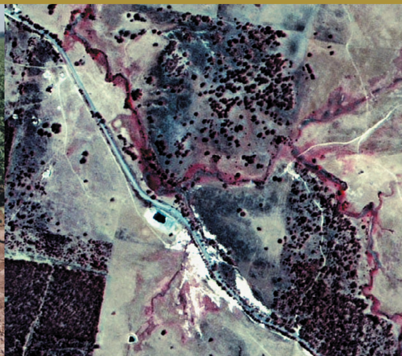
Brian Spies and Peter Woodgate

SALINITY MAPPING METHODS IN THE AUSTRALIAN CONTEXT

PREPARED FOR THE NATURAL RESOURCE MANAGEMENT MINISTERIAL COUNCIL



Brian Spies

Brian Spies' 30 years experience in research and management has been in fields as diverse as mining, petroleum, nuclear and environmental sciences; and in industry, government and academia. He has worked in mineral and geothermal exploration, non-destructive testing and monitoring deep petroleum reservoirs. Brian has held senior positions at CSIRO and the Australian Nuclear Science and Technology Organisation, and was director of the CRC for Australian Mineral Exploration Technologies.

Brian is an active promoter of the science and profession of geoscience and has held numerous editorial and honorary positions. He was elected a fellow of the Australian Academy of Technological Sciences and Engineering in 1998 and is a recipient of the Australian Centenary Medal.

Brian is science manager at the Sydney Catchment Authority, and is responsible for research and science outcomes relating to drinking water, catchment and environmental management. He was formerly with CSIRO Exploration and Mining where the current study was initiated. He lives with his family in Sydney and is a keen kayaker.

Sydney Catchment Authority
PO Box 323
Penrith NSW 2750
email: brian.spies@sca.nsw.gov.au

Peter Woodgate

Peter Woodgate is the Chief Executive Officer of the Cooperative Research Centre for Spatial Information involving over 50 partners from industry, government and university sectors.

Prior to taking up this role, Peter was the Chief Executive Officer of the Geospatial Science Initiative at RMIT University, where he helped create their first spin-off company, Spatial Vision Innovations Pty Ltd, as well as the Risk & Community Safety Research Centre and the Global Sustainability Institute. Peter has worked for many years in the Victorian public service leading development of various business units in natural resource management and spatial information. He has a long-standing interest in forest management, salinity research, the greenhouse effect and use of remote sensing for monitoring natural resources.

Peter lives in Melbourne with his family, and he and his wife Janet are keen supporters of their children's various sporting interests including cricket, equestrian eventing, basketball and netball.

Cooperative Research Centre for Spatial Information
723 Swanston St
Melbourne, VIC
email: pwoodgate@crcsi.com.au

Brian Spies and Peter Woodgate

SALINITY MAPPING METHODS IN THE AUSTRALIAN CONTEXT

Results of a review facilitated by the Academy of Science and the Academy of Technological Sciences and Engineering for the Programs Committee of the Natural Resource Management Ministerial Council through Land and Water Australia and the National Dryland Salinity Program

This book has been prepared for Programs Committee of Natural Resource Management Ministerial Council, through Land and Water Australia and the National Dryland Salinity Program.

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FOREWORD

Our ability to effectively manage dryland salinity depends upon our understanding of its causes, location and behaviour in any landscape. Accurate mapping of the saline landscape and the hydrogeological pathways that control the movement of water and dissolved salt is critical if we are to understand its causes and develop measures for remediation. This book and its accompanying user guide describe the various methods that can be used in Australian environments to acquire and present information about dryland salinity.

This book contains detailed descriptions of each method and is designed to help the potential user determine how their mapping needs can be best met. The accompanying user guide presents a short overview of the material contained in this book, and is directed towards a broader readership. This book can be read in conjunction with, or independently of, the user guide.

These publications arose from a review of mapping methods that was commissioned by Programs Committee of the Natural Resource Management Ministerial Council on the recommendation of its Science and Information Working Group. Following a public call for submissions, 36 organisations and individuals took the opportunity to make a contribution providing over 3000 pages of material. The project was overseen by a steering committee selected by the Operations Committee of the National Dryland Salinity Program.

The Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering were invited by the Australian Government on behalf of the Programs Committee to review the outcome reports.

Salinised former freshwater lake – Lake Dumbleyung, WA.

In order to fulfil their review function the joint academies undertook a number of activities as follows.

