depicting the signal from K in red, ${}_{e}$Th in green, and ${}_{e}$U in blue; overlaid by the distribution of thick clay soils which act as salt stores (in scarlet). The thick clays are mapped by the deviation of the received signal from the mean bedrock signal (Wilford *et al.* 2001): the thicker and more weathered the soil, the greater the depletion of the relatively mobile potassium and the greater the accumulation of thorium. This relationship holds in eroding landscapes where down-slope mixing of the soil maintains a link between the bedrock and the topsoil from which the radiation is detected. More generally, *digital elevation models* derived from radar or laser altimetry, combined with radiometrics, show landforms associated with salt stores and, also, conduits – coarse-textured materials such as stream channels and alluvial fans. This can be used to project knowledge won from the relatively costly AEM surveys to wider areas.

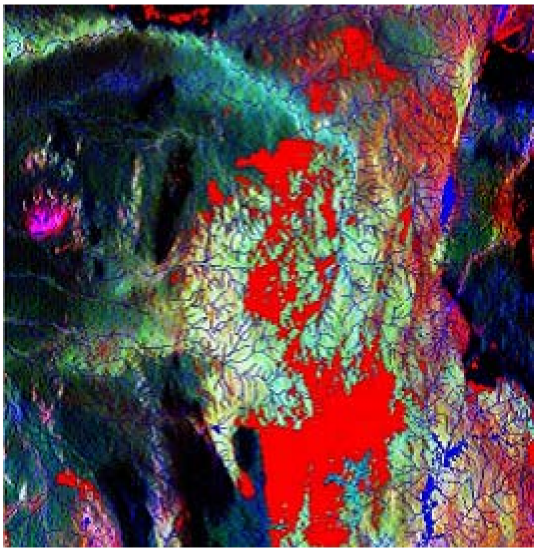

Figure 3. Ternary radiometric image straddling the Lachlan-Murrumbidgee watershed, New South Wales: thick clay soils (in scarlet) overlying the Young granite.

Where is it going? *Airborne magnetics* reveals geological structure; features include magnetic gravels that may serve as conduits, dykes and sills that may be barriers to groundwater flow, and fault lines that may either transmit or intercept groundwater. It is difficult to infer the depth of features from magnetic intensity but sharp-edged, and typically shallow, features such as buried channels may be picked out in the First Vertical Derivative (1VD) image that measures the rate of change in magnetic intensity. Combining the 1VD with CDI for the Mid-Broken catchment (Figure 4), we see that the salt lies:

1. In a graben delineated by a fault line trending WSW-ENE. Salt streams draining from the ranges to the south intersect (and break up) the Hume Freeway but once it reaches the sump, this salt isn't going anywhere; it will be a problem only if the groundwater rises close to the surface;
2. In buried channels draining north from the fault line towards the Shepparton irrigation area.

Magnetics does not reveal whether the conduits are carrying fresh water or brackish, or none at all. We must drill for confirmation.

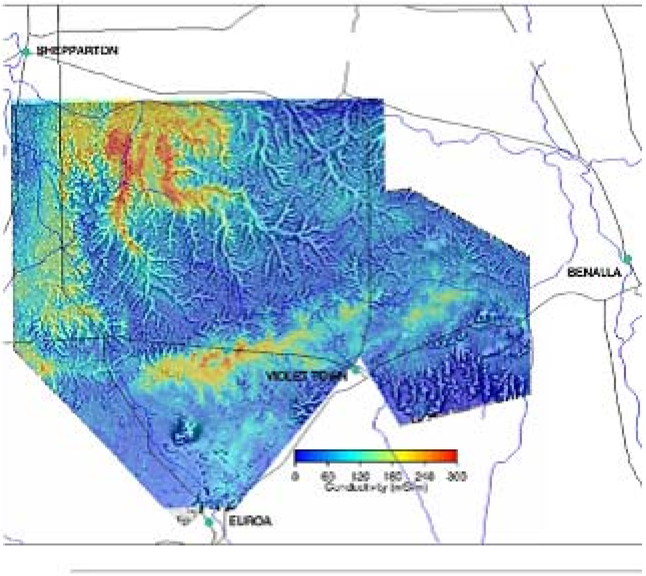

Figure 4. Mid-Broken catchment: CDI overlaid on 1VD image.

