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Application of Airborne Geophysical Techniques to the Investigation of Salt Stores and Stream Salinity in the Bremer Hills, South Australia

A synthesis of research carried out under the South Australian Salinity Mapping and Management Support Project [SA SMMSP]

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EXECUTIVE SUMMARY

The SA SMMSP represents a significant departure from previous studies seeking to apply airborne geophysics in land management, in that it was the first occasion in Australia where geophysical data were deliberately acquired as part of a broader natural resource management strategy that was already in place. A carefully targeted approach was taken, giving due consideration to the problems being addressed. Particular importance was attached to ensuring that the geophysical data could provide a product of value and perhaps more importantly, how that product could be incorporated into implementing appropriate management strategies. This approach reflected the thinking promoted earlier by George and Green (2000) on the relevance of airborne geophysics to land management.

The primary goal of the Bremer Hills site was to provide information to support decisions on managing stream salinity. Previous understanding led to prioritisation of certain geologies, which were thought to be associated with high salt stores. However, deeply weathered zones associated with ancient land surfaces have been shown to be important salt stores elsewhere in Australia. A hypothesis underlying this study was that higher salt exports are derived from catchments with high fractions of deeply weathered materials.

Geochemistry studies show that, on average, more than 90% of salt found in groundwater and streams is derived from wind-blown oceanic sources (‘cyclic’ salt) rather than directly from rock weathering[1]. This cyclic salt is very low in concentration in rainfall, but concentrates with evaporation at the surface, before being transported or accumulating in soils, weathered materials, ground or surface waters. Thus, any ‘hotspots’ of stream salinity are not caused by rocks breaking down to release high concentrations of salt, but are to do with mobilisation processes.

Radiometrics were used to detect areas of deep weathering. Weathering leads to a change in the proportions of the radionuclides[2] at the soil surface. Thus, they can be detected as being different from the background rock. This mapping was validated with drilling.

The primary factor governing salt stores was rainfall. In the higher rainfall areas, higher rates of water movement lead to decreased salt concentrations compared to low rainfall zones. Nonetheless, the salt export (tonnes/year), which is a product of water exports and salt concentration will generally be as high or even higher in these areas. For a given rainfall zone, salt stores are higher for deeply weathered zones.

It is generally thought that the larger volume of water in the deeply weathered regolith[3] and low permeability means that it takes longer to leach the salt out than areas of shallow regolith. Groundwater modelling also suggests that the impact of recharge reduction takes longer in these areas.

It is recommended that some investigations be undertaken in the areas mapped as (having a higher probability of comprising) deeply weathered materials, to determine more accurately the real risks of salinity and look for best management solutions.

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[1] However, it was also found that in a few landscapes throughout the study area, less than 25% of salt (chloride) can be derived via rock weathering.

[2] Radionuclides are radioactive forms of elements. In this case the radiometrics technique utilises naturally occurring forms of Potassium, Thorium and Uranium.

[3] Regolith comprises the soils and weathered material that overly fresh (unweathered) bedrock.

The methodology used here has broader application to fractured rock areas, where salinisation of water resources is an issue e.g. some of the eastern Murray-Darling Basin catchments. For many such areas, some radiometric data is generally available, albeit at a coarser resolution. The combination of such data with digital elevation models could be used to broadly define occurrences of deep regolith. It is recommended that existing data be used across broader areas of the eastern Mt Lofty Ranges.

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INTRODUCTION

This report is one of a series of final site reports summarising results for the South Australian Salinity Mapping and Management Support Project (SA SMMSP). With investment provided by the Australian and South Australian Governments under the National Action Plan for Salinity and Water Quality (NAP), the project had the following aims:

- to test airborne geophysical techniques (in particular electromagnetics [EM], radiometrics, and magnetics) to determine their value in application to salinity management,
- to further refine and adapt the technology to suit this application, and
- to provide specific information to assist with salinity management in five key areas of South Australia.

The SA SMMSP adopted a pioneering approach compared to traditional research programs involving the acquisition of geophysical data. Instead of accepting data collected in an arbitrary manner, which may add to knowledge but be of little use for management, considerable thought went into how the data generated could contribute to the implementation of salinity management options applicable at each site.

By providing interpreted, appropriately targeted, spatial geophysical data and associated decision support tools, the program seeks to reduce the impacts of salinity on land, surface water quality, groundwater quality and biodiversity.

Advancing considerably on existing knowledge, the outputs of the SA SMMSP offer:

- Detailed knowledge of the distribution and causes of dryland and irrigation-induced salinity.
- Potential land and water management solutions, using a multidisciplinary approach.
- Salinity and materials mapping, and on-ground calibration information, which will enable regional bodies to develop and refine their respective Integrated Natural Resource Management (INRM) Plans.
- More effective targeting of planning controls, development incentives, trading schemes and protection zones in INRM plans and subsequent investment under NAP.
- Identification of both current and future impacts of salinity on natural ecosystems, and biodiversity assets at risk.

This report describes the component of the program conducted at the Bremer Hills site, one of 5 study areas in the SA SMMSP. The sites were chosen on the basis of priority for salinity management as well as representing a range of different landscapes, assets at risk, potential management options and maturity of regional planning. All the sites are shown in Figure 1. The other sites were the Riverland (Lock3 to the state border), Tintinara (mallee highland and coastal plain), Angas-Bremer Plain, and Jamestown.

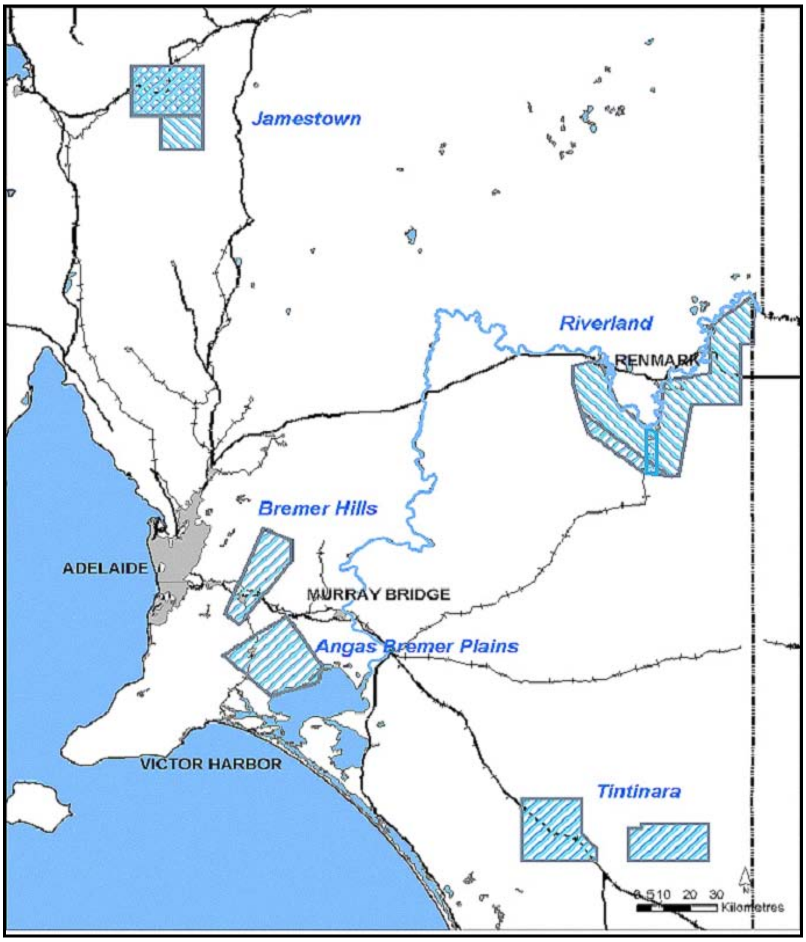

Figure 1. Location of the 5 SA SMMSP study areas

The Bremer Hills site was the only one in the SA SMMSP, which represented fractured rock areas. The asset of concern was the salinity of streams on the eastern Mt Lofty and the Bremer River, in particular, the Bremer Catchment, which had been used in previous salinity studies.

The aim of this report is to summarise the study and main findings from the Bremer Hills site. Issues of extrapolation to other catchments in the Mount Lofty Ranges and Eastern Murray-Darling Basin are discussed. Similar reports have been written for each of the other study areas and a final report exists for the overall program.

The report is divided into 4 parts, comprising:

A. Discussion of the resource management issues,

B. Definition of the role and capabilities of airborne geophysics in addressing these issues,

C. Summary of findings from the geophysics and associated modelling / decision support tools, and

D. Assessment of the lessons and outcomes of the project for future management decisions.

The contracted objective for the Bremer Hills site was to:

Determine the relationships between geology, geomorphology, groundwater and stream salinity.

In the original schedule, any flying in the Bremer Hills was dependent upon cost savings elsewhere in the flying program. These savings resulted from reviewing the required line spacing for the flying program and through negotiating a large body of work.

Contracted outputs included:

(i) Map and associated products including soil and regolith maps demonstrating soil stores, solute transport pathways, salt sinks, synthesis of all available data to indicate hazards and management options; and

(ii) Report on stream salinity in the Bremer River and comparison with soils, regolith and groundwater.

