A geological systems approach to understanding the processes involved in land and water salinisation

The Gilmore project area, central-west New South Wales

KC Lawrie, TJ Munday, DL Dent, DL Gibson, RC Brodie, J Wilford, NS Reilly, RA Chan & P Baker

Australia is experiencing widespread degradation of land and water as a consequence of salinisation, and the problem is growing. Urgent action is required to derive appropriate management strategies that will minimise future socioeconomic and environmental impacts of salinity. However, while the causes of dryland salinity have been established, processes operating at a catchment scale are not as well understood, and a new approach that integrates all the relevant datasets is required for mapping and predicting salinity.

A multi-disciplinary 'geological systems' approach has been tested to better map and quantify key physical properties/factors and processes that determine the susceptibility of a given catchment to salinisation. The approach benefits from the recent development of new geophysical technologies—notably airborne electromagnetics (AEM) systems (e.g. TEMPEST), and significant improvements in AEM data processing software (e.g. EMFlow) and data visualisation techniques. New insights into landscape evolution have been equally important. The new airborne geophysical datasets, calibrated by surface and targeted drillhole information, permit rapid delineation of the sub-surface geology and regolith architecture, and salt distribution. These datasets allow linkages between salt stores and groundwater distribution systems to be examined, and the salt hazard to be assessed.

The pilot study (Gilmore project) area straddles the Lachlan/Murrumbidgee watershed in the Murray–Darling Basin, central-west NSW. The area contains a complex regolith developed in floodplain, incised undulating hill and upland landscapes. Ground calibration of AEM datasets has enabled the spatial and vertical conductivity structure to be modelled with reasonable precision. Previously unidentified salt stores have been recognised, and saline–sulphate and 'fresh' groundwater delivery systems mapped in the sub-surface. Saline groundwater has been identified in transported materials and in saprolite. Differential weathering and erosion of bedrock has produced a complex buried palaeo-topography that controls valley-fill architecture. Lateral groundwater flow occurs through a network of sand and gravel-filled palaeo-channels and buried alluvial fans within Cenozoic cover sediments. Narrow, restricted connections between buried (drainage) basins confine lateral groundwater flows. A similar geological systems approach in upland areas, requiring a different mix of technologies, has delineated sub-catchments where saline groundwaters are sourced and stored.

Some three million hectares of Australian farmland suffer from dryland salinity, or saline seepage, caused by saline groundwater rising to the surface. The costs in terms of lost agricultural production and infrastructure are substantial.[1] The costs of contamination of shallow freshwater resources and the impact on freshwater ecology are also significant. In NSW alone, approximately 120 000 hectares of land are affected by salinity,[2] with a further five million hectares considered at risk.[3] The salt concentration in many streams and rivers, particularly in the southern half of the Murray–Darling Basin, is thought to be rising steadily.[3, 4] Urgent action is required to derive appropriate management strategies that will minimise the future socio-economic and environmental impacts of salinity.

The accumulation of salt in the regolith is a natural phenomenon that has occurred in Australia over many thousands (or millions) of years. The processes responsible for the development of saline land and water are complex, and relate to the chemical processes of weathering, deposition and redistribution of soluble salts in groundwater flow systems.[5] Most salt originated from the oceans. It was deposited in rainfall and redistributed in the landscape through surface and groundwater flow over time. Dryland salinity has been attributed to human disruption of the hydrologic cycle. Clearance of native vegetation and a system of agriculture dependent on shallow-rooted annual crops and pastures that use less water than the natural vegetation have resulted in an increase in groundwater recharge. The consequence is rising watertables and in places a mobilisation of salts stored in the regolith. Saline waters flow to lower parts of the landscape along preferential paths. Where watercourses (including major rivers) intercept these seepages, their salt loads are increased. Where saline groundwaters reach close to the soil surface, they restrict crop growth and damage roads and buildings.

While the causes of dryland salinity have been established, processes operating at a catchment scale are not as well understood. A new approach therefore is required for mapping and predicting salinity. A new methodology, termed a 'geological systems' approach, takes advantage of new geophysical technologies and increased understanding of landscape evolution. It provides a better understanding of processes responsible for salinisation in areas of complex regolith cover.[3, 6, 7] The methodology draws on previous studies that recommended an integrated approach to the problem, including the use of high-resolution airborne geophysics.[3, 6] Initial results from the application of the geological systems approach in central-west NSW suggest the methodology has particular relevance in areas of complex bedrock geology, regolith cover and landscapes considered prone to salinisation, such as that of the Murray–Darling Basin of eastern Australia.

Geological systems approach

Conventional methods of assessing salinity include soil surveys, airphoto interpretation, regional geological mapping, ground geophysics and drilling. In areas of complex regolith cover in particular,[7] these methods do not allow the building of an accurate three-dimensional sub-surface picture of the spatial distribution of saline groundwaters and/or the flow systems that deliver salts to discharge sites. The integration of conventional datasets with ground and borehole geophysics and studies of drillhole materials has similarly been hampered by the difficulty of interpolation between calibration points.

New methods are needed to provide a sound basis for management of salinisation. The National Airborne Geophysics project concluded that airborne magnetics has the ability to map geological structures not always apparent from outcrop or airphoto interpretation, and to map geological structure at a paddock scale.[8] Airborne electromagnetics (AEM) have the potential to map the sub-surface distribution of salt and variations in the nature of regolith materials.[6] However AEM data is difficult to interpret, with high conductivity measurements attributable to a complex interplay between saline and/or sulphate-rich waters and the host regolith materials. Expert teams are required to derive meaningful results and to avoid spurious conclusions.[9]

A holistic, multi-disciplinary geological systems approach, previously recommended by a national study,[6] is being tested in central-west NSW.[10] This builds on a methodology recommended in development of a national catchment classification scheme.[3] A key objective is to better map and quantify key physical properties/factors that determine the susceptibility of a given catchment to salinisation. These factors include:

- the hydrogeomorphology;
- bedrock architecture including composition and structure;
- regolith framework including palaeo-topography, sediment facies distribution, saprolith thickness, and saprolith and sediment composition, texture and fabric;
- the distribution and composition of soils;
- the spatial distribution, connectivity and hydraulic conductivity of groundwater flow systems;
- salt sources and stores and their connectivity to the groundwater distribution systems; and
- the identification of recharge and discharge areas.

