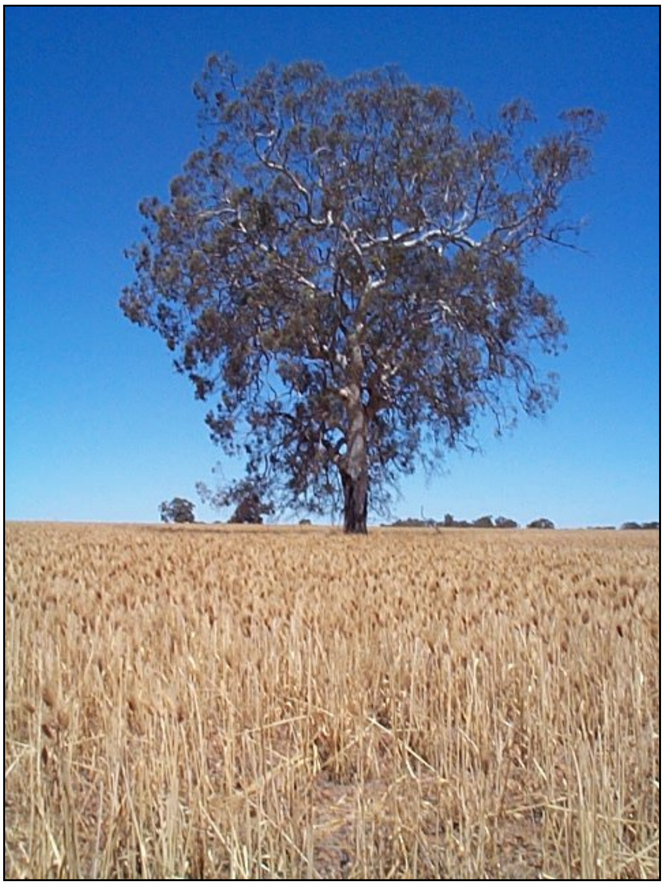
TOOLIBIN LAKE

UPGRADING CATCHMENT INTERPRETATION

MARCH 2000
VOLUME 1: REPORT



DEPARTMENT OF CONSERVATION AND LAND MANAGEMENT PROJECT

By G. J. Street. and G. Pracilio
Farm Map Consulting

For Fugro Airborne Surveys

CALM Ref: R7.8 RFQ 4655/99
Fugro/WGC JOB #6099

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EXECUTIVE SUMMARY

This Project analysed available environmental data in the Toolibin Lake Catchment and is a supplement to work carried out in National Airborne Geophysics Project (Pracilio et al, 1998). General agreement between data confirms the structure and controls within the catchment. The geology is transitional between gneissic terrane to the east and granite to the west. The west of the catchment is rejuvenated drainage with shallow regolith and the east is covered by a deep laterite regolith. A regional fault divides the catchment and controls a deeply weathered zone under Toolibin Lake enclosing a palaeodrainage system.

Numerous dolerite dykes transect the area. Dolerite dykes control weathering patterns in upland parts of the catchment as well as the path of the palaeochannel.

A soil map created using radiometric, topographic and soil pit data resulted in better resolution of individual soil units than previous maps. This technique for soil mapping shows great promise.

Multispectral data using a prototype system, OARS, assisted in further division of the soils by detecting the presence of two different clay types. Further development in processing, expected by July 2000 and a catalogue of Australian plant/soil spectra is needed to make this system more effective.

Airborne electromagnetic system and processing improvements gave superior conductivity resolution. TEMPEST data correlated well with drillhole data and ground geophysics. Older SALTMAP data generally agreed with TEMPEST although some responses can be misleading.

Potential low yields of potable water are located in deep sands upslope of dolerite dykes in the upper parts of the catchment. The greatest saline water resource is from deep Tertiary sands in the palaeochannel. AEM data suggest these sands are up to 200 metres across and 20 metres thick.

Salt Hazards were reviewed and a new rating created using the bore data. Salt Hazards were also interpreted at constrictions in the palaeochannel.

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Karina Tedesco who assisted with editing the final report gave up her office and computer for the final stages of this project. Richard Lane gave great assistance with the analysis of TEMPEST data. Matt Owers as usual provided good quality images in double quick time. Prasanth Nallan Chakravatula helped with final layout of maps. Tim Munday and Marty Ladyman were always supportive in provision of facilities. David Triggs for project management from Fugro Airborne Surveys. Peter Hausknecht for assistance with understanding the implications of hyperspectral profiling data. Kirsty Beckett for assistance in classification of data. Richard George was always ready to offer advice. Shawan Dogramaci and Jayath de Silva gave quick assistance with drilling results. Joe Tedesco for invaluable assistance in data transfer. Jeannine Argus and Wing Chan who carried out an excellent project in GIS for water targeting and spatial analysis. Amanda Smith and Ken Wallace, CALM were a great help in sourcing the varied datasets in this project.

TABLE OF CONTENTS

LIST OF TABLES:

LIST OF FIGURES:

APPENDICES:

VOLUME 2 - LIST OF MAPS:

1 INTRODUCTION

1.1 The Project

This interpretation report, referred to as the "Project", presents the interpretation of geophysical survey and other environmental data over the Toolibin Lake Catchment, Western Australia. The Project is a supplement to a previous report (Pracilio et al, 1998) commissioned by the National Dryland Salinity Program (NDSP), National Airborne Geophysics Project (NAGP). Extra data withheld for evaluation purposes and data collected during and post the NAGP have been incorporated to update Pracilio et al (1998).

Geographic Information System (GIS) interpretation and spatial analysis tools partially used in Pracilio et al (1998) were developed and implemented. More detailed results were produced in less time than the more laborious and subjective manual process of the original interpretation.

1.2 Location

Toolibin Lake catchment is located approximately 24 kilometres east of the Town of Narrogin, in the wheatbelt of Western Australia (see Figure 1.1). The town of Wickepin is immediately north of the survey. The hamlets of Yilliminning, Toolibin, Tincurrin, Harrismith and Dudinin lie around the southern and eastern extremities of the survey. The Toolibin Lake catchment with an approximate area of 492 km^2 is part of the headwaters of the Blackwood River catchment.

In the NAGP, a magnetic/radiometric survey covered the Toolibin Lake catchment, whilst a SALTMAP airborne electromagnetic survey covered the eastern portion of the catchment.

Subsequent to NAGP, a TEMPEST airborne electromagnetic (AEM) survey (Lane et al, 1998; Lane and Pracilio, 2000) and an OARS (Optical Airborne Research Spectrometer) survey covered an area of 107 km^2. These included Toolibin Lake, sandplain to the east and alluvial flats north of the lake. Interpretation of the data from these surveys has been incorporated into this Project.

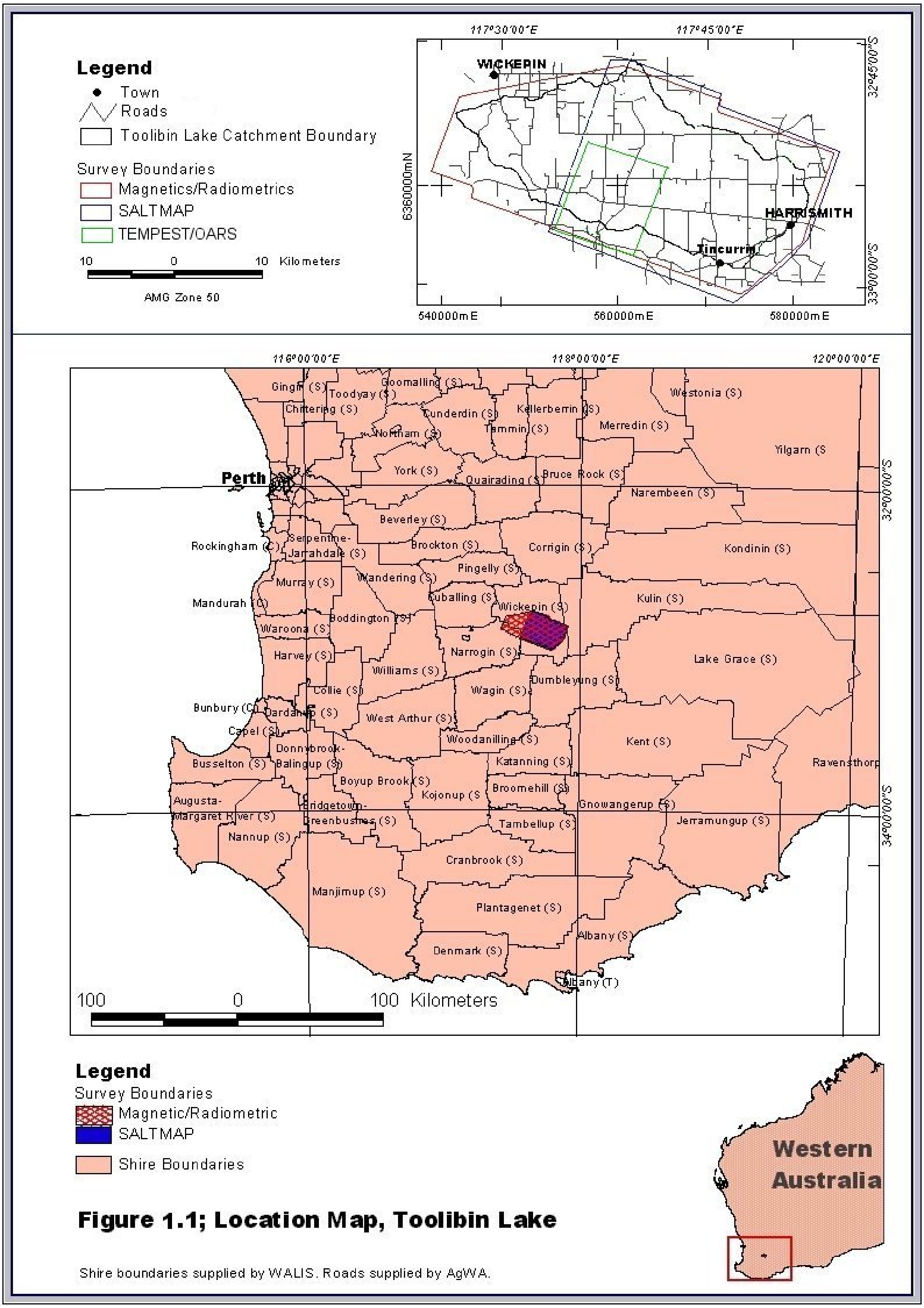


Figure 1.1; Location Map, Toolibin Lake

1.3 Objectives

The primary aim of the Project was to "produce a Geographic Information System (GIS) platform for the Toolibin Lake catchment that incorporates and interprets available data on catchment hydrology, soils/regolith, remnant vegetation, salt store, salt hazards and water resources" (CALM, 1999). The Project presents an updated interpretation of the available data over the Toolibin Lake catchment from that done in NAGP (Pracilio et al, 1998).

Six interpreted map products, this report and the GIS project on CD-ROM are the primary outcomes of the Project. The maps produced were:

- An upgraded geological interpretation to finer detail than that carried out under the NAGP.
- An upgraded soil map using a more rigorous analysis of radiometric data, combined digital terrain data, field inspection and soil data from Agriculture WA and incorporated new data from the OARS multispectral system.
- A new water resources target map incorporating a more rigorous analysis of potential good quality water sites. An additional interpretation of saline resource targets based on the position of palaeodrainage channels beneath the valley floor.
- An upgraded “Salt Hazard Map” using upgraded geological and soil interpretations, with sites checked through GIS analysis and a new rating factor that incorporated groundwater levels.
- A remnant vegetation map from preliminary data set, as at December 1999, resulting from the National Land & Water Resources Audit Project.
- A contour map generated from Land Monitor Digital Elevation Model (DEM).

The report on the Project, outlines the GIS project, validation on TEMPEST AEM system and a chapter for each upgraded interpretative product.

2 GIS PROJECT

Data collated and interpretation maps created in this Project and previous studies have been amalgamated into a Geographic Information System (GIS) database using ArcView 3.1 software. The major output of the Project was an ArcView project based on new maps and converted data.

Toolibin has been an area of intensive study since 1977 and most environmental government agencies have been involved. In sourcing data, interpretation and creating the GIS project, problems were encountered particularly with regard to units, accuracy, position and naming conventions.

2.1 Data conversion

CALM, DOLA, AgWA and WRC supplied reports and external digital data in Microstation, excel, text, ERMapper and bil formats. These were converted into an ArcView compatible format including database files for tabular data and shapefiles for located point and vector data. The collation, conversion of data and creation of the GIS was a significant proportion of the Project.

Data conversion concentrated on files related to the interpretation of the maps produced for the Project. Final file names and directory structures represent what the file mostly contains. Abbreviations have been avoided. Reference to the shape files (*.shp) in the GIS have been made throughout this report. The reader is should refer to accompanying CD-ROMs for ArcView project, which contains the major results of the Project.

Large and diverse sets of data were incorporated into this Project. Not all data was the same quality and/or resolution. In cases where the quality of information was variable the authors have tried to assess what is appropriate to use in the Project.

The next stage in the wide use of the GIS project is to produce Metadata for all data collated and created. Metadata is data about data. This involves an audit and documentation of data layers beyond the scope of the current Project. Data quality issues such as projection, units of measurement and the bore data base discussed below need to be linked in a format that is readily accessible within the digital environment, preferably within ArcView. This report could be used as a basis for the metadata content, particularly for the layers created from this Project.

A Metadata standard and format should be established using WALIS and international guidelines. All future spatial data projects by state agencies, contractors, landholders and catchment groups in the Toolibin catchment should include the provision of spatial data and metadata according to these standards.

2.2 Projection and Datum

The accepted datum for Australia since 1987 has been AGD-84 (Australian Geodetic Datum) based on the US Defence Department's WGS-84 (World Geodetic System). The Intergovernmental Committee on Surveying and

Mapping (IGCSM) has recommended that Australia adopt the Geocentric Datum of Australia (GDA) by the year 2000. Commonwealth Agencies will begin to implement the new datum in all products from 1 January 2000.

A “datum” is a mathematical surface on which a mapping and coordinate system is based. The GDA, known as an Earth-centred datum, has its origin at the centre of the Earth. It is a best-fit model maximising compatibility across geographic systems at the local, regional, national and global level. This is the main reason that the GDA will form the basis for the ASDI. A key advantage of the GDA over Australia’s current local AGD datum is that the GDA is totally compatible with satellite-based navigation systems such as the Global Positioning System (GPS). See website for more details (http://www.auslig.gov.au/pipc/csdc/gda_ps.html).

On 4th December 2000 Western Australian will move to implementation of the Geocentric Datum of Australia, GDA94. More details can be found at (www.dola.wa.gov.au/lotl/survey_geodesy/gda2000/index.html). The grid projection will be Map Grid of Australia (MGA) and differ to AMG (Australian Map Grid) with a different datum and ellipsoid. The new datum will result in an approximate shift of 200m towards the northeast. In Australia's coordinate system *or* the GDA coordinates for a point will be to the south-west by approximately 200m, relative to the AGD grid (DOLA ,1998). At Toolibin this shift will be around 195 +/-1 metres. Elevation measurements will not be affected.

The data presented is projected in AMG Zone 50 with a Datum of AGD-84 with the exception of the salt monitoring data (saltmon_1_1.bil) provided by DOLA in AGD-66. The difference between AGD-84 and AGD-66 is approximately 4m at the most (Allen, pers. com.). AGD-84 was created to take into account the geoid-spheroid separation which is equal to +4.9m at Johnson Geodetic station near Canberra (Veenstra, 1985). The main difference is to be in elevation measurements and may be greater than 4 metres in elevated areas.

2.3 Units of Measurement

The Project units of measurement have followed the Australian Standard 1000-1979. In particular recommendation 6.2.5 "The use of prefixes representing 10 raised to a power, which is a multiple of 3, is especially recommended" has been followed where appropriate. Millisiemens per metre (mSm^{-1}) was used as the unit of conductivity rather than Siemens per metres because of the widespread acceptance of mSm^{-1} in land management work.

Units of measurement is not a trivial issue in studies such as this which draw data from a wide range of sources and projects. An example of confusion has been in the tabulation of bore data between units such as µS/cm (microsiemens per centimetre) and mS/m (millisiemens per metre). The use of µS/cm (Chemistry Centre WA) should be discouraged. Imperial units for salinity such as grains (grains per gallon) are still widely used even by younger farmers. Education by government agencies may remove such use of units.

2.4 Bore database

Bore data was combined into one file (all_bores.shp) with the project, AHD, cap height and surveyor or survey type tabulated using the bore datasets listed in Table 2.1. Quality of bore data was variable. The most useful bore data was from WRC projects that were fully documented with detailed bore completion reports. Such reports should be fundamental given the cost of drilling. They could be better extended by an analysis of results. Catchment bores have little to no documentation.

Table 2.1: Bore data collated for the Project

Final File Name	Source	Reference
AEM Toolibin Correl Dec 15.xls	AgWA,	George, 1998
AgWA_dgps_coord.xls	AgWA,	George, 1998
Catchment_bores.xls	CALM	N/A
COMBORT_groundwater_ monitoring.xls	AgWA	N/A
P11_p14.xls	WRC	Dogramaci, 1999
Taarblin_Millers.xls	CALM	N/A
Whites_Davenports_bores.xls	CALM	N/A
WRC_AgWA_Coords.xls	AgWA, WRC	DeSilva 1999, George, 1998

Bores with SWL, groundwater salinity, and bedrock depth from George (1998) were separated and tabulated in bores_swl.shp. Bores that have data within the Combort file were separated into bores_gw_monitoring.shp (only the location is within this file). The ArcView project has been set up to view the groundwater trends in a chart from the database containing the Combort data, in the ‘Groundwater Chart’. This data has been stored in Combort_gw_monitoring.dbf. Dates were converted from days elapsed since 1/1/1977 for graphing purposes in ArcView. The original dates are contained within the dbf file.

Many files are in the Combort file provided that they did not appear related to the located bores in ‘all_bores.shp’. Not all located bores were included in the Combort database, such as some catchment bores labelled No*.

There is considerable confusion in naming of bores particularly the bores labelled LT and TL. There appears to be two series of bores with LT 1 to LT 9 and another series of bores labelled TL. Some of the LT bores are fully labelled as LT01, LT02 etc whereas others are given names LT1, LT2 etc. In De Silva (1999) the palynology report refers to TL bores whereas the remainder of the report refers to LT bores. Pumping bores all have a P somewhere in the bore name, some at the front and some at the end. This needs to be standardised.

Salinity from bores has been calculated from various methods. In De Silva (1999) both field and laboratory measurements were made and recorded as such. In other reports no explanation of the method is given.

Location of the pump bores also varies from different sources. When converting point data into a GIS the method of locating the bore should be noted. For example differential GPS (dGPS) is more accurate than GPS. This was noted where documentation existed in the all_bores.shp file.

Additional work is required on the bore data for it to be readily usable in GIS and database format. This was attempted as part of this project but proved too large a task. A Toolibin bore database should be created to include all shallow, deep or intermediate bores (and slotting depth) for the catchment. Almost as many bore details appear to be lost as are in database. There are also competing databases between government agencies. For example, the WRC bores are not included in the Combort database. Data from bores drilled by Martin (1982, 1986 and 1990) were not supplied during the course of the project and need to be included in such a database.

Table 2.2 : Proposed information required for bore database

Old name	eg LT1 or LT01
New name	A new series of naming conventions needs to be worked out. Possible new names could read: G/ =GSWA eg M.W. Martin bores W/ =WRC bores A/ = AgWA bores C/ = CALM bores F/ = Farmer LCDC and/or catchment bores
Project Reference	eg WRC Hydrogeology report 126
Date of drilling	
Drilling technique	
Depth	(metres below surface), end of hole or bedrock reached
Slot interval	(metres below surface)
Salinity	(mS/m) method of measurement also needs to be quoted plus date
Water level	(metres below surface) plus date
Aquifer	weathered granite/ perched/Tertiary sediments
Yield	(m3/day or m/sec) Method of yield estimation also needs to be quoted - plus date
Location	Easting, Northing, AMG (or MGA after December 2000)
Location method	dGPS, GPS, survey accuracy etc
Geological log	Should include name of geologist
Log of clay percentage	
Geophysical log	
Sampling techniques	
Chemistry Data	
Palynology	

2.5 Digital Terrain Models (DTM)

2.5.1 Radar altimeter DTM

A digital terrain model (DTM) was created from data collected during the airborne geophysical survey. The radar altimeter samples at 10Hz or approximately every 7m. Relative accuracy of the radar altimeter along line was better than one metre.

DTM limitations from the airborne survey are due to the radar altimeter. Typical aircraft radar altimeters use wavelengths in the 8 to 10cm range. The instrument sends out a radar pulse and detects the return signal. It essentially measure the 'first return' back from the ground to give a minimum altitude although it also has to reach a threshold response level before the response is sufficiently distinguished from noise sources. In areas with a rough surface such a ploughed field the radar signal may be reflected in many directions and not reach the aircraft. In comparison where the surface is smooth such as from roads the reflection threshold is reached quicker and thus it is significantly higher than surrounding rough terrain. At Toolibin the roads appear higher than the surrounding terrain from DTM calculated using the aircraft altimeters.

2.5.2 Land Monitor DEM

Contours at 1m intervals were generated by WGC from the Land Monitor DEM data during the NAGP. A 2m contour map of digital terrain data was created from the 1m contours. These were used in the contour map at 1:50,000 scale. The 1m contour file was clipped to each sub-catchment for the management of a large data set. The sub catchments boundaries in file ‘sub_catchment.shp’ were defined in Pracilio et al., (1998). The Land Monitor DEM was probably created from airphotos although no documentation regarding the method was supplied. Land Monitor produces contours of 2m interval and is probably the accuracy limit.

2.6 Remnant Vegetation Map

A remnant vegetation map was created for the Toolibin lake catchment using:

- Data captured by AgWA from original mapping by J.S. Beard (1969 - 1984) of "Pre-European Vegetation" and:

- Perennial vegetation cover for 1:100,000 scale mapsheet derived from Landsat TM satellite imagery 1995/96 processed for the National Agricultural Land Cover Change Project (1990-1995). A joint project between Bureau of Rural Sciences, Agriculture WA and DOLA (Satellite Remote Sensing Services).

The vegetation theme is a preliminary data set, as at December 1999, resulting from the National Land & Water Resources Audit Project. The remnant vegetation theme was derived from Landsat TM satellite imagery 1995/96 and checked with digital orthophotos (acquired post 1993).

The final remnant vegetation map was created by intersecting Beard's data with the preliminary vegetation cover. This assumed that any present day remnant vegetation was similar to that existing prior to European settlement. Limited field observation in the Project of remnant vegetation types suggests that the remnant vegetation map could be improved.

2.7 Data used in interpretation

Data used within the interpretation (Chapters 3 to 7) are based on data sets in the GIS project. Data chosen for analysis were based on measurements within the same depth range. For example, radiometric data, soil site data, airphoto interpretation, field observations and the digital terrain model have all been used in creating a soil map, as they are closely related to properties in the top 0.4 m of the soil profile. Lesser input from EM and magnetic data was used as these relate to physical properties deeper in the profile.

Remote-sensed data is widely used to map soils but duplex soils and compositional changes that are not seen in the visual spectrum make the integration of radiometric data into soil mapping a very powerful tool. When OARS hyperspectral data was integrated in this project the spectral response could be separated to show changes that were not seen in the radiometrics but were very much surficial responses.

TEMPEST data shows a future in also discriminating soil type. TEMPEST conductivity in the top 4m is closely related to surface indications of soil salinity.

The solid geology interpretation used mostly magnetic data with some input from EM and radiometric data. Remote sensed data from Landsat and airphotos has been widely used in areas of outcrop to map geology. In the deeply weathered terrain in the southwest these methods only see the top one micron of the surface and cannot "see" the subsurface geology. Magnetic data is far more appropriate for the purpose while airphoto interpretation can be misleading and wrong. The 1:250,000 geology map was only a rough guide to major rock types.

Extra information can lead to better decision making in catchment planning. However, that information needs to be appropriate in resolution and sampling density for the task. Not all regional data were found useful at catchment and finer scales.

2.8 GIS Project on CD-ROM

Two CD-ROMs, TL_GIS1 and TL_GIS2, were produced. TL_GIS1 contains the majority of the data collated with ArcView and ArcExplorer projects that will run off the CD or Hard Drive. These only require TL_GIS1 to operate. TL_GIS2 contains data that is mostly used for detailed investigations. These are the individual orthophoto tiles and the 1m contour files. The orthophotos were clipped if the majority of the view was outside the catchment. ArcView and ArcExplorer projects are also supplied on LT_GIS2. See Appendix 1 for the catalogue of files in GIS.

3 GEOLOGY MAP

All magnetic data were reduced to the pole. The most useful images for interpretation were greyscale first vertical derivative (1vd) and various automatic gain control enhancement (ae) images. Other data utilised included radiometrics, TEMPEST AEM, SALTMAP AEM, DTM and a few field traverses. Interpretation was carried out from raster images in GIS software package ArcView 3.1 using World Geoscience Corporation, Interpretation Analyst extension.

In the Pracilio et al (1998) study of Toolibin Lake the aeromagnetic data were interpreted to a geology map at 1:25,000 scale. In this study, interpretation of the aeromagnetic data has been attempted for 1:10,000 scale.