PART A. RESOURCE MANAGEMENT ISSUES

1 Salinity in the Eastern Mt Lofty Ranges

The Eastern Mount Lofty Ranges form the western boundary to the lower Murray Darling Basin. Dryland salinity occurs throughout the eastern ranges, mainly along narrow valley floors, and there are numerous saline soaks along watercourses, at the base of footslopes and breaks of slope. The saline areas are often small patches, a few hectares or less, so that the amount of agricultural land directly affected is not great. The undulating to hilly terrain tends to restrict the potential for this area to increase significantly, although new saline patches did emerge and others expanded following the extreme rainfall events of 1992. Whilst the area affected is unlikely to expand greatly, the fragmented nature of salt affected land in this region presents significant management challenges. The lack of vegetative cover on salt affected ground along drainage lines, often on sodic and/or acidic soils, has led to severe soil erosion. This can be more severe in areas of acid sulphate soils.

An important consequence of dryland salinity in this region is saline seepage directly into watercourses, and ultimately the River Murray, and as wash-off into agricultural and domestic surface water storage. The eastern ranges are mainly characterised by local groundwater flow systems in fractured rock aquifers, the drainage lines becoming groundwater accumulation zones. Recharge and groundwater flow are greatly influenced by geology and weathering, that can be variable throughout this area, and there is evidence of significant ‘hot spots’ for salt loads to stream flow.

The current recommended management options for the Bremer Hills include:

- Fencing off salt affected land for protection from grazing;
- Strategic revegetation to reduce recharge;
- Restoration and conservation of existing native vegetation; and
- Siting farm dams off-stream.

Several previous studies have improved our understanding of dryland salinity in the eastern Mount Lofty Ranges, most notably at the Herrmann and Keynes catchments (e.g. Fitzpatrick *et al*. 1994, Cox *et al*. 1996, Ecker 1998, Cox and Ashley 2000, Fitzpatrick *et al*. 2003). Groundwater flow processes are now quite well understood for these small catchments and there is also considerable data relating to soil physical and chemical properties.

Despite the detailed knowledge emerging from these studies, it has not been possible to extend this to the wider catchment, in order to interpret the cause of salt load ‘hot spots’. This study intended to extrapolate processes outside of these intensively studied catchments across the eastern Mt Lofty Ranges.

PART B. ROLES AND CAPABILITIES OF THE AIRBORNE GEOPHYSICS

2 Airborne geophysics technologies and target definition

One of the prime objectives of the SA SMMSP was to assess the usefulness of airborne geophysics as an information gathering tool to be applied in addressing salinity and water quality issues. Throughout the 5 key sites, 4 distinct geophysical techniques were employed, with each technology used for a different but complementary purpose. The main features of the techniques are summarised in the box on the next page.

Airborne electromagnetics (AEM) can be used to define 3-dimensional conductivity structures of a region to describe the salt-water-materials relationships in terms of their defining electrical conductivity signal. This can potentially spatially define high (and low) salinity groundwaters and zones of high (and low) salt load. It may also indicate sub-surface variability in materials, specifically the clay: silt: sand contribution.

AEM requires careful calibration to determine the relative contribution of conductive materials, but is the only geophysical technology that has the potential to map salt load directly in the sub-surface with good vertical resolution.

Radiometrics can give a spatially precise picture of soil and rock variability across a landscape. Flood plain, or alluvial sediments can be contrasted with the coarser slope, or colluvial, deposits and the bedrock on ridges.

Magnetics detects the presence of iron-rich minerals which are commonly associated with older sub-surface drainage lines – palaeochannels – that may act as conduits for groundwater flow. Geological structures (eg. faults, dykes, etc) are also often emphasised using this technology.

Altimetry / Elevation information is required to process the geophysics data but also can be of great value in helping to understand and / or model landscape processes.

2.1 LIMITATIONS

Airborne geophysical techniques have 3 significant limitations:

1. All surveys represent a snap-shot in time of the geophysical properties of the landscape. As such, they are only an approximate indication of the average ambient conditions across a region and the observations must be carefully evaluated with respect to their position in time and relative to ambient climatic conditions.

2. Careful, systematic and accurate ground-truthing, or calibration, is a vital pre-requisite for realistic interpretations of the airborne geophysical signals. This will add a cost of at least as much as that required to fly the surveys.

3. Each technology has its own strengths and weaknesses, and AEM, in particular, comes in a number of guises, each with peculiarities that allow it to be tailored to address the most prevalent issue for a given area. Forward modelling, or scenario-testing, is a useful exercise that should be carried out on dummy data sets representative of conditions expected to be met over the real survey.

Airborne Geophysical Technologies

AIRBORNE ELECTROMAGNETICS (AEM)

A pulse of EM radiation is emitted from the aircraft which interacts with conductive material in the ground. A modified, secondary signal 'bounces' back to a towed receiver that collects parcels of data in either time or frequency domains. These signals can then be modelled, or 'inverted', to define the 3-dimensional conductivity structure of the survey area. From the electrical conductivity signals and appropriate ground-truthing, the relative composition of salts, water and materials in the profile can be defined. Potentially, this can spatially define high (and low) salinity groundwaters and zones of high (and low) salt load. It may also indicate sub-surface variability in materials, specifically the clay: silt: sand contribution.

Vertical reliability and resolution is strongly dependent on the modelling routines used to convert the raw data into depth images and this is highly constrained by the interpretation of drill-hole data and pre-conceived ideas about the landscape and nature of the sub-surface (e.g. Hunter, 2001; Christensen, 2002). Interpreted data must, therefore, be treated with extreme care.

RADIOMETRICS (GAMMA)

Radiometrics detect the natural gamma radiation signal given off by near-surface (< 30cm) materials and can give a spatially precise picture of soil and rock variability across a landscape. The relative amounts of radioactive elements, namely potassium (K), uranium (U) and thorium (Th), are indicative of source minerals and hence soil and rock-types. This can help contrast regions of differing clay, silt and sand compositions. The ratio of different gamma intensities can give clues to a landscape's development. For example, potassium depletion may indicate an older and hence thicker weathering profile which may be correlated with elevated salt loads (Wilford, et al., 2001). It should be noted, however, that, with existing technology, radiometrics cannot measure salt directly.

MAGNETICS

Airborne magnetics detects the subtle variability in the earth's magnetic field caused by the presence and absence of ferromagnetic minerals such as magnetite (Fe_3O_4), maghemite (□-Fe_2O_3), pyrrhotite (FeS) and ilmenite ($FeTiO_3$). These minerals are commonly associated with stream-bed deposits and have been used elsewhere (e.g. to the north around Jamestown (Wilford, 2004a) and to the east across Honeysuckle Creek, Victoria (Cresswell, et al., 2004)) to pick-out sub-surface drainage lines – palaeochannels – that may act as conduits for groundwater flow (Cresswell, et al., 2004). Further, these minerals are common in many igneous rocks, both as primary and secondary minerals, and can often be used to depict geological structures in the sub-surface from discontinuities seen in the airborne images.

ALTIMETRY

As a necessary by-product of flying any of the other 3 geophysical techniques, a precise digital elevation model (DEM) is generated from the radar and laser altimetry used to precisely locate the aircraft above the ground. The resolution is a function of the spacing of the flight lines and the signal repeat time, but generally this results in a spot measurement taken every 10m along the flight path, with flight paths typically 100m to 400m apart.. The resultant data is interpolated to give an exact surface on which to "hang" the other data sets and provide a surface reference for other studies. The DEM also often gives new insights into the evolution of landforms and landscape relationships (Gibson, 2004).

Bearing these limitations in mind, airborne geophysics provides a suite of powerful tools that can give un-paralleled insights into landscape form and function, providing a quasi-continuous image of ground conditions and hitherto unprecedented spatial analysis of fundamental environmental features. Used without due diligence, however, the data can also give misleading, or even quite erroneous, results.

2.2 SELECTING THE GEOPHYSICS TECHNIQUE

The high costs associated with calibration and ground-truthing of AEM in fractured rock hills (ie. having multiple, discontinuous aquifers / conductivity zones) made this technique too expensive to use in the Bremer Hills.

However radiometrics, at around a tenth of the cost of AEM, was believed to be suitable for identifying zones of deep weathering (thought to be strongly associated with potential salt storage), with characteristic geochemical signals able to be detected from the surface (See section 8 – Deep Weathering & K Residual method). Magnetics is typically flown simultaneously with radiometric surveys.

2.3 AIRBORNE RADIOMETRICS – IN MORE DETAIL

The air-borne gamma-ray spectrometry, or radiometrics, techniques measure gamma-rays, that are emitted from the top 30 cm of the soil. The response is dependent on the age and type of material and hence can be used to investigate the regolith. They have been used widely for detecting radioelements in mineral exploration. Because gamma-rays are not masked by vegetation to the same extent as in satellite imagery, this makes it more useful for determination of surface soils in vegetated areas such as the Adelaide Hills. Radiometric imagery is already available across much of the Mt Lofty Ranges at 400 m line spacing and PIMA mining has used 200 m line spacing in the area (see Figure 2). For this project, a component of the Bremer River catchment that consisted of wetter, steeper areas, was flown at 100m line spacing.

The cost of flying the radiometrics was around $55,000. While ground-based electromagnetic (EM) induction techniques are used in a targeted way in the area, the cost of flying EM in steep terrain is prohibitive. For comparison with flying costs (data acquisition), the cost of the associated field work, data collation, analysis and report writing was around $144,000. It is unclear how this cost will vary for future surveys. Some of the validation work would not need to be repeated, however, some field-truthing would always be required. Savings in data acquisition are possible if wider flight line spacings are chosen (eg. 200m spacing as per the PIMA Mining survey, or 400m), however data resolution would drop and some narrow areas of deep weathering may be missed.

The natural radiation from potassium (K), thorium (Th) and uranium (U) is inferred through direct measurement of the emissions of ^{40}K, ^{208}Tl and ^{214}Bi. The gamma rays are detected using a large crystal pack over 256 channels. Corrections include noise reduction, removal of cosmic, aircraft and radon backgrounds; micro-levelling of flightline data for each band and the application of a minimum curvature algorithm to produce grids at 20 m cell size.