- They first convened a workshop at the Academy of Science office in Canberra in September 2003, where 24 leading scientists were invited to critically examine the first working draft of the review and to offer advice on its further revision. The workshop was hosted by Dr Jim Peacock, President of the Australian Academy of Science and opened by the Secretary of the Department of Environment and Heritage of the Australian Government, Mr. Roger Beale. It had as its guest Lord May of Oxford, President of the Royal Society. The day was chaired by Professor Brian Kennett of the Research School of Earth Sciences at the Australian National University.
- The academies then facilitated the involvement of leading scientists in the examination of specific issues as they arose in the re-drafting and we are grateful to the people who reviewed without prejudice relevant sections of the text of the draft reports as they were prepared.
- The academies then hosted a public forum at the Shine Dome, Canberra on 17 October 2003. The public forum was chaired by Dr Phil McFadden, Chief Scientist of Geoscience Australia. Over 70 participants spent the day reviewing the modified draft reports in a series of sessions that were guided by presentations from leading scientists in their field. The full transcript of the forum is available through the Academy of Science website at <www.science.org.au/conferences/salinity/>.

A panel of five scientists chosen by the joint academies undertook a final review of the reports. The panel members were Professor Kurt Lambeck (Chair), Dr Andy Green, Dr John Ive, Professor John Lovering and Dr Ian Rae. The panel was pleased with its positive interaction with the authors of the review reports.

The resulting user guide and book represent a thorough process of consultation, public examination and scientific review that will contribute to our ability to better map dryland salinity and its associated risks and hazards.

The Academy of Science and the Academy of Technological Sciences and Engineering are pleased to have facilitated the review and contributed to its successful completion through our consultative processes. We expect that the reports of the Review of Salinity Mapping Methods in the Australian Context will be an invaluable resource for a wide range of natural resource managers.

Dr Jim Peacock, AC, FAA, FRS, FTSE,
President, Australian Academy of Science

Dr John Zillman, AO, FTSE, FAIP, FAIM, FEIA, FRMetS,
President, Australian Academy of Technological Sciences and Engineering

CONTENTS

APPENDICES

ABBREVIATIONS

AEM	airborne electromagnetics
AGSO	Australian Geological Survey Organisation
ALS	airborne laser scanning
ALTM	airborne laser terrain mapper
ANSTO	Australian Nuclear Science Technology Organisation
API	aerial photo interpretation
ASCE	American Society of Civil Engineers
ASEG	Australian Society of Exploration Geophysicists
BRS	Bureau of Rural Sciences
CALM	Conservation and Land Management
CDI	conductivity depth image
CEC	cation exchange capacity
COAG	Council of Australian Governments
CC	catchment characterisation
CMA	Catchment Management Authority
CRC LEME	Cooperative Research Centre for Landscape Environments and Mineral Exploration
DAFF	Department of Agriculture, Fisheries and Forestry
DEM	digital elevation models (also DTM)
DEH	Department of Environment and Heritage
DIPNR	Department of Infrastructure, Planning and Natural Resources, NSW
DNRE	Department of Natural Resources and Environment, Vic
DTM	digital terrain models (also DEM)
EAGE	European Association of Geoscientists and Engineers
EEGS	The Environmental and Engineering Geophysical Society
EC	electrical conductivity
EM	electromagnetics
GIS	geographic information system
GFS	groundwater flow systems
GPS	geographical positioning system
GPR	ground penetrating/probing radar
HEM	helicopter electromagnetics
IP	induced polarisation

ISFETS	ion-specific field-effect transistors
LEI	layered-earth inversion
LIDAR	light detection and radar
LMU	land management unit
LPLMC	Liverpool Plains Land Management Council
LWA	Land and Water Australia
MDBC	Murray-Darling Basin Commission
MDBMC	Murray-Darling Basin Ministerial Council
MSS	multispectral scanner
NaCl	sodium chloride
NAGP	National Airborne Geophysics Project
NAP	National Action Plan for Salinity and Water Quality
NDSP	National Dryland Salinity Program
NHMRC	National Health and Medical Research Council
NHT	Natural Heritage Trust
NLWRA	National Land & Water Resources Audit
NMR	nuclear magnetic resonance
NRM	natural resource management
OP	osmotic pressure
PC	principal component
PMSEIC	Prime Minister's Science, Engineering & Innovation Council
PRISM	practical index of salinity models
PUR$L	Productive Use and Rehabilitation of Saline Lands
R&D	research and development
SAR	sodium adsorption ratio
SWIA	south-west irrigation area
TDR	time-domain reflectometry
TDS	total dissolved solids
TM	thematic mapper
TEM	transient electromagnetics
TOR	terms of reference
US EPA	United States Environmental Protection Agency
WHO	World Health Organization

(see also risk definitions, p. 24)
(see also electromagnetic definitions, p. 45)

ACKNOWLEDGMENTS

The authors would like to thank the 36 organisations and individuals who responded so willingly to the call for submissions from the public to the report and to the many individuals involved in the review. The submissions and reviews comprised over 3000 pages of reports and papers in addition to the maps and CDs which are summarised in the appendices to this report.