Critically, the geological systems approach provides a better understanding of the groundwater aquifer systems, and their connectivity and spatial variability. In turn, this provides a framework within which the impact of other more variable factors such as land use, vegetation type/condition, climate, palaeo-climate, and groundwater recharge rates can be considered.[3] These datasets should help constrain groundwater distribution systems, and the water–rock interactions that lead to salinisation in a catchment, and assist with construction of predictive models.

The methodology integrates geophysical, bedrock geological, regolith, soil, hydrogeological and hydrogeochemical datasets. The approach benefits from recent development of significantly improved geophysical technologies, notably AEM systems (e.g. TEMPEST[11]), parallel improvements in processing software (e.g. EMFlow[12]), and data visualisation techniques[13]. High-resolution airborne magnetic data are also useful in delineating bedrock structure and (where there is a magnetic sediment fill) for identifying palaeo-channels that may be part of a sub-surface drainage network.[14, 15]

Airborne geophysical datasets assist in the rapid delineation of the sub-surface geology and regolith. Of particular importance is their value in helping determine the architecture of aquifer and groundwater flow systems in the regolith. However, experience has emphasised the importance of ground calibration to help constrain the modelling of geophysical data and the hydrogeology. This necessitates gathering available surface data, and a limited aircore and diamond drilling program to recover pore fluids and materials. Multi-parameter geophysical and geological logging of boreholes is deemed essential for calibration and modelling of AEM and airborne magnetic datasets.

New insights into landscape evolution have been equally important. It is generally recognised that the regolith (and bedrock) framework exerts critical controls on salt distribution and hydrogeological models of groundwater flow and salinisation in areas of complex regolith cover.[16] The integrated datasets allow linkages between salt sources and stores, groundwater distribution systems to be examined, and the salt hazard to be assessed. An expert decision-support system is required to reduce the complexity of the data and deliver an effective toolbox for land managers and communities. This approach has the potential to provide a basis for defining appropriate management options from paddock to catchment scales.

Gilmore project

The geological systems approach is being tested in a pilot study (the Gilmore project[17]) in an area on the eastern margin of the Murray–Darling Basin in central-west NSW. The project area was chosen because of its overlapping mineral exploration (Au–Cu) and salinity management issues, the availability of high-resolution geophysical datasets and drillhole materials, and datasets available from the minerals exploration industry.

The project, coordinated by the Australian Geological Survey Organisation, involves more than 50 scientists from 14 research organisations. Research partners include:

- Cooperative Research Centres for Advanced Mineral Exploration Technologies (CRC AMET) and Landscape Evolution and Mineral Exploration (CRC LEME), the CRC for Sensor Signal and Information Processing, and the Australian Geodynamics Cooperative Research Centre (AGCRC);
- Land and Water Sciences Division, Bureau of Rural Sciences (BRS);
- NSW Department of Land and Water Conservation and Department of Mineral Resources;
- various universities including the Australian National University, University of Canberra, Macquarie University, Monash University, University of Melbourne and Curtin University of Technology; and
- Australian National Seismic Imaging Resource (ANSIR).

The project has research agreements with the minerals exploration industry and is collaborating with rural land-management groups and the Grains Research and Development Corporation.

The study area (100 x 150 km), straddles the Gilmore Fault Zone, a major north-north-west-trending crustal structure that separates the Wagga–Omeo and the Junee–Narromine Volcanic Belts in the Lachlan Fold Belt. The project area includes tributaries of the Lachlan and the Murrumbidgee Rivers (figure 1) which are considered two of the systems most at risk from rising salinities. In parts of the

Murrumbidgee, salinities are increasing at 15 per cent per annum. This is having significant impact on downstream uses such as drinking water and irrigation.[3] The project area was chosen to compare and contrast salt stores and delivery systems in floodplain (in the Lachlan catchment) and incised undulating hill landscapes (Murrumbidgee catchment). The study area is characteristic of other undulating hill landscapes on the basin margins, areas within the main and tributary river valleys, and the footslopes and floodplains of the Murray–Darling Basin itself.

The bedrock geology in the study area has a complex architecture. The Gilmore Fault Zone consists of a series of subparallel, west-dipping thrust faults[18] that juxtapose, from west to east, Cambro-Ordovician meta-sediments and granites of the Wagga Metamorphics and, further to the east, a series of fault-bounded packages comprising volcanics and intrusions, and siliciclastic meta-sediments. Large-scale hydrothermal alteration and structural overprinting, particularly in the volcanics, has added to the complexity within the bedrock architecture.

Two AEM surveys were flown in smaller areas within the two catchments. In the Lachlan catchment, alluviation of the palaeo-Lachlan River system during the late Tertiary[19] largely buried the Bland Creek palaeo-valley. Up to 120 metres of sediment infill is recorded in the north-east of the AEM survey area. However, sediment thickness is markedly variable because of complex bedrock palaeo-topography. This has resulted from differential weathering and erosion of bedrock lithologies in the palaeo-landscape.

In the Murrumbidgee catchment, there are undulating hills incised by two main valleys largely infilled with up to 60 metres of transported sediments. There is an elevation difference of 100–200 metres from current valley floors to the crest of local divides. Siluro-Devonian volcanic and intrusive lithologies form higher hills in the east. The two main present-day creek systems within the western and eastern valleys, Houlaghans and Billabung Creeks respectively, flow south to the Murrumbidgee River.