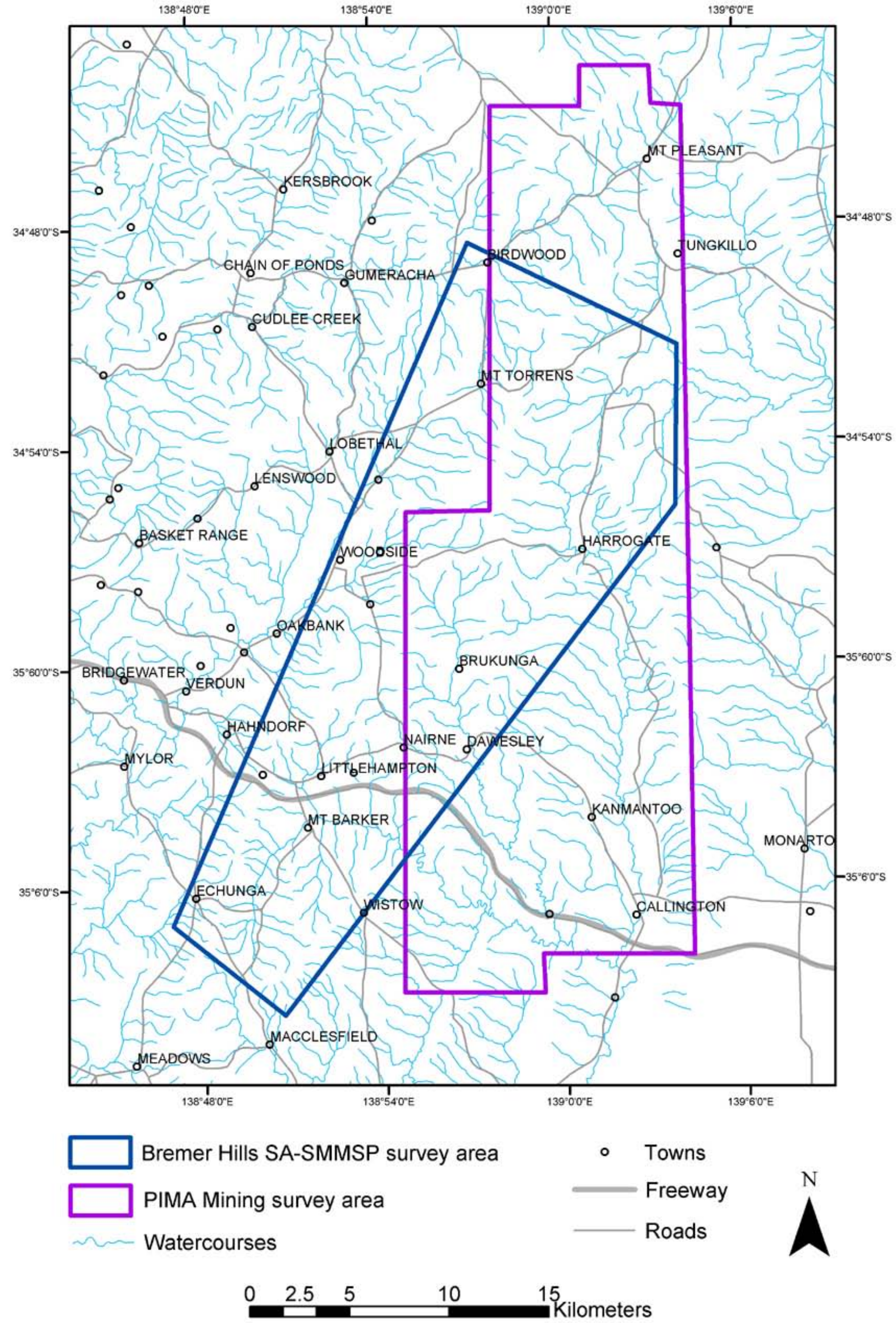

Figure 2. Location of the current study area (100m flight line spacing) and the previous PIMA Mining survey (200m flight line spacing).

3 Approach

While the emphasis of the SA SMMSP is on airborne geophysical techniques, a great deal of effort was put into analysing existing data, and using complimentary techniques, in order to get maximum benefit from the study (noting that the study was dual-purpose in nature - ie. gaining better insight for management in the study area, and testing the geophysics techniques).

The Bremer Hills project consisted of six steps:

(i) *Review of previous studies*

Previous studies have included:

- o Detailed site studies at Hermanns and Keyneton Catchments (CRC for Soil and Land Management/CSIRO; see references);
- o Geochemical studies in Bremer area (CRC-LEME, CSIRO);
- o Interpretation of stream salinity data in Bremer Catchment (Ecker; see references);
- o Salinity mapping (provided by Chris Henschke, Rural Solutions SA); and
- o Local monitoring and drilling (CSIRO, DWLBC, CRC-LEME).

(ii) *Collation of existing data*

Existing datasets included:

- o Stream gauging data at Mt Barker Creek, Bremer River at Hartley and others;
- o Meteorological data at Mt Barker, Callington and Palmer;
- o Soil maps;
- o Geological maps;
- o Land salinisation (PIRSA);
- o Digital elevation data; and
- o Previous radiometric data.

(iii) *Airborne radiometric survey*

- o Contracting; and
- o Data checking and analysis.

(iv) *Development of terrain and weathering indices*

- o 25m DEM;
- o K-residual modelling;
- o Wetness Index;
- o MRVBF [Multi Resolution Valley Bottom Flatness index]; and
- o FLAG [Fuzzy Landscape Analysis GIS index].

(v) *Collection and analysis of further field samples*

- o Stream analyses;
- o Groundwater samples;
- o EM survey; and
- o Analyses including:

- full ion analysis on water samples, including bromide,
- stable isotopes of water on water samples, and
- EC on soil samples.

(vi) *FLOWTUBE modelling*

The FLOWTUBE modelling of selected catchments in the Adelaide Hills (Hermmans', Keynes', Mt Eagle and Escort Hughes') showed:

- Catchment response times to land-use change varied from 50-150 years;
- Revegetation within Mt Eagle significantly lowered groundwater levels throughout the catchment;
- Longer, narrower catchments take longer to equilibrate than shorter wider valleys; and
- For the Hermmans', Keynes' and Escort Hughes' catchments, engineering may be the only option to lower the watertable in the valley floors.

PART C. SUMMARY OF FINDINGS

Only key results are discussed in this summary final report. Readers are referred to the publications and references sections for detailed reports.

4 Publications

The publications arising from work conducted under the SA SMMSP in the Bremer Hills, in addition to this summary report, are listed below:

- Cox, J., McEwan, K., Davies, P., Smitt, C., Herczeg, A., and Walker, G., (2002). Salt Transport in the Bremer Hills, SA. Report for the NAP South Australian Salt mapping and Management. CSIRO Land and Water Technical Report 50/02.
- Smitt, C., Herczeg, A., Davies, P., and Cox, J. (2004.) Identifying Sources of Salt and Its Mobilisation Processes in the Eastern Mt Lofty Ranges, South Australia 2004. In Proceedings of the 9th Murray Darling Basin Groundwater Workshop.
- Smitt, C., Cox, J., McEwan, K., Davies, P., Herczeg, A., and Walker, G., (2003). Salt Transport in the Bremer Hills, SA – FLOWTUBE Modelling. 2nd Report for the NAP South Australian Salt Mapping and Management. CSIRO Land and Water Technical Report 06/03.
- Smitt, C., Cox, J. and Davies, P. (2003b). Salt Transport in the Bremer Hills, SA. Interpretation of Spatial Datasets for Salt Distribution. Fourth report for NAP South Australian Salt Mapping and Management. CSIRO Land and Water Technical Report 49/03.
- Wilford, J. (2004b). Regolith-landforms and salt stores in the Angas-Bremer Hills. CRC LEME Open File Report 177. Cooperative Research Centre for Landscape Environments and Mineral Exploration. ix + 100pp.

5 Sources of Salt

Salt is generally considered to come from 3 sources:

- cyclic salt – from atmospheric deposition of salt from aerosols derived from the ocean, salt lakes, etc;
- connate salt, derived from weathering of rock; and
- marine salt, derived from marine deposition of rocks or inundation by the ocean.

For the Adelaide Hills, marine salt is considered to be negligible. Fitzpatrick *et al*. (pers comm.) have shown that certain minerals in the Adelaide Hills have high concentrations of salt. Acidic conditions have led to aggressive weathering of these minerals. However, the high export rates of salt seen in streams would not be supported by weathering.

Figure 3 (a, b, and c) shows data on sodium, sulfate, bromide and chloride data from stream sampling in the Bremer hills (in November 2002), relative to the seawater dilution line. The data show that most of the solutes are derived from marine aerosols delivered via rainfall. There is evidence of a small fraction of weathering, as evidenced by:

- a slight excess of Na above the seawater dilution line for 2 samples;
- elevated concentrations of sulfate for 2 samples relative to seawater indicating sulfide oxidation; and
- Up to 25% of the chloride in only small parts of the landscape could have come from rock weathering.