3.1 Limits of interpretation accuracy

The 150m line spacing employed in this project makes interpretation at 1:10,000 scale beyond the normal limit of accurate interpretation using raster based data. A line spacing of 100m or less would be more appropriate for 1:10,000 scale interpretation. Townrow (1988) showed that 200m line spacing data at Yornaning was sufficient to detect all dykes greater than 20m wide. George (1998) found that the airborne magnetics at 150m was sufficient to detect all dykes seen by ground magnetics. The resolution of individual geological structures such as dykes and faults is sufficient at 150m or even 200m in terrain with wide spaced discrete bodies. The interpretation shows that most dykes are around 400m apart. Thus, anomalies from separate bodies do not interact. Difficulties arise where magnetic bodies cross and the anomalies due to individual sources are compounded and not well resolved.

A good understanding of the geology and the interaction of magnetic responses from close-spaced sources makes the interpretation carried out usable at 1:10,000 scale. However, at 1:10,000, or at more detailed scales, it is strongly recommended that the interpretation be used in conjunction with the magnetic images in order to relate the interpreted position with the original data.

All data have been reduced to the pole to remove asymmetry due to the inclination of the earth's magnetic field at this latitude. However, this mathematical transformation assumes a regional change in inclination which may not be the case at local scale. In addition, the amount or direction of remanent magnetism is unknown. The presence of many reversely magnetised dykes indicates that remanance is probably strong in the dolerite rocks. The remanance may alter the anomaly position relative to true position especially after reduction to pole. This error in raster images may be as much as 50m. Remanance may also reduce the actual anomaly magnitude.

The strong magnetism of geological structures can obscure the magnetic anomaly due to less magnetic and/or smaller structures. Thus, when a strongly magnetised dyke meets a weakly magnetised dyke the latter is discontinuous. To approximate a 1:10,000 scale at 150m line spacing, assumptions were made about the geological structures. Dykes are intrusions into linear zones of weakness in the granitic basement. Thus, the present day dyke close to the surface should be more or less linear. Therefore, except where there is some obvious break due to a fault, it has been assumed that the dykes are more or less continuous linear intrusions. In the case where the weakly magnetised dyke meets the highly magnetic dyke, in most case it was assumed the weaker dyke is continuous although it may not appear so from the magnetic data.

Supporting evidence for such an approach is seen in the drill results. Drilling at bore 95/01D (renamed 95/01S) encountered dolerite. The magnetic data shows the intersection of two major dykes both around 100m from this hole. The magnetic data does not indicate a dolerite at this point. However a weakly magnetic linear feature interpreted as a minor dyke terminates approximately 250m west of the hole. The stronger magnetism due to the major dykes may obscure the anomaly due to this less magnetic feature.

3.2 Major geological units and structures

3.2.1 Granitoids

Previous studies (Chin, 1986) conducted in the Toolibin area divided the granitoid rocks into an older gneissic suite and a younger group of intrusive granites. Wilde et al (1996) placed the area within the Lake Grace Terrane. The Lake Grace Terrane is described as charnockites and post tectonic granodiorite.

Lack of outcrop makes detailed geological mapping difficult and thus Wilde based his interpretation on regional geophysical data collected by the Bureau of Mineral Resources. That regional data shows a distinct change in texture of the magnetic data to the west of Toolibin catchment (Tucker and D'Addirio, 1987)

The more detailed magnetic data collected for Toolibin NAGP suggest gradational changes between the gneissic rocks and the later granites. Many boundaries are along regional faults which have a demagnetised (or magnetic low) signature. Well formed granite intrusions are evident but where the boundaries are not along faults they are more gradational. This new interpretation is considered to better represent the basement geology than Pracilio et al (1998).

Radiometric data does not distinguish between the various granitoids. Where granitoid rocks are exposed they generally exhibit a higher potassium signature. Shallow subcrop areas also show a high potassium response.

Pracilio et al (1998) interpreted three granitoid lithotypes in the Toolibin Lake Catchment; an older gneissic basement and two younger granitic intrusives. The interpretation presented here has divided the rocks into granite and gneiss alone. Field inspection suggested great spatial variability in the rocks over short distances. Granitic and gneissic textures appear in close proximity in outcrops. Where gneissic rocks are present, evidence of partial melting is common with widespread migmatisation. Pegmatite phases and leucocratic dykes are also common. The rocks in the area appear to be transitional between the more gneissic terrain to the east and a more granitic terrain to the west.

In this interpretation boundaries of granite and gneiss have been marked as solid lines. No boundaries could be seen in field inspection of the area. Boundaries are probably gradational except along regional faults. Large inclusions of gneiss can be expected in granitic areas and large areas of partial melting to granite, pegmatite or other small acid intrusives can be expected throughout the gneiss terrain.

In the electromagnetic data there is no clear division in the weathering of the granitic and gneissic units. However, in general the gneiss has more areas of deep weathering than the granite. The eastern and central parts of the catchment have less outcrop but electromagnetic data suggests that weathering is limited to around 30m except in a few isolated cases. The prevalence of outcrop to the western edge of the catchment can also be attributed to rejuvenation of the drainage from the west rather than differential weathering.

Weathering is not uniform across the landscape. There are many areas where changes in geology, which are reflected in the magnetic signature, are associated with deeper weathering. The most significant of these is a deeply weathered area across and south of Browns Road approximately 6.7 km NE of Toolibin Lake. The TEMPEST electromagnetic data shows a deep weathering area in a zone of relatively quiet magnetic response surrounded by dolerite dykes. This preferential weathering feature may be associated with a later intrusive pipe or may be due to the influence of the dykes on groundwater movement.

In the North Wedin catchment the drainage from the granite to the gneissic unit becomes less defined at the contact zone. In the granite regolith the stream is a well-defined narrow valley in the DTM, whereas to the west the stream is undefined and drainage may take any path down the valley during flooding. This may represent an area of preferential recharge where regolith becomes more permeable.

3.2.2 Dolerite

3.2.2.1 The Binneringie Dyke

The Binneringie Dyke is present in the northwest corner of the survey area. It defines the catchment boundary in this area. It is described in Pracilio et al (1998).

3.2.2.2 Major and minor dykes

Major dykes have been reinterpreted at a more detailed scale and separated from minor dykes. The separation of these two classes is based primarily on the strength of the magnetic response. Those linear anomalies with strong magnetic anomalies are interpreted as dykes greater than 50 metres across while weaker linear anomalies are interpreted as dykes less than 50 metres across. It is not possible with these data and with limited outcrop in the field to distinguish between dolerites and other linear magnetic structures. In this interpretation linear magnetic anomalies have been interpreted as dykes. Should the magnetic anomalies be gneissic banding then the influence on groundwater flow (Engel et al, 1987), surface drainage and weathering may be similar to dolerite dykes.

Most of the major dykes strike:

- ~120°
- 090°
- 140°-150°
- 045° to 055°

Dominant strike directions for minor dykes are less defined. Many strike parallel to the major dykes as well as a series that align around 060° and 110°.

Dykes, particularly those interpreted to be major structures and thus approximately 50 metres across generally influence drainage patterns particularly in the colluvial slope areas. The influence on surface drainage should be less on the alluvial flats due to sedimentary cover but there is still a close relationship between the position of salt lakes and dolerite dykes. The southern boundary of the lake at 557,500mE 6,358,900mN is along a dyke and the southern boundary of Toolibin Lake both west and east of the palaeochannel is close to a dolerite dyke. This relationship may indicate areas of groundwater discharge.

Weathering across dolerite can be variable. Dykes in the southwest can commonly be associated with a deeply weathered red clay regolith but they can also be associated with bedrock highs that may be attributable to contact metamorphism of the surrounding country rock. These differences may be related to the composition of the dyke, surrounding granite and the temperature at which it intruded.

Dolerite dykes are often associated with sharp edges in conductivity data indicating, the dolerite, dolerite derived regolith profile or associated bedrock high has influenced salt concentration and probably groundwater flow. These relationships are present in the northern parts of the catchment particularly along dykes that strike southeast to northwest. George and Bennett (1995) drilled a hole 35m deep to fresh dolerite and found very low yield, whereas a bore drilled 60m away to a depth of 54m encountered fractured granite and yielded 51 kL /day.

There is no definable radiometric signature associated with dolerite dykes.

3.2.3 Faults

3.2.3.1 Regional faults

Regional faults have been interpreted along breaks in other bedrock structures such as dykes and linear zones of low magnetic intensity. Most faults are considered old deep crustal features. It is most likely that pressure and temperature conditions at the time of formation lead to either ductile deformation and/or recrystallisation along any zones of failure. Wilde et al (1996) recognised extensive chanockitisation in the gneissic rocks. The introduction of high CO_2 along zones of weakness in this process may also have resulted in recrystallisation of fault zones.

However, angles between interpreted faults are small and usually have an intersection less than 60°. This may indicate conjugate sets developed during brittle failure. More drilling information is needed. Only one bore (95/01P) was reported to encounter fractured rocks. This was close to an intersection of regional faults (see section 6.4.2.2.)

Recrystallisation and sealing of fault zones may leave zones of weakness and or mineral assemblages that become zones of deeper weathering close to the surface. Destruction of magnetite during faulting along regional fault zones is evident in most cases due to lower magnetic signature. The change in mineralogy may result in areas of preferential weathering. The effects of crustal unloading due to erosion are unknown for this area but may lead to fracture formation in the near surface.

The position of the palaeochannel under the Flats around Toolibin Lake and to the north is controlled by a major north-south regional fault along the west side. Other faults crossing the channel (as well as dykes) control the meanders of the deepest parts of the channel down the palaeo-valley.

3.2.3.2 Minor faults

Minor faults were interpreted at dyke offsets. These offsets may predate intrusion of dolerite and are not necessarily fracture zones.

The southwest of Western Australia is a zone of recent intra-plate tectonic activity and recent fault scarps have been detected by the authors elsewhere in the Yilgarn using digital terrain models. In those cases the fault scarps appeared to control the drainage pattern. These recent faults being failures in the upper crust may be associated with shallow zones of brittle fracturing.

Examination of digital terrain model at Toolibin Lake did detect some minor lineaments that could have been fault scarps. Field inspection showed no evidence to support this interpretation.

4 SOILS MAP

Pracilio et al (1998) carried out a predominantly manual interpretation of radiometric data for soil mapping. Bebbington (1998) at the suggestion of the authors of this report carried out supervised classification and a manual interpretation of radiometrics, airphotos and field checks to produce a regolith map, which was more accurate than those created by conventional techniques using airphotos and field checking (Verboom, pers comm).

This Project uses more automated techniques using topographic, radiometric and data from soil pits. Limited field work was also carried out. Preliminary OAR's data was used to create an additional layer over the soils map created from the radiometrics.

4.1 Radiometrics

4.1.1 New advances in radiometric for soil mapping

Wong and Harper (1999) showed that plant available (exchangeable) potassium could be measured indirectly by Total K by ground gamma ray spectrometry in the Jerramungup area. This relationship will vary in different regions as Total K represents both exchangeable and non-exchangeable potassium. The sources of potassium include potassium feldspars from granitic and granitic soils and potassium illite clays. These make up the non-exchangeable sources (Wong and Harper, 1999).

Total K was also related to clay content, where the dominant clay types were illite and kaolinite (Wong and Harper, 1999). Illite being the principal source of non-exchangeable K. Total K was also related to organic carbon content, silt content, Tamm-Fe and pH to some extent. These are somewhat related to each other and require calibration between areas, as relationships may differ (Wong and Harper, 1999).

Radiometrics was also related to crop yield data for an area near Wyalkatchem. In that area Cook (pers comm) found that crop yield was closely related to Thorium concentration as determined by airborne radiometric surveys.

4.1.2 Methods

4.1.2.1 Radiometric data Conversion

Gridded (35m grid) radiometric and DOLA DEM (10m grid) data were converted between ArcInfo and ERMapper grids through ASCII conversion. A grid cell size of 35m was used in the spatial analysis of the combined data sets.

4.1.2.2 Radiometric response of soil units

Average and standard deviations of potassium, thorium, uranium, and total count were calculated for each of the soil-landscape units mapped by Verboom and Galloway (1998). Potassium, thorium, uranium, total count, elevation and slope values were tabulated for each AgWA soil site location.

4.1.2.3 Classification of Radiometric Data

Statistical and unsupervised classifications were applied to the radiometric data so that ground data or knowledge of the area did not bias results. Statistical and unsupervised classifications were based on a standard deviation and ISOCLASS technique, respectively.

Statistical Classification

The standard deviation classification is based on a simple High, Medium and Low classification of potassium, thorium and uranium data sets (Beckett, 1999). A normal distribution was assumed. The Medium class is defined by values between plus and minus half the standard deviation. Low and high classes were defined by values below and above half the standard deviation, respectively. These were then merged to produce one image where each pixel represents, in the following order, potassium, thorium, uranium classes as low (1), medium (2) or high (3). For example the 231 class is medium potassium, high thorium and low uranium. A total of 27 classes are then possible (Beckett, 1999).

In order to identify smaller variations, statistics for each region were calculated (Beckett, 1999). Regions were defined as areas identified by a common cell value bounded by different classification values. Different regions may have the same classification value but the geology related to these regions may be different. Consequently, the statistics calculated for each region were treated separately. A buffer of two cells was used to eliminate gradational changes of continuous data for each radiometric classification. Plus or minus one standard deviation was used to identify the regional extremes of potassium, thorium and uranium (Beckett, 1999).

Unsupervised Classification

The ISOCLASS classification algorithm was applied in ERMapper using routines that generate clusters using an iterative self-organising method. This method dissects the data space so that a class represents a region of similar geophysical and topographic properties. Geophysical data is continuous and thus does not cluster like spectral data but Anderson-Mayes (1999) has demonstrated that this type of classification produces realistic classes comparable with manually interpreted regolith units.

Normalised potassium, thorium, uranium, DOLA DEM and slope were the final input parameters chosen. The final classification chosen was based on the number of manageable classes produced and a reasonable comparison with the radiometric ternary image.

The colours displayed in the GIS and on the maps for both classifications were manually chosen to approximate the radiometric ternary image with reference made to the statistics of the classes generated.

4.1.2.4 Soil Point Data

Field checking of the radiometrics (primarily the radiometric ternary image) was carried out at 55 observation sites across the catchment. These sites were located using a GPS receiver. Photographs and field texture of samples taken from 0-30cm were recorded for the majority of sites (see fieldwork_sites.shp).

Soil descriptions for 209 located soil sites from AgWA were summarised into the 0-40cm and 40cm+ intervals. This interval was chosen as 90% of the radiometric gamma rays are emitted from the top 30-45cm of dry soil (Gregory and Horwood, 1961). Soil profile descriptions were reduced to columns of soil texture, ferruginous ironstone gravel content, quartz content and pH for each interval. Duplex soils and any other comments such as parent material were also noted. Tables contained in the Verboom (1998) were attributed in the GIS and used in the final soils map analysis. These tabulated attributed data are contained in agwa_soilsites_attributes.shp. Many of the columns in the table are empty as not all data points were attributed by Verboom (1998).

4.1.2.5 Final Soil Map

Each soil data point was assigned with the Standard Deviation and unsupervised ISOCLASS class labels. Soil sites on edges of ISOCLASS classes were also manually noted. The final soils map was based on a manual supervision of the soil point data and the unsupervised classification. The soil point data was examined within the GIS environment along with the classification statistics to assign landform and soil descriptions.

4.1.3 Results

4.1.3.1 Radiometric response of soil landscape units

The potassium, thorium, uranium and total count average and standard deviations for each soil landscape unit from Verboom and Galloway (1998) are displayed in Figures 4.2 a to d.

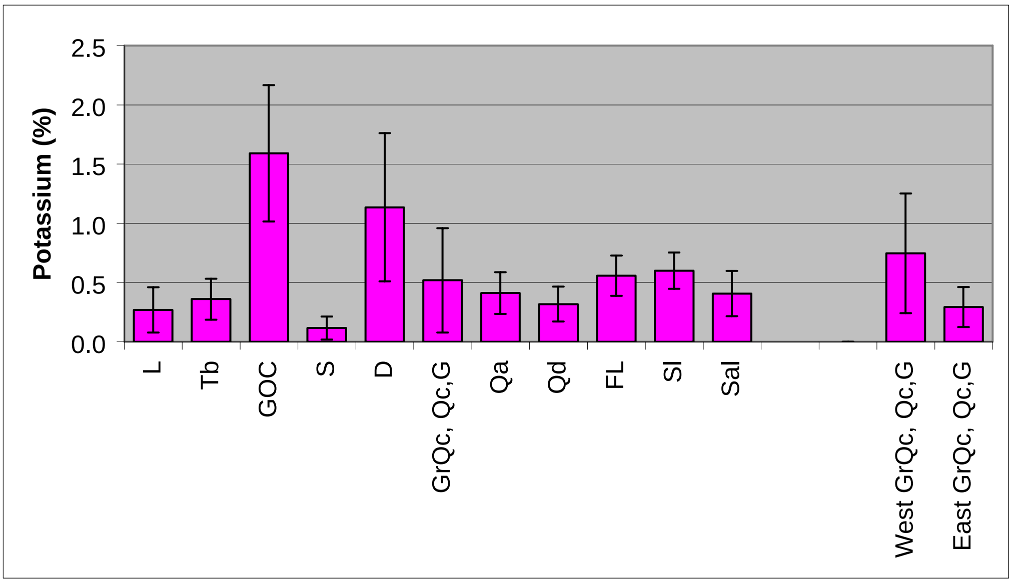
The sands are consistently lower in radiometric count than all other mapped units. A comparison with the radiometric ternary and the mapped soil units indicates that the low total count extends beyond the mapped soil boundaries. The granitic unit GOC was also well identified by high potassium (Figure 4.2 a) but there are discrepancies between those mapped by the airphoto and high potassium areas from the radiometrics.

The doleritic unit D was high in potassium and other radiometric channels. This differs to ground based results by Cook et al., (1996) where low emissions were recorded from the mafic minerals. The airborne survey is less likely to detect small-scale dolerite dyke variations due to the larger footprint of the airborne system (Cook et al., 1996). The dolerite dykes at Toolibin may be associated with chilled margins forming granitic bedrock highs alongside the dykes. Thus, over dolerite dykes the response seen at the aircraft may be a higher potassium response.

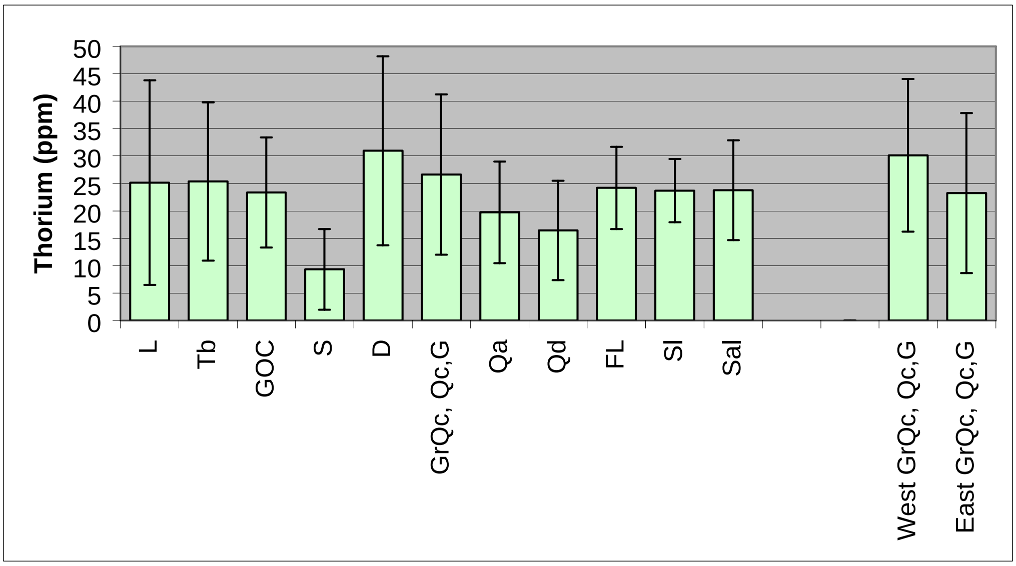
Laterite and the etched laterite units are difficult to distinguish from the other units in the thorium and uranium channels. This is unusual, as these units are associated with elevated thorium and uranium responses (Cook et al., 1996; Dickson and Scott, 1997; Dauth, 1997; Wilford et al., 1992; Bebbington, 1998; Pracilio et al., 1998).

The fresh water, salt water and saline areas tend to be higher in counts relative to other lower lying such as units Qa and Qd. This may be due to discharge of radon.

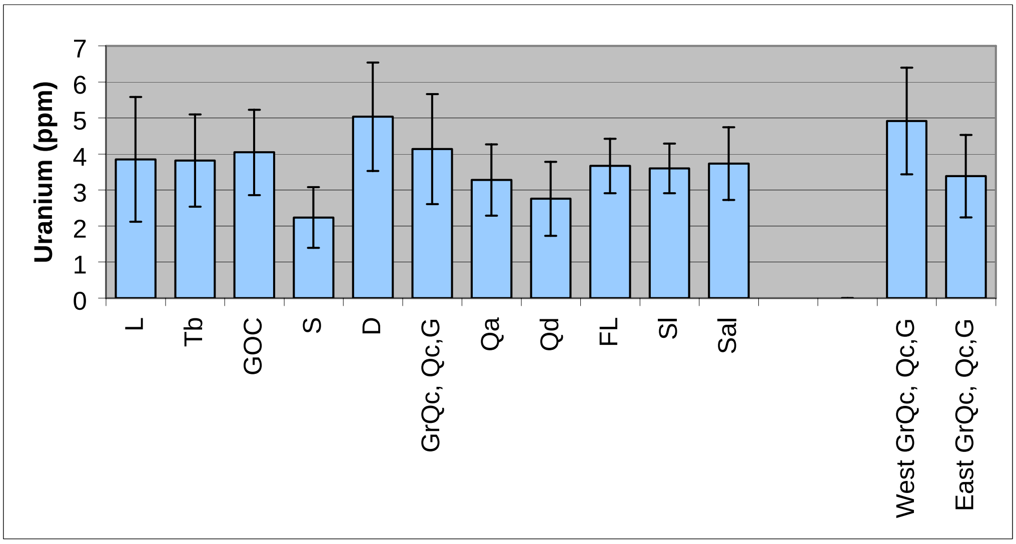
The soils-landscape map (Verboom and Galloway, 1998) does not differentiate between the two distinct geomorphological domains (Pracilio et al., 1998; George 1998). The GrQc, Qc and G combined unit were separated into west and east catchments to illustrate these differences. The western catchment was higher in all radiometric channels. The west is dominated by high potassium due to the outcropping granite and east by lower emissions from the extensive sand-plains.



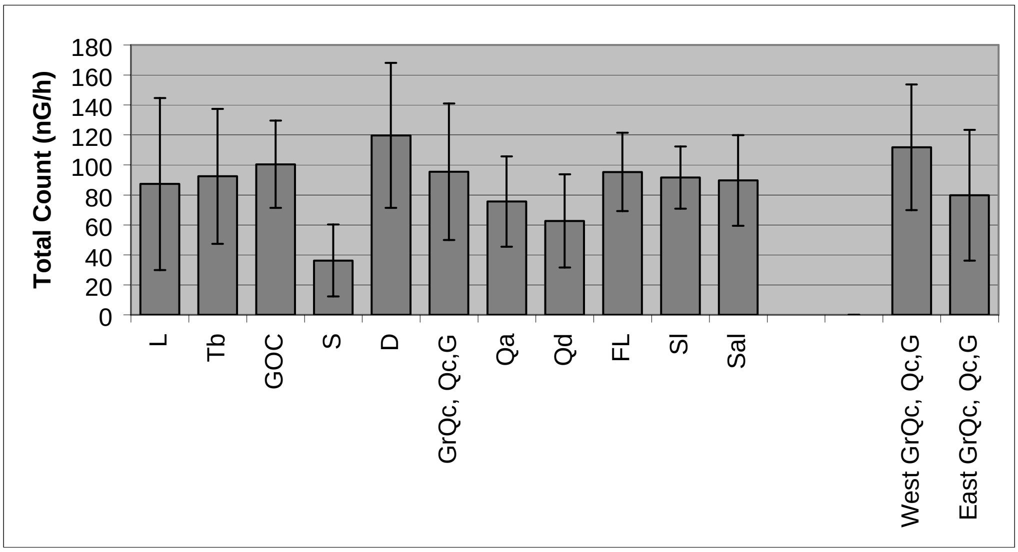
a) Potassium,



(b) Thorium,



(c) Uranium



(d) Total count

Figure 4.2: Mean, plus or minus the standard deviation for soil landscape units from Verboom and Galloway (1998).

Spatial comparison with the radiometrics ternary and the soil landscape map shows that there are many more units that can be defined by the radiometrics. The original aim was to compare the soils mapped by traditional methods (results which were not biased by the radiometric data) with the unbiased unsupervised radiometric classification. The short time frame in which the soil landscape map was prepared (Verboom pers. comm.) and larger scale of mapping resulted in the map being unsuitable for further comparison work with the more detailed radiometric data. Emphasis was given on using the original soil point data for classifying radiometric units to produce a supervised soil map.

The regolith map by Bebbington (1998) was described as the best map at the time (Verboom pers. com.). This was a partly supervised approach, which used a mostly manual interpretation of the radiometric ternary. A limited automated supervised classification was also used with some fieldwork. This Project incorporates an unsupervised investigation of the data to maximise the information from the data without bias to then produce a final supervised investigation incorporating in excess of 200 field points.

4.1.3.2 Statistical classification of radiometric data

Standard Deviation classification (ktu_merge.shp) compares well with the radiometric ternary image. It also assists in interpreting the radiometric ternary as it quantifies the statistics of the potassium, thorium and uranium into High, Medium and Low terms, often subjectively interpreted from the colours of the ternary image. An experienced ArcView Spatial Analyst user can generate the map manually in around two hours. If automated, the time and effort required to generate would be considerably less.