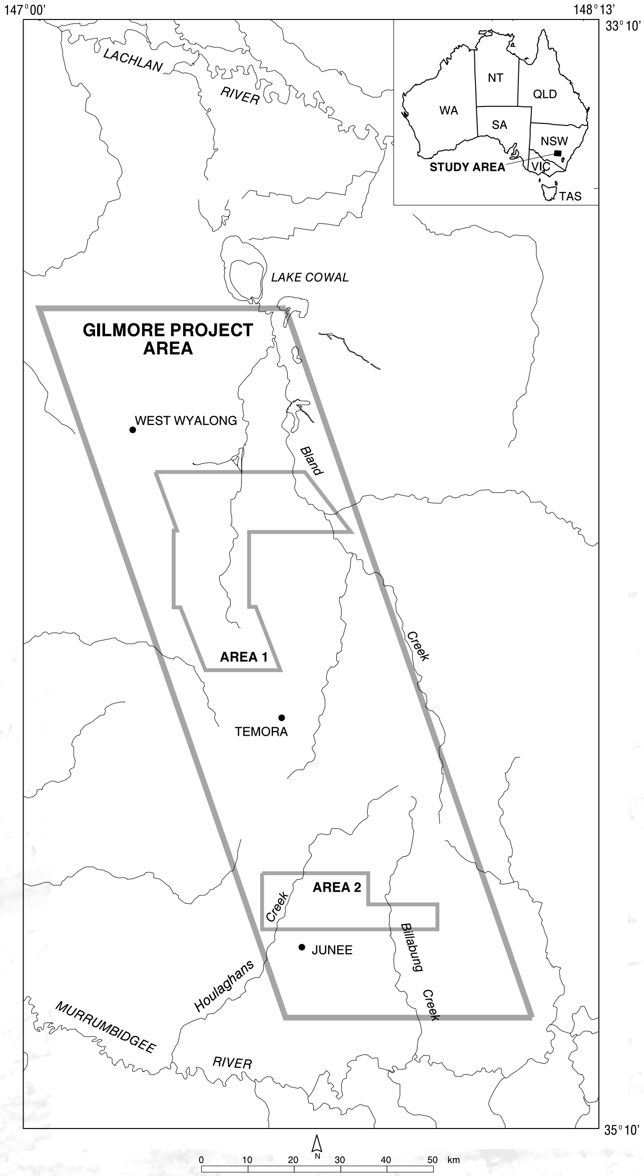

Figure 1. Diagram showing the location of the Gilmore project area relative to the Lachlan and Murrumbidgee Rivers. The two smaller AEM survey areas are also outlined.

Datasets

The Gilmore project has acquired new datasets including high-resolution airborne geophysical surveys, ground geophysics, hydrological datasets (surface stream flow and sub-surface borehole data), and regolith and bedrock geological mapping from extensive industry and government-funded drilling. Regional digital orthophoto and high-resolution digital elevation models provide an accurate reference framework for field studies and GIS referencing. Ground geophysical surveys, including shallow-penetrating seismic reflection,[20] seismic refraction,[21] ground penetrating radar, microgravity and electromagnetic surveys were carried out to attempt to calibrate palaeo-channel features evident on airborne survey datasets.

Hydrological datasets include surface stream flow and sub-surface borehole data measurements.[10] Multi-

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parameter geophysical borehole data acquisition comprised induction, gamma-ray and magnetic logs. Mapping of bedrock and regolith materials in 3D, analysis by Portable Mineral Infrared Analyser (PIMA), X-ray diffraction (XRD), X-ray fluorescence (XRF) and thin section studies of regolith and bedrock materials also were included.

At the start of the project, the minerals exploration industry gave access to core and chip materials from hundreds of drillholes within the study area. After examination of these materials, it was decided that a new drilling program was required to recover both regolith materials and pore fluids in order to calibrate the spatial and vertical conductivity structure within the AEM data. A drilling program was carried out between March and May 2000. Many of the holes are being completed as piezometer monitoring stations. Three drilling methods were used:

- a Rotary Air Blast (RAB) drilling program of 15 short holes was undertaken in upland areas and in the floodplains and incised valleys where drilling results from depths less than 25 metres were anticipated;
- an aircore drilling program of more than 30 holes drilled to saprock where possible (maximum depth 100 m); and
- a diamond core drilling program of five holes (maximum depth 80 m).

Drillhole materials were collected for laboratory analysis at one-metre intervals. Drilling with an air compressor rather than using water- or oil-based fluids was considered essential to help preserve materials and pore fluids.

To date, detailed descriptions, and PIMA, XRD and XRF analysis of regolith materials, limited grain-size analysis, moisture and electrical conductivity (EC1:5) measurements, and S:Cl ratios of pore fluid analysis have been carried out. Preliminary analysis of borehole fluid compositions has identified both fresh and saline (up to 2500 mS/m—half seawater salinity) groundwaters. EC1:5 and compositional analysis show that the pore fluids have saline–sulphate compositions, with S:Cl ratios varying from 1:6 to 1:1 (Astolfi E, 2000, pers comm). Regolith descriptions have been compared to downhole geophysical logs and the pore fluid and mineralogical data.

These data were acquired to compare and contrast salt stores and delivery systems in floodplain and incised undulating hill landscapes, and to develop a methodology for rapidly delineating areas in upland landscapes that generate and store saline groundwaters. Some preliminary results of the integration of Gilmore project datasets are given below.

TEMPEST AEM survey

From January to March 1999, 7721 line kilometres of electromagnetic (and aeromagnetic) data were acquired over two areas in the Gilmore project area using the TEMPEST system.[11, 22] The TEMPEST data set for Gilmore was transformed to earth conductivities using one-dimensional layered earth inversions (LEI)[23] and conductivity at depth, as well as spatial images of derived parameters such as average conductivities over nominated depth intervals (interval conductivities) and conductive unit parameters (e.g. thickness of conductive layer).

The inversion results were presented as both vertical cross-sections and spatial images. The vertical cross-sections are generated by splicing together results from individual inversions at each sample point (12-m intervals) along each flight line.

Layered earth inversions

A layered earth inversion (LEI) of the TEMPEST data was based on procedures previously described.[23] The conceptual model used was a three-layer earth consisting of a conductive layer sandwiched between a resistive upper layer and an infinitely thick resistive layer below. The inversion process calculates the conductivity of all three layers and the thickness of the upper two layers that best represents the observed data. In a geological sense, this model could represent a resistive alluvium–colluvium, overlying conductive transported material or saprolite, which sits over a resistive unweathered basement.