The authors are also grateful for the assistance of the Project Steering Committee of Dr Sharon Davis (Chair), Dr Richard George—for his insight and extraordinary support in so many ways, and Dr Mirko Stauffacher, the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering and the Operations Committee of the National Dryland Salinity Program. The representatives of the clients Mr Simon Veitch (Australian Department of Agriculture, Fisheries and Forestry) and Ms Annette Bleys (Australian Department of Environment and Heritage) are gratefully acknowledged for their fine guidance and helpful contributions throughout the review.

The authors gratefully acknowledge the significant input of the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering. In particular, Sue Serjeantson, Ian Rae, Andy Green and Chris Warris for organising the Scoping Workshop of 24 select specialists on 1 September 2003, the subsequent Public Forum on 17 October 2003 and the final technical review.

EXECUTIVE SUMMARY

Salt is a *hazard* when it has the potential to be moved to where it can threaten assets such as agriculture, infrastructure, water resources and biodiversity. Salt stored in the ground may be mobilised by water and transported vertically and horizontally. Australia's growing problem of dryland salinity cannot be reliably assessed without a thorough three-dimensional understanding of the landscape and the hydrological processes that operate within it.

Mapping is the means by which we gain an understanding of what lies on and beneath the Earth's surface. The major uses of mapping in the studies of dryland salinity are to delineate areas affected by surface or vegetation expressions of dryland salinity, and to identify areas not yet affected but at risk of salinisation.

At least 30 satellite, airborne and ground mapping techniques are available for mapping and delineating soils, landforms, water flow and pathways through the subsurface.

- Some can be used to detect or infer the presence of salt at the Earth's surface or contained in the soil profile.
- Satellite and airborne remote sensing techniques can reveal existing surface salinity and can track changes over time.
- Airborne geophysical techniques, combined with ground and borehole control, are important tools in understanding salinity and hydrology at depth at a variety of scales.
- Only borehole sampling and electromagnetics (EM) techniques can detect and resolve salinity in the subsurface at depths in and below the root zone. EM techniques can also give complementary information on palaeochannels and structures which often control groundwater flow.

Salt lake developed from rising saline groundwater – Arthur River catchment, WA.

Salinity risk is a measure of the chance that a salt hazard will cause harm to an asset at some time in the future. Risk should be assessed in the context of the assets to be protected, including agriculture, water quality, infrastructure and the environment. Cost–benefit analyses in salinity management should take into consideration total cost and total benefit in context with the value of all assets.

The optimum strategy for mapping salinity hazard and risk depends on the scale (farm, community or catchment) and resources available to the user. Users need to make best use of existing information and then integrate a range of the available mapping methods so that they best address their specific problem. No single method has primacy, nor is there a 'magic bullet' for salinity mapping or prediction. Effective use of mapping methods requires expert knowledge or access to trained personnel.

A lot is known about salinity in the top few metres of ground—from dying vegetation, salt scalds and saline water seeps. Each landowner has a good idea of what is visible on their property. A wide range of satellite and airborne techniques can be used to assist in mapping surface expressions of salt and have a useful role in extrapolating from the existing knowledge of surface expression of salinity, obtained by visual inspection and near-surface EM conductivity mapping.

Managing salinity more strategically is hampered by a lack of knowledge about the location of concentrations of salt in the subsurface and whether they are likely to be mobilised by groundwater and pose a risk to assets. Hydrology is the key to understanding how salt stores are mobilised through the earth, both vertically and horizontally. The only broadacre, remote sensing technique that can detect and resolve salinity in the subsurface deeper than the root zone is electromagnetics (EM). Interpretations of EM (and most other

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

techniques) needs to be done by specialists and be checked by targeted ground-truthing, including drill holes and borehole logging. Magnetics can give complementary information on palaeochannels and other structures that could be zones of preferential groundwater flow.

This book covers 26 different methods for mapping salt stores, dryland salinity hazards and risk. It sets out the benefits and limitations of each technique together with useful information on costs, scale, survey design and the depth to which each technique is useful. The book comprehensively summarises the science that justifies the use of each mapping method and refers the reader to a range of references that will provide an even fuller technical explanation if necessary.

This book describes the usefulness of all relevant mapping methods (in use and proposed) for mapping dryland salinity in Australia, and describes their efficacy in the assessment of salinity hazard and risk. The book has the following elements:

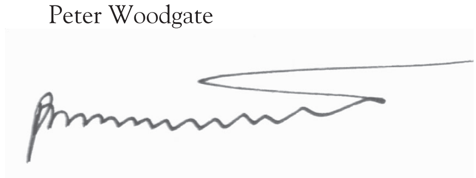
- background and context;
- typical questions posed at farm, community, catchment and national scales;
- a description of the interplay of salt and water movement in the landscape that controls salinity (framework factors);
- an assessment of salinity hazard and risk, and costs and benefits of mapping;
- information on mapping the landscape at different scales to solve salinity-related questions;
- a brief description of methods to map the landscape from the surface, boreholes, aircraft and satellites—salinity mapping methods are categorised as those that directly detect salt and those that use surrogate or indirect attributes to infer the presence of salt and are stratified by the level below the surface at which they operate;
- illustrative case histories describing the process of selecting appropriate mapping techniques for particular problems, including assessment of the future distribution of salinity as it is likely to affect the assets in the landscape such as agricultural production, biodiversity and infrastructure;
- appendices with expanded descriptions of each mapping method; and
- a glossary of key terms.