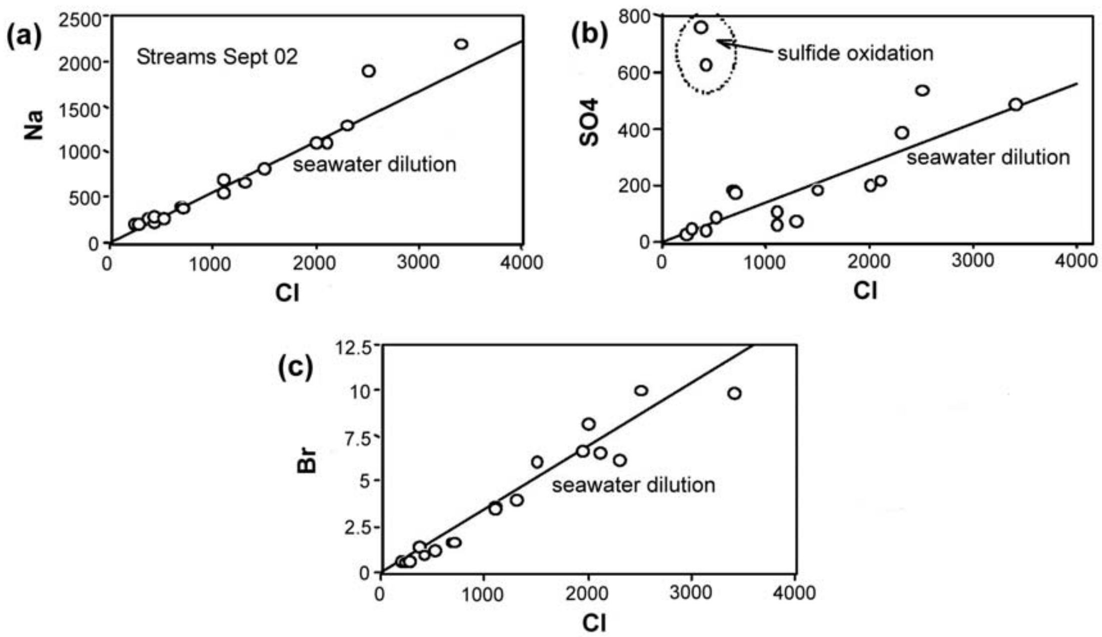

Figure 3. Chemistry of stream samples (Nov 2002), (a) Sodium/Chloride profile, (b) Sulfate/Chloride profile and, (c) Bromide/Chloride profile.

As the majority of the salt is derived from marine aerosols, 'hotspots' of salinity will only be occasionally related to weathering of minerals. Thus, any correlation between salinity and geology is likely to be due to hydrological characteristics.

6 Hydrogeological Provinces

Hydrogeological provinces are the way, in which hydrogeologists relate geology to groundwater characteristics. Of the 4 principal provinces occurring throughout the Mt Lofty Ranges, defined by Henschke (1997), 3 occur in this area:

- Landscapes and bedrock associated with the Adelaide geosyncline (Precambrian). These occur in the high rainfall western component of the catchment. Salinity is usually confined to poorly drained valley systems. Groundwater salinity is relatively low compared to the eastern catchment;
- Landscapes and bedrock associated with the Kanmantoo Group (Cambrian Rocks). Salinity is thought to be associated with the Nairne pyrite member and more regionally where geological controls (faults, lineaments, resistant bands of hard rock, quartz veining, shear zones) constrain groundwater flow. Groundwater salinities are in the range of 3,000 to 10,000 mg/L; and

- Landscapes associated with the sedimentary basins (Tertiary and Quaternary). These units have the highest groundwater salinities. Saline seeps are associated with perched water tables within these sediments and where creeks have incised into the valley alluvium.

Dooley and Henschke (2000) had mapped occurrence of land salinity in the eastern Mt Lofty Ranges, although a large component of the Bremer Catchment was not included. As expected, there was a higher correlation between salinity outbreak and alluvial valleys, with approximately 6% of the mapped salt overlying these recent Quaternary sand, silt and gravel alluvial valleys. Other geological formations showed little correlation with the mapped salt with less than 2% of the mapped salt overlying the Murray Group Limestone and between 2 and 5% of the mapped salt overlying the Backstairs Passage Formation, the Tapanappa Formation or the Nairne Pyrite member.

Within both the Adelaide Geosyncline and Kanmantoo Group, it is recognized that higher groundwater salinities are associated with deep weathering.

7 Weathering and landform history

Two prominent landform features are recognized in the Eastern Mount Lofty Ranges (e.g. Figure 4):

- A highly weathered paleo-surface, referred to as the 'summit surface'; and
- A series of major north south tending faults.

This paleo-surface is characterized by the presence of iron and mottling in the upper part of the weathered zone. In the study area, this surface is not so well defined as in other areas such as Kangaroo Island or Fleurieu Peninsula. The paleo-surface is an older smoother surface caused by continuous weathering and erosion over a long period of time. The process of chemical weathering, or breaking down of the rocks and sediments to produce clays and other minerals, often occurred down to considerable depths. However, except for preserved scattered remnants, this ancient land surface has largely been eroded away. The major faults, which occurred from ~40M to 14M years ago, and after 5M years ago, has created a number of eastern-facing tilt blocks. The faulting led to increased erosion on sloping areas and accumulation on lower areas. Slopes on the paleo-surfaces are 0-1 degree on the floodplains and 2-5 degrees on adjacent rises. This compares to the steeper eroded surfaces, which can be 20-30 degrees.

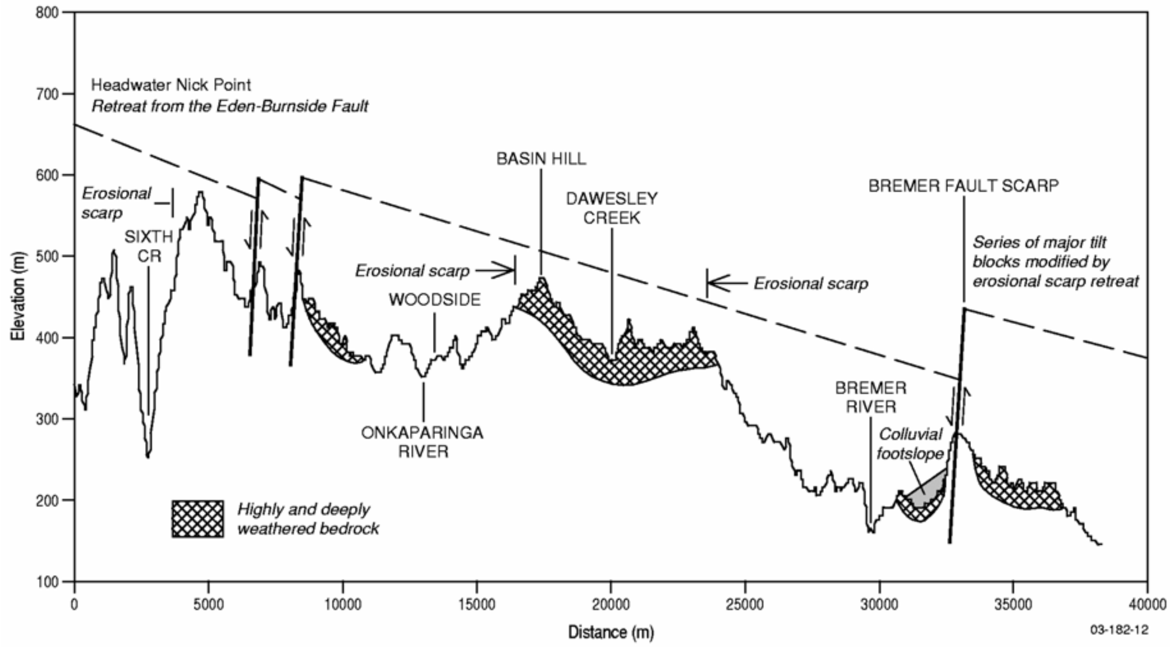

Figure 4. Topographic cross-section highlighting a series of easterly tilted fault blocks. Major fault scarps are associated with these fault blocks (e.g. Bremer Fault) as well as a series of local scale parasitic faults within the larger tilt blocks. Deep weathering associated with the palaeosurface is preserved on both the upper (often coincident with drainage divides) and lower parts of the tilt blocks. Headward erosion associated with a series of erosional scarps is actively stripping the older weathered palaeosurface. Thickness of weathered materials is not to scale.

8 Salinity and Deep Weathering

The distribution of salinity is related to rainfall (the higher the rainfall the lower the salt). In addition there is a clear relationship between salinity and depth of weathering:

- The older deeply weathered landforms have been associated with high salinity risk in southern Australia, especially in WA and Eyre Peninsula;
- The deep weathering provides a large pore space in the rocks in which saline water can be stored. The deeply weathered zones are also associated with lower slopes and hence smaller hydraulic gradients. The weathered zone often has low permeability except at the base where there is fresher rock. The low transmissivity and hydraulic gradients, and high storativity means that the older, sometimes saline, water takes longer to displace, leading to higher salt output to input ratios for long periods of time following clearing of native vegetation;
- The low transmissivity and low gradients also mean that the aquifer is less likely to transmit any recharge, leading to an expansion of waterlogged areas; and
- The broad valleys often associated with deep weathering give the potential for evaporation and transpiration processes to concentrate salt in the groundwater, particularly under native vegetation. This means that the streams may generate less, but more saline, water.

9 Deep Weathering and K-Residual Method

The 'K-residual modelling' approach uses a sophisticated methodology to separate bedrock from soil using a combination of gamma-ray imagery and digital elevation data. The deviation of the signal from the background bedrock signal can reflect the weathering of bedrock or the deposition of covering sediments. Alluvial and colluvial deposits can be identified separately and removed. The expectation is that for deeply weathered areas, K (potassium) is leached, while Th (thorium) is concentrated near the surface in association with clays and iron oxides. Figure 5 shows that the method detects depth of weathering, once sites with alluvial deposits are removed. An area of deep weathering near Tungkillo had low levels of K, but not elevated levels of Th, probably due to partial erosion of the surface materials.