In the Gilmore data, the layered earth conductivity-depth sections show good line-to-line correlation. This suggests that at the scale of the AEM survey (hundreds of metres laterally and a few metres vertically), the electrical structure across the study area is essentially layered. The best results were obtained in the northern survey area, where much of the landscape is characterised by an extensive layer of conductive regolith material comprising both transported and in-situ regolith materials. In these landscapes the conceptual model is suitable and the results are effective. In areas of extreme conductance, the chosen starting model influences the inversion results by increasing the thickness of the resistive first layer and reducing the conductance of the second layer. This problem was encountered particularly in the northern survey area.

Conductivity depth imaging

EMFlow software, which is based on the approximate source image algorithm for layered earths, was used to produce a set of CDIs.[12, 24] CDIs allow subtle conductivity variations to be modelled more realistically by comparison with those produced from three-layered model inversions as described above. Interval conductivity slices, formed by averaging conductivity values over a discrete interval, formed the principal product for interpreting spatial variations in conductivity as a function of depth across the study areas. An 'EM response map' of the Gilmore area is essentially a map of the variation in the depth to, and thickness and/or conductivity of, the transported cover and saprolite overlying varying basement lithologies.

Preliminary results

Comparison of LEI and CDI models of the Gilmore AEM data shows good agreement in the spatial conductivity distribution. Figure 2 (a–d) shows conductivity depth slices generated from EMFlow-modelled CDIs for the northern AEM survey areas. The CDI models have been validated by borehole measurements. Borehole induction logs and moisture and EC1:5 measurements of regolith materials were compared with vertical conductivity profiles displayed on conductivity-depth sections derived from both CDI and LEI modelling of the AEM data (e.g. figures 3a, 3b). Validation using borehole data assumes that variations observed in the drill hole data are representative of variations measured by an AEM system. However, an AEM system with the geometry of the TEMPEST AEM system resolves conductivity variations of the order of 100 metres horizontally and tens of metres vertically. With the drillhole data, variations of the order of more than one metre are measured. Therefore, when comparing parameters such as conductivity or regolith thickness derived from the inversion of the AEM data with those obtained from drill-hole measurements, the scales at which these natural variations are likely to occur becomes important—particularly when interpreting the results.

By their very nature, LEIs do not give adequate definition of the subtle differences in vertical conductivity structure observed in borehole

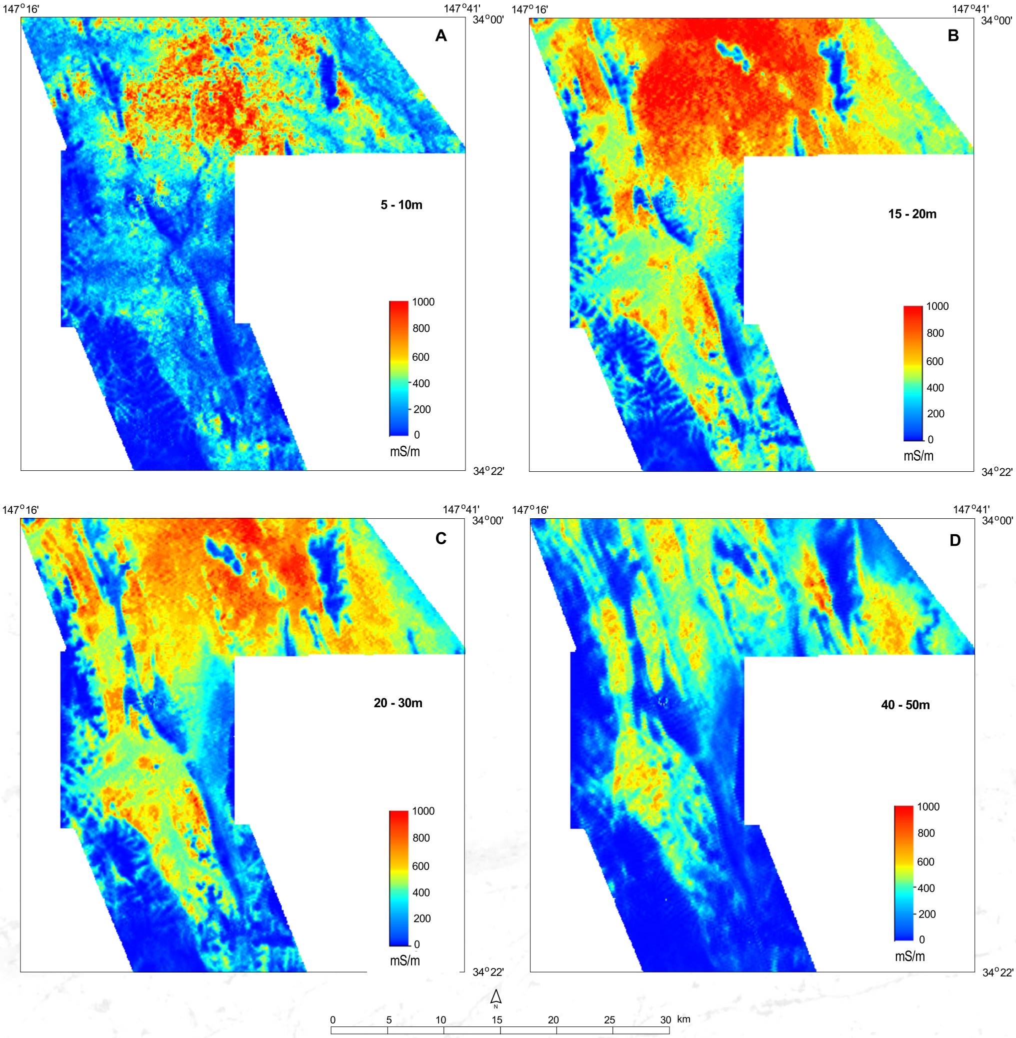


Figure 2. Conductivity depth slices for the intervals **a.** 5–10 metres **b.** 15–20 metres **c.** 20–30 metres and **d.** 40–50 metres, generated from EMFlow-modelled CDIs for the northern AEM survey area. Higher conductivities are indicated in red colours; resistive areas are blue.

measurements within the conductive layer. Hence no discrimination is possible between conductive transported sediments and saprolite. However, comparison with borehole data indicates that, overall, there is a good correlation between the modelled base of the conductor and the saprolite–saprock interface (e.g. figure 3b).