Brian Spies FTSE

Manager Science
Sydney Catchment Authority

<brian.spies@sca.nsw.gov.au>

Peter Woodgate



Chief Executive Officer
Cooperative Research Centre for Spatial Information
<pwoodgate@crcsi.com.au>

1. INTRODUCTION

WHAT THIS BOOK WILL TELL YOU

Salinity mapping methods in the Australian context provides up-to-date information about ways to map dryland salinity and strategies for making investment decisions for salinity management. The accompanying user guide provides a broad overview that is directed towards a general readership. This book contains an expanded description of techniques for salinity mapping, prediction and monitoring, as well as strategies for risk management. The book also contains references to published literature and extensive appendices with details of specific mapping techniques.

The book:

- looks at the information needs of four classes of user—the farmer at paddock level, the community at subcatchment level, the regional catchment planning authorities; and the State, Territory or national authorities;
- explains the difference between salinity hazard and risk;
- briefly describes the origins of dryland salinity; and
- provides detailed information about methods to map dryland salinity and its causative processes, including the investment decisions that need to be made, the cost, skill level, applicability and limitations of each method.

The information contained in this book should aid in the identification of the optimal approaches that can be used to obtain more information about salinity problems, and help in choosing between different management options.

This book assumes the reader has a good working knowledge of the science of mapping technologies. A plain English version of the report has also been prepared as a user guide and is intended for a broad readership of users who may not have an understanding of the science of mapping methods.

Salinised lakeshore of a former freshwater lake. Eucalypts are dead and halophytic (salt tolerant) plants have colonised the shore – Lake Dumbleyung, WA.

SCOPE OF THIS BOOK

This book reviews the range of available mapping technologies that can be used to support salinity management and multi-scale decision making. It is designed to fulfil the needs of a range of potential investors and users of mapping methods, including farmers and land managers; catchment and regional natural resource managers; State, Territory and Australian Government agencies; scientists; and vendors of mapping methods and systems.

This book covers mapping techniques that are useful in dryland salinity. While the same techniques are used for assessing irrigation salinity and primary (natural) salinity, and are sometimes useful for studying salinity in water bodies (lakes and rivers), the book is not explicitly designed to cover these other categories of salinity.

STRUCTURE OF THE REVIEW

This book has the following structure.

Chapter 1: Introduction, background, history and data sources

Chapter 2: Outline of user needs

Chapter 3: Simple description of the processes that govern the movement of salt in the landscape

Chapter 4: Process for the identification of risk, drawing on the explanations contained in Chapter 3.

Chapter 5: Use of the various mapping systems in mapping the landscape, soils, hydrology and salinity

Chapter 6: Process of integrating results from multiple techniques to generate maps of salinity hazard—data collected by mapping systems also have a key role in assessing risk to various asset classes for land and catchment management

Chapter 7: Survey design and data management

Chapter 8: Case studies that help illustrate the use of mapping systems for hazard and risk assessment

Chapter 9: Conclusions

Appendices with details of the mapping methods

References

Glossary of terms

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A BRIEF HISTORY OF SALINITY MANAGEMENT IN AUSTRALIA

Salinity in the form of salt scalds and saline seeps was recognised by the early settlers in Australia. Walter Ernest Wood, a railway engineer, is credited with first observing the link between land clearing and the development of salinity in railway dams in Western Australia. His distinguished and far-sighted observations regarding this relationship were first published in the *Journal of the Royal Society of Western Australia* in March 1924.

However even earlier records exist of the onset of salinity. John G Robertson, wrote in 1853 of his experiences in 1843 as an early settler in the Wannon district of western Victoria (Bride 1898). He observed that the introduction of sheep to the grassy plains of that area coupled with a severe frost and fire resulted in the sudden loss of tree cover in the gullies. Soon thereafter the deep-rooted herbaceous plants began to disappear, exposing the clay soil to cracking and slipping. Then

> *…the only soil is getting hard trodden with stock, springs of salt water are bursting out in every hollow or watercourse, and as it trickles down the watercourse in summer, the strong tussocky grasses die before it, with all others.*

The accelerating impact of salinity on Australia's wellbeing was brought into focus in December 1998 when the issue was put before the Australian Government by the Prime Minister's Science, Engineering and Innovation Council (PMSEIC 1999), and further reinforced by the National Land & Water Resources Audit (NLWRA) in 2000 (NLWRA 2001) which painted a grim picture of the extent of salinity in Australia. The flurry of large-scale studies made over the last five years to measure the extent of salinity, and to develop and test techniques for salinity mapping, hazard assessment and prediction are summarised by Stauffacher and English (2002), from which much of the following material is drawn.