How soon will it be there?

This is the big issue. If there will be significant contamination of water supplies, farmland and freshwater habitats within a few years, then something must be done now. If the situation is stable or the time scale is centuries, then it is not so pressing. Groundwater flow systems may operate over a few km, closely coupled with local variations in rainfall and land use, or up to thousands of km and responding only slowly to regional changes. Once the architecture of the groundwater flow system is known, a variety of dynamic models may be used to estimate the movement of water and salt. Figure 5, an LEI from the country around the St George shows salt (in red) in the uplands, adjacent to: 1) fresh groundwater resources in the floodplain alluvium of the Culgoa-Narran to the SW and the Maranoa-Balonne to the NW, and 2) surface water storage in the Beardmore reservoir. Recent years have seen great expansion of irrigation using spate flows stored in earth ring tanks close to the floodplain. These storages are huge (on Cubbie Station, for instance, they occupy 40 000ha) but limited in depth to 4m (now 8m) by State regulations. Does potential leakage from these storages pose a threat to river or groundwater resources?

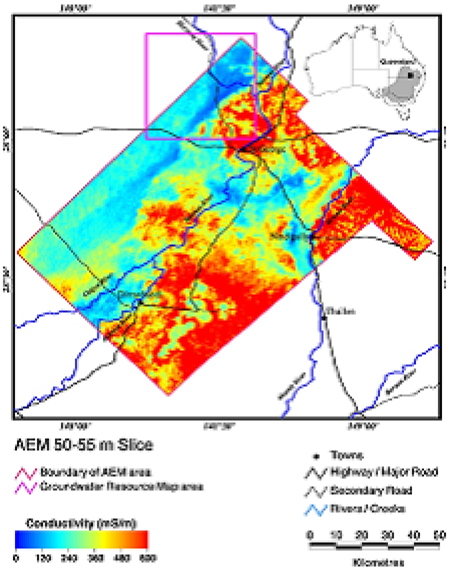

Figure 5. St George, Queensland: LEI 50-55m.

Most of the salt is in deeply weathered mudstones of the Cretaceous Griman Creek Formation; peak concentrations are between 15-20 and 50m below surface (Kellett and Mullen 2003). Hydraulic conductivity was measured using the inverse auger hole method in bores drilled in the unsaturated zone along the presumed flow lines; values are low in the upper 6m (0.1 to 0.15m/day) and lower still in the substrate where vertical drainage is disrupted by silcrete. Figure 6 depicts accessions to the water table from 100 years of irrigated cotton, simulated using the simple *FLOWTUBE* model (Dawes *et al*. 2000): a localised groundwater mound builds up, reaching the natural surface within 15 years. The head drives groundwater, and with it salt, towards the floodplain but half of the head is dissipated within 2000m, all within 7000m, so that mobilisation to the floodplain is not predicted – although there may be local waterlogging and salinity. Land clearance across the uplands would have less effect than irrigation, modelling indicates there will not be mass flow to the streams (Macaulay and Mullen 2003).

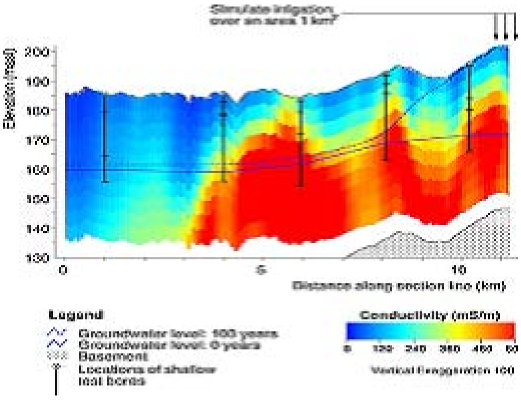

Figure 6. St George: vertical LEI section with FLOWTUBE simulation of 100 years' irrigated cotton.