Initially, a poor vertical correlation was obtained from CDI models using standard survey parameters derived from experience in Western Australia, and EMFlow software. Re-examination of survey acquisition parameters, software modelling inputs, and datum corrections followed. A significant improvement in modelling vertical electrical structure was obtained. The re-calibration of survey parameters and EMFlow model inputs has resulted in a correlation coefficient of 0.79 between average borehole-conductivities and CDI model conductivities over 10-metre vertical intervals (figure 4).

The limitations of airborne systems in imaging the conductivity structure in the top 10 metres has been noted previously.[6] However in this study, significant improvement in the modelling of the vertical conductivity structure was produced by corrections to survey geometry (on the basis of comparison with borehole induction logs), height corrections to radar altimeter readings, and both EMFlow inputs and output use. There is now reasonable confidence that the spatial and vertical patterns observed in the CDI-modelled AEM data are a good representation of the conductivity structure within five to 10 metres of the surface (figure 2a), and that the zero- to five-metre depth slices are representative of bulk conductivities over this interval.

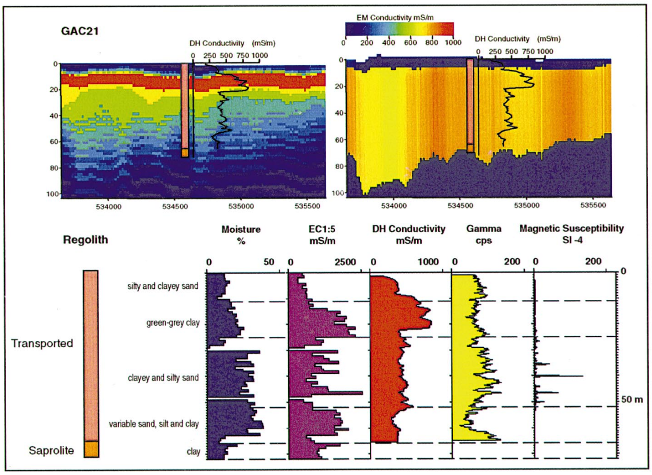
Problems still exist with modelling more complex vertical conductivity structures in the data, particularly in areas where several highly conductive layers are stacked above one another. This occurs in the northern survey area, where there are saline–sulphate groundwaters in near-surface aquifers and at depth in saprolite. In these cases the vertical resolution of the AEM system is simply not high enough.

Floodplain landscapes

The northern area lies within a shallow inland basin, the Bland Creek palaeo-valley. It is a north-south-trending palaeo-valley system 60 kilometres across and 130 kilometres long (figure 1). This palaeo-valley controlled the discharge of Tertiary palaeo-rivers northwards into the main westward-flowing Lachlan River system. The northern AEM survey area lies within the western flank of the palaeo-valley, in an area of relatively flat alluviated plains with a few low hills. The latter consist of granites or silicified hydro-thermal alteration zones associated with Au and Au–Cu deposits. North-north-west-trending, discontinuous topographic ridges consist of siliciclastic meta-sediments and/or granites. The streams flowing from the hills mostly disappear into alluvial fans or into the alluvium of the flood plains. The main north-flowing stream, Bland Creek, varies in salinity, receiving low salt waters from its left bank but, occasionally, very high salinity waters from the right bank.[10]

Mineralogical, grain-size and textural (fabric) analysis of regolith materials are compared with EC1:5s and moisture content of materials, and multi-parameter geophysical borehole logs results (e.g. figures 3a, 3b). These data displays are used to help with interpretation and correlation of regolith materials and to calibrate models of geophysical data. Preliminary results suggest that the sediment infill in the Bland palaeo-valley involved deposition in low-angle aggrading fans and in palaeo-river systems. Present-day analogs occur on the perimeter of the present Bland alluvial plain. Significant vertical and lateral variations in clay mineralogy are mapped. Throughout the study area, a zone of weathered bedrock (saprolite) that varies from 10 to 100 metres thick, forms the base of the regolith. Preferential groundwater flow is interpreted as being through more transmissive sediment-fill in buried palaeo-channels, and by inter-layer flow in alluvial fan deposits, and at the transported sediment–saprolite interface, and through fracture networks (macropores) in saprolite.

3a



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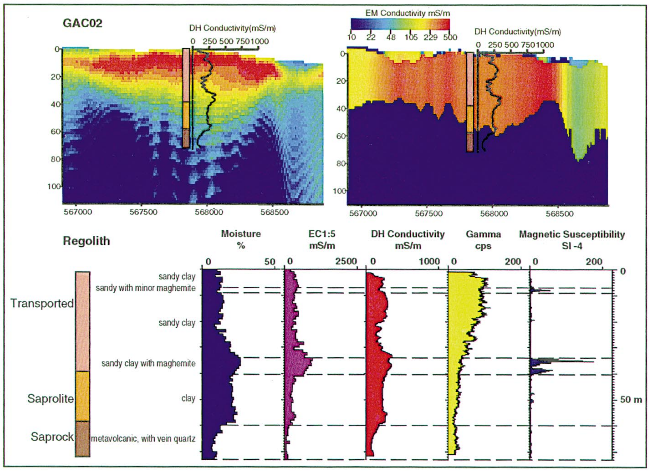

Figures 3a & 3b. Borehole induction logs, and moisture and EC1:5 measurements of regolith materials were compared with vertical conductivity profiles displayed on conductivity-depth sections derived from both CDI and LEI modelling of the AEM data. Mineralogical, grain-size and textural (fabric) analysis of regolith materials are compared with EC1:5s and moisture content of materials, and multi-parameter geophysical borehole logs results. These data displays are used in interpreting and correlating regolith materials and calibrating models of geophysical data.