The distinction between the two catchments is clear. The laterites are well mapped by several units. The Standard Deviation classification and the radiometric ternary display similar ovoid characteristics, with uranium and thorium decreasing from the centre of a laterite core. Rings of different classes around units represent this gradational effect. A manual interpretation is less likely to represent as many units in the transitional zone.

However, there still remains more detail in the radiometric ternary image than the statistical classification. The three classes for each radiometric channel is a simplification of the original data. For example, the unit 111 in the eastern catchment is an extensive unit that can be further divided from obvious distinctions into sand plain and alluvium. Apart from the obvious topographic differences, there is also a subtle radiometric difference within this unit evident in the ternary from black in the sand plains to a dark brown in the alluvium. The extremes calculated for each region (pot/ tho/ ura_extremes_f.shp) assist in dissecting the 111 unit further. The potassium extremes are evident in the alluvium, whilst the thorium and uranium extremes occur surrounding the lateritic units. The disadvantage of using the extremes is that it makes little sense to view these at a regional scale as they are specific to a region.

There are also other instances where the input of a topography and slope data set would assist in differentiating classes. For example, unit 222 occurs mostly in the low lying region as an alluvial unit but in some cases the same radiometric response occurs on hill slopes and would thus be a different soil-landform type. The area just above the salt lakes upslope of Toolibin Lake was classified as 233. This is a typical laterite unit but a different landform soil type is likely for this class in the alluvial flats. Visualization of the radiometric ternary indicates that these are not quite the same by the lack of the ovoid structure in the unit occurring in the Flats when compared to the other classes related to laterites.

In summary, the Standard Deviation classification is easy to generate and is useful as it classifies and merges potassium, thorium and uranium statistics into High, Medium and Low classes creating 27 classes. These classes need to be further dissected into soil-landscape units by other methods. The next step would be to incorporate the digital terrain model to differentiate landform with similar radiometric responses.

4.1.3.3 Unsupervised classification of radiometric data

The unsupervised ISOCLASS technique was also tested on the radiometric data (see file cl_ktues_f.shp). The letters signify a classification of potassium, thorium, uranium, elevation and slope with a majority filter applied. The 27 units compare well with the radiometric ternary when transparent polygons are overlaid in most cases. The exceptions compare well when units of similar statistics are grouped. Like the Standard Deviation classes, gradational units unlikely to be manually interpreted were also evident in the ISOCLASS results.

The difference between the two catchments is evident in the ISOCLASS classification. For example, the alluvium from the west and central area were classed as GridCode 2 and those to the east as 1, the former being higher in potassium due to the granite derived alluvium.

The ISOCLASS was also compared visually with the Standard Deviation classes where the introduction of topography data was thought to improve the classification into soil-landscape units. The area of 233 discussed above has been differentiated from the lateritic units as class 11. This is associated with low-lying areas and is primarily an alluvial unit, although to some extent it is still associated at the edge of laterites. Likewise, class 222 is also differentiated by landscape position. The sand 111 class is made up of approximately 4.5 classes (3,4,5,8, part of 1) with a distinction from sandplain, colluvial derived from sandplain and alluvium.

The ISOCLASS technique was not successful at mapping an isolated gneissic outcrop mapped by both the radiometric ternary and standard deviation class as a potassium high. This is located north of Brown Road and colloquially referred to as “Akubra Hill” by participants in the NAGP (Clarke, pers. comm). Other localised changes such as laterite gravels along a road causing a thorium high were not mapped by the ISOCLASS but were by the ternary and standard deviation.

More time is involved to generate the results from the ISOCLASS and is partly dependent upon the computer specifications. A number of re-iterations were involved by testing different input data sets and control parameters. Statistics were generated, imported into a spreadsheet, results examined and referenced back to the class in the GIS. In comparison, the classes of the statistical method represent the statistics of the radiometric data. The statistics presented for the ISOCLASS represent normalised values.

For a more in-depth investigation of the classes, statistics were generated for each class. The radiometric means, topographic means and standard deviations for each class are graphed in Appendix 2. The potassium mean and standard deviation of the classes generated generally shows that there is a smaller spread of data that the other input parameters. The histograms for each input data set also reflect a smaller distribution of potassium data. As a result the majority of classes were unlikely to be differentiated by potassium alone, except for the class 14 and 25 (see Appendix 2). It is expected that this would have been exacerbated if the data sets were not normalised based on results by Anderson-Mayes (1999).

The classes were divided into Low, Moderately Low, Medium, Moderately High, High and Very High (See Table 4.2). Sandy (low radiometric values), granitic (high potassium), lateritic (high to moderately high thorium and uranium) and alluvial (low slope) classes can be quickly determined (see 4.1.3.4).

In summary, there was an improvement in class discrimination by the introduction of topography and slope. Localised changes and potassium are unlikely to feature strongly in the ISOCLASS classification. Thus, it is still important to use the other radiometric and soil data in conjunction with the classifications produced.

Table 4.1 Relative level variable for the derived classes

Class	Potassium	Thorium	Uranium	DEM	Slope
1	Low	Low	Low	Low	Low
2	Mod. Low	Medium	Medium	Low	Low
3	Low	Low	Low	Medium	Low
4	Low	Low	Low	Low	Medium
5	Low	Low	Low	Mod. High	Mod. High
6	Mod. Low	Medium	Medium	Low	Medium
7	Mod. Low	Medium	Medium	Medium	Medium
8	Low	Low	Low	High	Medium
9	Mod. Low	Medium	Medium	Medium	Low
10	Mod. Low	Medium	Medium	Medium	Mod. High
11	Mod. Low	Mod. High	Mod. High	Low	Low
12	Mod. Low	Mod. High	Mod. High	Medium	Medium
13	Medium	Mod. High	High	Mod. High	Medium
14	High	Medium	Mod. High	Mod. High	Medium
15	Mod. Low	High	High	Medium	Medium
16	Mod. Low	High	Mod. High	Mod. High	Medium
17	Low	Medium	Medium	Mod. High	Medium
18	Medium	Mod. High	High	High	Mod. High
19	Medium	High	Very High	Medium	Mod. High
20	Medium	Very High	Very High	Medium	Medium
21	Low	Medium	Medium	High	Mod. High
22	Medium	Mod. High	Mod. High	Mod. High	High
23	Medium	Very High	Very High	Mod. High	High
24	Medium	Medium	Medium	Mod. High	Very High
25	High	Medium	Mod. High	High	High
26	Medium	Mod. High	High	High	Very High
27	Medium	Medium	Mod. High	High	Very High

4.1.3.4 Supervised classification of Radiometric Data

The soil types occurring within each class were tabulated (see Appendix 2). Within a class between 0 to 29 soils had been sampled. Alluvial classes contained the most samples. These soil sample data were interrogated in GIS to assign final landform and soil units.

Alluvial Units

Class 1 represents an alluvial unit (As in final map). Class 1 occurs in both the west and east parts of the catchment but is dominant in the eastern half.

There are subtle colour differences in the radiometric ternary across this unit ranging from black, brown and dark red/pink. From the soil sites, deep to shallow sandy duplex is black in the radiometric ternary, grey clay or sandy duplex are the brown colours of the ternary and duplex soils with a clayey sand A-Horizon occurs are dark pink, in the North West Creek catchment.

Soil sample data from 21 sites within this unit were used to further divide this unit. Total count classified into ¼ standard deviation separated out the deep and shallow duplex's within the black areas on the ternary (Asd in final soil map). In the North West creek catchment the dark red units were separated

The classification did not distinguish between the Scriveners and North Wedin catchments that is included in class 1. The alluvials within Scriveners tends to have grey clay or shallow duplex whereas North Wedin has loamy sand or shallow duplex. The loamy sands could not be distinguished from the grey clay. It was postulated that the loamy sands may be derived from potassic sources upstream within North Wedin giving rise to a slightly higher count than other loamy sands in the eastern catchment.

Aeolian sands surrounding lakes were also included in the class 1 unit. This is probably due to their similar elevation and radiometric count.

Class 2 represents another alluvial unit within the flat valleys of the western catchment (Al, Alf, Ali and Alc in final map) and also occurs at the edge of the class 1 alluvial unit in the eastern catchment. Isolated patches occur on low sloping ridges and low elevations (R). The latter were separated manually.

In comparison to class 1 radiometric values of class 2 are higher. Colours in the radiometric ternary within class 2 vary but the intensity is similar. Units were separated after the following relationships were noted. Alluvium to the west (Ali) is higher in potassium. The soils sampled in Ali were predominantly sandy loam to clayey sand in the A-Horizon of a duplex soil. Ali was identified as the area within class 2 that was greater than the average potassium of the surveyed data set. Grey clay was sampled in the central alluvial (Ac) producing a characteristic moderate potassium, thorium and uranium response. Ac was manually interpreted from the radiometric images.

Class 11 represents a gradational unit between lateritic colluvium to loamy/clay alluvium. Of the units discussed, class 11 has the highest mean radiometric values. The soil texture sampled within this unit varies from loam to clays with less sand content. Some samples had evidence of gravelly soils. The unit typically occurs at the edge of lateritic units. To identify areas with more gravel, areas greater than 40ppm thorium were separated (AClf). In some cases these were the gradational ring structures surrounding the ovoid lateritic units.

Sandplain

Sandplain classed 3,4,5 and 8 were defined by low radiometric counts. The units are mostly differentiated by elevation and slope. The deepest sandplain area is postulated to be class 5 with the lowest counts and highest slope (relative to the other sandplain classes). The slopes may assist in the deposition of aeolian sand.

Unit 8 occurs mostly at higher elevations. Unit 3 occurs in low sloping regions occurring in alluvial and flat hilltops. Unit 4 tends to occur in lower elevation. This is associated with lower slope colluvium or sandplain in lower elevations east of Toolibin Lake.

Lateritic Units

Classes 15 and 16 could be grouped based on their similar radiometric statistics (Lle, L). These classes form part of the outer onion/ovoid weathering pattern evident in the radiometric data. Full lateritic profiles and hard caps are expected at the core of the weathering pattern in Class 20, where very high thorium and uranium is present (Lhc).

Class 19 is a lateritic unit with a very high uranium response relative to other moderately high to high thorium units (L/D). It is often adjacent to granitic areas. The granites of the region appear to contain higher uranium. The granites are probably the source of elevated uranium in the lateritic profiles of the western catchment. The linear nature of this class suggests that doleritic soils exist within the vicinity of this unit. This requires field checking.

Class 17 is a lateritic unit common in the north east corner of the catchment divide. It differs to other lateritic units having medium thorium and uranium content. The lower counts indicate a sandier profile (Ls).

Class 18 with a very large standard deviation in the potassium range, reflects variable colours in the radiometric ternary from pink to aqua blue. This is distinguished from all other units by the very high elevation mostly occurring in the western catchment (Lw). Soils are likely to be more granitic in the ternary pink areas and more lateritic in the blue. Soil samples for 18 were only taken in the ternary, blue lateritic unit. The unit requires further field checking and possibly further division. It typically occurs adjacent to granitic units.

Colluvial Units

Class 12 represents colluvium derived from ferricrete (Cf). It often occurs as gradational ring around the lateritic units. This circular feature occurs at the top of a ridges and around the bottom of slopes.

Like class 18, class 13 has a high potassium standard deviation. Loamy duplex was sampled within the pink colour of the ternary image whilst gravelly duplex soils were sampled within a blue ternary region, within class 13 (Cgf). This requires splitting and further field checking and possibly grouping with other units.

Class 21 is an upper colluvial unit derived from lateritic and sandplain areas occurring in the upper landscape (Csf).

Class 6 is a colluvial unit that is derived from a number of sources (Acsl). Soils occurring within this class include gravelly duplexes and duplex soils with no gravel content. These can be differentiated from the colours of the radiometric ternary by investigating the possible upslope sources of colluvium. Pinker areas are more likely to be duplex soils without the gravel content. This class also occurs as isolated pixels within the alluvial class 2. From the slope grid they represent the lowest sloping regions but it is unclear why they were included within class 6. These isolated pixels require further field investigation to determine whether to incorporate with class 2.

The difference between class 7 and 6 is the latter is lower in radiometric count and therefore probably related to thicker sand in the A-horizon of duplex soils. It also tends to occur at higher elevations and closer to sand source near sandplain.

Of the similar colluvial classes 6,7,9 and 10, the latter (CHs) is the highest sloping. Gravelly sands are prevalent in the eastern catchment and loamy granitic soils are more common in the western catchment. Class 6 is very similar to class 9 in radiometric data. The major difference is class 9 occurs at higher elevations and lower slopes, mostly in upper valleys or localised areas of accumulation. It has been reclassed as an alluvial unit. Class 6 represents transition from colluvial to alluvial areas.

Units with high slope-piedoment angle

In order of increasing slope, classes 22, 23, 24, 26 and 27 represent the highest sloping, each occupying a small proportion of the survey area, mostly in elevated areas of the western catchment. These soils are at greater risk of water erosion. They have been described as piedmont angles (P) representing sharp transitions between a hill and a plain. Very few soil samples were taken within these classes.

Class 23 unit is similar to the lateritic unit 20 with very high thorium and uranium. Class 26 is moderately high to high in thorium and uranium. Of the four high sloping units class 23 and 26 are more likely to be associated with lateritic units. Such sharp changes in slope are likely to be a result of laterite breakaways exposing ferricrete and saprolite.

Classes 24 and 27 have a very large potassium standard deviation. Consequently the colour of the radiometric ternary images differ within the same unit. In the western catchment these classes are more likely to be associated with granitic areas. Granite boulders in the western catchment were observed within class 24. From the radiometric data these classes were associated with both granitic and lateritic regions in the eastern catchment. These are often linear in nature and may correspond with weathered dolerite. Dolerite derived soil was sampled within class 22. The radiometric response of dolerite expected to be lower than the average of the means associated with class 22. This unit requires field checking.

Granitic Units

Class 25 and 14 represent the granitic outcrop and sub-outcrop areas in the high elevations, with class 25 differentiated from 14 by higher potassium and slope (Ghs).

Soil sites within class 14 were described as gravelly duplex at a site with another four closely spaced samples of gradational loams on weathered granite. The soils were described as gritty with an approximate average of 10% quartz content within the top 40cm. Bedrock is close to the surface as indicated by the dominance of potassium.

Isolated outcrops of lower elevations adjacent to the Flats, north of Brown Road (colloquially referred to as Akubra Hill in NAGP) and sub-outcrop south of this, were not classed into a high potassium unit. The former two outcrops were classed as 4, low in all radiometric counts. From the standard deviation classification these were classified as 311 (high potassium and low thorium, uranium). This reinforces that potassium was not a dominant input parameter in the ISOCLASS technique.

A new shape file was created granite_outcrop.shp, identifying granitic sub/outcrop areas in the central and eastern catchments only. It was determined by Boolean expression, high potassium (from Standard deviation classification) and low layer two conductance (less than 4S). This was chosen over a manual interpretation of granitic outcropping areas, as that method was more likely to overlook potential granitic outcrops not inspected in the field. The granite outcrop shapefile is to be overlayed on the final soil map.

4.1.4 Final Map (soilmap_cl_ktues.shp)

The final soil map description in Table 4.2 is based on the above discussion, data management in the GIS and the compilation of the soil sites within each unit (see Appendix 2).

Table 4.2 Final soil map description

Label	Grid Code Class	Major Landform	Landform Description	Soil Description	Notes relative to other units within Major Landform
AClc	11	Alluvial/ Colluvial	Break in slope region, alluvial areas dominate with some lower slope colluvium	Gradational red loam, Morrel, Grey vertic clay, Sandy to clay loam	
AClf	11	Alluvial/ Colluvial	Break in slope region, alluvial areas dominate with some lower slope colluvium	Gravelly loams, Loamy gravel	Higher thorium, gravels more likely
ACsl	6	Alluvial/ Colluvial	Colluvial to alluvial plain, break in slope	Gravelly sandy to loamy duplex, sandy to loamy duplex, saline areas	
Ac	2	Alluvial	Valley flat/alluvial plain includes dry lakes	Grey vertic clay	
Af	9	Alluvial	Minor upslope drainage, lower slopes	Sandy gravels, Gravelly sand, Loamy gravels	
Al	2	Alluvial	Valley flat/alluvial plain includes dry lakes	Loamy sand to sandy loam duplex, Grey vertic clay, Stratified alluvium	
Alf	2	Alluvial	Valley flat/alluvial plain includes dry lakes	Loamy sand to sandy loam duplex, Grey vertic clay, Stratified alluvium	Higher thorium than other Al units, inferred gravel content
Ali	2	Alluvial	Valley flat/alluvial plain includes dry lakes	Shallow clayey sand to sandy loam duplex, Loamy duplex	
As	1	Alluvial	Valley flat/alluvial plain includes aeolian deposits/lunettes	Sandy duplex, Grey clays, Saline and waterlogged	Mostly western catchment
Asc	1	Alluvial	Valley flat/alluvial plain includes aeolian deposits/lunettes	Sandy duplex, Clayey sand A horizon, Saline and waterlogged	Mostly north western part of survey
Asd	1	Alluvial	Valley flat/alluvial plain includes aeolian deposits/lunettes	Deep sandy duplex	Western catchment
Atl	2	Alluvial	Valley flat/alluvial plain includes dry lakes	Grey clay over silty clay	
Cf	12	Colluvial	Colluvial slopes, colluvium derived from ferricrete	Gravelly sand to loamy sand	
Cgf	13	Colluvial	Colluvial slopes, colluvium derived from granite and ferricrete	Sandy to loamy duplex, Gravelly duplex	
Chs	10	Colluvial	Colluvial slopes	Sand to gravelly sand, Loamy granitic	High slope
Clf	7	Colluvial	Colluvial slopes	Sandy to loamy duplex, gravels	
Csf	21	Colluvial	Colluvial slopes, colluvium derived from sand and laterite	Clayey sand to sandy loam, Loamy duplex (gravel at depth), Gravelly duplex	High elevation, slope
D	22	Dolerite	Doleritic ridges and upper slopes	Medium to heavy clay, doleritic derived soils	High elevation, high slope

G	14	Granite	Granitic crests, ridges, upper relict and colluvial slopes	Granite outcrop, Gradational loam, Gravelly duplex over freshly weathered granite	
Ghs	25	Granite	Granitic crests and ridges	Sandy granitic soils, Granite outcrop	Higher slope
L	16	Laterite	Lateritic crests and colluvium derived from ferricrete	Gravelly soils	
LD	19	Laterite/ Dolerite	Lateritic upper slopes, associated with dolerite	Gravelly soils: gravelly duplex, gravelly clayey sand to sandy loam	High uranium, associated with dolerite dykes
Lhc	20	Laterite	Lateritic hard caps	Laterite hard cap, Gravelly soils greater than 50% gravel content	High thorium and uranium
Lle	15	Laterite	Lateritic crests and colluvium derived from ferricrete	Gravelly soils greater than 50% gravel content, Gravel over ferricrete	Low elevation
Ls	17	Laterite	Laterite ridges, breakaways and upper slopes	Edge of gravel break-away, Sandy to gravelly loamy sand, Gravelly duplex	Low uranium, mostly north eastern part of survey
Lw	18	Laterite	Lateritic ridges and crests	Gravelly, clayey sand to sandy loam, Gravel content 20 to 50%	High elevation, high slope, western catchment
Pd	26	Piedmont Angle	Erosional piedmont angle	Gravelly soils, ferruginous gravel content 20 to 80% , exposed ferricrete	
PDfg	24	Piedmont Angle	Erosional piedmont angle	Western catchment: colluvium and granite sub/outcrop; Eastern catchment: colluvium and exposed ferricrete/saprolite	
Pf	23	Piedmont Angle	Erosional piedmont angle	Gravelly soils, ferruginous gravel content 20 to 80%, exposed ferricrete	
Phs	27	Piedmont Angle	Erosional piedmont angle	Western catchment: colluvium and granite sub/outcrop; Eastern catchment: colluvium and exposed ferricrete/saprolite	
R	2	Ridge	Isolated ridges, low elevation	Loamy sand to sandy loam duplex	
S	3	Sand Plain	Sand plain, crests, upper slopes and valleys	Loamy sand duplex, Gravelly duplex	
Sd	5	Sand Plain	Sand plain, upper slopes	Thick yellow sand plain, white granitic sand	
She	8	Sand Plain	Sand plain, crests and upper slopes	Sand to loamy sand often with ferruginous gravel	
Sle	4	Sand Plain	Aeolian sand plain, lower colluvial slopes, isolated low slopes within alluvium	Sandy to loamy Duplex	

4.1.5 Limitations and improvements

The potassium channel did not significantly influence the final classification. The distribution histogram despite normalisation, the data was not as broad as the thorium and uranium data sets. Different preparation of the data may be required or another classification technique not so dependent on the normal distribution of the data.

An improved classification of the topography that separated low sloping ridges from valley floors using a calculation of curvature is likely to improve the overall output of the unsupervised classification. For example, the typical alluvial unit Class 1 (As) was located on low sloping ridges (R). Sandplain (S) dominant on low slopes and high elevation occurred on ridges and upper catchment alluvial areas. In general the final map is not an ideal landform map as the curvature has not been taken into account and there is a mixture of different landforms within a unit. Those dominating were chosen as the Major Landform type.

The grid cell analysis size was 35m. This reflects the maximum resolution of the data sets used. Small-scale features such as alluvium that varies over short distances (50m) are unlikely to be to be detected by the gamma ray spectrometer and thus the classification. Doleritic soils are also localised soil features and unlikely to be detected by airborne systems (Cook et al., 1996). Some units with linear spatial patterns were postulated as weathered doleritic. The radiometric signature of these units is not a typical low radiometric response of dolerite particularly in potassium (Dickson and Scott, 1997). The authors are not aware of studies on the limitation of airborne systems detecting low radiometric features of limited width such as dolerite dykes, within high radiometric background from granite or laterite. The linear features require further field investigation.

It was noted that the soils of North Wedin, North West Creek and Scriveners Catchment differed but that one class covered this region. An improved method of alluvial discrimination may be to assess the source material by calculating the radiometric statistics upslope. More investigation is required. Time did not permit the development of an *automated* approach to a supervised classification within this project. These alluvials could become training areas or the data set cut into specific regions to identify more subtle changes.

Field checking of the soil map should be undertaken. The radiometric ternary was checked in the field and related very well with observed soil changes. As the final soils map approximated the ternary image in the majority of cases, the output was considered reasonable with much more detail than previous maps. Classes that are similar in radiometric and soil composition could be grouped, but there may be reasons unknown to the authors that may be significant on the ground. In ArcView, polygons can be split or amalgamated to better represent the local knowledge of the area. The tables can be edited to update the soils map as new information arises. The map is not designed to be a rigid end product. All data sets in the GIS should be reviewed, improved and updated with time.

Subtle differences not defined by the classification techniques used could be identified from a Principal Component (PC) analysis from later PCs. The NASVD (Noise Adjusted Singular Value Decomposition) method is similar to PC analysis (Minty, 1998) and should be investigated. Classification techniques such as Angle Mapper as used with spectral data (Hausknecht and Milne, 1993) can allow the integration of soil, topographic and radiometric properties to be used. The different processing techniques such as those described in Minty (1998) and classification techniques available need to be assessed in terms of producing an ideal soil map. Radiometrics for soil mapping is relatively new and Toolibin is an ideal case study with such high-resolution data available.

4.2 OARS (Operational Airborne Research Spectrometer)

4.2.1 OARS Research

As a Government and industry initiative WGC/Fugro in collaboration with CSIRO are currently developing the OARS instrument (CSIRO and WGC, 1999). The primary aim of this development is to provide a new tool for mineral mapping in airborne geophysical exploration. The instrument is a prototype, operating at an altitude of 80 to 100 m above ground in the same aircraft as other airborne geophysical and/or remote sensing devices (CSIRO and WGC, 1999).

OARS' samples the reflected solar light of the ground surface beneath the surveying aircraft in about 190 spectral channels (CSIRO and WGC 1999). In contrast to other hyperspectral systems, it is a profiling device rather than a scanner. The sensors measure the spectral reflection from an area of ground around 8 to 10 m across directly below the aircraft. The aim of the project is to use spectral features in the reflected ground spectra to give mineral composition of the ground surface. Mineral abundance maps can then be created using 2-D interpolation. The same data can be used for chlorophyll detection and possibly plant species discrimination.

The OARS instrument is designed with two unique operational features:

1. The single pixel measurement beneath the aircraft gives very high signal to noise ratio in all relevant spectral channels and allows operation over long periods of the day, even under less favourable atmospheric conditions.
2. A second spectrometer unit looking upward monitors the incoming solar radiation to allow for an improved atmospheric correction of the ground data. Both design features are not present in existing airborne spectrometers (CSIRO and WGC, 1999).

As part of the OARS project, new processing and analysis software is currently being developed (CSIRO and WGC, 1999). The raw data from the airborne instrument is calibrated and converted to ground reflectance. Using information from existing spectral libraries, spectral end-members (such as pure minerals) will be selected. Then a mineral abundance calculation is performed and a pixel purity index determined. As a final step all the line-profiling data is converted into maps using special gridding and interpolation software.

OARS information allows the identification of metamorphic alteration, mineral enrichments or other geological relevant surface composition. The information created from mineral abundance mapping is often valuable to geoscientists in mineral exploration. Within a GIS environment, mineral abundance maps can be interpreted with other geophysical data into an integrated geological interpretation of an exploration area.

The potential of the technology for soil mapping is untested but may show greater application than mineral mapping. In addition, plant species discrimination may be an important application although at present, spectral libraries for Australian plant species are not well developed.

Following test flights, the first geologically orientated application surveys were flown. Toolibin Lake was chosen as a test site for soil mapping in the agricultural area.