The **NLWRA** in 2000 identified large areas of agricultural land (5 million hectares nationwide) that were adversely affected by salinity, and predicted that 17 million hectares could be at risk by 2050 through shallow or rising groundwaters. In addition, substantial areas of remnant native forests, streams and lakes, rural and urban infrastructure, and wetland ecosystems are being rapidly degraded by rising saline watertables and stream salinity.

An important component of the NLWRA dryland salinity report is the understanding of groundwater-related aspects. This was published as the National Classification of Catchments (Coram 1998) and Groundwater Flow Systems Classification (Coram et al. 2000b) and used as the basis for 'Hydrogeology and groundwater flow systems' (p. 20) of this book.

The National Action Plan for Salinity and Water Quality (NAP) was drawn up by the Council of Australian Governments (COAG) in 2000 and provides a basis for a national approach to salinity and water quality solutions by engaging the Australian Government, the States, Territories and communities. It represents an initial step in identifying high priority, immediate actions to deal with salinity, particularly dryland salinity, in key regions across Australia to assist regional communities prevent, stabilise and reverse trends in dryland salinity where they affect the sustainability of production, biological diversity and/or infrastructure. The focus is on 21 priority regions across Australia. The plan fosters the development of community-based, integrated plans to tackle salinity in the respective regions. The regional plans vary substantially from catchment to catchment to address specific needs and realisable targets.

The **Natural Resource Management Ministerial Council** draws representatives from governments of all States and Territories and the Australian Government. It was established to develop a coordinated approach to issues affecting natural resource management, including salinity, in Australia. A set of Resource Condition Indicators has been developed to provide details on how to monitor each 'matter for target' set out in the National Framework for Natural Resource Management Standards and Targets. The Resource Condition Indicators <www.ea.gov.au/nrm/monitoring/indicators/> include the 'land salinity' indicators of depth to groundwater, groundwater salinity, and location and size of salt-affected areas. Accurate assessments of salinity, and changes in salinity, are an important component of salinity management under this program.

The Murray-Darling Basin Commission (MDBC) is the executive arm of the Murray-Darling Basin Ministerial Council (MDBMC) and is responsible for managing the River Murray and the Menindee Lakes system of the lower Darling River, and advising the Ministerial Council on matters related to the use of the water, land and other environmental resources of the Murray–Darling Basin. The MDBC is an autonomous organisation equally responsible to the governments represented on the MDBMC as well as to the MDBMC itself. It is not a government department nor a statutory body of any individual government. The first Salinity and Drainage Strategy was adopted in 1988 (MDBC 1987, 1988). A subsequent strategy noted that, in the ten years to 1999, the initial strategy had achieved a net reduction in River Murray salinity (MDBMC 1999a, b).

The Salinity Audit for the Murray-Darling Basin (MDBMC 1999b) formed the basis for framing the Basin Salinity Management Strategy for 2001-2015 (MDBMC 2001). This strategy provides a 15-year basin-wide framework for implementing the NAP, State Salinity Strategies (South Australia, Victoria, New South Wales and Queensland), and regional salinity or catchment management plans. A key feature of this strategy is the adoption of salinity targets for each tributary valley and a Murray–Darling Basin target for the Lower Murray to maintain salinity at less than EC 800 µS/cm (i.e. drinking water quality) for 95% of the time. The targets are a performance indicator for measuring progress across the basin and a basis for accountability for the partner governments.

The Heartlands initiative (Cresswell 2004) is a long-term program combining research and on-ground works. It aims to develop sustainable land use in the Murray–Darling Basin. Heartlands is part of the CSIRO Healthy Country (Revitalising our Landscapes) Flagship Program. The Heartlands project is run as a consortium led by CSIRO and the MDBC, with the participation of State natural resource management agencies, catchment management boards, Landcare groups and landholders.

The National Dryland Salinity Research, Development and Extension Program (NDSP) was initiated by Land and Water Australia (LWA) in 1993 to facilitate cooperative research across disciplines, organisational boundaries and State/Territory borders to address the management of dryland salinity. The first five-year phase of the program was completed in 1998, and focused on improving the understanding of the causes of dryland salinity and on establishing a collaborative national focus on the research and development (R&D) effort. Outputs include *Salt Magazine* and the *Focus on Salt* newsletter <www.ndsp.gov.au/15_publications/publications.html>.

In 1998 the NDSP published Occasional Paper No 20/98 (revision number one) *Assessing the causes, impacts, costs and management of dryland salinity* by Martin and Metcalfe. This excellent report provides guidance on the causes of dryland salinity, options for mapping, and land use options and their costs.

A larger, second five-year phase extended from 1998 to 2003. This phase continued to identify and research the knowledge gaps in understanding of the causes and impacts of dryland salinity. It also investigated socioeconomic arrangements that encourage or impede appropriate management of salinity, new production options using saline resources and management of saline landscapes.