Using this method, Figure A-1 in Appendix 1 gives mapped predictions of where deeply weathered sediments (blue areas) are expected, compared to areas of shallow soils or fresh bedrock (red areas).

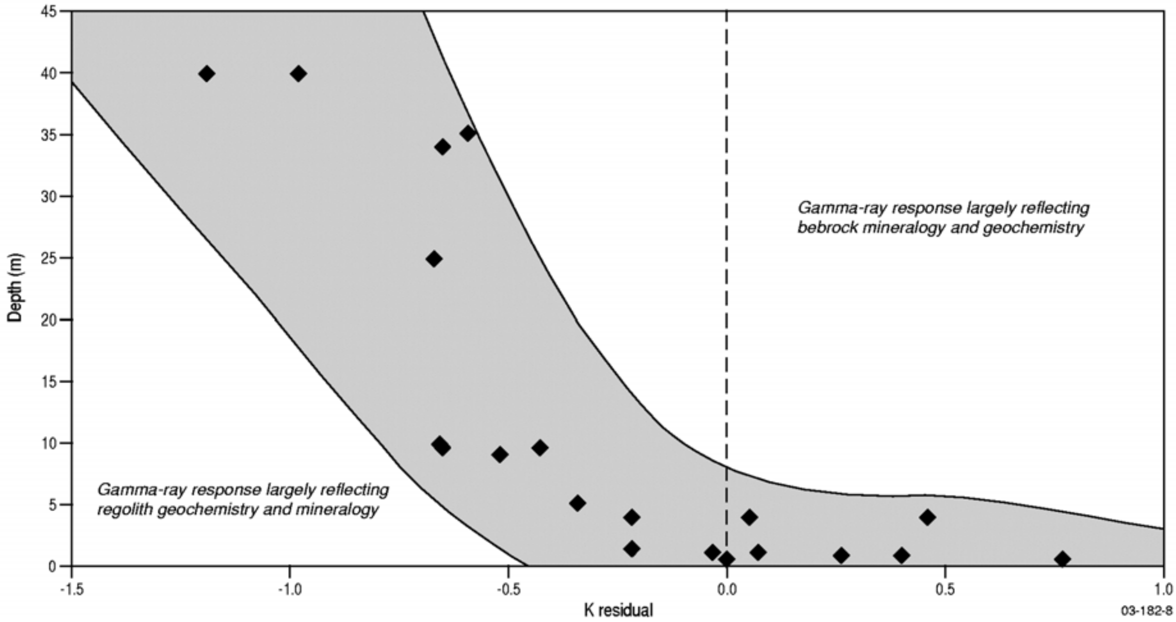

Figure 5. The 'K-residual modelling' approach. Shows depth of weathering against the K residual index. Data includes only drill holls that intersected saprock[4] and also excludes holes drilled into transported regolith (ie. excludes depositional environments). More negative K residual values correspond to lower than average levels of Potassium (due to leaching) and are associated with deeper weathered profiles.

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[4] Saprock is the clay-rich material formed by the in situ chemical weathering and decomposition of igneous or metamorphic rocks.

10 Topographic Indices

One of the most widely available datasets is digital elevation. For areas of high relief, such as the Mt Lofty Ranges, many other datasets are correlated with topography or slopes e.g. rainfall, soils, groundwater fluxes, groundwater salinity, waterlogging, weathering, vegetation and land use. For this reason, there have been a number of indices developed for different purposes (further discussed in Wilford, 2004b):

- MRVBF (Gallant and Dowling, 2003) uses slope as calculated on different resolution elevation data to delineate valley floors.
- WETNESS index (Beven and Kirkby, 1979) is a widely used index to define waterlogged areas.
- FLAG (Roberts *et al.*, 1997) uses 4 separate topographic indices as well as a combination of these to produce another 2 indices that are considered to be relevant for salinity studies:
    - HIGH – normalized topography;
    - LOWNESS – deviation of topographic surface relative to smoothed surface – can detect areas at risk of seepage below break of slope;
    - CONCAV – curvature of topographic surface – can be used to define blockages and bottlenecks to flow;
    - UPNESS – an index of contributing area;
    - LOW – large contributing area but relatively low areas; and
    - CC – convergent drainage lines with large contributing areas.

Different indices are likely to be important for different hydrogeological provinces. In the north of the study area, the FLAG LOW index was seen to overestimate the area of land salinity. However, when combined with the K-residual method, the overall prediction was fairly accurate. To the east of the catchment area, the WETNESS index predicted the broad alluvial valleys that have the potential to store large amounts of salt. This information can be used in conjunction with salt mapping and other techniques.

MRVBF provided an excellent first pass separation of valley floors and low-lying depositional alluvial plain from hill slopes and edge ridges. The MRVBF algorithm was also useful in highlighting bedrock constrictions or bottlenecks along river channels. In many places, the bottleneck corresponds to a nick point in the stream.

11 Salt Storage and Salt Balances

Despite the notion that deeply weathered zones are considered to be high salt stores, there was a poor correlation between salt storage within the regolith and K-residual. On the other hand, there was a significant relationship with rainfall, with high salt storages at low rainfall. This is not surprising since higher recharge fluxes would be associated with higher rainfall. Salt deposited from the atmosphere would not be so concentrated under both native vegetation and current land use. However, the quantity of salt being exported can still be high from high rainfall areas as this equates to the product of the recharge flux and the salt concentration of the groundwater. So while the salt concentration is low for high rainfall areas, the recharge flux is high. Similarly, the stream water yield is higher and hence the salt concentration lower. Ecker (1998) found that the highest salt output to input ratio (tonnes of salt exported in streams compared to atmospheric deposition of salt) was highest for the Mt Barker catchment in the higher rainfall area of the catchment. This area of the Mt Barker catchment has predominantly deeply weathered profiles.

When one compares the salt storage between deeply weathered profiles and elsewhere within a given region, and hence a similar rainfall zone, the highest salt stores are associated with valley alluvium, colluvial fans and deeply weathered regolith.

Statistical analysis of salinity at gauging stations in the Bremer Hills shows that the stream EC in Mt Barker Creek at Mt Barker (GS 426557) is significantly decreasing[5] (see Figure 6) whereas, downstream, in the Bremer River at Hartley (GS 426533) stream EC is not significantly changing[6]. Stream EC trends are summarised in Table 1.

Calculated values for the salt output/input ratio (So/Si) for these two gauging stations are shown in Table 2.

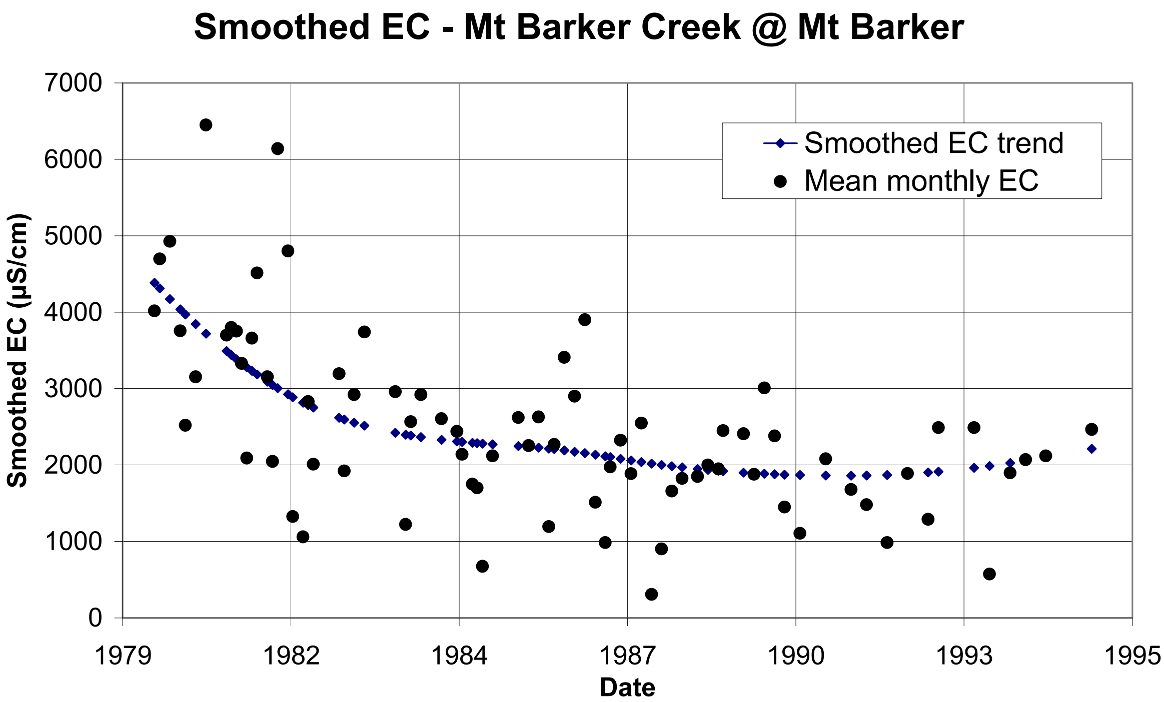

Figure 6. Mean monthly EC and smoothed EC trend, corrected for flow and seasonal variation, for Mt Barker Creek @ Mt Barker (GS 426557).

[5] EC trends for Mt Barker Creek at Mt Barker are based on grab sampled EC and flow data from the period May-79 to Aug 94 (Jolly et al., 2000). However the values in Table 1 include additional data from 1995.