4.2.2 OARS survey specifications

The OARS data were collected over two days during late winter, 22 and 23 August 1999. The weather was windy with some high level cloud. Some rain had fallen in the preceding days.

Flight line spacing	150m
Altitude of sensors	80m
Flight line direction	020^o – 200^o
Tie line spacing	1,500m
Tie line direction	110^o – 290^o
Radar altimeter cycle rate	10Hz (0.1s), ~7m
Barometric altimeter cycle rate	10Hz (0.1s), ~ 7m
Humidity sensor cycle rate	10Hz (0.1s), ~ 7m
Temperature sensor cycle rate	10Hz (0.1s), ~ 7m
GPS cycle rate	1Hz (1s), ~ 70m
Datum	AGD84
Zone	50
Central Meridian	117 degrees East

4.2.3 OARS system specification

OARS is a highly sensitive optical spectrometer with two separate instruments for upward (sky) and downward (ground) monitoring. Each instrument consists of 3 individual spectrometers. The instrument used for the survey at Toolibin Lake was a prototype instrument from commercial development work being carried out by CSIRO and WGC. The optical design and building of the optical set up was carried out by CSIRO, DMS in Melbourne. Significant deviations from the initial design were found during testing.

Characteristic	**Requirement**
Basic wavelength range	500 - 2500nm
Wavelength dispersion by	Diffraction grating
Number of spectrometers	3 up and 3 down
Wavelength ranges of individual spectrometers	a) 503-960nm
b) 940-1760nm	
c) 1740-2500nm	
Spectral sampling interval	a) 8nm
b) 12nm	
c) 11nm	
Spectral resolution	a) 16nm
b) 19nm	
c) 18nm respectively	
Total number of channels	Nominal: Total180 a) 52 b) 60 c) 68
Detector type	a VNIR: silicon array b)VNIR silicon array c) SWIR PbS array
Signal to Noise Ratio at 0.5 target albedo in full sunlight	
At 800nm	*> 3000*
At 1600nm	*> 1000*
At 2300nm	*> 700*
Instantaneous Field of View	0.23*5.5deg or 0.4m*10m at 100m
Nominal Field of View (pixel)	5.5*5.5deg or 10 m * 10m at 100m
Wavelength calibration	+/- 1nm or better using lab calibration. and intrinsic data characteristics
Radiometric calibration	+/- 5% or better via on-board calibration.
Geometric calibration	3 axis pointing sensor (aircraft), GPS
Ground orientation	panchromatic. digital, CCD camera,
Data acquisition	Picodas P1000 (WGC standard) incl. all sensors ,GPS, radar altimeter, flight attitude sensors
Upward looking sensor	Diffuse cosine receptor
Downward looking sensor	Quartz glass window, direct measurement
Size (each sensor)	~ 700 mm * 280 mm * 100 mm

4.2.4 CCD imager specifications:

Characteristic	Requirement
Field of View	88deg or ~190m at 100m
Basic wavelength range	1 channel panchromatic 500-750nm
Dynamic resolution	8 bit , automated gain control
No. of CCD elements	256
Ground resolution	At 100 m altitude: ~1.6 m at nadir, ~2m at 44 deg. across track

4.2.5 Methods

Initial data processing of OARS is under development. The results presented are thus preliminary but represent what can be currently achieved. It is expected that rapid development of the system and processing will be achieved by July 2000.

Full atmospheric correction was under review at the time of the Project. Logarithmic Residuals of spectra data has been successfully used by others (Green and Craig, 1985; Kruse, 1998) and was used for the preliminary processing of Toolibin data.

The clay ratio was identified from the short wave data. The ratio was determined between 2.2 and 2.1 micrometers. All clay minerals have an absorption feature of aluminium hydroxide at 2.2 micrometers. This ratio is interpreted as indicating the presence of clay minerals. Due to the camouflage effect of crops and remnant vegetation, clay minerals may be present but were not detected. It is important to use the NDVI image created from the survey data to identify areas of high crop/vegetation density that may mask the presence of clays and other soil features.

A decorrelation stretch was applied to the 2.1 and 2.2 spectra data. Reliable results can only be achieved with narrow band high-resolution data in comparison to the wide band Landsat data. The decorrelation stretch identified areas of different clay type.

Eleven “edge members” were identified from the visible spectrum in log residual space prior to calibration. This was treated with the initial Mineral Mapping process as being developed for the OARS research project. Edge members represent spatial extreme components of the survey data, which are spectrally abundant with different spectral signatures.

The hyperspectral profile data were gridded and images viewed in ArcView GIS with other surface features such as Landsat, airphoto, drainage and soil data.

4.2.6 OARS Interpretation

4.2.6.1 Short wave clay ratio

In the preliminary data set differing survey flight days show as shifts in the observed data making interpretation across the area difficult.

A clay ratio image was created from the OARS data. However, areas of high NDVI correspond with a low clay ratio due to the camouflage effect of crops. Thick vegetation cover will obscure any clay minerals present. Thus, it is only appropriate to check areas that indicate a low NDVI and a high clay ratio against collected soil data. The majority of the soils sampled occur on edges of high clay ratio or high NDVI. More field checking is required. The NDVI was interpreted into high, medium and low classes using Spatial Analyst software (ndvi.shp).

An area of grey vertic clay corresponds with a moderately high but patchy clay ratio response. A saline flat area at the break in slope region with heavy clay corresponds to a high clay ratio.

Areas of clay minerals occur within the sandplain region to the east of Toolibin Lake where the soils are expected to be sandy. The clay ratio does not indicate the amount or type of clay but the presence of clay minerals at the very surface. The amount of clay is possibly very low, with Toolibin Lake as the likely source for the aeolian distributed clay. The sands in this area are also higher in potassium than other sandplains in the catchment. This may indicate the presence of illite clay minerals. Alkaline conditions (pH of 8.3 at 0.5m from bore LT06) from the lake may cause illite clays to be redistributed on the sand plain. Wong and Harper (1999) found that potassium counts decreased exponentially with distance from a playa lake. A similar relationship is indicated east of Toolibin Lake.

The decorrelation image shows that one colour band (blue) corresponds with high NDVI. These are areas in which the presence of clay minerals cannot be determined. Higher intensities of the other two colour bands represent areas of high clay ratio indicating different clay types, with one more dominant than the other (clay type A). Generally the latter clay type occurs in the upper landscape within and adjacent to the sandplain. The clay minerals within alluvial areas differ by low and high intensities of the green colour band. The highest of intensities are associated near or within Toolibin Lake, saline areas, salt lakes and alluvial areas (clay type b).

An additional layer was created for the final soil map over the OARS survey area (exposed_clay.shp) using conversion of image data to grids into the three colour bands. The exposed clay ratio was determined from the high clay ratio and termed “exposed” as other areas with clay content may exist under vegetated areas.

The exposed clay ratio was then divided into two clay types based on the decorrelation stretch.

4.2.6.2 OARS Visible Edge Members

The spectrum observed by the OARS system was processed to separate the dominant spectra. Eleven “edge members” were identified from the visible spectra. See Appendix 2 for spectral signatures.

The spectral signature of edge member 1 is similar to the absorption relating to high reflectance. The spatial data viewed in ArcView shows that the highly correlated areas (white or high values) reflect bare regions identified from field observations within Toolibin Lake, scalded saline areas, wet and dry lakes. These areas also correspond with low NDVI. Sandplain to the east of Toolibin Lake is moderately correlated with this.

Edge member 2 is undistinguished by its spectral signature. Spatially it resembles a dendritic flood plain area occurring in the low sloping areas.

Edge member 3 represents a signature similar to water. It includes wet lakes that also have a low total radiometric count indicating presence of water. The main bitumen road is also highlighted. This may reflect pools of water adjacent to the road.

The spectral signature of edge member 6 shows the green chlorophyll absorption signature of green vegetation. It is correlated with high NDVI and relates to sown crops.

Edge member 11 correlates well with low NDVI. Well-correlated areas relate to wet lakes, the bare Toolibin Lake, sandy gravel regions of upland areas, saline and waterlogged flats.

Edge member 4, 5, 8 and 9 were postulated to represent native vegetation from the dry cellulose component of the spectral signature. They do not relate to the remnant vegetation mapped from the Landsat and airphoto. Spatially and spectrally the members are similar, with the most correlated areas relating to wet lakes.

The spectral signature of edge member 10 is related to iron rich areas. It is correlated with bitumen, gravel roads, saline areas, wet lakes and a gravel pit. It is unsure why there would be iron rich areas in wet lakes and saline areas. Lateritic areas were identified from the radiometrics and are expected to be iron rich. These do not necessarily correspond with the edge member 10 data. This may be attributed to a low gravel surface component. OARS detects surface spectra whereas the radiometric spectrometer measures gamma rays from greater depths. These areas are mostly cropped so any iron present at the surface will be masked. It is useful to incorporate the NDVI into the interpretation.

For soil mapping, precipitation records, dryness of surface soils and vegetation cover should be considered when planning an OARS survey. A few days after data acquisition field investigation showed that an average of 20% vegetative cover was evident in the paddocks with many soils moist at 0.5 to 1cm below the surface.

4.2.7 Conclusion

The data processing and products were preliminary and only limited use was possible. It is hoped to continue the analysis of these data with WGC/Fugro during 2000. The edge members incorporating the short wave and thermal infrared need to be determine. The next stage in the development of OARS for soil mapping is the mapping of minerals such as kaolinites, illites and quartz and their abundances. From the analyses in the Project this shows some promise. The lack of a spectral library specific for Western Australian plants and soils is likely to be a limiting factor in the OARS analysis.

5 TEMPEST AIRBORNE ELECTROMAGNETIC SURVEY

The SALTMAP airborne electromagnetic (AEM) system initially used at Toolibin Lake eastern catchment appeared to produce unreliable results in areas with a conductance greater than 10S (Pracilio et al., 1998). SALTMAP data also lacked resolution in the 0 to 10 m depth range (George, 1998). Layered earth inversion models applied to the data were also limited to 3 layers (2 layers and a halfspace) for reasons of computation time and stability of the inversion. Subtle variations in a complex geoelectric section could not be resolved, thus restricting the amount of information that could be extracted from the data. Since 1998 data quality and processing of AEM measurements for near surface applications has been improved by application of the new TEMPEST AEM system (Lane et al., 2000).

TEMPEST data were acquired by WGC for CRC-AMET as part of equipment testing. Toolibin Lake was the first survey flown with this system. The survey was completed in three flights on 29 July and 30 July 1998.

The validation and interpretation of TEMPEST data at Toolibin Lake was carried out by CRC-AMET (Lane and Pracilio, 2000) and under the present CALM project. Results from both investigations have been amalgamated in this report. Methods were mostly based on Lane and Pracilio (2000). Results were updated from data that has become available during the Project. In addition the discussion of results and application of related parameters have been expanded.

5.1 TEMPEST System Specifications

5.1.1 TEMPEST System Specifications

Table 5.1: TEMPEST specifications

Base Frequency	25 Hz
Transmitter area	186 m^2
Transmitter turns	1
Waveform	Square
Duty cycle	50%
Transmitter pulse width	10 ms
Transmitter off-time	10 ms
Peak current	300 A
Peak moment	55,800 A m^2
Average moment	27,900 A m^2
Sample rate	75 kHz
Sample interval	13 microseconds
Samples per half cycle	1500
System bandwidth	25 Hz to 37.5 kHz
Altitude of transmitter	120m
Altitude of sensor	~50 m

EM sensor	Towed bird with 3 component dB/dt coils
Sensor area of each coil	5959 m^2
Tx-Rx horizontal separation	100 m (nominal, actual value determined)
Tx-Rx vertical separation	55 m (nominal, actual value determined)
Stacked data output windows	15
Window centre times	15 windows from 13 microseconds to 16.2 milliseconds
Magnetometer	Stinger mounted caesium vapour
Magnetic compensation	Fully digital
Magnetometer output interval	200 ms (~12 m)
Magnetometer resolution	0.001 nT
Typical noise level	0.1 nT
GPS cycle rate	1 second (~60 m)

5.1.2 Data Quality and Noise

A square transmitter waveform and fast sampling of EM field data by the receiver combine to give very broad bandwidth, 25 to 37500 Hz, ideal for modelling and for operating in both resistive and conductive areas (Lane et al., 1998). The broad bandwidth of TEMPEST compared with other Airborne EM systems is evident in Figure 5.1.

TEMPEST has improved signal to noise ratio due to monitoring of both receiver bird position and transmitter orientation (Lane and Pracilio, 2000). This monitoring allows calculation of relative position of transmitter loop, the ground and the receiver coils (system geometry). Corrections can then be applied for changes in system geometry. This has removed one of the greatest impediments to obtaining high resolution near-surface information from a fixed-wing, towed-bird AEM system. Comprehensive calibration procedures and sophisticated digital signal processing routines ensure that accurate ground response information is extracted from the measured data.

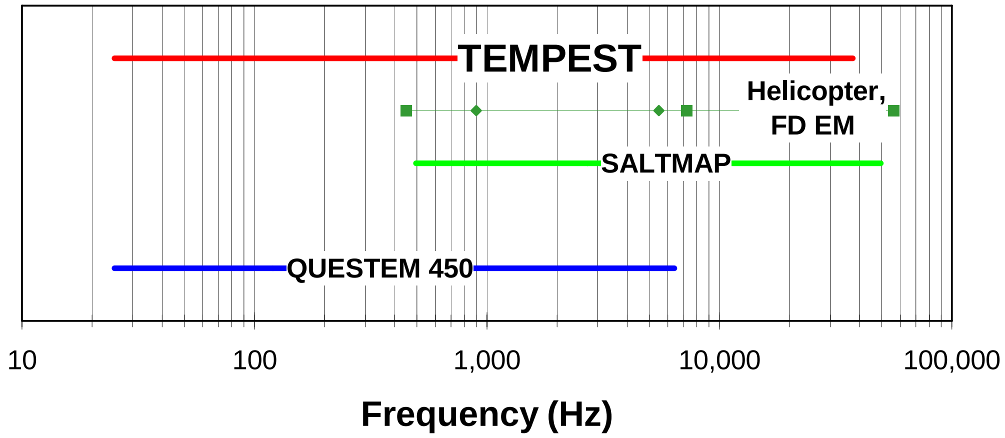


Figure 5.1: Comparison of airborne electromagnetic systems

5.1.3 TEMPEST processing

Conductivity depth images (CDIs) (Macnae et al., 1991) were produced by new EMFlow software developed by the CRC-AMET (Macnae et al., 1998). EMFlow works well on well calibrated, broadband and low noise AEM data to produce more appropriate results than 3 layer inversions used for SALTMAP data (Pracilio et al, 1998). CDIs allow subtle conductivity variations to be portrayed resulting in more realistic 1D models. Toolibin Lake has conductivity values that approximate a 1D situation over the scale of the individual observations.

Images of the results from conductivity depth inversion can be achieved by stitching together CDI values for each site into cross sections or averaging conductivity values over discrete intervals and creating 2D map images for particular depth-layers.

Thirty-four, four metre thick horizontal layers were created starting at 0-4 metres overlapping by two metres to a depth of 70 metres. Images were created from these layers with an identical linear stretch of log scaled data.

Using computer software, individual images from both vertical or horizontal slices can be combined into a semi-3D visualisation of the data using sequential projection of a succession of sections or depth images on screen. Other parameters can be extracted in a similar manner such that conductivity surfaces can also be viewed and rotated in 3D.

5.2 Methods

The methods of validation with ground conductivity data and other parameters are discussed below. The location of validation data is presented in Figure 5.2. Validation data used was limited to the available data at the time of analysis.

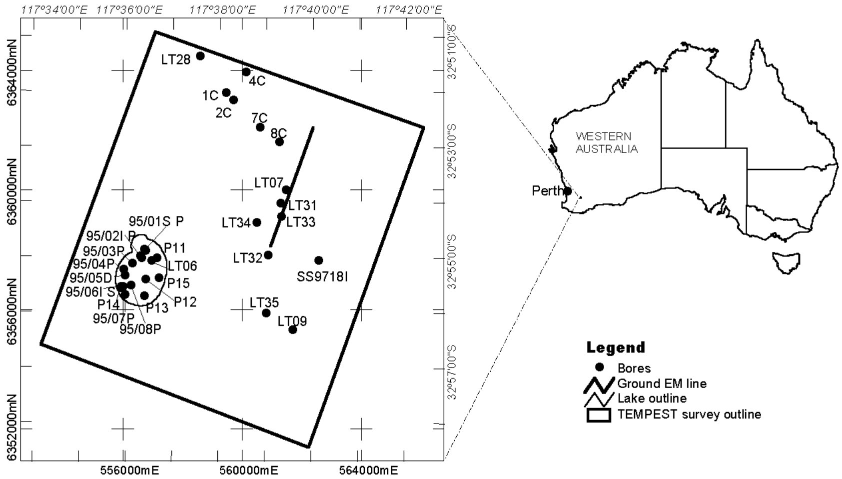


Figure 5.2: Location of bores and ground EM transect (Lane and Pracilio, 2000)

5.2.1 Electromagnetic Validation

5.2.1.1 EM39 borehole

TEMPEST CDI values for observations within 75 m (half the line spacing) of 9 boreholes (SS9718I, LT06, 07, 09) were compared to downhole EM39 (McNeill, 1986) conductivity measurements. TEMPEST CDI values spaced at 4 m vertical intervals closely approximate the average of the more finely spaced EM39 measurements over the same intervals. Conductivity was plotted using logarithmic intervals since this reflects the resolution characteristic of EM measurements.

5.2.1.2 Broadband ground EM

A ground EM line was acquired across the valley area, within 50 m of TEMPEST flight line 10250. A single turn 50 by 50 m transmitter loop, Zonge TEM/3 central in-loop receiver coil, Zonge GDP16 receiver and station spacing of 50 m were used. Ground based systems such as these have the ability to stack multiple reading over a long period to converge on a response for each site. This stacking should result in a more accurate reading by averaging the ambient electromagnetic "noise".

5.2.1.3 Single frequency EM31

A comparison was made between EM31 measurements and TEMPEST CDI average conductivity values for the 0 to 4 m depth interval. The EM-31 operates at 9.8kHz and has an effective depth of penetration restricted to less than 6m (McNeill, 1986a). The EM-31 outputs a conductivity value based on low induction numbers (McNeill, 1980a). The EM-31 is not calibrated for high conductivity and may diverge from actual values at conductivities greater than 500 mS/m.

5.2.1.4 SALTMAP

Spatial patterns in SALTMAP data were compared with TEMPEST images and EM-31 data. Particular attention was paid to areas where the SALTMAP inversion was known to be unreliable. These included the lower landscape around and north of Toolibin Lake and areas of known granitic outcrop.

5.2.2 Comparison of TEMPEST with related parameters

5.2.2.1 $EC_{1:5}$ borehole sample

$EC_{1:5}$ values are a measure of total soluble salt content. Conductivity measured by TEMPEST or EM39 is a function of porosity, saturation and clay content as well as electrolyte content which is principally NaCl in this environment (Pracilio et al, 1998). Downhole $EC_{1:5}$ for bores 1C, 6C-10C, LT31 - 34 and LT28 were compared with TEMPEST observations within 75m.

5.2.2.2 Depth to bedrock

Depth to bedrock was derived from TEMPEST CDI data by mapping the transition depth from conductive regolith to resistive saprock/basement. This was calculated as the depth to base of a "conductive unit" defined by the log10(conductivity) value midway between the maximum and minimum values at each observation. This was compared to depth to bedrock determined by drilling. Twenty nine drillholes, which were drilled to basement, were used for the analysis.

5.2.2.3 Groundwater salinity

There are eighty-seven bores within the TEMPEST survey area. However, only Waters and Rivers Commission bores (DeSilva, 1999; Dogramaci, 1999), had sufficient groundwater salinity and slotted depth information to compare with TEMPEST data. Field sampled groundwater salinity from these bores was used in the analysis. Most of the other bores were shallow catchment monitoring bores with little documentation.

5.2.2.4 Surface salinity

Existing surface salinity was mapped by Land Monitor project using Landsat data and by AgWA using airphotos. A summary of the data supplied and areas defined as "saline extent" for the purposes of this project are outlined in Table 5.2. The saline extent areas were converted to ArcInfo grids and compared with the 0-4m TEMPEST grid and image.

Table 5.2: Summary of Saline Extent Data (adapted from Land Monitor Product Information Sheet and P. Raper pers.comm.)

Source	Legend & colour values	Description	Saline Extent
Land Monitor	**1 Cream**	Background	**-**
	2 Green	Bush / perennial vegetation cover (from the latest image used for the salt mapping)	**-**
	3 Orange	Mapped as salt-affected land in earliest time period (between 1987 and 1991)	"Saline Extent"
	4 Red	Mapped as additional salt-affected land in latest time period (between 1994 and 1997)	"Saline Extent"
	5 Cyan	Water	**-**
AgWA	**1 Blue**	Background	-
	3 Red	Mapped extent of saline land (**1998/9?)**	"Saline Extent"
	5 Pink	Predictions of maximum future extent of salt affected land	-

5.2.2.5 Conductivity, Dykes and Stream lines

The relationship between shallow conductivity and dolerite dykes was investigated within the alluvial Flats area, The aim being to determine if there was any influence from lower permeability dolerite saprolite on shallow groundwater flow. Point observations of conductivity highs associated with major dolerite dykes from the 2 to 6 m depth slice were recorded in the GIS. Points where dolerite dykes also appeared to control the drainage pattern were also included. These sites included stream lines and lake boundaries aligning with dolerite dykes. These locations were then compared with the other TEMPEST layers and interpretations.

5.2.2.6 Palaeochannel

Anomalous patterns in SALTMAP data (Pracilio et al, 1998) reflected a dendritic palaeochannel beneath the alluvial areas in the lower parts of the Toolibin catchment. However, SALTMAP inversions were not considered reliable, conductivity values were not definitive and the position of the channel was best interpreted from a map image display of principal component analysis.

Similar dendritic patterns from CDI processing gave a more defined pattern. The position of the channel at various depths was interpreted at a series of depth layers starting at 10-14 metres. The intersection of these areas was created as the area of thickest palaeochannel sands.

5.3 Results and discussion of TEMPEST validation

5.3.1 Validation of TEMPEST against other EM measurements

5.3.1.1 EM39 borehole data

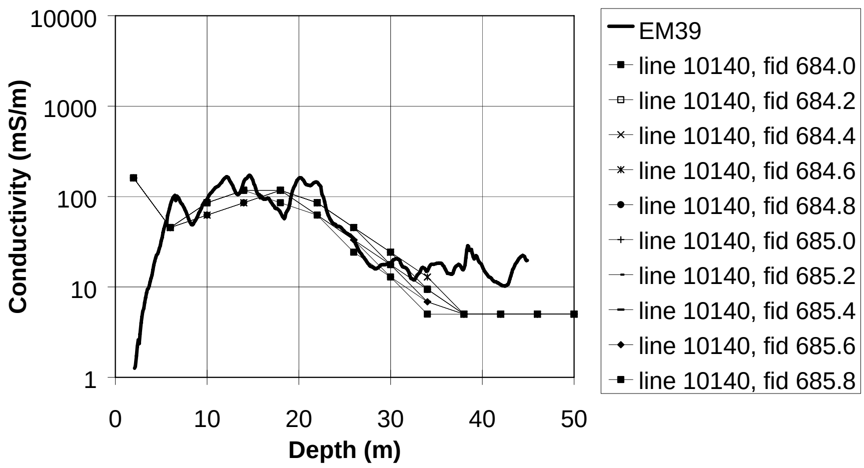
Lane and Pracilio (2000) showed an r^2=0.81 correlation between CDI and induction log conductivities (re-sampled to 4m intervals). The relationship is almost one is to one. The inclusion of more recently available data from P11 to P15 decreases the correlation to r^2=0.41. These additional bores are all located in Toolibin Lake.

The reduction in the correlation is evident in the scatterplot and by downhole EM39 and CDI plots (Figure 5.3). The major difference is in the P11 to P15 bores. In these bores at depths greater than 25m the EM39 values remain at a high conductivity around 1000mS/m whereas the CDI values decrease with depth (Appendix 4). The correlation from 0-25m is expected to be as good as that reported by Lane and Pracilio (2000). The samples are now biased towards a particular profile type described below. More samples are required for a spatially representative sample set.

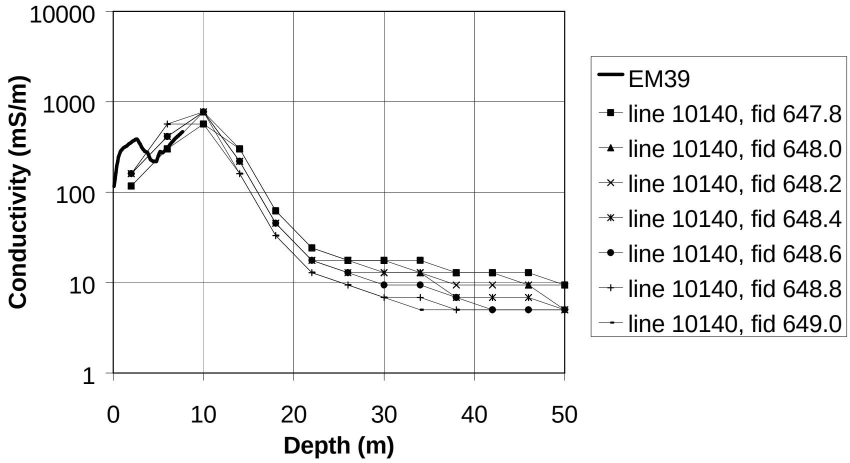
The EM39 data show the weathered saprolite and sediments of the P11 to P15 bores as highly conductive and relatively homogeneous over the complete regolith section, with conductivity values around 1000mS/m. The drilling data suggest that the saprolite and palaeochannel sediments sit directly on fresh basement rock. There is a sharp transition between the high conductivity of the sediments/deeply weathered saprolite to granitic bedrock which has a conductivity less than 1 mS/m (Palacky, 1987). The CDI fits a continuous gradual change in conductivity to the observed secondary field data. This is in contrast to the sharp boundary evident in the EM-39 data from P11 to P15 bores. A three-layer (LEI) model would better reflect such sharp transitions, although the LEI process does not allow good definition of subtle regolith conductivity variations.