Are there useful fresh water resources? Salty and fresh are two sides of the same coin, defined by the use intended, and large AEM surveys also reveal a 3-dimensional picture of shallow groundwater resources. Figure 5 shows resistive material, interpreted as fresh groundwater, in the alluvium of the Maranoa-Balonne and Culgoa-Narran floodplains. However, bedrock of low water content is also resistive, so interpretation is not straightforward; a reliable interpretation has been built up from several lines of evidence. Once again, calibration is critical - to derive an accurate representation of the alluvium-bedrock boundary and to estimate of water quality.

Bulk conductivity is a function of pore fluid conductivity (groundwater EC in the saturated zone), porosity and the conductivity of the soil/rock medium - which are non-linearly related by empirical constants that have to be derived from bore data. Statistical analysis of the relationship between AEM conductivity and groundwater EC from known depth in sampling bores at 122 sites across the survey area gave an r^2 of about 0.7; not high enough to confidently predict groundwater salinity from the regression equation; but a reliable 3-D map of the groundwater resource was derived by an interpretative approach – contouring each LEI depth interval in terms of interpreted groundwater salinity moderated by available bore data and patterns in EM39 logs.

Figure 7 shows the derivation of a groundwater quality map from the NW part of the survey area: the resistive lobe trending SW is interpreted as fresh water in a buried valley extending 150m below surface and recharged by leakage from the Maranoa and Balonne Rivers.

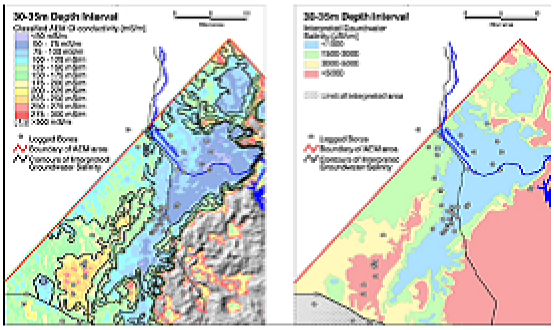

Figure 7. St George NW, 50 - 55m: classified AEM conductivity and interpreted groundwater salinity.

Applications: Combination of several techniques provides new insights into soils, water resources and groundwater flow systems. The three dimensional maps can be extended into a fourth dimension by forward modelling while, for detail, an enhanced soil map may be built up from the digital elevation model produced by radar or laser altimetry, topsoil parent materials from radiometrics, deeper resistive and conductive layers from AEM, adding to any existing conventional soil survey.

The outcomes of various management options can be forecast at local and regional scales, for example:

1. *Mid-Broken*: The previous management plan envisaged wholesale afforestation of the ranges to protect irrigation streams from salinity: we now see that the two systems are not connected. Damage to the Hume Freeway may be arrested by tree planting in the local catchments of the offending seeps; the most attractive options to intercept salt transport to the Shepparton Irrigation area are pumping of saline groundwater from prior stream channels to evaporation basins, and improved irrigation efficiency to control the water table.
2. St George: The newly established existence of sub-artesian aquifers has already led to development of this resource in areas of good water quality. Aquifer storage and recovery is an attractive alternative to storage of spate flows in ring tanks - where about half the water is lost by evaporation. An enhanced soil map, incorporating geophysical data, can provide a basis for design of artificial recharge basins on the most permeable soils of the flood plains. Seepage from existing ring tanks and irrigation areas is not a hazard to flood plain water resources and a rigorous study of the effect of land clearance may demonstrate that its salinity effects will be only local.

AEM requires significant financial outlay; high mobilisation costs dictate that large areas must be flown to bring costs down to an acceptable $US 3/ha. But the knowledge won can be projected over larger areas using information from magnetics, radiometrics and radar altimetry at one tenth of the cost of AEM per line km, and by use of landscape analogues. Minerals exploration companies already hold geophysical data for regions worldwide that are short of water and plagued by salinity; these data might be reinterpreted for water resources at marginal cost.

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