[6] EC trends for the Bremer River at Hartley are based on grab sampled EC and flow data for the period May-73 to Nov-98 (Jolly et al., 2000).

Table 1. Summary of the salinity trends for Mt Barker Creek @ Mt Barker (GS 426557) and Bremer River @ Hartley (GS 426533).

Gauging Station	Mean Flow (ML/day)	Mean EC (uS/cm)	Mean Saltload (tonnes/day)	EC Trend (uS/cm/yr)
Mt Barker Creek @ Mt Barker (Smitt et al., 2003a)	38	2484	21	-129.6 ± 31.8
Bremer River @ Hartley (Jolly et al., 2000)	98	3330	73	-18 ± 19 (not statistically significant)

Table 2. Estimates of salt output/input ratios.

Gauging Station	Smitt et al. (2003a)	Williamson (1990)
Mt Barker Creek @ Mt Barker	5.9 (based on grab sampled data, 1980-1993)	5.5 (based on grab sampled data, 1980-1987)
Bremer River @ Hartley	3.3 (based on 1 year [1996]- of continuously sampled data, as remaining data considered poor quality.)	5.7 (based on grab sampled data, 1974-1986)

1. Note: Values of So/Si were also calculated by Ecker (1998) but are not directly comparable to the figures above, derived from gauging station data, due to differences in the delineation of subcatchments.

Despite a declining trend in stream EC for Mt Barker Creek, the So/Si ratio calculated for this period is still relatively high (5.9 at Mt Barker), but is not expected to increase. This high value reflects both the relatively large salt storage in the deeply weathered zones of the Mt Barker catchment, and also that it is being mobilised out of the catchment due to the high rainfall.

Future trends in stream EC are expected to be dependant on rainfall variability.

12 Potential for Improving Soil Landscape Mapping

Generally, there is a good relationship between gamma-ray patterns as inferred from the K-residual approach and existing maps of soil landscape units. This is because radio-element responses will relate to soil chemistry and geomorphic processes that are largely controlled by landform morphology. Ground validated gamma-ray data inform directly on specific soil attributes and can be used to sub-divide or modify soil landscape units over the study area. The technical report by Wilford (2004b) gives examples where soil landscape modelling can be improved.

PART D. IMPLICATIONS FOR MANAGEMENT

13 Land Management Options

Assessment of suitable land management options was made using the groundwater model, FLOWTUBE. The results show that the low conductivity, low slopes and long flowpaths typically associated wth deeply weathered areas mean that groundwater response times can be slow with respect to changing land management / recharge reduction. Hence the deeply weathered zones may be difficult to manage, or slow to respond, with a recharge reduction (higher water use) approach.

If recharge reduction will not produce acceptable results, this suggests that the following approaches (in addition to established management options listed in Part A) could be investigated:

- Engineering – to improve drainage (eg. shallow surface drains).
- Living with salt – eg. establish / enhance wetlands in poorly drained (/saline) areas.

Further work to establish various situation-specific, best-bet management options is recommended.

14 Transportability for the Approach

The methodology used here should be transferable to other fractured rock areas. The 'K-residual method' requires rocks to contain K (potassium). Most of the hard-rock areas in Australia have been mapped with radiometrics at either 200 or 400 m line spacings. Using radiometrics alone at 400 m line spacing will mean that some narrow areas of deep weathering will be missed. The use of radiometrics and digital terrain modelling together will detect a greater fraction of the area. This can be used at relatively low cost across the Eastern Mt Lofty Ranges. The EM may also be useful, but is expensive unless used in a targeted fashion.

The approach used should be extended over a larger part of the Adelaide hills but at a scale useful for the Bremer Barker Catchment Group and Mt Lofty Ranges Integrated Natural Resource Management Group. This may include detailed on-ground measurements in selected local catchments to help with prediction of land management changes.

15 Conclusions

- The extent of deeply weathered regolith (which provides significant potential for salt storage) is more widespread than previously mapped. A long history of weathering combined with more recent tectonic activity (and associated faulting, uplift and erosion) has produced complex landscapes in the Eastern Mt Lofty Ranges. Highly weathered ancient landforms are juxtaposed with youthful landforms with little regolith development. The highly weathered profiles are often associated with the remnants of an old deeply weathered paleosurface (referred to as the 'summit surface'). However, some of these deeply weathered profiles have been downfaulted and examples can occur in lower parts of the landscape.

- The 'K-residual' interpretation of gamma-ray imagery mostly separates highly weathered landforms from areas, characterized by thin soil and weathered bedrock. The method, which relies on leaching of Potassium and elevated concentrations of Thorium in association with iron oxides and clays, detects leached ferruginous soils, mottled colluvial and alluvial sediments and highly weathered kaolinised bedrock. The K-residual method requires ground validation since certain rocks can give similar responses to highly weathered materials.

- Digital terrain imagery using a specific index, MRVBF, proved to be useful in detecting valley fill sediments and broad valley systems, often associated with relic paleo-landscapes. However, there was, overall, a poor correlation, between the index and the depth of weathering. The index was very effective in highlighting local constrictions in local drainage lines. Thus, MRVBF was more effective than the 'K-residual method' in depositional areas.

- The gamma-ray imagery has the potential to improve existing soil-landscape and geological mapping. In conjunction with terrain modelling and field verification, it should provide a robust map of hydrogeomorphic units. As similar gamma-ray responses can relate to different materials at the surface it is recommended that the imagery be interpreted within different geological formations and landform units.

- Salt derived from aerosols and rainfall formed at least 90% of the salt found in groundwater and streams. While weathering of rock can be locally important, it forms only a minor component of mobile salt. If salinity risk is to be correlated with geology, it is not through high salt concentrations in the rock, but rather characteristics of the geology that are related to the storage and mobilisation of salt.

- While regolith thickness provides the landscape with a capacity to store salts, regolith thickness does not directly correlate with the quantity of salt stored. Rainfall has a much larger effect on the salt concentrations with higher salt concentrations being found in the eastern lower rainfall areas. For a local region within a rainfall zone, the highest salt stores are associated with valley alluvium, colluvial fans and highly weathered bedrock.

- There were no conclusive results regarding the relationship between deeply weathered areas and salinity risk. High salt output to input ratios tend to be higher from catchments with a high proportion of deeply weathered regolith compared to other catchments. Similarly, stream salinities tend to be higher in parts of catchments with a higher proportion of deeply weathered zones. However, rainfall is a more dominant factor across the Hills in general and within a rainfall zone, deeply weathered zones become an important determinant of salinity. There was only limited mapping of land salinisation in the Bremer Catchment. Widening the study area to outside of the Bremer catchment, land salinisation was mainly found in the broad alluvial and deeply weathered valleys.

- Previous studies have shown that the salinity problem is not obviously getting worse in this area, but fluctuates with rainfall variability.
- Modelling illustrates that the deeply weathered zones may be difficult to manage through recharge reduction.
- The methodology used here should be transferable to other fractured rock areas, and could be used at relatively low cost across the Eastern Mt Lofty Ranges.

16 Products

The following products are outputs from the SA SMMSP Bremer Hills project site (refer to technical reports for more detail):

- A radiometric map of the higher rainfall areas of the Bremer Catchment;
- A map of deeply weathered zones as inferred from the radiometric imagery (see Appendix 1, from Wilford, 2004b);
- This site summary report and various technical reports (see section 4);
- 6 landscape models associated with deeply weathered zones (see Wilford, 2004b);
- Digital elevation model (20 m grid cell); and
- Map of terrain indices (see Wilford, 2004b).

17 Community Extension

- Public Seminar at CSIRO, Urrbrae SA. 22nd April 2004;
- Presentation to Bremer Barker Catchment Group at Mt Barker Catchment Centre 22nd April 2004; and
- Presentation to Mt Lofty Ranges Integrated Natural Resource Management Group at Mt Barker Catchment Centre 23rd April 2004.

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This report is but one of component of a much larger project looking into the value of airborne geophysical techniques in gathering information to assist with salinity management.

Successful results came from the combined skill base of the assembled multidisciplinary team. Team members came from the following organizations: CSIRO Land and Water, CSIRO Exploration and Mining, Bureau of Rural Sciences, the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Geoscience Australia, (SA) Department of Water, Land and Biodiversity Conservation (DWLBC), Rural Solutions SA, and consultants.

Valuable local input and insight has resulted in a more meaningful study and special thanks should go to members of the Bremer Barker Catchment Group and the many farmers in the area that allowed access to properties and gave freely of their knowledge and time.

REFERENCES

Beven K.J. and Kirkby M.J. 1979. A physically-based variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*. **24**, pp 43-69.

Christensen, A. 2002. Calibration of electromagnetic data. Pp. 20-38 *in* Dent, D.L. (ed) MDBC Airborne Geophysics project, Final Report. BRS Technical Report, Canberra.

Cox, J.W. and Ashley, R. 2000. Water quality of gully drainage from texture-contrast soils in the Adelaide Hills in low rainfall years. *Australian Journal of Soil Research* **38**: pp 959-972.

Cox, J.W., Fritsch, E. and Fitzpatrick, R.W. 1996. Interpretation of soil features produced by modern and ancient processes in degraded landscapes: VII. Water duration. *Australian Journal of Soil Research* **34**: pp 803-24.

Cox, J., McEwan, K., Davies, P., Smitt, C., Herczeg, A., and Walker, G., (2002). Salt Transport in the Bremer Hills, SA. Report for the NAP South Australian Salt mapping and Management. CSIRO Land and Water Technical Report 50/02.