The outcomes of the NDSP, which concluded in 2004, have been integrated with other research on dryland salinity conducted in Australia into three manuals which comprise the *Managing Dryland Salinity in Australia* resource kit, all of which are available on CD ROM:

- the key findings that have emerged from 10 years of the NDSP;
- dryland salinity and catchment management; and
- on-farm decisions and catchment outcomes.

The first of these documents, *Breaking Ground* (van Beuren & Price 2004) summarises the six key messages that emerge from a decade of research into dryland salinity. These messages provide:

- a broad sweep across the evolution of understanding during that time;
- the options available for and the limitations imposed on salinity managers; and
- the important remaining gaps in knowledge that need to be addressed in future programs.

The other two documents (Robins 2004, Powell 2004) are resource directories, designed to enable the user to access desired information at the appropriate level of detail (see the NDSP website <www.ndsp.gov.au> for details).

National Airborne Geophysics Project (NAGP) was the first national trial of airborne geophysical techniques in salinity investigations. It was carried out in 1997/98 as the National Airborne Geophysics Project (NAGP 1998) under the auspices of the NDSP.

Notwithstanding a cautionary note on the need for skilled interpreters to guide analyses, the potential for airborne geophysics techniques to provide new insights into the subsurface geology and regolith, and into the distribution of salt and saline groundwater has gained wide attention (George et al. 1998). Airborne geophysical surveys are underway in strategically important areas of the NAP priority regions.

State/Territory salinity strategies for the control and management of salinity are now in place in most States and Territories. Typically, the State/ Territory strategies:

- outline the key issues pertaining to natural resource management of respective regions;
- delineate the actions being undertaken and planned to achieve desired outcomes and solutions;
- set priorities and targets for catchments; and
- highlight regional imperatives in terms of the required scientific research.

Victoria, South Australia, Western Australia and New South Wales have had salinity programs for around two decades. Now all States and Territories have strategies and plans.

The above list highlights the large amount of past and current investment in salinity research and evaluation in Australia. The quality and impact of these investigations have naturally been evolutionary in nature. Some of the early initiatives were enthusiastically embraced and supported, yet had mixed results due to an inadequate understanding of the science underpinning the techniques, and an often ill-informed approach to political and economic processes.

Significant advances in knowledge in the last few years include the recognition that biophysical evaluations and modelling scenarios need to be coupled with socioeconomic impact studies. The primary objective of much of the current work is to strengthen the scientific underpinning of mapping techniques and prioritise government and community expenditure where it is most cost-effective.

The goal of this book is to present a robust scientific basis for salinity mapping and risk assessment.

Severe salt scalding resulting from excess groundwater recharge from adjacent slopes – Warrenbayne, Strathbogie Ranges, VIC.

2. USER NEEDS

THE FOUR CLASSES OF USERS

Many individuals and organisations have an interest in salinity and a need to understand the presence and extent of current salinity. They may need to assess potential risks and management options arising from changes in salinity. Users range from individual farmers, to communities, catchment groups and regional authorities. Questions related to salinity depend to a large extent on the needs and budget of the user. Answers to these questions help users to make better management decisions.

Farm scale

Farmers have immediate, personal and business-related interests in salinity and while some may know about salinity indicators, others may not. Farmers usually focus on obtaining useful information at the paddock scale.

Key questions the farmer is likely to ask are:

- *Are there any indicators of salinity on my land?*
- *If so, how much more salinity am I likely to get, and when?*
- *Are my land management activities contributing to the problem?*
- *Is this salinity currently damaging any of my assets?*
- *If not, are there risks to any of my assets in the future?*
- *What can I do to stop it?*

Farmers often consider the cause of the salinity to be of secondary importance, except in the context of how the salinity can be best managed and the desire to be a good community or catchment citizen by minimising impacts to others.

Local community

A local community may consist of between 10 and 20 neighbouring farms that may have similar soils and hydrological flow system, located within a subcatchment. Their questions are likely to be similar to those asked at the farm scale, but with a greater community orientation.

- *How much salinity are we likely to get, and when?*
- *How serious is it now and how serious will it be in the future?*
- *What can we do to stop it?*
- *Is there anything we need our neighbours to do to stop it?*
- *Is there anything we can do to prevent us making it worse for our neighbours?*

Depending on their location within the landscape, some individuals in the community will find that their salinity problem will become worse, while others find that the problem will lessen as a result of the remedial action taken by themselves and/or their neighbours. This can raise the shared issues of equity and cost.