LT09 displays the best fit apart from an anomalously high 2m TEMPEST sample. This bore is located in the upper landscape within saprolite and has a typical salt bulge profile in the EM-39 data. The CDI is better able to fit a gradational curve in such circumstances. Saprolite grit was mapped at 28m, which corresponds with the midpoint between maximum and minimum data values of TEMPEST data and where the EM39 values decease to less than 20mS/m.

SS9718I, is an intermediate bore not drilled to basement. The TEMPEST data indicates that the regolith extends to 20m at this site.



(a)



(b)

Figure 5.3: Comparison of EM39 borehole conductivity measurements with CDI conductivity values derived from TEMPEST observations within 75 m of (a) LT09, and (b) SS9718I (Lane and Pracilio, 2000)

The TEMPEST data in the near surface 2m and 6m samples corresponds well with the EM39. However, the 2m TEMPEST sample is generally lower than the EM39 by 300 mS/m or by 500mS/m with the LT09 2m value removed.

LT06 and LT07 are located within the palaeochannel and are more conductive than LT09. In these bores the 2m TEMPEST sample is lower than the EM39 value by 300mS/m and 160mS/m, respectively. TEMPEST conductivities do not fit well and are both above and below the EM39 data. This was similar to the P11 to P15 bores within Toolibin Lake.

5.3.1.2 Broadband ground EM

CDI sections for both ground broadband TEM and TEMPEST data are shown in Figure 5.4. Lateral discontinuities in the ground EM CDI section are suspected to be due to variations in transmitter loop size, loop geometry and receiver coil position.

Ground EM and TEMPEST CDI sections have very similar conductivity distributions. Thus, the same results can be obtained from a rapid airborne system compared to a slow ground based operation.

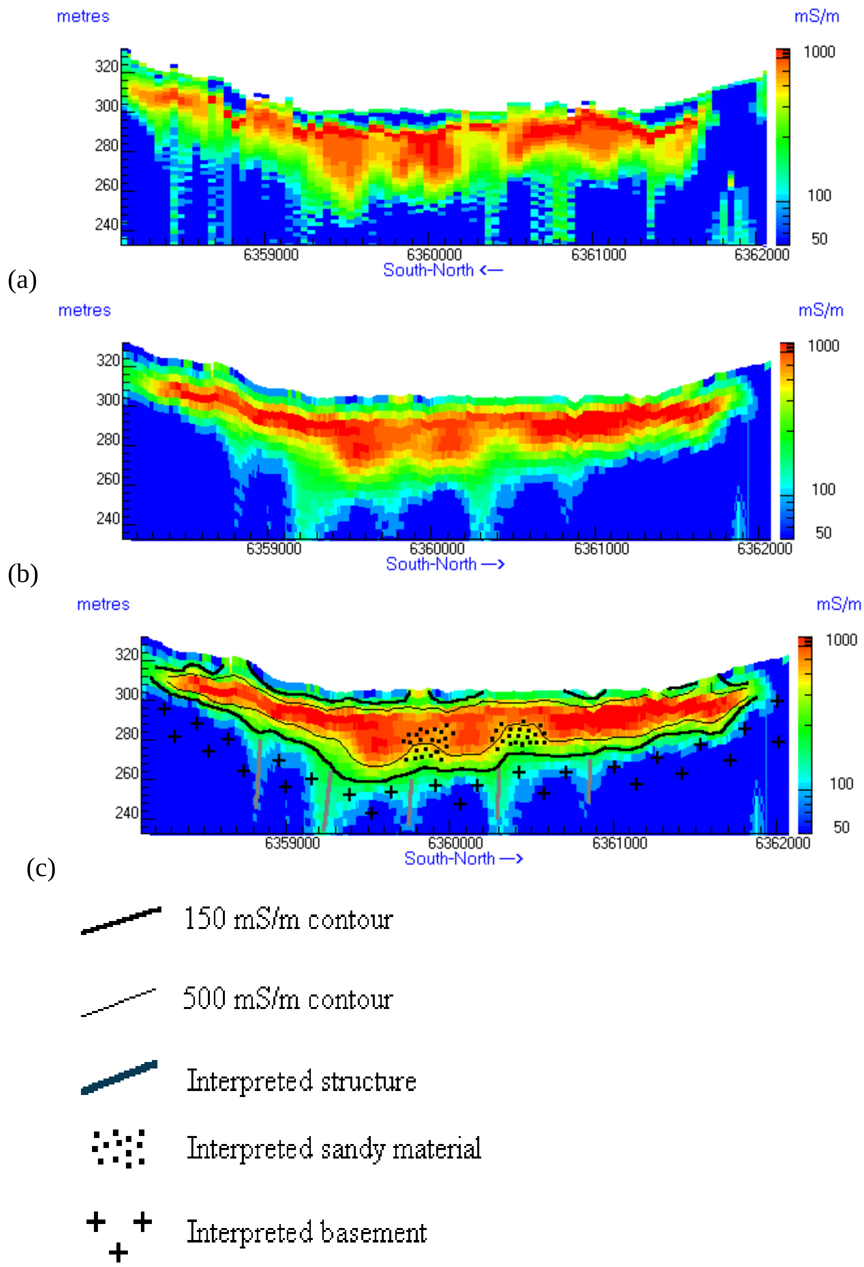


Figure 5.4. CDI sections for (a) broadband ground EM, and (b) TEMPEST (part of flight line 10250). (c) Annotated TEMPEST CDI section. (Lane and Pracilio, 2000)

In areas of conductive cover the base of the 150 mS/m contour corresponds closely to the base of the regolith. Areas of lower conductivity within the conductive region at the base of the 500 mS/m contour (see 6359850mN and 636400mN, Figure 5.4c) are significant subtle features and correlate well from line to line. These features with slightly lower conductivity and slightly shallower basement can be interpreted as reflecting palaeochannel sands.

The section data can be used similarly to the plan image data to locate the position of the channel. However, in the absence of other evidence the anomaly due to the palaeochannel sands in sections is not diagnostic of such geology. Thus, although ground based isolated lines could be used to locate possible channels, it would not show the depositional patterns that are reflected in the TEMPEST plan images. In sections the channel could be misinterpreted as bedrock highs. Isolated electromagnetic soundings would not be appropriate because it is not possible to recognise the response associated with palaeochannel sands from a 1D inversion profile. Resistivity soundings would not detect the channel for the same reason. In addition, with resistivity surveys the high conductivity surface would mask any response from the channel.

5.3.1.3 Single frequency EM31

There is a good correspondence between TEMPEST CDI average conductivity values for the 0-4m depth interval and EM31 measurements (Figures 5.5). The same colour scale was used to image the TEMPEST and EM31 data (Figure 5.6). Both indicate that the lake bed has the highest conductivity with surrounding lunette the lowest.

The intermediate pumping well 95/06I shows a localised circular low with an approximate radius of 100m from the TEMPEST data and 50m from the EM31 data. This circular feature is most likely attributed lowering of watertable by the pumping bore.

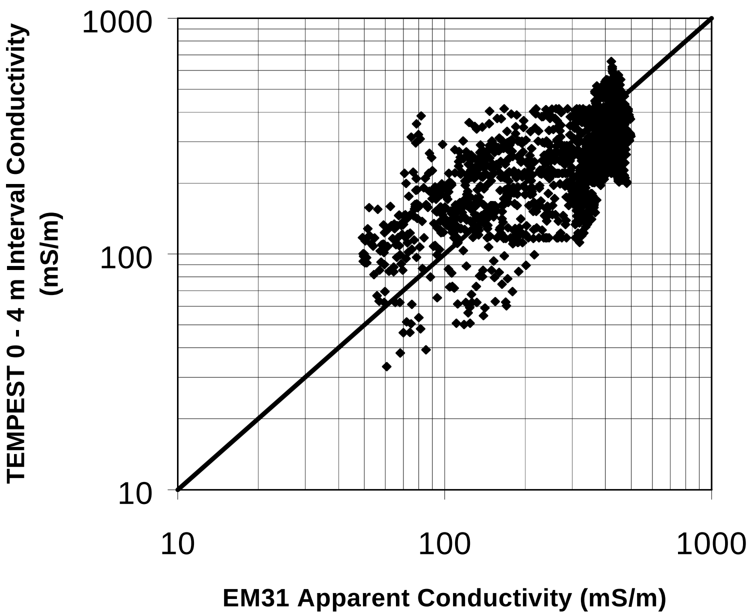


Figure 5.5 Comparison of EM-31 with 0-4m layer conductivity from TEMPEST CDI.

The deeper pumping wells 95/04P and 95/03P are within a lower conductivity zone from both EM data sets relative to adjacent lake bed. It is unclear whether these lows are attributed to pumping. Data collected prior to pumping is required to confirm this.

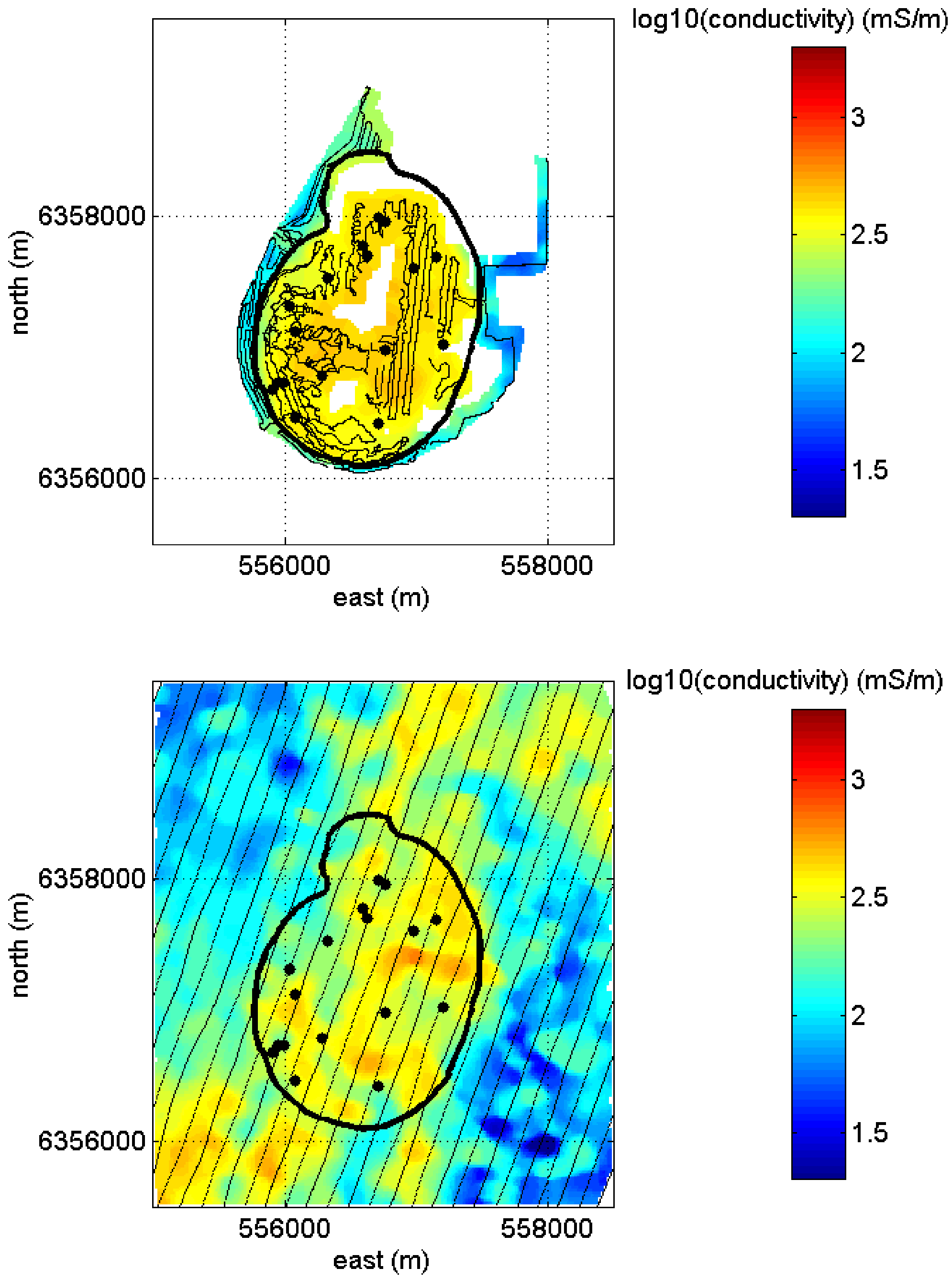


Figure 5.6. Comparison of (a) EM31 ground conductivity measurements with (b) TEMPEST 0 to 4 m CDI interval conductivity. Observation points are shown as small black dots. The outline of Toolibin Lake and selected bore holes are shown for spatial reference (Lane and Pracilio, 2000)

The EM31 operates at 9.8 kHz and has an effective depth of penetration restricted to around 6 m. In areas where ground conductivity exceeds 100 mS/m, the EM31 apparent conductivity values underestimate the true conductivity and a correction factor needs to be applied. For ground with 1000 mS/m conductivity, the EM31 will read a maximum of approximately 500 mS/m (McNeill, 1986a). No correction was applied to the EM-31 data and the upper limit of EM-31values reaches 500mS/m in Figure 5.5, whereas TEMPEST conductivity range up to 700mS/m.

5.3.1.4 SALTMAP

Examination of the newer TEMPEST airborne EM data showed good agreement with drillhole data. A qualitative interpretation of SALTMAP data showed a general agreement with TEMPEST. Notable exceptions occur in areas where the Layered Earth Inversion becomes unreliable.

Initial inversions of the SALTMAP data in the area around the lake were considered unreliable (Pracilio et al, 1998) due to difficulty in primary field removal. The SALTMAP system was a full duty cycle system with no off-time in which to measure the secondary field. Removal of the primary field from observed data was achieved using the value at the end of each pulse as the primary field. However, in the highly conductive terrain at Toolibin, the secondary field persisted for longer than normal and a significant proportion was present at the end of the pulse. Removal of this with the primary field resulted in conductivity lower than actual values. A number of attempts were made to better remove the field but full confidence in the process was never achieved.

Pracilio et al (1998) estimated that the Layered Earth Inversion (LEI) of SALTMAP was unreliable at conductances greater than 10 S. A mask at this level was used on all the SALTMAP inversion products. In this study qualitative comparisons of SALTMAP and TEMPEST patterns suggest that the SALTMAP inversion was reliable at higher conductances than 10S. The greatest divergence between the two datasets occurs close to the middle of the Flats. In this area, a broad lower conductivity is defined in SALTMAP data. Parts of this low are possibly related to palaeochannel sands and parts to the limit of inversion. It is not possible to distinguish these two effects.

Over the remainder of the area, qualitatively the results of the SALTMAP LEI compare favourably with the TEMPEST CDI data. The use of LEI may be more appropriate in some instances. The TEMPEST CDIs were found to have good general agreement with drillhole EM and $EC_{1:5}$ data except in the area of the Tertiary palaeochannel. In this area the sudden change in conductivity from around 1000 mS/m to less than 1 mS/m would probably be better resolved by a LEI. The LEI however is not as good for detecting subtle changes with depth compared to the CDI.

George (1998) found a poor relationship between SALTMAP bedrock depth and depth from SALTMAP LEI.

Despite George's finding and despite the limit of reliable inversion the SALTMAP LEI produces depths to bedrock close to that from TEMPEST and over most of the catchment a close relationship in spatial patterns. For example deeply weathered zones are seen in the lower landscape either side of the palaeochannel in both SALTMAP and TEMPEST although SALTMAP underestimates the conductivity in parts of this area. SALTMAP data is more smoothed possibly due to data filtering although the same spatial patterns can be seen.

There are some major diversions however. SALTMAP LEI data is misleading in areas of granitic outcrop. The LEI routine fits a conductive layer to the observed data where no such layer exists. This results in a very thick low conductivity layer and deep holes in the regolith thickness map. In this project GIS tools were used to identify areas with both thick regolith and low early time conductivity as bedrock outcrop. The inversion attempts to force the 3-layer model when there is no data to support the presence of layer 1 or 2. Thus these layers become very thick and low in conductivity to fit the observed data. George (1998) data also shows major diversions from 1 to 1 relationship between bore depth and LEI depth for areas of low conductivity in deep sand.

In the deepest part of the catchment represented by the deeply weathered area under Brown Road, SALTMAP LEI results indicate a depth to basement of around 68 metres. TEMPEST shows in excess of 75 m. Recent drilling had not intersected basement at 69m. Both SALTMAP and TEMPEST are within a reasonable order of accuracy for such a deep conductive feature. Despite the limitation of the LEI inversion, the SALTMAP data does give a relatively accurate depth to bedrock in these deeply weathered areas. Similar confidence in regolith depth results were seen by the authors in deeply weathered palaeochannels at Trayning.

The answer to the apparent paradox between the methods lies in the different processes of inversion. The LEI works well where there are three well-defined layers. In the palaeochannel area, for instance the conductivity of the regolith is uniform and there is a sharp break with basement. In these areas, although conductivity values may not be correct the inversion can calculate the depth of the sudden change to bedrock. Where sudden changes are not present the best fit for depth may be greatly different to true depth. This will cause all other parameters also to be in error. The interpreter only has recourse to using individual channel conductivity and amplitude data. These problems of equivalence of data have long plagued the interpretation of soundings both using resistivity and electromagnetics. They can only be partly overcome by rapid sampling of the secondary field and increased signal to noise ratios.

CDI inversion does not calculate a depth but the conductivity with depth. In a sharply defined regolith, the CDI produces a long tail of conductivity to fit the gradually decaying response. Regolith depth, therefore may appear deeper than true if set at a conductivity threshold. In this project it was found the inflexion between highest and lowest conductivity response was the most appropriate reflection of depth.

Thus, both the LEI and CDI processing can lead to results that may be misleading. The new TEMPEST CDI, however, can be used with more confidence and less risk than SALTMAP LEI data.

Removal of outliers due to outcrop/subcrop and deep sands from the correlation with bedrock depth by drilling and regolith thickness by SALTMAP in George (1998) plus the addition of the results from the deep hole would improved the correlation. However, obviously outcropping bedrock areas cannot be used as they were in the correlation of TEMPEST data.

Despite differences in processing of the two AEM datasets they show many similar patterns in conductivity images.

SALTMAP AEM and the newer TEMPEST AEM data showed there was a zone of moderate conductivity in a dendritic pattern under the alluvial flats to the north of Toolibin Lake. Drilling proved this to represent a palaeochannel with sands of deposited in a broad channel, which on the AEM data is almost 200 metres wide.

The palaeochannel was detected by SALTMAP and particularly by the principal component analysis of SALTMAP data. The SALTMAP layer 2 conductance, although not presented in Pracilio et al (1998), also reflected the channel although wider than in TEMPEST depth channel data. The LEI process averages conductivity of the whole regolith. The base of the channel drops only 20m in 14 kilometres and thus deposition of sand has most likely been from a meandering river. The SALTMAP results reflect the total area of deposition, which is an broader area than at discrete depth intervals. In addition, the limit of SALTMAP inversion was reached along the edge of the channel where high conductivities are indicated in the TEMPEST data. These are the areas where SALTMAP inversion is definitely in error and make the palaeochannel appear wider. The limits of the palaeochannel as defined from SALTMAP thus only define the maximum possible extent of the channel.

Comparison of SALTMAP and EM-31 data in the upper catchment shows a similar pattern is present in both data sets. Areas of lowest and highest conductivity correspond in both datasets. Part of the palaeochannel runs through the EM-31 survey area. Although it is obvious in the SALTMAP data it is difficult to see in EM-31 probably because of lower depth penetration. Early time conductivity images from SALTMAP indicate the surficial conductivity above and around the channel are similar over half the length of the palaeochannel through the EM-31 survey area.

The better-calibrated TEMPEST system indicates that SALTMAP was performing better than reported in Pracilio et al (1998). SALTMAP achieved many of the aims for a low cost airborne electromagnetic system for conductivity mapping in saline areas as predicted by Buselli (1990, 1993). However, the inversion of the data was often misleading to untrained interpreters. If proper care is exercised in interpretation, the SALTMAP data is usable for land management decision of the greater part of the survey area.

5.3.1.5 Near surface conductivity, EM 31, TEMPEST and EM 39

The EM39 logs indicated that the TEMPEST 2m data was likely to be less than the EM39 log. However, the spatial data comparison with EM31 data suggests that it is realistic with the EM31 underestimating conductivity in some areas. Discrepancies exist between all these systems which measure electromagnetics. Shallow TEMPEST values may be underestimated from the EM39 data and EM31 data is underestimating values relative to TEMPEST data. Nevertheless, the trends in all these data sets are realistic. More development is required in the 0-4m data range of TEMPEST. The radar altimeter is expected to be a limiting factor of such near surface data and requires improvement.

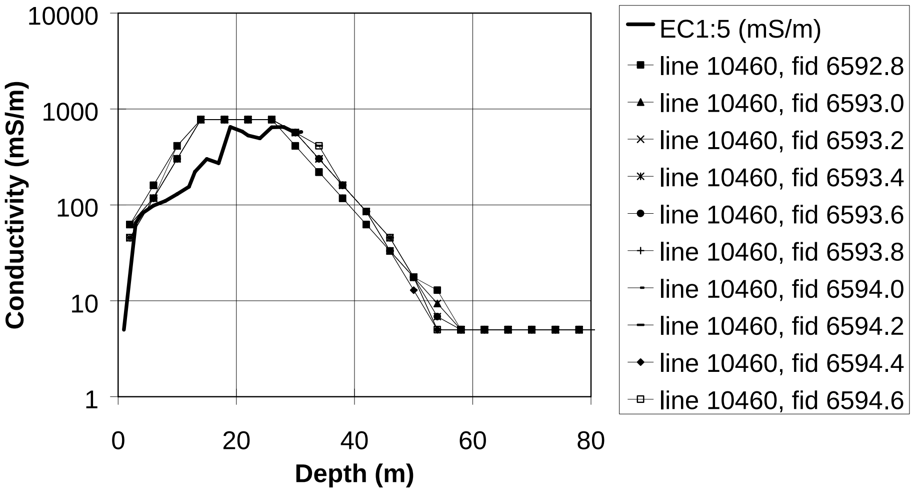
5.3.2 Validation of TEMPEST against other parameters

5.3.2.1 $EC_{1:5}$ borehole sample

George (1998) found a good correlation (r^2=0.89) between $EC_{1:5}$ and EM39 conductivity for data in the Toolibin Lake Catchment. EM39 conductivity values in mS/m were just over twice the corresponding $EC_{1:5}$ in mS/m. This factor is due to the different mode of measurement. An $EC_{1:3}$ as used in India would give a value closer to the EM-39.

George (1998) also found there was a poor correlation (r=0.35) between EM-39 and clay content and concluded that salt content is the dominant influence on conductivity measured in the regolith in this environment. The $EC_{1:5}$ measurements like the EM-39 match well with TEMPEST CDI profile trends and conductivity values (Figure 5.6).

Some unexplained discrepancies in the shape of TEMPEST CDI values and $EC_{1:5}$ values at depths greater than 20 m were noted (Lane and Pracilio, 2000). This is attributed to the CDI processing, creating a gradual changing conductivity profile rather than a sharp boundary. Such discrepancies were identified in bores LT31, LT32, LT34, 1C, 6C, 7C, 9C and 10C.



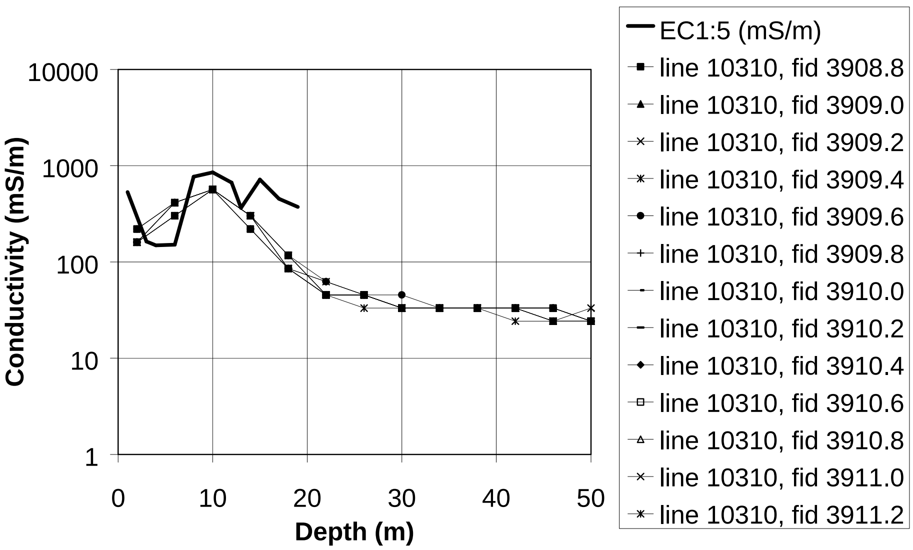


Figure 5.6: . Comparison of $EC_{1:5}$ borehole sample conductivity measurements with TEMPEST CDI conductivity values from observations within 75 m of (a) hole 1C, and (b) hole 8C (Lane and Pracilio, 2000)

In most holes the $EC_{1:5}$ decreases gradually below 25m. The best fit for TEMPEST data with this gradual decrease was with the C bores (McFarlane et al., 1989). In these results the shape and the values are well approximated by the $EC_{1:5}$. The LT bores did not have such a good fit.