Interval conductivity slices of the AEM data reveal a complex pattern beneath the valley and floodplain surfaces (figure 2a–d). A geological systems approach to interpreting these patterns is essential. Ground-truthing of AEM data demonstrates that conductivity structure exhibits a strong lithodependence. A layered vertical structure is evident with, in general terms, a highly conductive sediment infill overlying a variably conductive saprolith, and resistive bedrock. This is evident in the conductivity depth slices which show increasing correlation with bedrock geological lithology distribution with depth (figure 2).

A very thin (<1 m) upper resistive soil layer is present over much of the floodplain. Within the transported sediments, AEM images displayed as interval conductivities suggest that extensive stores of saline (and sulphate-rich) groundwater are perched within clay-rich sediments within five to 30 metres of the surface. Spatial patterns in the AEM data that relate to variations within the transported regolith sediments are caused by a complex relationship between saline–sulphate groundwater content and variations in the nature of the saprolite and/or sedimentary facies.

A strong lithodependence is observed between bedrock lithologies and the later-time AEM data (figure 2d).[25] The Wagga Metamorphics, the Combaning Formation (Fm), and Late Devonian intrusions correlate with regolith landform units that comprise topographic highs and form relatively electrically resistive ridges. In contrast, volcanics, intrusions and meta-sediments of the Gidginbung and Belimebung Volcanics have a more conductive electrical structure. Drilling results show that the conductive areas correlate with an increase in conductive transported overburden and an increase in the total depth to base of saprolite.

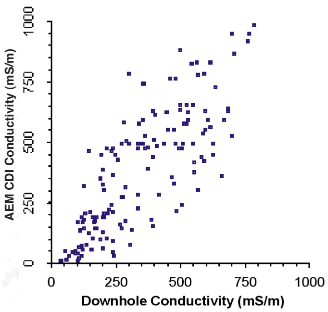

Figure 4. A correlation coefficient of 0.79 is observed between average borehole-conductivities and CDI model conductivities over 10-metre vertical intervals.

Although there is a significant lithodependence between the volcanic/intrusive belts and high conductance, a second-order patterning is also discernible in the data. Traverses along the Gidginbung Volcanics reveal a complex patterning at the same depths below surface. Areas of higher near-surface conductance appear to correspond with saprolite that is not siliceous. Other domains of moderate conductance coincide with thicker transported regolith sediments, and appear to indicate the presence of restricted, shallow, depositional basins (figure 5) that were confined to the west by Wagga Metamorphics, and to the east by Combaning Fm sediments. Similar 'basins' are identified at depth over the Belimebung Volcanics further to the east. Drainage from these restricted basins appears to have been through narrow gorges (figure 5) incised to relatively shallow depths in the Combaning Fm. Both saline–sulphate and 'fresh' groundwaters have been sampled at depth in different palaeo-channels (figure 5), and attest to the complexity of the sub-surface groundwater distribution systems in this area.

On the western palaeo-valley margin, numerous magnetically delineated east-north-east- to north-north-east-trending buried palaeo-channels cut through palaeo-ridges of Combaning Fm siliciclastic meta-sediments.[15] Some of these palaeo-channels are perched within alluvial sediments; some occur at the base of the transported sediment fill; and some channel-fill sediments were deposited in drainages incised into saprolith.[14, 15] Some palaeo-channels, targeted by drilling anomalies in the AEM data, have no magnetic signature (figures 5 & 6). The AEM signature of palaeo-channel deposits appears to vary depending on the character of the channel fill, its landscape position, and connection or disconnection with sub-surface hydrogeology. Palaeo-channels north of West Wyalong, delineated by maghemite channel-fill deposits, are broad, shallow channel-fill deposits with a low conductivity response. Higher conductivities are observed in narrow bands within saprolite bordering both banks. The channel-fill deposits appear to have a relatively high hydraulic conductance. Ephemeral run-off may flush any salts from these channel-fill deposits, with some salt accumulation in less-transmissive saprolite banks.

Upland landscapes

Several small upland basins occur within the Siluro-Devonian bedrock in the south-eastern margins of the Gilmore project area. These upland landscapes have concave lower slopes at elevations between 450 and 600 metres above sea level and carry a thin, silty topsoil over clay on deeply weathered colluvium (<8 m) and a variable saprolith. Surface stream flow salinity data, combined with soil and regolith mapping, demonstrate that in the project area salt is exported from these upland landscapes to the plains and major rivers. It comes mainly from sediment-filled upland basins with restricted outflows, and from areas that are overlain by thick clay soils that coat the footslopes and gently sloping upland basins.[10] Springs issuing from upper slopes with granite saprolite at the surface are clear and fresh. Saline stream flow from the hills mostly disappears into alluvial fans or into the alluvium of the Billabung Creek of the southern area, and flood plains of the Bland palaeo-valley in the north.

A different mix of technologies was used as part of a geological systems approach to mapping salinity within these upland landscapes.[26] This involves interpretation and modelling of high-resolution airborne gamma-ray spectrometry, primary and compound topographic indices derived from a high-resolution digital elevation model, and bedrock geological data. These data are used to map regolith materials and quantify geomorphic and hydrological processes in individual catchments. Field calibration of the derived regolith and soil data was required to validate interpretations. The study found relationships between regolith type, depth of weathering, geomorphic process and hydrologic gradients with salt mobility and storage in the landscape.[26] For remedial management purposes, catchments in these upland landscapes can be ranked according to their dryland salinity risk or potential risk.

Incised undulating hill landscapes

Houlaghans Creek

The modern morphology of Houlaghans Creek is a relatively linear, broad, gently concave valley floor bounded by steeper slopes developed on saprolith. The incised palaeo-valley appears to be localised by north-north-east-trending basement fault structures that transect Ordovician granites and Palaeozoic meta-volcanic and meta-sediments on a regional scale. Sediment infill of this palaeo-valley has alluvial fan and palaeo-channel deposits up to 60 metres thick. Some tributary palaeo-channel deposits, evident in the AEM data, occur at depth where there are no current surface creeks. The axial system lies beneath or offset by less than 200 metres from the present surface channel of Houlaghans Creek.