Catchment management groups

The operating area for regional-level planning for dryland salinity is the catchment level, where one or more catchment management groups have overall responsibility for developing an integrated management plan. The Australian Government is working with State and Territory governments, and catchment management groups to achieve effective action to manage salinity. In such regions typical questions are:

- *What is the overall level of the problem in the region?*
- *How do managers get that right mix of actions that tackle, prevention, recovery, containment and adaptation?*
- *Where are the best locations to put in salinity management options (e.g. drainage, revegetation works, salt interception schemes) that will deliver the salinity target (e.g. mg/L of salt being exported to the river, or lowered watertable) in the most cost-effective fashion?*
- *What information is needed to make sound investment decisions at this level?*

Investment decisions might be expressed in terms of an investment framework of where is it best to invest funds to maximise benefit (e.g. into mapping, modelling, new research and development, or into on-ground interception works).

Other dryland salinity management scales such as the expanse of the Murray–Darling Basin also exist.

False-colour 2.5 m resolution SPOT5 image near Boorowa, NSW, November 2003 (©CNES 2003).

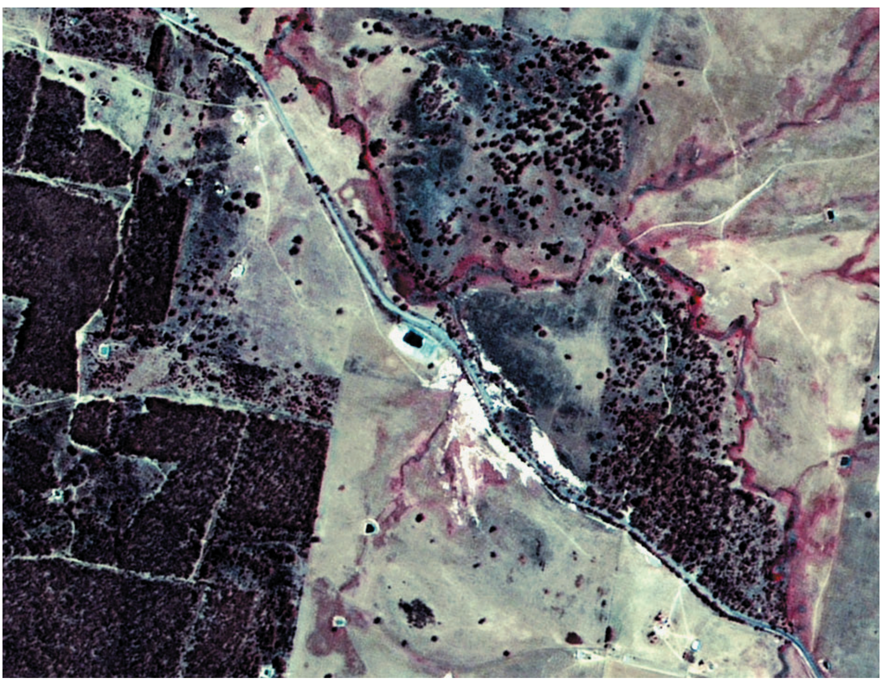


Image courtesy Spot and Raytheon

State/Territory and national land and natural resource management agencies

State/Territory and Australian governments have responsibilities and roles in managing dryland salinity. Questions at these levels include:

- *How much salinity is present, what is the distribution (both in land and rivers) and what are the trends (e.g. mg/L of salt, hectares affected or depth to watertable)?*
- *What is the impact likely to be on various classes of assets, and what are the priorities for management?*
- *What are the management options (e.g. where to locate interception schemes to achieve a target of a certain concentration measured in mg/L at Morgan?)*
- *Which environmental asset is of greatest priority, is at greatest risk and can be viably managed?*
- *What will the impact be on other areas if funds are insufficient for management? What resource sharing is required for investments outside the asset to manage the long-term ecological function and use of the asset?*
- *What are the overall effects of management options on whole communities through time?*
- *What are the priorities for management of other forms of land degradation and the opportunities for synergies for actions to tackle them together?*
- *In which initiatives should Australian governments invest to generate the best outcomes in relation to sustainability and profitability?*

Overall

At all scales the user needs to consider whether the existing information or knowledge base is adequate to address the hazard, risk and management responses. Additional questions a user might ask are:

- *Am I sure of the cause of the salinity?*
- *Will additional knowledge increase my capacity to more effectively manage the risk?*
- *Is new mapping, modelling or research and development required (and how much does it add to what do I have access to now)?*
- *Can I conduct this mapping myself or is other expertise needed?*
- *What are the relative costs and benefits?*
- *Who will bear the cost and who will gain the benefit?*

These questions are more complex for statutory land managers since they need to:

- understand salinity hazard and risk at all scales;
- balance competing interest groups; and
- use available funds to generate maximum return for public investment.

The key stakeholder is identified as the one who has the capacity and responsibility to study and manage the problem.

INVESTMENT DECISIONS (COSTS AND BENEFITS OF MAPPING AND MANAGING SALINITY)

The issue of investment analysis is complex and will vary in detail for each level of user and according to the identification of assets at risk (e.g. production capability versus infrastructure assets). At one level, investment analysis can be related back to the specific needs of the user (see Chapter 4).