The TEMPEST inversion fits well with $EC_{1:5}$ (as with the EM39) in the top 8m of the intermediate bore SS9718I. The inversion from LT35 is also a good fit to the shape of the $EC_{1:5}$ curve with a slight tapering off after 20m. Bedrock depth is well represented by the shape of the TEMPEST inversion plot.

LT32 and LT06 show a uniform $EC_{1:5}$ profile in both $EC_{1:5}$ and EM-39 but there is a larger variance in the TEMPEST data than other plots.

A shallow and much more bulged profile was identified from the TEMPEST data in LT34 compared to $EC_{1:5}$, with a very good fit from 2 to 7m. The gridded plan data indicates that this is near an edge between a shallow and more deeply weathered profile. The borehole has probably sampled the deeper edge of this feature while TEMPEST has averaged a larger area including shallow basement. LT33 is also located on a similar edge.

There is a reasonable fit with LT07 bore although the TEMPEST bulges more than the $EC_{1:5}$. The EM39 data for the same hole shows a close relationship with TEMPEST inversion. This is similar to LT09, which has the best fit with the EM39 data but does not fit with the $EC_{1:5}$.

At Toolibin, various drilling methods including auger, diamond hole, aircore and RAB techniques have been used over the past 20 years. These different drilling methods may introduce discrepancies between the $EC_{1:5}$ and EM results. Sampling strategies, which were not reported, may also differ between drilling programs.

5.3.2.2 Depth to bedrock

Depth to basement was originally determined at a conductivity threshold of 150mS/m. This identified depth to basement accurately in conductive alluvial and deeply weathered regions but did not perform well in less conductive areas. From observations of the EM39 and the $EC_{1:5}$ downhole plots, the depth to basement from drilling corresponded better with the inflection or the midway point between the maximum and minimum values on the inversion plot. This method of determining bedrock depth from TEMPEST was found to improve the overall relationship and was chosen as the final bedrock depth output.

Discrepancies between bedrock depth inferred from drilling and those from TEMPEST data (Figure 5.7) can be partly attributed to the subjectivity of the five different drilling programs and scale differences between TEMPEST observations and drillholes. Four different generations of drilling programs were used in the evaluation. Each used different drilling methods with different objectives and budget.

In the auger drilling program (McFarlane et al., 1989) the average depth of the C drill holes used in the analysis was 20m. In comparison, the average bedrock depths from the other drilling programs are over 33 m. The total depth of the auger holes may have been constrained by the drilling method.

A small population size (n = 30) particularly in the 0 to 20 m range limits any rigorous statistical analysis. Two samples of bedrock outcrops noted by field evidence and correctly determined by TEMPEST were added to the analysis. Two outliers (x~12, y~35m, 4C and LT28) were also removed. They were both attributed to localised bedrock highs within a depositional environment. Drillhole 4C was also drilled with an auger rig, which may have been limited by auger refusal.

An additional value at 70m was also added to the data set. A drillhole completed into the deepest area detected by the TEMPEST systems during the writing of this report intersected a deeply weathered laterite profile to a depth of 69 m (George, pers. com). The drillhole was terminated at this depth due to lack of drilling rods. Inclusion of this hole makes the relationship r = 0.86, r^2=0.74.

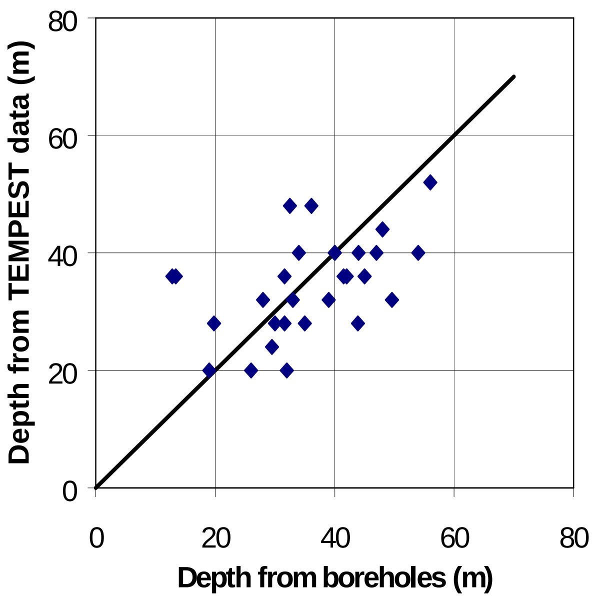


Figure 5.7, Bedrock depth estimated from TEMPEST and drillhole data.

5.3.2.3 Seismic refraction line

In early hydrogeological investigations a seismic refraction line was surveyed across Toolibin Lake (Kevi, 1980). The aim of the survey was to determine depth to bedrock. The survey showed three velocity layers (table 5.4). The line was positioned in the GIS from the location map in Kevi (1980) and compared to the TEMPEST depth to basement image. It is not reported but it is not considered likely that the line was accurately surveyed. The location map only shows scale and a few topographic contours and therefore position is approximate only.

Table 5.3. Observed seismic velocities (after Kevi, 1980)

	Longitudinal velocity m/s	Probable equivalent
First layer	400 to 500	Unconsolidated surface material
Second layer	1900 to 2400	Weathered granite or indurated lake sediments
Third layer	5000 to 5800	Fresh granite

The central part of the lake shows depth to basement of around 35 to 40 metres shallowing slightly to the west. This agrees in general with TEMPEST depths of around 40 metres and drilling data. The TEMPEST data indicates shallowing basement towards the east and west, which is not reflected in the seismic data.

The SALTMAP regolith thickness shows results between the TEMPEST and seismic data but may be just a more fortuitous colour stretch of the image. Shallow bedrock is located off the western end of the seismic line. This bedrock high is larger on TEMPEST data and the LEI may be more appropriate for determining bedrock depth in this area than conductivity depth inversion.

The seismic data shows little significant difference in the second layer velocity across the area interpreted as palaeochannel. The velocity is uniform at 2000 to 2300 m/s. The western end of the line approaching the bedrock high shows lower velocity of around 1800 m/s. This may reflect granitic saprolite with lower water content.

From these results seismic refraction is not an appropriate technique for detection of sand channels within weathered basement. The seismic data agrees with AEM and drilling results in determining depth to bedrock but does not resolve velocity changes associated with changes in regolith type. Salama (1997) presented result over the Salt River system to the north of Toolibin, which also showed little contrast between channel and surrounding regolith. More modern seismic reflection systems would be more appropriate. These may be able to resolve layering within the sedimentary sequence.

5.3.2.4 Surface salinity

“Saline Extent” was determined in the Land Monitor Project from Landsat and DTM data. In addition Agriculture Western Australia interpreted saline extent from airphotos. These were compared (see table 5.1). The area of overlap is 1025 ha which indicates that most of the Land Monitor saline extent is within the airphoto saline extent area. The airphoto results includes the "Water" class and some of the remnant vegetation in the Flats from Land Monitor. The Land Monitor shows only minor areas in the upper landscape and many of these were found to be related to other causes such as roads, sands, sheds etc.

The average TEMPEST 0-4m conductivity and standard deviation for the surface salinity classes are outlined in Table 5.1. The "Water" class has the highest average conductivity of around 320 mS/m (Log_{10} conductivity = 2.5 mS/m) with the smallest standard deviation. Salt lakes and Toolibin Lake are within this class. Surface waters of Toolibin Lake are not saline although the 0-4m data indicates that the salt concentration is comparable with the salt lakes even in areas where there is no evidence of surface salinisation.

The average conductivity of the Land Monitor and air-photo non-saline classes is lower than all other classes. (Table 5.4), although the standard deviation overlaps with other classes.

Comparison with airphotos indicated most of the areas of conductivity greater than 200 mS/m (log_{10} 2.3 mS/m) in the 0-4 m depth slice corresponded with existing saline lakes and areas within Toolibin Lake. Field inspection found that outside of the defined lakes areas of such high conductivity were salt affected areas within healthier shrub lands of the saline Flats region.

High conductivities in excess of 200 mS/m in 0-4m depth slice are sites which are presently saline not all saline sites will be detected by the 0-4 m layer in TEMPEST data. High conductivity although related to salt content is not diagnostic of saline soils. Some sites can show evidence of soil salinisation without the high salt concentrations observed around the salt lakes.

Secondary salinity is relatively recent in geological time. It may result from factors not related to high salt content concentrations in the top 4 m such as evaporation of fresher water. Examples in the TEMPEST survey area are salt concentration from sandplain seeps. In addition shallow salt concentrations in the top 4 m over bedrock highs will show very low conductivity although salt degradation in such areas can be severe.

Table 5.4; Area and conductivity of interpreted saline areas within the TEMPEST survey, Toolibin Lake

		Saline	Non-saline	Water	Remnant Veg.	Future saline
Area (ha)	**Land Monitor**	1077	8041	221	1445	-
	Airphoto	2139	5845	-	-	2663
Average 0-4m log10 conductivity ± Standard Deviation	**Land Monitor**	2.149 ± 0.179	1.895 ± 0.448	2.491 ± 0.132	2.175 ± 0.338	-
	Airphoto	2.207 ± 0.198	1.805 ± 0.486	-	-	2.139 ± 0.276

5.3.3 Groundwater salinity

There is a linear relationship between groundwater salinity and log (10) TEMPEST conductivity data taken at the corresponding depths (Figure 5.8). The correlation is r=0.83, r^2=0.68 (n=11). Two outliers LT28 and P14 were removed. LT28 was also an outlier in the bedrock depth analysis. From the TEMPEST data bedrock depth is expected to be deeper. Sands described in the log in 0-1m do not correspond with sands in the radiometrics.

The relationship is not expected to be as good as the relationship with $EC_{1:5}$ as groundwater salinity may not necessarily represent the salt content bound within the soil matrix.

Based on laboratory results (DeSilva, 1999) salinity increases within a few months after the bores have stabilised. Drilling water may have removed some salt and/or salt is leached from the soil profile into the bore. It is suggested that analysis of groundwater conductivity/salinity be redone using results from all the bores once the salinity levels have stabilised.

5.3.4 Interpretation of plan maps

The EM39 analysis shows the continuous nature of CDI processing is likely to underestimate true conductivity below 25m. This was identified in the 20 to 24m depth slice as areas greater than 300 mS/m. In these regions bedrock depth is best approximated at the 150 mS/m conductive threshold. Although the true conductivity of bedrock is likely to be less than 1mS/m.

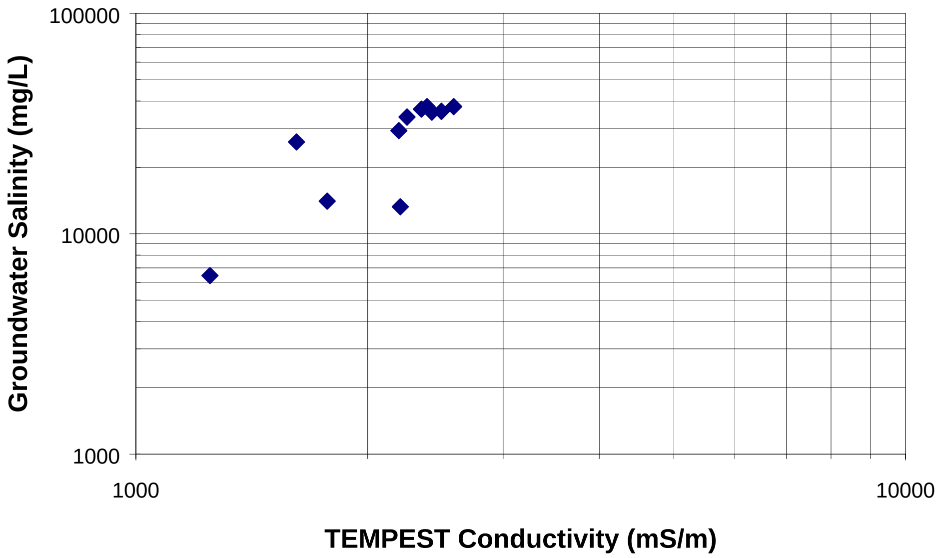


Figure 5.8: Groundwater salinity and log (10) TEMPEST conductivity data taken at corresponding depths.

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The single point downhole CDI profiles did not adequately define the differences due to the palaeochannel. The spatial patterns in gridded data from sections and particularly in plan view clearly showed the position of a palaeochannel.

5.3.6 Palaeochannel

The TEMPEST data shows a broad deeply weathered zone extending under the Toolibin flats and under Toolibin Lake. The western side of this zone is controlled by a regional fault and the zone of deeper weathering lies east and parallel to it.

A dendritic pattern is present in the TEMPEST data, which reflects the same palaeochannel sediments detected by SALTMAP (Pracilio et al, 1998). Drilling shows the sediments are deposited in a 40m deep channel within a broad zone of deeply weathered bedrock.

The deep channel in which the sediments sit suggest the river which deposited the sediments was cut into relatively competent rocks. Prior to sedimentation and filling of the valley the surrounding rock was most likely unweathered. The highly saline water in the channel with low pH (De Silva, 1999) may explain the extent of deep weathering to either side. Salama (1997) reported similar weathering around the palaeochannel of the Salt River System to the north of Toolibin. Both the TEMPEST data and drilling information suggest that the base of the channel is close to bedrock.

The palaeochannel was best reflected in the SALTMAP layer 2 conductivity particularly in the upper catchment although principal component analysis (PCA) of SALTMAP data improved the resolution of the dendritic pattern in the lower more conductive areas. Layer 2 conductivity is a reflection of all the conductivity of all material below the resistive surface and above bedrock. The palaeochannel interpreted from SALTMAP in this Project therefore is wider than that interpreted from TEMPEST data. The limit of inversion in section 5.5.1.4 also explains the greater width of channel seen in TEMPEST data. The interpretation of the palaeochannel width in this Project reflects the maximum extent of the channel sands.

The SALTMAP data indicates that the palaeochannel extends towards the upper catchment to areas of deep sands in some cases. Recharge may occur directly from these sources.

TEMPEST data showed the palaeochannel in greater detail in the layers from 10 and 30 metres. Above 10 metres Quaternary clays were logged in all drillholes. Salinity in bores is uniform for those drilled into the channel and the TEMPEST data detects the lower porosity of the sands versus the overlying clays. High salt storage is present in the saprolite to either side of the channel.

The position of the palaeochannel was interpreted from TEMPEST data for individual depth channels 10-14m; 16-20m; 20-24; and 28-32m. These show that the channel sediments have been deposited in a continually varying river course. The width of the channel also expands towards the surface. The channel has been interpreted in each of the layers as more than 200 metres wide. The actual river course depositing the sediments at any given time was most likely much narrower. Sands and clays would have been deposited depending upon the position of the river and flow rates.

The TEMPEST data indicates the base of the regolith drops by 20 metres in 14 kilometres. This probably represents the maximum drop in the base of the channel also. With such a low slope the palaeo-river could be expected to meander within its valley.

Drillholes within the interpreted palaeochannel area from geophysical data have mostly intersected the targeted palaeochannel. A notable exception is P15, which was drilled into granite saprolite. The bore yield and salinity are almost the same as for the channel. It thus has similar conductivity and also displays similar groundwater statistics. It may be close to the channel and in hydraulic connection.

Obstructions and/or constrictions to the channel are indicated in a number of places. These appear to be close to major cross cutting dykes. The TEMPEST data may reflect various scenarios such as:

1. A bedrock high associated with metamorphosed basement beside a dyke with deeper channel sediments to either side.
2. Higher clay content in the palaeochannel sediments, which would reduce permeability/transmissivity in the channel.

Analysis of the conductivity patterns in each depth layer and interpretation of possible flow regimes would assist in targeting the thickest accumulations of sands. Interpretation of possible point bars or other sand accumulations may be possible. In particular the intersection of the main palaeochannel with a major tributary from the west may be a likely site for bar formation inside the bend near P12 bore.

The position of the palaeochannel beneath the eastern parts of Toolibin Lake may explain lateral flow towards Taarblin Lake hypothesized by Martin (1986, 1990) and is considered a more likely conduit than the fault suspected as being the conduit by George and Bennett (1995).

An analysis of bores drilled into the Tertiary sediments and/or into areas interpreted as Tertiary sediments is present in section 6.4.2

5.3.7 Age of palaeochannel sediments from palynology

Palynology data (De Silva, 1999) indicate the age of deepest sediments in the palaeochannel as late Miocene to early Pliocene. In particular the presence of species such as *Densoisporities implexus, Polyporina, ganulata*, and *Rhoipites ampereaformis* give a late Miocene age (>5.3 million years before present) whereas the persistence of *Nothofagidites* indicate the sediments are younger than early Pliocene (~ 5 million year before present). Nothofagus is a genus common in the high rainfall temperate rainforest of Tasmania, New Zealand and South America. It is a prolific pollen producer and is usually over represented in most palynology samples (White, 1994). In the Toolibin samples Nothofagus is rare. This may indicate a climate that was becoming more arid.

During the late Miocene to early Pliocene the climate in Australia was changing from wet sub-tropical to temperate to more arid conditions. Rainforest gradually was reduced to small remnants on continental margins and Myrtaceous species were becoming dominant. By the Quaternary (last 2 my) when the surficial clays were laid down in the valley, woodlands were probably dominant through the Toolibin area and the climate went through periods of glacial and interglacial periods with widely fluctuating rainfall (White, 1994).

Climates have been drying since the mid-Miocene around (14 million years) concurrent with sedimentation at Toolibin. The pollen assemblage would appear to confirm a wet warm environment was present at Toolibin during the late Miocene to early Pliocene. The thick sandy sediments would appear to indicate less vegetation cover probably from a warming climate resulting in increased erosion rates.

Rainfall was no longer sufficient to carry sediment down the channel as it had in prior to the Miocene. Choking of the drainage by sediment proceeded with increasing aridity.

5.3.8 Conductivity, dykes and streams

Outside the interpreted palaeochannel, dolerite dykes were spatially related to drainage and conductivity patterns in the near surface. Above the palaeochannel the salt lake at 557430mE, 6358980mN upslope of Toolibin Lake is located upslope of a dolerite dyke. See the file ‘condhi_2_6_dykes.shp” for such areas.

In the palaeochannel dolerite dykes are unlikely to have any influence in the near surface groundwater flow. In areas of thinner alluvial sediments towards the edge of the present day alluvial Flats, major dolerite dykes are associated with salt storage accumulation within the top 2 to 6m and with drainage alignment. These areas are dominated by a granite saprolite regolith with only thin alluvial cover. In the TEMPEST data these areas show high conductivity at depths of 10 to 20m indicating high salt storage in saprolite clays. Bore LT33 and LT31 confirm that saprolite clay is present below 4m.

The western salt lake in the lake chain at 557430mE, 6358980mN, upslope of Toolibin Lake on Wickepin-Harrismith Road, appears controlled by the dolerite dyke which lies directly to the south. In this region the palaeochannel becomes less defined in the TEMPEST data. The elevation of the base of the conductive unit (bedrock surface) also shows a constriction in this region. The data indicates a bedrock high in the channel between two dolerite dykes. This shallowing of the palaeochannel base may cause increased pressure on overlying clays and cause the groundwater to discharge forming a salt lake.

All bores intersecting the Tertiary sands have standing water levels within $\pm$1m from the surface indicating the palaeochannel is under pressure. Thinning of palaeochannel sands would increase the pressure and may result in surface discharge. Macumber (1988) showed similar structural controls exist in the riverine plains of northern Victoria where the Tyrell-Wahpool-Timboram Lake complex lies immediately upslope of the Tyrell fault. Macumber (1988) also showed that discharge from deep leads (palaeochannels) along a hinge line occurred through sandier sections of an overlying clay aquiclude under hydraulic pressure.

At 34 to 38m, the patterns are more obviously related to major dykes and regional faults. For example, major dykes and a regional fault bound the deeply weathered feature located beneath Brown road. The main conductivity structure under the alluvial flats is fault controlled on the western edge.

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6 GROUNDWATER TARGET MAP

The aim of the hydrogeology interpretation in the Project was to produce a map outlining potential areas for beneficial groundwater extraction. Pracilio et al (1998) produced a Hydrogeological Target Map based on manual interpretation of the data collected under the NDSP project. That target map focussed on good quality potable water potential in the upper parts of the landscape. The potential area was small compared to the overall catchment.

The focus of the work being carried out in the Toolibin Lake Catchment is aimed at preventing rising groundwater leading to salinity of the lake and agricultural land. The environmental importance of the lake as a RAMSAR wetland of international importance means that options for remedial works might be more varied than in other catchments in the agricultural area.

Many options may need to be considered in the medium to long term for lowering the water table by groundwater extraction. The Project recognises that farm properties are the dominant land management unit at least in an economic sense. Properties are relatively small compared to the catchment and each property may not have areas with potential for good quality water. Thus farmers may want to consider other options for use of groundwater. The interpretation of areas of possible potable water has been extended to include other areas with lower potential and more saline water in surrounding areas.

In rural areas there is an increasing focus on alternative uses for brackish to saline water. Therefore catchment management planning may benefit from identification of areas with potential recoverable lower quality water. In this Project, areas with high potential for large volumes of saline water have also been identified.

The map has outlined areas with groundwater potential. However use of a map at 1:50,000 scale is not considered appropriate for optimal siting of bores. Some guide-lines are provided on how to use the GIS data for final site selection.

6.1 Groundwater occurrence

In most of the wheatbelt potable water occurrences are rare and generally confined to the upper parts of the landscape. High evaporation rates and poor drainage has resulted in concentration of soluble salts in the regolith over millions of years. These salts have been concentrated towards the lower parts of the landscape except where some barrier to groundwater flow has created pockets of salt concentration in upper parts of the landscape. Where the landscape is freely drained there may be potential for better quality water although these areas by very nature do not hold large volumes of water.

In the lower landscape water is almost inevitably saline. However sandy layers in alluvial sediments do provide opportunity to install high yielding bores to recover large amounts of saline water to use in aquaculture, salt harvesting or other enterprises.

6.2 Controls on Groundwater

6.2.1 Regolith depth

As most of the groundwater is contained within the regolith above the freshrock, the depth of the regolith is a primary control on groundwater occurrence. Mean drilling depth of bores is approximately 30m. Regolith depth was determined for this study from layered earth inversion (LEI) of SALTMAP data. This process has limitations, as set out in Pracilio et al (1998) although on a regional scale appears to agree with drilling information, that is the mean regolith depth from SALTMAP is also approximately 30m. Recent TEMPEST survey using improved system and software inversions (CDI) agrees with general patterns of regolith thickness produced by the SALTMAP Inversions (LEI) process.

Isolated pockets of deeper weathering, may be due to preferential weathering of more susceptible rocks. These deeper areas have potential for water from a deep weathered rock aquifer although clays may reduce bore yield. In general the gneissic units is more deeply weathered than the granite and in part this relationship may explain the shape of Toolibin catchment.

6.2.2 Dolerite Dykes

Dolerite dykes can commonly act as barriers to groundwater flow (Engel et al, 1987). In the Toolibin catchment, dykes control drainage patterns in the upper catchment, as well as the conductivity patterns seen in both SALTMAP and TEMPEST data.

It was not expected that dykes appreciably influence shallow groundwater within alluvial areas of the flats. However there are close spatial relationships between dykes and positions of lakes, which are likely areas of groundwater discharge. Dykes, except within the immediate vicinity of the palaeochannel, control the southern edge of Toolibin Lake (555900mE, 6,356,500mN and 557,000mE, 6,356,500mN). Saline lakes north of Toolibin Lake also appear to be controlled by dykes (557,400mE, 6,358,900mN and 558,400mE, 6,358,60mN). Macumber (1991) reported similar structural relationships on the riverine plain in northern Victoria.

In addition, dykes and other geological changes control palaeodrainage patterns. This control is greater within deeper parts of the channel interpreted from the TEMPEST data. Geological control on the palaeochannel at shallower depths is restricted to extremities and tributaries.

Most dykes are interpretable from airborne magnetic data as linear magnetic highs (see section 3.11).

6.2.3 Soil type and regolith permeability

Most of the regolith throughout the southwest is a deeply weathered laterite derived from deep chemical weathering of pre-existing granite/dolerite basement. The laterite profile is usually low in permeability and bore yield except in areas of higher quartz content from quartz veins and/or pegmatite weathering.

Aeolian sands up to 2m thick in places often overly the laterite profile. Sandplain mostly occur in higher landscape positions. These can act as high matrix recharge areas due to the high permeability of sands. Relatively fresh perched aquifers are common and water seepage may occur at the edge of sandplain from a perched groundwater system overlying the laterite regolith.

A deeper aquifer may also be present where water has percolated to greater depths, although this water may be higher in salinity. In the deeper aquifer, areas upslope of dykes or other groundwater obstructions have the best potential for higher yields.

Sandplain areas were interpreted from low total radiometric counts. SALTMAP and TEMPEST data map conductivity lows at depth, indicating a regolith that is flushed of salts through high recharge.

6.2.4 Alluvial sediments

Alluvial sediments within the broad valley flats are predominantly clays or shallow duplex soils. Low water extraction rates are expected from clay sediments.

Within the alluvial sequence however, both SALTMAP and TEMPEST data show areas of slightly lower conductivity. These were interpreted and confirmed as palaeochannel sands (or sand seams). The lower conductivity is directly related to the lower water content of sands relative to clay. Sands usually have a water content less than 30% whereas clays due to the nature of the crystal structure can hold 40% or more water in the matrix.