Upstream of Junee, Houlaghans Creek is a freshwater drainage. Like most of the creeks in the area, surface flows are ephemeral. However, drilling of the main and tributary palaeo-channels, targeted using interval conductivity slices derived from EMFlow processing of AEM datasets, confirmed the presence of saline–sulphate groundwaters within channel fill materials (figure 6). North-west-trending dykes, evident on aeromagnetic images, exhibit a smaller-scale control on conductivity structure. Some, but not all of these dykes appear to localise saline groundwater flow and localise ponding of groundwaters where they intersect the main palaeo-channel.

Billabung Creek

The present day Billabung Creek valley has a broad, flat floor characterised by alluvial deposition. Alluvial fan sediments are evident on the eastern valley footslopes. The valley is at the base of higher hills to the east, and appears to have etched out a course parallel to north-north-west-trending bedrock faults within more erodable Lower Palaeozoic lithologies. The Billabung Creek system, which is eight to 12 kilometres in width, is fed by both fresh and saline surface stream flow from tributaries. The palaeo-valley beneath is filled with at least 50 metres of sediment.

Saline surface stream flow waters are sourced from small, restricted, clay-filled upland basins in the higher landscapes in the hills to the east. Surface flows from the west are generally fresh, but recharge by saline groundwaters appears to occur through sub-surface drainage networks. Alluvial fan deposits in the footslopes of the hills on the eastern valley margins may be important aquifers for delivery of recharge groundwaters.

Undulating hill landscapes

The hills between the Houlaghans and Billabung Creeks are largely covered with thin sediments that increase in thickness downslope (<15 m). Higher crests generally have thin veneers of sediment over a saprolith that is between 10 and 80 metres thick. The sediment cover includes 'parna' deposits that are preserved on the leeside (eastern side) of drainage divides.[27] These re-worked aeolian deposits are linked to salt introduction and storage elsewhere in NSW.[28] In the Gilmore project area, multi-parameter borehole geophysical studies demonstrate significant differences between parna and underlying saprolite.[29] EC1:5 measurements and downhole induction logs suggest that conductivity is primarily controlled by textural variations rather than soluble salt and moisture contents of these materials. Ground EM (EM31) survey areas covered by parna exhibit marked lateral variations in average conductivity, attributable to differences in the thickness and proportion of parna in these materials.[29] Salts, once entrained in parna deposits, may have been mobilised into lower parts of the landscape and stored in accumulations of transported regolith in palaeo- and contemporary drainage.

Conductivity anomalies between the two main creeks were drilled, and four main types of anomaly were found. Conductive regolith materials drilled near Illabo contain up to 40 metres of fine-grained sediment-fill (figure 3b). Saline–sulphate groundwaters within this basin are largely perched within the transported sediment-infill, with some seepage of these waters into underlying saprolite. There is evidence of erosion of this landscape infill material.

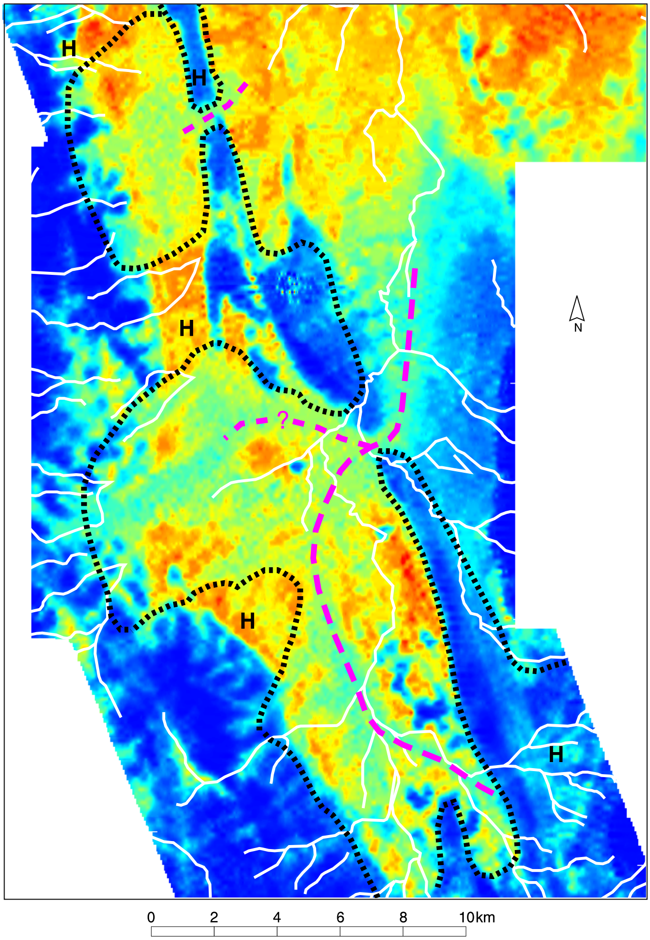

Figure 5. Interval conductivity slice (30–40 m) from the northern AEM survey area. Annotations point out a palaeo-drainage, the former course (pink dashed line) of which is picked out by moderate conductivities (green) at depth. Saline waters were intercepted at depth within this old river channel. Drainage basins containing thicker alluvial sediments are also evident from the spatial conductivity patterns. The blue areas are mostly resistive bedrock outcrop and buried ridges (area inside dotted line and 'H' symbol), except where there is flushing of regolith sediments by freshwater run-off from adjacent hills (eastern side of diagram).

Other conductive materials in the areas of relatively thin sediment veneer relate to the ponding and channelling of saline–sulphate groundwaters in thin regolith sediments, and ponding in saprolith adjacent to large quartz veins that form topographic highs and groundwater barriers. Significant saline groundwaters were found towards the saprolite–saprock boundary up-slope of quartz veins. Magnetic dykes also localise conductivity anomalies. Where these dykes transect drainage lines, they appear to confine the flow of saline groundwaters, in both hill and valley landscapes. Localised conductivity highs were also found to correlate with saline groundwaters at the base of deeply weathered outliers of siliciclastic Combaning Fm Palaeozoic meta-sediments. Conductivity lows relate to areas where there is no sediment veneer, with saprolite and/or saprock at the surface.