Cresswell, R.G., Dent, D.L., Jones, G.L. and Galloway, D.S., 2004. Three-dimensional mapping of salt stores in the southeast Murray-Darling Basin, Australia. 1. Steps in calibration of airborne electromagnetic surveys. Soil Use and management, **20**, pp 133-143.

Dooley, T. and Henschke, C. 2000. Dryland salinity management within the Eastern Hills and Murray Plains LAP area. A technical report produced for the Eastern Hills and Murray Plains Catchment Group INC. PIRSA Rural Solutions. June 2000 (unpublished report).

Ecker, S. 1998. Groundwater modelling and salt balance analysis to determine target areas for recharge reduction in the Bremer catchment. University of Adelaide MSc thesis.

Fitzpatrick, R.W., Cox, J.W., Fritsch, E., and Hollingsworth, I.D. 1994. A soil diagnostic key to manage saline and waterlogged catchments in the Mt Lofty Ranges, South Australia. *Soil Use and Management* **10**: pp 145-152.

Fitzpatrick, R.W., Cox, J.W., Munday, B. and Bourne, J. 2003 Development of soil-landscape and vegetation indicators for managing waterlogged and saline catchments. *Australian Journal of Experimental Agriculture* **43**: pp 245-252.

Gallant, J.C. and Dowling, T.I. 2003. A multiresolution index of valley bottom flatness for mapping deposition areas. *Water Resources Research 39* (12) 1347.

George, R. and Green, A. 2000. Position paper on airborne geophysics for salinity and land management. Sustainable Land and Water Resources Management Committee (SLWRMC) ftp://ftp.ndsp.gov.au/pub/general/10_NDSP_projects/15_project_reports/RG_R_VH_SLWRMC.pdf

Gibson, D.L. 2004. An enhanced framework for natural resource studies in the Angas-Bremer Plains area, South Australia. Technical Report to SA-SMMSP/ CRC LEME

Open File Report 172. Cooperative Research Centre for Landscape Environments and Mineral Exploration.

Henschke, C.J., 1997. Dryland salinity management in the Mount Lofty Ranges. Primary Industries South Australia Technical Report No 254. May 1997. 43pp.

Hunter, D. 2001. Interpretation of conductivity depth transform (CDT) visualisation products. CSIRO Exploration and Mining Restricted Report 838R, v + 8pp.

Jolly, I., Walker, G., Stace, P., van der Wel, B. and Leaney, R. 2000. Assessing the impacts of dryland salinity on South Australia's water resources. A sub-project of the National Land and Water Resources Audit – Dryland Salinity Theme Project 1. CSIRO Land and Water, Technical Report 9/00. 85pp.

Roberts, D.W., Dowling, T.I. and Walker, J. 1997. FLAG: A Fuzzy Landscape Analysis GIS Method for Dryland Salinity Assessment. CSIRO Land and Water Technical Report 8/97.

Smitt, C., Cox, J. and Davies, P. 2003a. Options analysis for salinity management in the Lower Murray of South Australia. Milestone 4: Catchment Salt Balances. Report for Lower Murray Irrigation Action Group. CSIRO Land and Water.

Smitt, C., Cox, J. and Davies, P. 2003b. Salt Transport in the Bremer Hills, SA. Interpretation of Spatial Datasets for Salt Distribution. Fourth report for NAP South Australian Salt Mapping and Management. CSIRO Land and Water Technical Report 49/03.

Smitt, C., Cox, J., McEwan, K., Davies, P., Herczeg, A., and Walker, G., 2003. Salt Transport in the Bremer Hills, SA – FLOWTUBE Modelling. 2nd Report for the NAP South Australian Salt Mapping and Management. CSIRO Land and Water Technical Report 06/03.

Smitt, C., Herczeg, A., Davies, P., and Cox, J. 2004. Identifying Sources of Salt and Its Mobilisation Processes in the Eastern Mt Lofty Ranges, South Australia 2004. In Proceedings of the 9th Murray Darling Basin Groundwater Workshop.

Wilford, J.R. 2004a. 3D regolith architecture of the Jamestown area – implications for salinity. Report to SA-SMMSP/ CRC LEME Open File Report 178. Cooperative Research Centre for Landscape Environments and Mineral Exploration. vii + 46pp.

Wilford, J.R. 2004b. Regolith-landforms and salt stores in the Angas-Bremer Hills. CRC LEME Open File Report 177. Cooperative Research Centre for Landscape Environments and Mineral Exploration. ix + 100pp.

Wilford, J., Dent, D.L., Braaten, R. and Dowling, T. 2001. Running down the salt in Australia 2: Smart interpretation of airborne radiometrics and digital elevation models. The Land, **5**, pp79-101.

Williamson, D.R. 1990. Effect of dryland salinity on selected water resources in South Australia. CSIRO Division of Water Resources, Perth. v + 60pp + 2 appendices.

APPENDIX 1 – K RESIDUAL MAP & TOPOGRAPHIC X-SECTIONS

(from Wilford, 2004b)

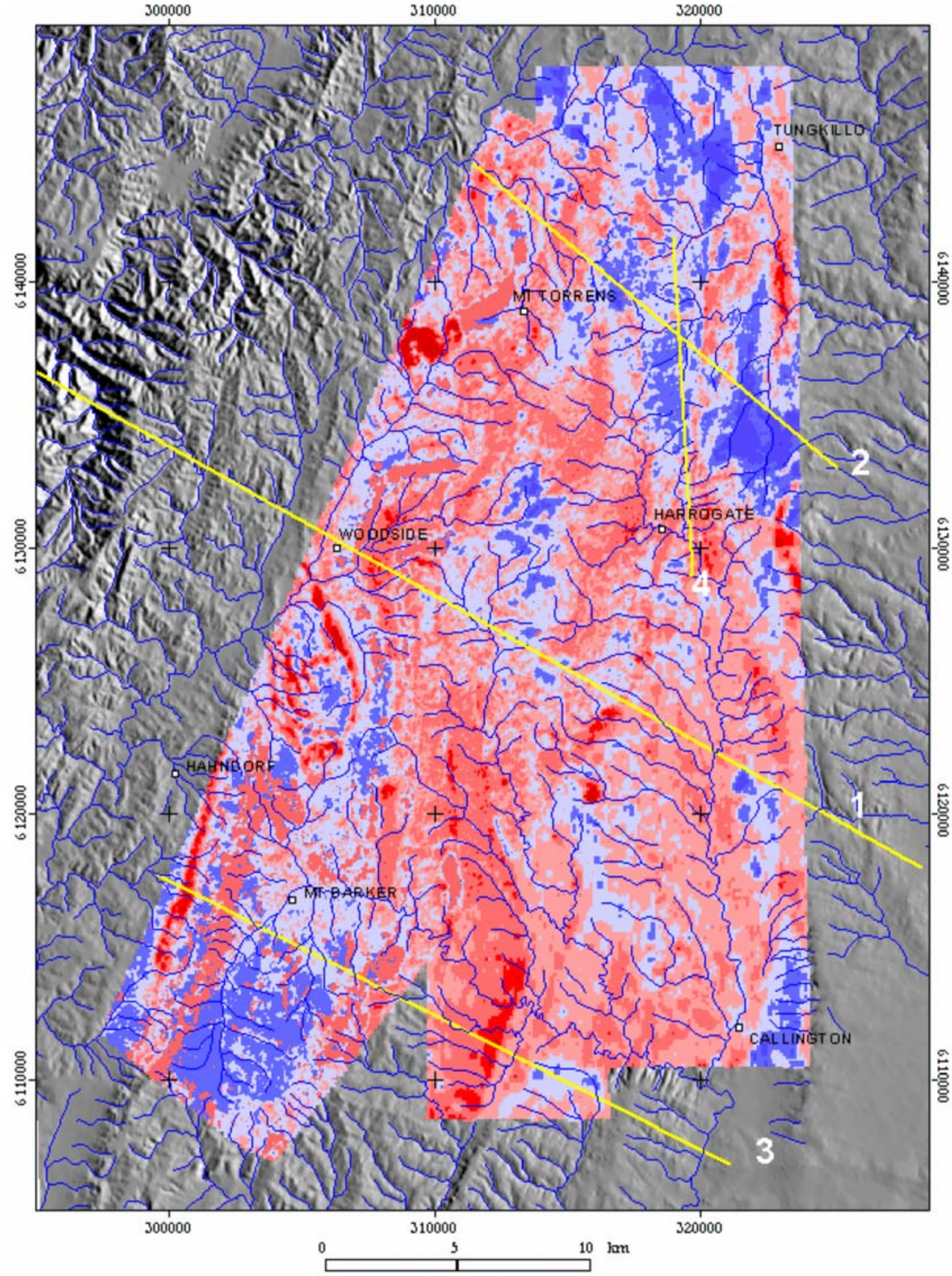

Figure A-1. K-residual map and location of the topographic x-sections (see following pages). Blue areas correspond to predicted zones (having a higher probability of comprising) of deeply weathered material while red areas correspond to predicted areas of shallower regolith or fresh bedrock. More detailed ground-truthing is recommended before this map should be used for localised management decisions. The map combines the SA SMMSP and PIMA Mining survey areas.