6.2.5 Bedrock highs and outcrops

Granite outcrops are widely exploited for small town water supplies in the southwest eg Wave Rock at Hyden. Water can be collected on bare rock or from large runoff, which soaks into surrounding granitic sandy soils. Farmers have commonly installed bores in the granitic sands around outcrop.

Bedrock outcrops were mapped using high radiometric response of the potassium channel and very low AEM conductivity. Most outcrops occur towards hilltops and are areas of remnant vegetation. The airphoto and DTM can thus assist in distinguishing outcrop.

Surrounding granite outcrops, areas of high radiometric potassium count may indicate an accumulation of granite sands that are potential potable water resources.

6.3 Potable water

6.3.1 Potable water

Typical conceptual models for locating potable water resources are:

- Deep sands in the upper landscape where high recharge rates result in flushing of the regolith of any evaporative salts. Due to the higher permeability water will not accumulate so the ideal targets are above potential barriers such as dykes or bedrock highs, with largest catchments. In addition deep sands have potential to hold significant quantities of fresher water as perched aquifers above the laterite regolith.

- High runoff from granite outcrops into granite sandy soils are potential areas of small quantities of potable water.

6.3.2 Areas with potential potable water

The catchment was analysed using the Spatial Analysis extension to ArcView by Argus and Chan (1999). They used conceptual models for interpreting most likely areas for potable water supplies. The authors of this report set the basic rules used by Argus and Chan.

Table 6.1 Characteristics used to determine areas of potential potable water (after Argus and Chan, 1999)

Characteristic	Recognisable parameter in data
Areas of high potential recharge dominated by deep sands	Low total radiometric count
Areas high in landscape	High on DTM
Thick regolith	High regolith thickness from AEM data
Areas low in salt content	Low conductance from AEM data

Sands were identified from radiometric data as those areas with low radiometric count. Low radiometric count from water in lakes can be distinguished by landscape position from the DTM and removed from the analysis. Low salt storage were identified from SALTMAP layer two conductance. Regolith thickness was also calculated from the SALTMAP inversions.

A layer in the GIS was created based on the analysis by Argus and Chan (1999). This analysis is considered to represent the most likely areas for potable water. Areas less than 10 hectares were removed as too small to hold significant amounts of potable water.

Other factors, which may assist in further refinement of potential water resource targets, are:

- Regolith thickness from TEMPEST
- Conductivity from TEMPEST
- Slope of surface
- Slope of basement surface
- Vegetation

Areas of sandplain were also separated from the soil map as likely sites for perched potable water supplies. Areas of sandplain smaller than 10 hectares were removed as too small for significant water supplies.

Suitable catchment and slope positions relative to groundwater barriers such as bedrock highs and/or dolerite dykes may result in better yielding bores. This process must be applied manually with no suitable functionality identified in ArcView Spatial Analyst. Ideally final siting of bores should be carried out using a series of rules to optimise the likelihood of success.

6.3.3 Bore data

Bore data that intersected mapped potable water resources were discussed below.

LT08
LT08 was drilled into a mapped area of highest potable water potential. The SALTMAP data indicated low conductivity with a thick regolith. Radiometric data showed a low radiometric count and thus the area was selected in the GIS classification. Examination of the ternary radiometric image suggests a duplex soil may be present.

The LT08 drill-log indicates thin sand cover. EM-39 and EC1:5 data shows a distinct bulge at ~5 metres depth in saprolite clay. Water yield from the lowest section of the bore at 56 to 62 metres was low although quality was good and potable at 390 mg/L. The bore confirms the interpretation except for an over-estimation of sand thickness.

SS9716D
The SS9716D bore is located on the edge of a prospective water resource area. Geophysical data indicates SS9716D was drilled into deeper regolith and sands than LT08, although the conductivity is higher. Drillhole data shows EC1-5 log less than 6mS/m for complete

hole to 47m. No flow was recorded from the base of the hole although it not reach bedrock.

LT25

LT25 was drilled into the edge of a sandplain to 9m. The log shows moderate $EC_{1:5}$ around 50-60mS/m. The low conductivity in this case my be due to shallow bedrock rather than deep flushed regolith. Better bore sites are indicated from the Layer 2 inversion data 700m to the northeast.

LT04

LT04 was drilled into an area interpreted as highest potable water potential. Data shows the site close to the edge of a deep sand; in moderately deep regolith; with low conductance. The bore was drilled to 45.45m. A yield of $10.8m^3$/day of low salinity (670mg/L) was obtained.

SS9709D

This hole was drilled into the edge of a moderate to high potential area. $EC_{1:5}$ data is generally low with a bulge between 7m and 10m. Geophysical data indicates a probable duplex soil with low conductance and moderate regolith thickness. Drillhole data showed the deep aquifer was dry.

The bore data confirms some areas interpreted as potential for potable water have small yields of potable water or in cases may be dry. The factors that contribute to potential for potable water may result in a well drained profile. However there is not enough bore data to be conclusive. From the results success even in areas interpreted as highest potential may not be great. Good potable water however is rare and valuable. A low overall success rate may be acceptable for such a resource.

6.3.4 Guide for potable water target selection using GIS data

1. Locate economic land management unit (farm property) within the catchment and then within sub-catchment.

2. Overlay farm and catchment boundaries on areas selected as prospective for potable water.

3. For shallow targets select area most likely to have fresher water within area of interest. Select areas towards centre as most likely to contain perched aquifers. Radiometric images can be checked for low response as a further refinement.

4. For deeper targets examine slope through area of interest where there is deeper regolith and pick targets upslope of dykes using dyke interpretation. Target areas should be prioritised by catchment area. Magnetic images can be checked for further verification.

6.4 Saline Water

6.4.1 Saline water

This study assumes that small quantities of saline water are of little economic interest. Only areas with good potential for high yields have been outlined on the Water Resource Target Map. Smaller quantities of brackish to saline water may be present in laterite regolith particularly upslope of basement highs or dolerite dykes.

The best source of non-potable water is the palaeochannel sand under the alluvial flat upslope of Wickipin-Harrismith Road and under Toolibin Lake. These sands are likely to yield high volumes of saline water with potential use in catchment management options. Bores drilled into the thickest parts of the channel indicated by the TEMPEST data have yields around 250 m^3/day. P15 bore drilled into weathered basement close to the channel at 557,204mE, 6,356,747mN gives a yield similar to the Tertiary sediments and may be hydraulically connected to channel sands.

Bores located in the lower parts of the catchment indicate the groundwater in the channel sand is under some pressure. Standing water levels in the bores are around 1 metre below surface.

Other potential higher yielding bores may be possible in more permeable sections of the regolith associated with quartz veining or pegmatite as well fractured rock aquifers in the weathered basement.

6.4.2 Bore data

6.4.2.1 Palaeochannel targets

P11

P11 bore was drilled into the edge of area interpreted as the thickest section of the Tertiary palaeochannel. Tertiary sediments were intersected between 8m and 37m. The bore was pumped for 10 hours at a rate of 94.7L/min and water level dropped from 0.35m to below the Quaternary clay cover at 9m. Water salinity was 6860 mS/m (38,000 mg/L). at the end of drilling

P12

This bore was drilled into an area that was interpreted to be Tertiary sediments on the shallow and deepest conductivity depth images from TEMPEST. However it is not in the area interpreted as thickest sands. Although on the edge of areas interpreted from TEMPEST intermediate depths. The bore did not intersect Tertiary sediments. A pumping test for 18 hours at around 20L/min resulted in a drawdown to 9.4m or just below the maximum thickness of Quaternary alluvium. Water salinity was 6860mS/m (38,000mg/L) at the end of drilling.

P13
This bore is situated in the centre of the interpreted thickest section of channel at the south side of Toolibin Lake. The bore intersected palaeochannel sediments between 9 and 39m. The bore was pumped at 94.7L/m and after 1 hour had dropped to 9.74m. After 18 hours of pumping the water level dropped a further 1.12m. Water salinity was 6670mS/m (36,700mg/L) at the end of drilling.

P15
This bore was drilled into the area interpreted as thick palaeochannel sands. The bore intersected Quaternary clay cover but no Tertiary sands. Weathered granite was intersected between 8 and 31.6 metres. Pumping of the bore for 11 hours at 48L/min resulted in a drawdown to 8.55m or just below the Quaternary clay cover. This may indicate the bore is close to the edge of the channel and in hydraulic connection with it. Dogramaci (1999) interpreted this bore as in fractured bedrock. Water salinity at the end of drilling was 6480mS/m (35,700mg/L) or very close to the salinity of the palaeochannel sands.

LT01
This bore was drilled into an area interpreted as palaeochannel sediments from SALTMAP data. Tertiary sands were intersected between 6 and 22m. Water salinity was 39,800 from laboratory analysis and a yield of 86.4m3/day was obtained.

Upper catchment bores
LT18 and LT03 were drilled into areas interpreted as possible palaeochannel from SALTMAP. Only minor sands were seen in LT 18 with little indications of sands from LT03. While the yield was higher (10.8m3/day) from LT03 the salinity was low (288 mg/L field measurement). LT 18 intersected ~2 metres of Quaternary sands at shallow depth above granite saprolite.

In general bores are in agreement with the interpretation of AEM data. Where there is disagreement the bore is close to the edge of the interpreted palaeochannel. Hydraulic connection with the palaeochannel is suggested by pumping and salinity data from one bore into saprolite close to the palaeochannel. A more complete analysis of pumping data would assist in the interpretation. In most bores drawdown is limited to the depth of Quaternary clays.

The EM data was more successful in finding saline than fresh water in the Toolibin catchment. EM remains a tool for measuring conductivity and as such works better in conductive areas. The TEMPEST data inversions are a great improvement on the SALTMAP data used in the NAGP. SALTMAP inversions despite the limitations in conductive terrain did map the general outline of the palaeochannel and within certain limitations are valid in the upper landscape.

6.4.2.2 Fractured rock aquifers

95/01P
This hole was drilled into faulted bedrock (George and Bennett, 1995). An intersection of regional faults was interpreted 150m to the west with two major dykes intersecting in the vicinity. One of the regional faults striking at around 032° forms the western boundary of the deeply weathered zone in which the palaeochannel sits. This strong structural control and the associated fracturing indicated in 95/01P make this fault of interest for fractured rock aquifers along its length. In addition faults with similar strike direction as well as conjugate sets are probably of interest. Conjugate sets in brittle rocks should be at an angle of less than 60°, thus the intersecting regional fault at this site may be from the same period of faulting. Another intersection prospective for fractured rock aquifers lies around 2.9km to the northwest at 554,200mE, 6,359,250mN.

6.4.3 Guide for saline water target selection using GIS data

1. The SALTMAP data layer 2 conductivity was interpreted to show areas that appear to be related to a palaeochannel structure. Despite the limitations of the inversion, SALTMAP data defines a dendritic pattern extending from the upper catchment through Toolibin Lake to the south-west corner of the survey area. This interpretation can be used as an approximate guide for the maximum likely area of the channel. TEMPEST data is more reliable in the lower catchment.

2. Where TEMPEST data exists, individual depth channels for depths 10-14m; 16-20m; 20-24; and 28-32m have been interpreted. These show that the channel sediments have been deposited over slightly different course at different times.

3. Thickest palaeochannel sands were interpreted by intersecting the interpretation of TEMPEST data from all interpreted depths.

4. Obstructions and/or constrictions to the channel are indicated in a number of places. These may result in greater pressure on the groundwater on the upslope side and easier recovery of water. Particular sites which should be considered in selection include:

    a) At the southern edge of Toolibin Lake at around 556,250mE; 6,356,200mN
    b) Close to P12 which was drilled into granite but positioned into indicated channel an don other side of dolerite dyke at around 556,800mE 6,357,100mN.
    c) North of Toolibin Lake and close to Wickipin-Harrismith Road at around 558,000mE 6,358,400mN.
    d) Above dyke at 557,900mE 6,359,000mN
    e) On north branch of palaeochannel at 559,500mE 6,362,000mN.

5. Lower yields may be possible from fractured rocks located along faults. Regional faults have been located on the Water Resource Target map but minor faults may also have potential aquifers and should be examined in GIS. Intersections of conjugate regional faults are considered to have the highest potential.

6.4.4 Water Resource Target Map

A Water Resource Target Map (Map 5) has been prepared at 1:50,000 scale to accompany this report. This map shows the main areas of groundwater potential in the catchment. The scale used is considered too coarse for final bore siting and extensive use of the data in the accompanying GIS project is strongly recommended for final site selection

Areas marked on the target map have been taken from the GIS project. These are:

1. Potable water resource targets
    a) Target areas for potable water in deep sands in upper regolith based on model parameters created by authors and analysis carried out by Argus and Chan (1999).
    b) Remaining sand areas interpreted from computer analysis of radiometric data (see Section 4).
    c) Granite outcrops and surrounding granitic sands from both computer and manual analysis of radiometric data.

2. Saline water target areas
    a) Outline of palaeochannel interpreted from SALTMAP data showing maximum likely extent of channel.
    b) Polygon showing area of palaeochannel interpreted from 16-20 metre layer calculated from TEMPEST data.
    c) Intersection of where the TEMPEST depth layers have been interpreted to show a palaeochannel.

In addition the dykes, regional faults, position of present bores, roads and drainage has been placed on the map. It is strongly recommended however that the final target selection be carried out using the full GIS database. This allows existing bores information and other data to be used in final selection.

7 SALT HAZARD INTERPRETATION

The Salt Hazard interpretation (Pracilio et al, 1998) was updated to address the extra information layers produced from and post the NDSP Project and criticisms by George (1998). The differences between other methods of salinity prediction were investigated and the stages of Salt Hazard development reviewed.

7.1 Definition of Salt Hazard

The Salt Hazard Map represents the spatial location of Salt Hazard models identified using geophysical and environmental data sets. It is based on salt stored in the regolith, source of water (catchment size and drainage), increase in recharge and impedance to groundwater flow (Salt Hazard models). The Salt Hazard is an area where these four factors may act to produce groundwater discharge causing the initial points of salinisation. It is NOT a map of present or future saline extent. To guide land management decisions each Salt Hazard is linked to a cause. The Salt Hazard process was initiated at the local farm planning scale so that potential discharge sites were addressed.

Agriculture Western Australia (AgWA) produced an airphoto and topographic interpretation of future saline extent. The AgWA and Land Monitor methods predict saline extent approaching or at "equilibrium" (when discharge equals recharge and water table approaches surface in many valleys). The AgWA predictions are mostly located within the major valleys. A visual comparison of this and the Salt Hazard interpretation highlights the different components of salinity prediction.

The Salt Hazard process predicts the ***initial*** discharge location that occurs before the whole valley has become saline (valley salinity). Salt Hazard prediction is based on identifying landscape variability likely to cause groundwater discharge sites that may become saline. It therefore does not assume that the valley is homogeneous. They do not represent the extent of each Salt Hazard (George,1998) and are not intended to predict salinity extent. There is insufficient information on the development and growth of saline areas from the initial discharge (or localised groundwater table rise). It is assumed that the saline site will develop adjacent to the initial discharge point as water tables rise over time.

The Salt Hazard sites for the Toolibin catchment are based on models outlined in Pracilio et al (1998). It is recommended that the Salt Hazard models and locations be reviewed over time as new sites of soil salinisation appear.

7.2 Exiting Saline Sites

AgWA and Land Monitor existing salinity maps were reviewed. The review concentrated on the upper to mid landscape where salinisation is presently developing. The accuracy of the Land Monitor Project data is outlined in Appendix 3.

Commission errors identified by the Land Monitor project (Appendix 3) were investigated within the SALTMAP survey area (Table 7.1). Once defined into a class, these sites were excluded in the analysis.

The total commission inaccuracy was calculated to be 16.7%. This may be an overestimate as it is larger than the 8% reported by the Land Monitor project. Areas of difference may be sites such as road commission errors. These may be saline as roads may act as barriers to water flow, but in other cases the reflectance of the road in a valley will be classified. Considerable field checking is needed.

Only 4.2% of the areas presented, as saline by the Land Monitor project in the upper landscape was assessed as actual soil salinity in this analysis. This is the “other” class unit in Table 7.1. This represents potential saline classes as mapped by the Land Monitor project after the commission errors were addressed. AgWA aerial photo interpretation excludes any saline sites in the upper catchment. From limited field observations, upper catchment salinity was more prevalent in the western than the eastern catchment. This was mostly attributed to the shallow regolith expected in the western catchment (Pracilio et al., 1998).

Table 7.1: Land Monitor salinity monitoring commission errors investigated in the GIS.

Reclassification of Land Monitor Saline Class	Commission Factor	Method	% area
Valley salinity	-	Intersect with airphoto salinity	67.2
Lakes/ water	-	From Landsat	11.9
Sand	Consistently poor condition areas within paddocks (eg. Light soils)	Intersect with sands from soils and water resource target maps	8.3
Roads	Mixed pixels along paddock / road edges	Within 70m of DOLA roads	4.2
Remnant Vegetation	Poor condition or sparse remnant vegetation	Within 30m of Landsat remnant vegetation	4.2
Other	-	Undefined from above	4.2

The airphoto mosaic was viewed in ArcView and possible/potential saline sites within the mid to upper landscape position were noted in a point them (saline_shp). No degraded areas were identified in North Scriveners catchment. A waterlogged site that corresponded with the Land Monitor area was identified in East Scriveners. This area may become saline by evaporation in summer months. Scriveners catchment shows evidence of salinity within duplex soils of the valley. A saline or water eroded hillslope was identified in North Wedin catchment. Saline degradation was also identified within the North Wedin valley. Apart from the obviously saline areas within Dorakin catchment, saline areas were not identified by Land Monitor Project, but the airphoto showed potentially salt degraded areas further upslope. Within the Flats the majority of the Land Monitor sites are presently saline. The Northern Flats catchment also appears degraded in places.

Neither the Land Monitor nor AgWA existing salinity data sets mapped the majority of the potential saline sites described in the mid to upper landscapes. Although these are small in terms of percentage area, they are important for future salinisation development in the catchment. Thus, these could not be used in the review of Salt Hazard models and locations. The Land Monitor and AgWA data sets are most likely aimed at mapping the majority of the saline extent. They are thus biased towards and more correct in mapping the extensive and severely degraded saline sites in the valleys.

Areas of possible saline degradation in the upper catchment require field checking. The next stage of catchment management requires mapping of surface indications at farm scale. The shape and indication of most severe area within a site mapped in the field are required for the Salt Hazard analysis. It is recommended that the Salt Hazard models, locations and ratings be reviewed again once this data is available.

7.3 Palaeochannel and Dolerite Dykes

Salt Hazards where dolerite dykes were overlaid by thick Tertiary sediments were considered speculative by George (1998). These were reviewed and reclassified to better represent the results of TEMPEST interpretation and the palaeochannel information.

It was observed that dolerite dykes often influence the pattern in the conductivity of the 2 to 6m TEMPEST depth slice (See Section 5.4.5). Many such areas occur within the present day, broad valley floor. Thus, it is not possible to generally assume, that dolerite dykes will not influence salinisation within a broad valley. Salinisation at such sites will be dependent on the thickness of the sedimentary cover. As old drainage patterns slowed with increasing aridity, sediments were deposited first in the old channel and with time a thin Quaternary layer right across the present valley. The influence of dolerite dykes is likely to be greatest where the sediments are thin. Mostly these sites are towards the outer edge of the valley but areas of thin sediment exist elsewhere across the valley floor. Some of these are associated with bedrock highs close to dolerite dykes.

All but one site where dolerite influences conductivity patterns were outside the interpreted palaeochannel and thus outside the area of thickest sedimentary cover. Generally the sites were within saprolite dominated areas. High conductivity in TEMPEST data adjacent to the palaeochannel was interpreted as saprolite clay and confirmed by the LT30 bore log with saprolite close to surface.

The exception located within the palaeochannel above the Wickipin-Harrismith Road, was interpreted as a bedrock high between two major dolerite dykes from the TEMPEST elevation of bedrock (ebot_l.tif). This decreases the thickness of the aquifer and reduces the carrying capacity of the palaeochannel. Such areas may be under significant hydraulic pressure causing discharge of the palaeochannel. The road at this site may also act as a barrier to surface and shallow throughflow ground water exacerbating the situation.

At greater depths, the conductivity structure from TEMPEST data indicated that the palaeochannel was controlled by dolerite dykes. Such controls include alignment of the channel, termination of thickest sands at the intersection and the palaeochannel widening upslope of dykes. These characteristics are seen in many present day streams in the wheatbelt.

Apart from the potential palaeochannel discharge at Wickipin-Harrismith Road no other present discharge sites within the TEMPEST study area were evident. Nevertheless the many of the dykes control the palaeochannel and were thus inferred to be potential discharge sites of the palaeochannel. Increased recharge from the upper catchment will increase hydraulic head in the palaeochannel aquifer. In areas with a thin or slightly permeable (more sandy) Quaternary cover, discharge of the saline palaeochannel aquifer may occur.

A new palaeochannel constriction model was postulated. These Salt Hazards were located using the thickest sands, the palaeochannel interpreted at 20-24m and 16-20m as the drainage layer and the dolerite dykes interpreted from the magnetics.

Discharge of deeper sedimentary aquifers is evident at Bears Lagoon, Upper Loddon Plain, Victoria (Macumber, 1991). In this case there was an interconnection between deep to shallow aquifers. The potentiometric head of the deeper bore was 1.8 m above the shallow bore and above ground. At Bears Lagoon 20m of sands are present at the base of the bore covered by 30m of surficial sediments including an 8m clay aquiclude (Macumber,1991). Similar stratigraphy is seen in the LT06 bore log in Toolibin Lake with 20m of sands, within 10m of the surface with a 9 m aquiclude. The piezometric water level is at 0.18m above ground level with no evidence of discharge within the lake bed. There is potential for the palaeochannel aquifer to become under pressure with increased recharge, causing such discharge at surface. Pumping will reduce this risk within the Toolibin Lake.

Martin (1987) reported groundwater outflow from the basal aquifer. Throughflow beneath Toolibin Lake was postulated to be discharging at

Walybring and Taarblin Lakes. An investigative study on these as potential palaeochannel discharge zones would help to establish whether the palaeochannel constrictions as mapped in the Salt Hazard process are areas at risk. There was insufficient data and information to confirm and rate these type of Salt Hazards. They were excluded from the rating process and are represented with a “0” in the rating column.

7.4 Salt Hazard Location

The location of Salt Hazards was updated with the improved catchment interpretation and use of GIS querying. In the 'Bedrock High' model sub/outcrop were identified by an early time conductance of less than 80 mS/m. All Salt Hazards that intersected these areas were checked. Human error in the first analysis showed 50% of the 'Bedrock High Salt Hazard' models were not identified.

All Salt Hazards that were located in deep sandplain were removed due to low salinity risk. Sixty five dolerite dyke Salt Hazards that were greater than 90m away from the new dyke interpretation were identified and updated. The roads network had not changed so this Salt Hazard position stayed the same. The soils at the break in slope were separated and the hazards within this area were reviewed. A buffer was created between the sandplain soils and the alluvial duplex soils to better define the region at which sandplain seeps were greater at risk. Existing saline sites and drainage within this area or at the edge of the deep sandplain were investigated.

Investigation in this Project gave greater confidence in the soil type change Salt Hazard model and its location than in Pracilio et al (1998). This was due to improved soil mapping (Section 4). Duplex soils were not well resolved in the previous work although these are at greater risk than gradational soils.

7.5 Salt Hazard Rating

Groundwater rise of the deep groundwater bores were investigated (see Figure 7.1). The lowest rate of rise occurs in the almost stabilised groundwater level of the Bush bore which is now close to surface. At this site groundwater has been gradually approaching the surface since monitoring began in 1978, when it was at 2.6m. At the other extreme in the highest points of the landscape annual rate of rise was 0.92m. Groundwater at this site was fresh (63mS/m) and depth of around 60m.

There is an approximate exponential decrease in the rate of rise, as water levels approach the surface (see Figure 7.1). Therefore it is not always accurate to use the existing rate of rise and linearly project that to estimate time groundwater reaches the surface. Figure 7.1 indicates that the majority of the bores sampled are increasing at a rate between 20 to 30 cm per year.

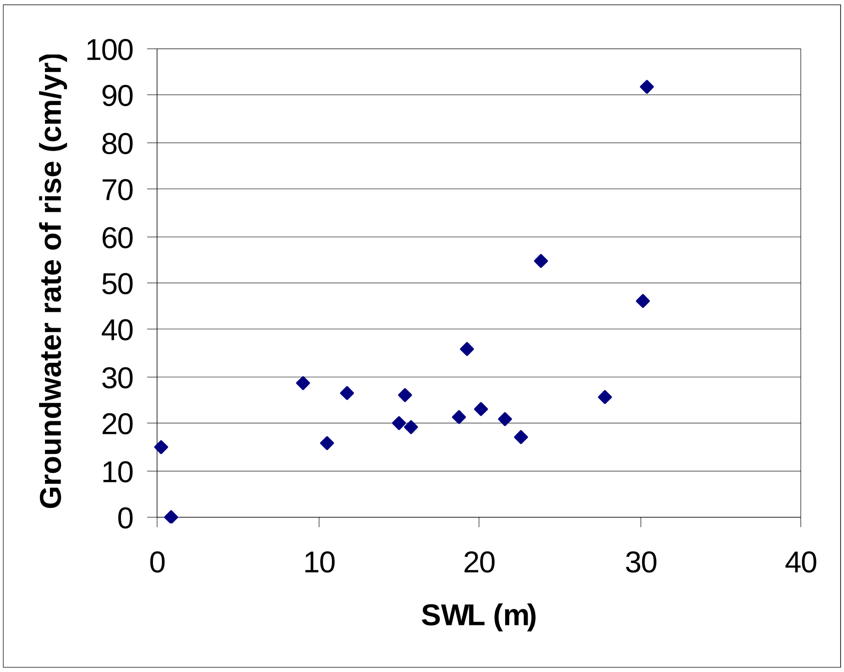

Figure 7.1: Rate of rise of bores in Toolibin catchment

Groundwater levels were not used in the rating of the Salt Hazards produced by Pracilio et al 1998 and the Salt Hazards were thus considered limited (George 1998). However, elevation was used in the classification of landscape units that were used to rate the Salt Hazards and since there is a positive relationship between elevation and SWL in the Toolibin catchment (George 1998), the ratings did take into account water level trends. Catchment size was also incorporated in the rating, which should also correlate with regional groundwater levels. Thus groundwater level was indirectly taken into account by the original rating system.