Conclusions

Initial results from applying a geological systems approach to problems of land and water salinisation in the Gilmore project area in NSW are proving to have particular value in delineating groundwater aquifer systems, their connectivity and spatial variability. One consequence is a better appreciation of the processes controlling dryland salinity in an area of complex regolith cover. New geophysical (particularly electrical) technologies have identified previously unknown salt stores and groundwater distribution systems (palaeo-channels) in the sub-surface. Studies are continuing with the intent of establishing the nature of the physical connections between salt stores and groundwater movement. Particular emphasis is being placed on establishing the hydraulic properties of materials in the area and recognising the aquifers.

Outputs of the geological systems approach provide an effective framework onto which more variable attributes such as land use, vegetation type/condition, climate, palaeo-climate and groundwater recharge rates can be added. When linked to a knowledge of the hydrological character (including water- and salt-balance relationships) of catchments, the methodology has value in defining appropriate and effective salinity management options.

An expert decision-support system is being developed to reduce the complexity of geological and geophysical data and deliver an effective toolbox for land managers and communities. The datasets generated by this approach will enable a more accurate prediction of salinity in these landscapes, and make targeted management of the hazards possible at catchment and paddock scales (figure 6).

The Gilmore study found that flexibility in the choice of specific technologies and research methodology is required for the landscapes studied. In footslope, valley floodplain or subdued landscapes with complex regolith cover, high-resolution AEM and airborne magnetic surveys are particularly useful in conjunction with new approaches to the mapping and modelling of bedrock and regolith materials and stratigraphy. In these landscapes, ground calibration of geophysical datasets by targeted drilling, along with near-surface sampling, is required to calibrate geophysical responses, bedrock geology architecture, regolith facies analysis, and groundwater distribution. These datasets provide a framework for understanding groundwater flow systems and hydrogeological models, and assist in the spatial delineation (in three dimensions) of salt stores and delivery systems in the sub-surface. Airborne gamma radiometric surveys are less important in these landscapes.

In contrast, airborne gamma-ray spectrometry is potentially a much more effective tool in upland landscapes, due to a generally thinner conductive regolith cover in upland areas. These data have been used to map regolith materials, and quantify geomorphic and hydrological processes in individual catchments. This requires integration of gamma-ray spectrometry with terrain attributes derived from a high-resolution digital elevation model. Field calibration of the derived regolith and soil data is required to validate interpretations. Examining the relationships between materials (soil and regolith) and landscape processes with salt loads in streams draining from these catchments provides new insights into salt movement and storage.

A similar geological systems approach is likely to provide similar benefits for hydrogeological and salinity modelling in other complex regolith terrains. The approach needs to be considered within the framework of a national catchment classification,[3] and tested in catchments in different climatic and geological regions. This multi-disciplinary approach can also be applied to the mapping of ore deposit mineral systems under cover. In particular, the integration of datasets has provided new insights into the modelling of hydromorphic dispersion of metals from concealed ore deposits.

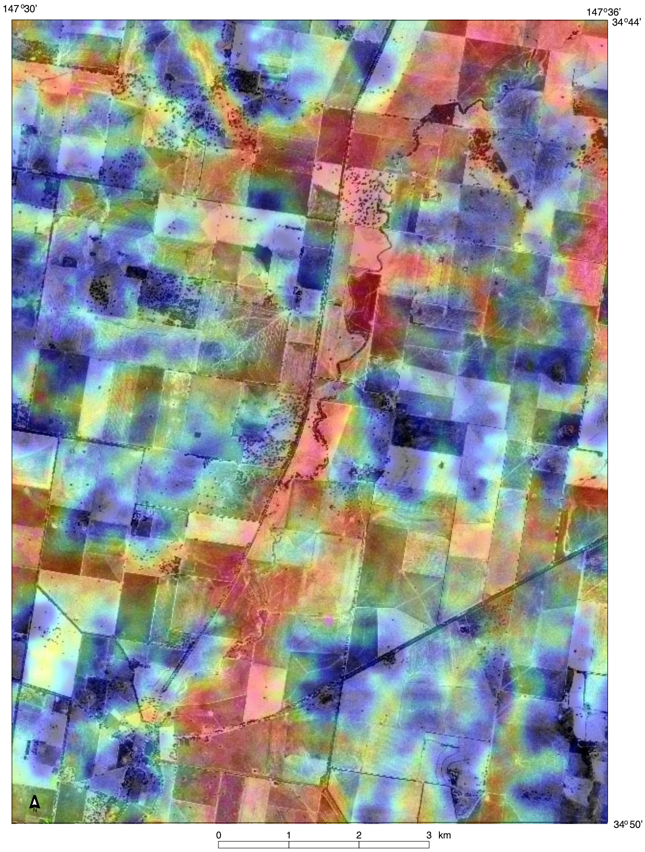

Figure 6. AEM (principal components) image draped over an orthophoto that shows creeks, roads and paddock boundaries. Red colours correlate with more conductive, saline groundwaters 20–40 metres underground in old river channels. In contrast, water is fresh in present-day creeks on the surface.

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- Dr Ken Lawrie, Gilmore project leader, AGSO's Minerals Division, phone +61 2 6249 9847 or e-mail ken.lawrie@agso.gov.au
- Dr Tim Munday, CRC AMET, phone +61 8 9333 6264 or e-mail t.munday@per.dem.csiro.au
- Dr David Dent, Land research group leader, Land & Water Sciences Division, Bureau of Rural Sciences, phone +61 2 6272 5690 or e-mail david.dent@brs.gov.au
- David Gibson, John Wilford, Nerida Reilly & Roslyn Chan (CRC LEME) & Ross Brodie (CRC AMET) can be contacted at AGSO by phone or e-mail (@agso.gov.au). Peter Baker can be contacted at BRS by phone or e-mail (@brs.gov.au)