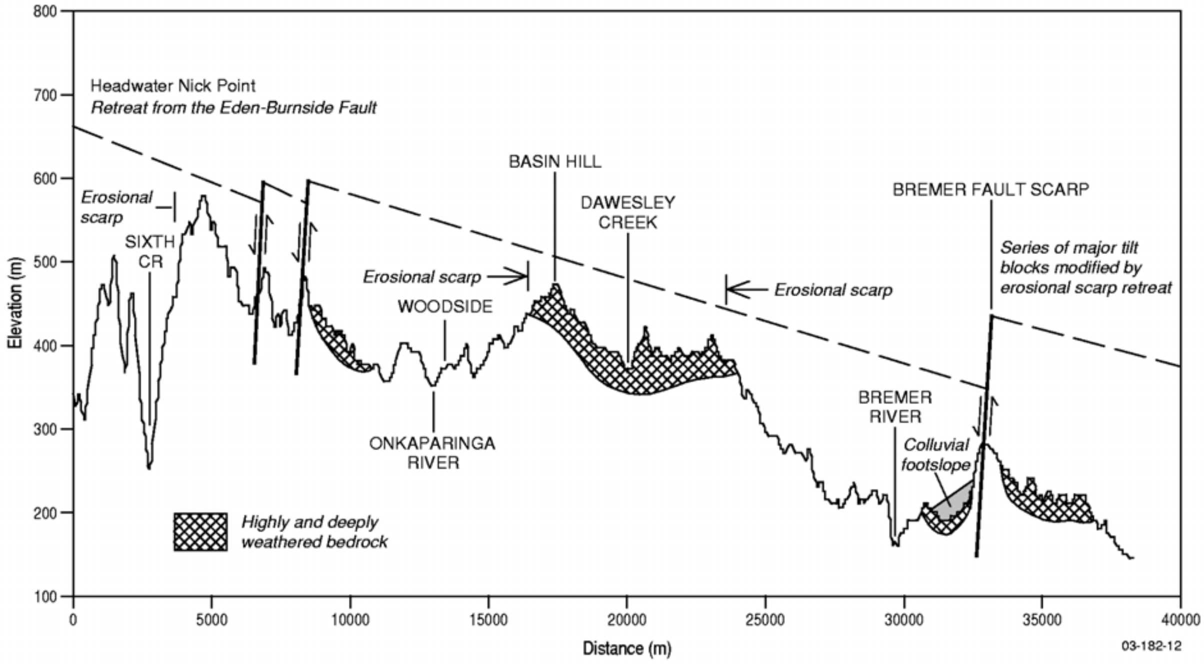

Figure A-2. Topographic x-section 1 - highlighting a series of easterly tilted fault blocks. Major fault scarps are associated with these fault blocks (e.g. Bremer Fault) as well as a series of local scale parasitic faults within the larger tilt blocks. Deep weathering associated with the palaeosurface is preserved on both the upper (often coincident with drainage divides) and lower parts of the tilt blocks. Head ward erosion associated with a series of erosional scarps is actively stripping the older weathered palaeosurface. Thickness of weathered materials not to scale.

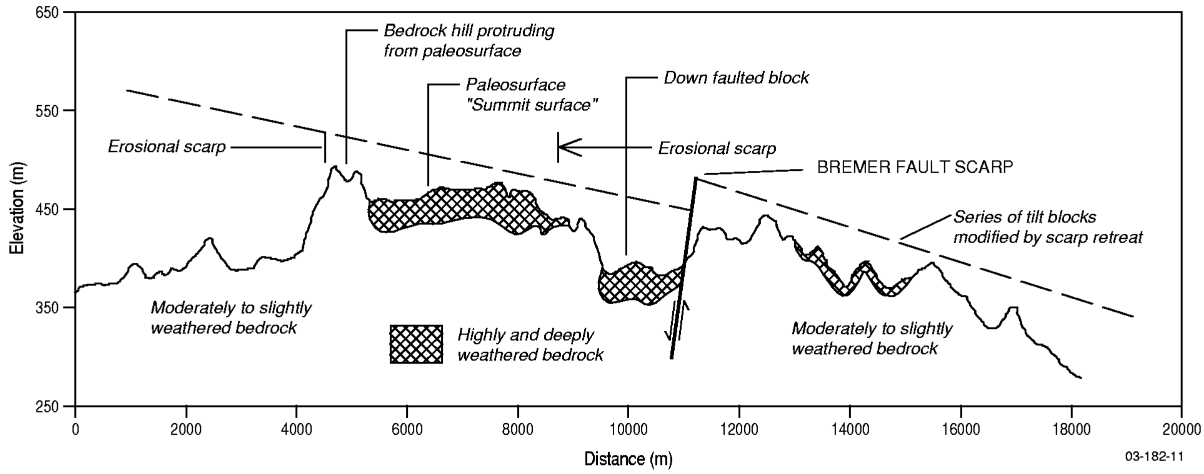

Figure A-3. Topographic x-section 2 - highlighting a series tilted fault blocks. Deep weathering associated with the palaeosurface is preserved on the upper (often coincident with drainage divides) sections of the tilt blocks. Local scale erosional scarps are now activity stripping the palaeosurface. Thickness of weathered materials not to scale.

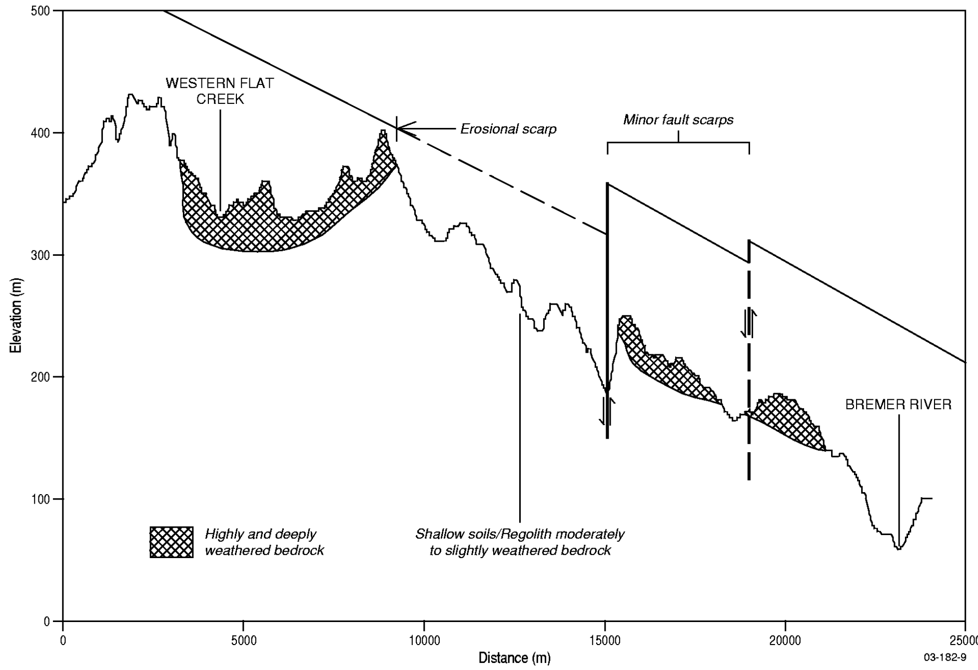

Figure A-4. Topographic x-section 3 - highlighting a series of easterly tilted fault blocks. Major fault scarps are associated with these fault blocks (e.g. Bremer Fault). Deep weathering associated with the palaeosurface is preserved on both the upper (often coincident with drainage divides) and lower parts of the tilt blocks. Head ward erosion associated with a series of erosional scarps is actively stripping the older weathered palaeosurface. Thickness of weathered materials not to scale.

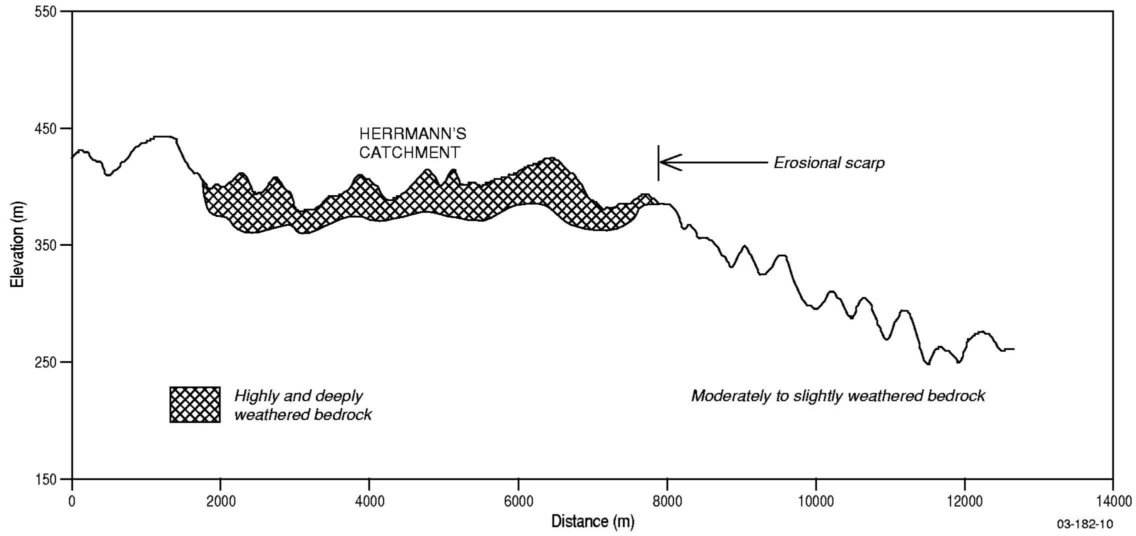

Figure A-5. Topographic x-section 4 - between Harrogate and the Herrmann's catchment. Headward incision associated with an erosional scarp is removing deeply weathered regolith as it migrates northward. Moderately to slightly weathered bedrock is exposed below the scarp edge. Thickness of weathered materials not to scale.