However, an investigation of bores labelled with SWL levels in the GIS indicates that within a drainage line, groundwater levels do not always increase downslope. For example at East Scriveners Catchment, water levels at 12.3m SS9708D (drilled to 26m) becomes dry further downslope at SS9705D. Thus at the local level changes in regolith impact on groundwater levels and the general relationship between SWL and elevation established by George (1998) breaks down. To incorporate such localised changes in the Salt Hazards, the SWL database created by George (1998) were used to rate Salt Hazards. Dolerite dykes were considered one of the major controls creating groundwater compartments in the landscape. Dykes interpreted from magnetic data were around 400m apart. Therefore ratings were adjusted according to groundwater levels within 200m of a Salt Hazard (Table 7.2). Ratings were checked and altered where appropriate on 44 of the 599 Salt Hazards.

Table 7.2: Rating system taking into account localised groundwater information

Deep Groundwater level	Criteria	Rating Change*
SWL	0-2m	-3
SWL	2-5m	-2
SWL	5-15m	-1
SWL	15-30m	No change
SWL:	>30m	+1
Groundwater rate of rise	>0.40 m/yr	-1

*Note highest Salt Hazard potential is lowest number rating from 1 highest to 9 lowest.

The new rating scheme is limited to only those sites close to bores. It is not possible to have a monitoring bore at each Salt Hazard location although it would assist in better rating of the development of the Salt Hazards. Visual observations with the combined interpretation of data are important in determining timing and severity of Salt Hazards. No such monitoring has occurred. This provides an opportunity for Landcare community to become involved in a monitoring scheme.

The authors assumed that undocumented catchment bores were shallow. This assumption was based on observation of deep water tables in observation bores adjacent to catchment bores with SWL within two metres of the surface. This trend was typical of most catchment bores. Perched systems are likely on the duplex soils which are common in the catchment. These are likely to have higher waterlogging and perched aquifer salinity risk relative to gradational soils.

It is suggested that the bore data base be reorganised in a more user friendly format where all the data from logs to aquifer type be compiled and using metadata standards as suggested in Section 2.1. The Salt Hazards should be reviewed with the full data suite of bores.

George (1998) suggested groundwater models be incorporated into Salt Hazard process. Groundwater models used to date do not take into account all the local variability accounted for in the Salt Hazard process. Groundwater models that did account for such changes would be very large and slow to run. In the absence of effective local scale models a more user interactive process has been used in determining the Salt Hazards. The result of most groundwater models is the extent of salinity at 'equilibrium'. The result of the Salt Hazard interpretation is the initial location and cause of likely groundwater discharge sites, which differs to the output of an equilibrium based groundwater model. Salt Hazards are an effective guide for land management because the cause can then be linked to remedial treatment.

In a groundwater model that incorporated local scale changes as an output from intermediate timescales (prior to equilibrium) would be a more rigorous representation of the Salt Hazards developed for this project. From such a model the time at which discharge first occurs for each Salt Hazard might be estimated. More development work outside of the current Project objectives, is required to investigate this.

8 GENERAL DISCUSSION

More than 10 different projects collecting environmental data in various forms have been carried out in the Toolibin Lake Catchment since 1977. There is general agreement between many of these datasets, which confirms the general structure and controls on the catchment.

Geologically the area is part of the Archaean Yilgarn Block. Pracilio et al (1998) interpreted separate individual granite intrusions within a gneissic terrane. The regional AGSO geophysical data shows a transition between later granites towards the west and a more gneissic Western Gneiss Terrane to the east.

Closer examination of the magnetic data in this study and inspection of rocks in the field suggest the magnetic data reflect the gradational boundary. The magnetic signatures reflect a varied basement made up of gneissic rocks with zones of partial melting. In places these zones of partial melting are large enough to be interpreted as separate granitic intrusions.

Over most of the catchment weathering depths are 25 metres or greater. Only minor outcrops of granite and gneiss are present. Field checking showed the composition of outcrops to be extremely variable. Both gneiss and granite were present in single outcrops with many veins of partial melting represented by quartz and minor pegmatite veins.

The gneissic unit is more deeply weathered in many places although weathering depth does not appear to be related to rock type. The absence of outcrop and/or basement samples from drilling makes interpretation of weathering/geology relationships difficult. In some cases though areas of preferential weathering were closely associated with patterns in the magnetic data. Such preferential weathering on geological structures may be important for land management options.

Dolerite dykes swarm through the area. The major Binneringie Dyke crosses through the northwest part of the catchment and forms the catchment boundary in this area. Many other major and minor suites are evident from the magnetic data particularly at strike angles of 120 and 090 . Dykes control weathering and salt concentration in the northern central parts of the catchment. Very few dykes outcrop and only the Binneringie has significant surface exposures.

The Project interpretation concentrated on better location of the dykes from magnetic interpretation. Some assumptions are necessary with a line spacing of 150m in relation to the form of dolerite dykes and the interference patterns observed in the data where dykes cross. Dykes were interpreted as continuous linear intrusions except in cases where obvious offsets at faults were present. In the Project it was considered the line spacing limits the quality of the interpretation at 1:10,000 scale. A closer line spacing may be more appropriate.

Zones of low magnetism in the magnetic data indicate major regional faults. One of these faults running slightly east of north controls the deeper weathering zone that runs north from Toolibin Lake and encloses an older drainage system.

Geomorphologically the catchment is situated on the change between rejuvenated landscape to the west and the relict deep laterite landscape to the east. Soils in the western part of the catchment are commonly derived from granite with more potassic responses in the radiometric data extending from the catchment boundary down the major drainages towards the Flats north of Toolibin Lake. In the east deep sand cover is common, weathering more pervasive with many areas of deep laterite regolith. Duplex soils are common and an alluvium derived from weathering of the laterite and sands extends down the valleys towards Toolibin Lake.

Radiometric data was used extensively with soil pits to produce a soils map with better resolution of individual soil units. Field checking of the radiometric data showed that the images could be used to differentiate between most of the major soils in the catchment. Supervised classification produced a map that brought together information from more than 250 soil pits along with radiometric, DTM and slope data. This method of creating soils maps shows great future because it can resolve realistic units not mapped in airphoto interpretations such as the difference between the granitic derived alluvium and laterite derived alluvium. In addition radiometric classification differentiated between shallow duplex soils and deep sands. It is also relatively unaffected by vegetation.

No work has been carried out on resolution of radiometric data particularly for units with low radiometric response. Airborne radiometric is by nature noisy. New routines for processing radiometric data such as MNF (minimum noise fraction) and NASVD (Noise Adjusted Singular Value Decomposition) attempt to remove noise from the spectra. Most of these appear to have some filtering effects on the data and subtle signals may be removed at the expense of stronger responses. In addition many different classification technique have been used on radiometrics to enhance differences between observed spectra. A rigorous evaluation of these methods is required.

Preliminary OARS multispectral data became available during the project. This system shows promise in assisting in further division of the soils by presence of clay types. Illite clays appear indicated from both radiometrics and OARS on the deep sands east of Toolibin Lake whereas other sandplain areas appear almost devoid of any clay content. OARS requires further development in processing and a catalogue of Australian plant and soil spectra is needed for easier interpretation.

SALTMAP layered earth inversions were considered to be unreliable in areas with conductance greater than 10S by Pracilio et al (1998) due to difficulty in primary field removal particularly in the area around Toolibin Lake. Examination of the newer TEMPEST airborne EM data showed good agreement with drillhole data. SALTMAP data showed a general agreement with TEMPEST over most areas where the surveys overlapped.

The SALTMAP LEI inversion routine fits three layers to the data. These are a resistive surface, conductive regolith and resistive basement. Where one or more of these layers is absent large diversions from reality can occur. Thus SALTMAP three layer, LEI data be misleading in areas such as granite outcrop. In such areas the inversion creates a very thick, low-conductivity, second layer in order to fit the observed data to a three layer model. Methods to distinguish these areas were developed in the project.

The TEMPEST CDIs were in general agreement with drillhole EM39 and $EC_{1:5}$ data particularly in the top 25m. Exceptions were found where there were sudden conductivity changes were three orders of magnitude from around 1000 mS/m to less than 1 mS/m. In these areas the LEI is probably more appropriate for bedrock detection. The LEI however is not ideal for detecting subtle changes with depth compared to the CDI.

Both the LEI and CDI processing can lead to results that may be misleading to untrained users. In general though the new CDI can be used with more confidence and less risk than LEI data.

SALTMAP AEM and the newer TEMPEST AEM data showed there was a zone of moderate conductivity in a dendritic pattern under the alluvial flats to the north of Toolibin Lake. Drilling proved this to represent a palaeochannel with sands of deposited in a broad channel, which on AEM data is almost 200 metres wide. Palynology indicated a Miocene to Pliocene age which represents a time when climates were becoming more arid over most of the Australian continent.

In the deepest part of the catchment represented by the deeply weathered area under Brown Road SALTMAP LEI results from both SALTMAP and TEMPEST agree with depth to basement of 72m +/- 5m. Recent drilling had not intersected basement at 69 m. Both SALTMAP and TEMPEST are within a reasonable order of accuracy for such a deep conductive feature.

The palaeochannel was detected by SALTMAP and particularly by the principal component analysis of SALTMAP data (Pracilio et al, 1998). The SALTMAP layer 2 conductivity although not presented in Pracilio et al (1998) also reflected the channel although wider than in TEMPEST depth channel data. The SALTMAP results reflect the maximum area of deposition over time. This area is expected to be wider than at discrete depth intervals. In addition the limit of reliable inversion in this area resulted in lower observed conductivity in most conductive areas at the edges of the palaeochannel. The PCA was better able to define the channel in the lower catchment whereas the layer 2 conductivity was better in the upper catchment.

The better calibrated TEMPEST system indicates that SALTMAP was performing better than reported in Pracilio et al (1998) particularly with regolith thickness trends. SALTMAP achieved most of the aims of a low cost airborne electromagnetic system for conductivity mapping in saline areas as predicted by Buselli (1990, 1993).

All datasets were used in the creation of a Water Resource Target map. More automation of this process was developed for this project than attempted by Pracilio et al (1998). In Pracilio et al(1998) only targets with high potential for potable water were interpreted. This study recognised that land management units are farms with areas of around 1000 ha. Potable water is a valuable resource and more effort was placed on distinguishing the most prospective areas.

Areas where radiometric data indicated deep sands were intersected with deep low conductivity regolith to produce most likely areas for potable water in perched and deep aquifers. Despite the amount of data and new interpretation, success and/or yield of bores is expected to be low.

Some of these farms may not have prospective areas for potable water. In the Project areas with lower potential for potable and/or brackish water were identified. This interpretation concentrated on sandplains as well as areas surrounding granite outcrop/subcrop. Small valuable resources may be present from well-sited bores. Data from bores although limited confirmed the interpretation. Best areas for potable water were considered to be in deep sands upslope of dolerite dykes. Recharge water reaches the deep aquifer quicker with less concentration of salts and is then held by the lower permeability of the dolerite saprolite.

Potential high yields of saline water presents the most interesting options for land management in the catchment. The greatest water resource in the area is in the deep Tertiary sands in the palaeochannel. AEM data suggest these sands may be up to 200 metres across and 20 metres thick. Drilling from the limited bores in the palaeochannel confirms the thickness and shows high yields can be obtained from the sandy aquifer. The deeply weathered saprolite close to the palaeochannel also gave high yield and may be in hydraulic connection with the channel sands. Lower yields appear possible from fractured rock aquifers.

Actis et al (1999) reported on the potential for commercial use of saline water at Toolibin Lake. Such studies indicate there may be other options for profitable enterprises in the area other than traditional grazing and cropping.

A discussion of the Salt Hazard definition and comparison with other salinity prediction tools and groundwater models was considered important in terms of the end use of the Salt Hazard product.

The Salt Hazard process was reviewed in terms of the models, location and rating. Detailed existing surface salinisation data was not available for the review to be fully completed. Newly developing sites mapped in the field were required to identify models causing salinity within the Toolibin catchment and to check on the location of Salt Hazards. GIS spatial analysis enabled checking of hazard locations relative to the newly produced data sets. Those missed by human error and readjustments of interpretations were updated. The rating of Salt Hazards incorporated localised water tables where data was available. The final ratings has a roughly estimated error of $\pm$ 2.

Salt Hazards mapped by Pracilio et al (1998) located within the palaeochannel were reclassified. Those related to palaeochannel shape and directions were interpreted as potential palaeochannel constrictions if hydraulic pressure within this aquifer increases. One such site that was a potential palaeochannel discharge site was located in a salt lake upslope of Toolibin Lake, just north of Harrismith Wickepin Road. If so this may have implications on the boundary conditions of the groundwater model of Toolibin Lake. Such discharge may reduce the expected inflow from the north.

It is recommended that the individual layers and particularly the intersection of these be incorporated into the boundary conditions of the groundwater model. An ASCII file of the depth to bedrock calculations from TEMPEST data provided in the Project, is likely to be a good representation of regional bedrock depth trends as indicated by the good correlation with drilling. It should be incorporated in the groundwater model to improve the quality of spatial data parameters.

9 RECOMMENDATIONS

9.1 Land management planning

The data is now in a format ready to be utilised by land managers. There are few catchments with the diversity and quality of data available for Toolibin. A project to turn these data into land management decisions both for the lake and for farmers throughout the catchment is strongly recommended.

9.2 Workshops with farmers

The data now in GIS has great implications for farm management. However, farmers who ultimately are responsible for the decisions on their properties have little understanding of the information content and how the data might be used in land management. Toolibin has more data than most catchments in the southwest. The farmers need an extension program in order to utilise the data thoroughly. Only through familiarity and practice will farmers come to use the collected data to make better decisions. A series of workshops and seminars are recommended for this future program.

9.3 Bore data base

Most projects in the Toolibin Catchment have a drilling component. The naming of bores over the past twenty-five years has not followed any convention. Different drilling methods including auger, RAB, diamond and aircore were used. Different methods were used for reporting hydrogeological data such as geological logging, salinity and yield. Different aquifers have been screened and tested. The purpose of drillholes is not always clear from available reports although such an understanding would assist the user of the data.

Reports incorporating bore completion reports such as the quality provided Water and Rivers Commission should be fundamental outcome from drilling programs given the cost of drilling. Such reports could be improved with an analysis of results. No analysis was available at the time of writing this report although another drilling program has already been completed (Dogramaci, 1999).

A proper review of the bore database was found to be beyond the scope of this project. However considerable funds have been spent on drilling and for future use it is considered imperative that all the available bore data should be amalgamated into one database. Some recommendations for this are contained in Chapter 2.

9.4 Bore Monitoring

Long term monitoring of bores is inconsistent. Only a few bores have good long- term records and some of these have not been monitored from some years. This is incongruous in a catchment that has been under investigation for over 20 years.

A strategy for long term monitoring network is needed both for the lake and the general catchment. The data collected into GIS in this project should be used as a guide for establishment of the network. Existing bores should be incorporated where possible. The monitoring strategy should be worked out with the catchment farmers and across agencies. In placement of future monitoring bores consideration should be given both to hydrogeology and ease of access for farmers to carry out measurements on a more regular basis.

9.5 TEMPEST data

To best determine depth to bedrock from AEM data the CDI results should be compared with three layer inversion. Analysis in GIS could be used to identify spatially those regions where the CDI is likely to be underestimate conductivity.

TEMPEST data in the upper catchment would assist in better evaluating the Salt Hazard rating using shallow versus deep conductivity.

The palaeochannel could be further investigated in terms of flow/depositional regime along its length. TEMPEST data could be used to reconstruct the river position at various times/depths. Possible positions of sandy fractions may be possible by interpretation of likely areas of sand deposition as point bars on inside of river bends etc. Such a study combined with test drilling would assist better location of pumping bores into other palaeochannels in the south-west.

9.6 Standards and Documentation

Greater efforts should be made in the future to standardise and/or fully document methods in salinity investigations. There are a number of projects carried out in the past at considerable expense with no proper documentation. Standardisation of units and a better education scheme for farmers who engage in Landcare activities is recommended.

9.7 Metadata

"Metadata is data about data. It is a description of the characteristics of data that has been collected for a specific purpose. If community access to land information is to be maximised, adequate descriptions of the characteristics of all geographically referenced datasets must be available and accessible to the community at large. anzlic@auslig.gov.au.

It was beyond the scope of this project to include all metadata with the layers in the GIS project. While this report does document where most of the associated reports are kept it would be useful for the long term use of the GIS to link all layers (shapefiles, images etc) produced to digital source documentation.

9.8 Projections

Accurate location of all environmental data should be practiced and use of non-standard projections should be discouraged. Consideration should also be give to conversion of all data to MGA coordinates after December 2000.

9.9 Involvement of Catchment Group

All reports seen in this investigation were aimed at a scientific audience. Catchment management must involve all stakeholders. More than 80% of the land in the catchment is owned and managed by farmers. More consideration should be placed on preparation of material for this sector. Farmers will feel more inclined to make efforts if they have a good understanding of the catchment. A more cooperative approach to a universal problem could result.

10 CONCLUSION

A large range of environmental data has been collected in the Toolibin Lake Catchment over the past twenty years. Where available these data were amalgamated into a GIS database in this Project. The primary layers for this database were the geophysics collected in the National Airborne Geophysics Project (NAGP) and bore data from around10 drilling programs.

Most of the geophysical data were extensively interpreted and evaluated in the NAGP (Pracilio et al, 1998; George, 1998). New data as well as data collected during the NAGP and data withheld for evaluation of the geophysics have been incorporated into a new interpretation in this Project. Key new datasets include bores, soilmaps and maps of saline extent. An evaluation of all the available data showed variable quality. There is general agreement between many of these datasets, which confirms the general structure and controls on the catchment.

A more automated and rigorous approach to interpretation of the spatial data was used in this Project harnessing the power of the GIS database by interrogation and classification of data in ArcView Spatial Analyst and ERMapper software,

Geologically the area is part of the Archaean Yilgarn Block in a transitional area between more gneissic terrane to the east and more granitic rocks to the west. The magnetic signatures reflect a varied basement made up of gneissic rocks with zones of partial melting. In places these zones of partial melting are large enough to be interpreted as separate granitic intrusions.

The gneissic unit is more deeply weathered in many places although weathering depth does not appear to be strongly related to rock type. In some cases areas of preferential weathering were closely associated with patterns in the magnetic data. Such preferential weathering on geological structures may be important for land management options.

Numerous dolerite dykes cross the area although very few dykes outcrop. Dykes control weathering and salt concentration in the northern central parts of the catchment and control the path of the weathering and a palaeochannel in the lower catchment.

The line spacing limited the quality of the interpretation at 1:10,000 scale particularly using raster images and on screen digitising. For more accurate placement of dykes at scales more detailed than 1:10,000 a closer line spacing is appropriate.

A zone of low magnetism along a regional fault controls the deeper weathering zone that runs north from Toolibin Lake and encloses an older drainage system. Radiometric data shows that this fault lies along the geomorphological boundary between the rejuvenated western catchment and the deeply weathered eastern catchment in the east.

Radiometric data was used extensively with soil pits to produce a soils map with better resolution of individual soil units. This method of creating soils maps shows great future because it can resolve geochemical differences in the soils not seen in more traditional methods. Soils in the west show a higher potassic response and are young soils derived from nearby granite outcrops. In the east deep sand cover is common and weathering more pervasive with many areas of deep laterite regolith.

OARS multispectral data became available during the project. This system shows promise in assisting in further division of the soils by presence of clay types. OARS needs further development in processing and a catalogue of Australian plant and soil spectra is needed for easier interpretation.

SALTMAP data were considered unreliable by Pracilio et al (1998) due to difficulty in primary field removal particularly in the area around Toolibin Lake. Examination of the newer TEMPEST AEM data showed good agreement with drillhole data. SALTMAP data showed a general agreement with TEMPEST over areas where the surveys overlapped.

Improvement in AEM processing from using LEIs to CDIs gives much superior resolution of conductivity changes within the regolith. Many of the misleading results in SALTMAP data have disappeared in the new CDI processing.

SALTMAP AEM and the newer TEMPEST AEM data defined a palaeochannel of sandy sediments deposited in a broad channel 200 metres wide. This structure is a major reservoir of saline water. Comparison with magnetic data indicates areas of possible constriction, which may cause discharge from the palaeochannel. Careful management of this resource is needed to prevent soil salinisation both within Toolibin Catchment and further down the Blackwood Valley..

The previous 20 years of investigations at Toolibin had not detected the channel although it was suspected in the earliest of the investigations (Martin, 1982). The difference in cost benefit ratio of airborne surveys over previous investigations must be significant, particularly in regard to drainage and/or pumping are land management options.

Water resources within the catchment were interpreted using a more automated approach than previously. Best areas for potable water were considered to be in deep sands upslope of dolerite dykes. The greatest water resource in the area is in the deep Tertiary sands in the palaeochannel. AEM data suggest these sands may be up to 200 metres across and 20 metres thick.

The data is now in a format ready to be utilised by land managers. There are few catchments with the diversity and quality of data available for Toolibin. A project to turn these data into land management decisions both for the lake and for farmers.

11 GLOSSARY OF TERMS

1VD - First vertical derivative. Used in magnetic data processing to enhance edges and sharpen features in the data.

AGC- Automatic gain control. Used in magnetic and seismic data processing to enhance low magnitude anomalies*.*

AMG - Australian map grid

Equivalence - A problem in resolving electrical parameters of a layered sequence. Combinations of layer resistivities (or conductivities) and thicknesses can give indistinguishable electrical (or electromagnetic) sounding responses.

Greyscale - Term applied to images prepared in black and white and shades of grey rather than in colour*.* Greyscale images can often show better resolution because the eye is less biased by colour.

Regolith – The layer or mantle of loose, non-cohesive or cohesive rock material of whatever origin that nearly everywhere forms the surface of the land and rests on bedrock.

RTP- Reduced to Pole. Mathematical transformation of magnetic data to make anomalies symmetrical as would be seen at the magnetic poles.

Salinity - A general term combining land and stream salinity. The area in which the user is active may govern usage.
Salinity of water meaning the amount of salt in the water
Salinity of land meaning land salinisation either from irrigation or dryland salinity
Salinity of soils synonymous with land salinisation

Salt affected soils " land which is saline, or sodic or strongly alkaline anywhere within the top one metre of the soil profile" Northcote and Skene 1972. A saline soil will generally have an electrical conductivity of a saturation extract in excess of 400 mSm^{-1} at 25 C. Salt affected soils will often be obvious due to the presence of salt tolerant plant species and/or development of salt scalds.

Salt Hazard – A point, which is interpreted to be likely to be a discharge (collection) point of saline water. In the Broomehill study the salt hazards were interpreted using a set of "rules" suggested at a LWRRDC workshop at Bunbury. The salt hazards were interpreted in order to give the farm planner guidelines on which to plan remedial actions. Thus each salt hazard had a "cause" identified.

The 'rules' applied for Broomehill looked for a reduction in transmissivity typically a dyke, thin regolith or road or increase in water due to stream confluence or dam. The size of the catchment and the amount of salt (as determined from SALTMAP data) were used to gauge the severity of the hazard. The “salt hazard map’ explained to the farmers the **cause** of each of the saline areas on their farm. This can then be used to guide remedial action. If the remedial action does not work then the farmer still has a salt hazard map to redesign his remedial actions.

SALTMAP – An airborne electromagnetic system in use 1993 to 1998 (Duncan et al, 1993).operating with a square waveform at 495 Hz with full duty cycle and receiver bandwidth from 495 Hz to 50 kHz. SALTMAP is an aid to mapping salt storage and regolith thickness through measurements that reflect the subsurface conductivity distribution.

Salt scald - Severe visible signs of salinity on the surface. Soils contain too much salt for plants to grow. Soils structure is severely affected and A horizon may be eroded.

Salt storage – The amount of salt stored in the regolith profile. It is usually held within the laterite saprolitic clay. Usually measured by the electrical conductivity of a soil/water extract.

Siemen - Unit of electrical conductivity; the reciprocal of ohm. Formerly called mho. Named after Werner (1816 - 1892) and Wilhelm (1823 - 1883) Siemens, German inventors who pioneered in electricity applications. The unit siemen is usually spelt with a small s, whereas the abbreviation uses a capital to avoid confusion with second.

Soils salinity - The characteristic of soils relating to their content of water-soluble salts. Soil salinity is normally characterised by measuring the electrical conductivity of a soil/water extract and expressed in mSm^{-1}.

TEMPEST- Broadband airborne electromagnetic system developed in 1998 and superseded SALTMAP (Lane, 1998).

Time constant - A measurement of the rate of decay of the electromagnetic signal in the ground. A poor conductor has a fast decay and low time constant.

TMI - Total magnetic intensity

WGS-84 World geodetic system adopted by US Department of Defence for GPS positioning

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