- *What do I want to know?*
- *How can I get the best information?*
- *How much will it cost?*
- *What is the value of the assets potentially at risk?*

Five-step plan for assessing the need for new information

For a land manager who wants to know more about the dryland salinity that may exist on their land, the central question is *what are the costs and benefits associated with obtaining further information?* In order to answer this question the following five-step plan, adapted from George et al. (2000) can be followed, The first four steps produce a prioritised list of areas for which new mapping is likely to yield useful information, the costs of doing so, and the value of the assets to be mapped or affected by salinity. Step 5 considers the likely cost of possible management actions following acquisition of new information and the likely benefit of undertaking these management actions.

Step 1: Determine the value of the assets potentially at risk

A number of categories of assets are at risk from dryland salinity including agricultural productivity, infrastructure (e.g. roads, townships), water resources and biodiversity. Maps showing the location and value of these assets can help target areas and concentrate the effort required to collect new information and undertake any land-use actions.

Severe waterlogging resulting from excess recharge from cleared slopes – Boho, Strathbogie Ranges, Victoria.

Step 2: Assess the current level of knowledge about dryland salinity in the area of interest

Areas where we currently have a poor level of knowledge of the natural environment may be more likely to benefit from new information. Existing information should always be compiled and assessed to gain maximum understanding of landscape and hydrological processes before additional mapping is undertaken. State/Territory governments often have geoscience spatial information freely available that may be of assistance in understanding dryland salinity.

Step 3: Consider whether the mapping techniques you are proposing to use are suitable for the specific environment

Not all mapping techniques are applicable in all environments—some may be better suited to specific problems or be more cost-effective. Sequential or combined use of two or more methods may provide the most cost-effective and timely information.

Step 4: Identify areas where no useful remedial action is possible

In saline areas where no remedial action is likely to be available or new data is unlikely to improve or support remedial action, the acquisition of new information may have limited merit unless it assists in the understanding of salinity changes in a regional sense or serves to assure stakeholders that the optimum course of action is already being followed.

Step 5: Apply the benefits of this approach

Evaluate the benefits and costs of the mapping and interpretation proposal. The budget should include costs of pre-survey design, data acquisition, ground-truthing and calibration with borehole control, and interpretation.

HOW IT ALL COMES TOGETHER IN THIS BOOK

Answers to the questions posed above will help users to make better management decisions. Usually the most immediate issue for the user is:

> *Do I have a salinity problem? Or is there salt in the landscape somewhere on or under the land area that I manage that has the potential of being mobilised by water to cause problems for me or for others?*

Mapping salinity hazards involves describing the current extent, depth and concentration of the salt store and salt expression in the landscape. Some mapping systems can directly detect salt in the landscape (e.g. soil or borehole sampling) and some can indirectly infer its presence (e.g. through its effect on vegetation or by observing changes to electromagnetic conductivity signals). As salt occurs naturally within much of the land area of Australia, a positive answer to this question does not necessarily lead to a concern. The presence of saline soil does not necessarily imply a risk of developing dryland salinity.

However the next question does imply more serious consequences:

> *Is the land area that I manage and the assets that I value at risk of being adversely affected by dryland salinity at some time in the future?*

This assessment of risk is far more complicated than salt 'hazard' because it requires an understanding of the factors that operate to govern the movement of salt through time in such a way that the salt is likely to end up damaging the value of assets, either locally or some distance away, at some time in the future. Risk implies a prediction about the severity of the damage that is likely to occur and a prediction about when the damage will occur, and the range of assets likely to be affected.

Salt can only move in the landscape if it is dissolved and transported by water, or picked up by wind at the surface—wind movement is a comparatively minor problem. Many factors affect the movement of surface water and groundwater. The following factors define the **hydrogeological framework**.

- Climate: the long-term cycle of droughts and rains, evaporation and precipitation. Climate modifies the water cycle over time.
- Weather: the local affect of rain and sunshine. Weather determines the water cycle over shorter periods.
- Land use and management: the effect of tree clearing, farming, borehole water use and drains. Land use and management practices are the most powerful human-induced activities affecting dryland salinity.
- Terrain: steepness, the location of streams and rivers and break of slope. The combination of terrain and gravity drags water through the landscape.
- Regolith: the unconsolidated material between the surface and fresh bedrock, including soil and weathered rock. The regolith varies in its ability to allow water to permeate and be transmitted elsewhere (hydraulic permeability and transmissivity) and may contain preferential pathways for water movement.
- Soils: the varied composition and structure of different soils affect their susceptibility to the development of salinity.
- Ancestral or prior river and stream systems known as palaeochannels: occur within the regolith. These old stream or river systems that are buried and difficult to detect by the naked eye can preferentially permit the passage of groundwater.

Dry lakebed and shoreline of Lake Toolibin, one of the last ephemeral freshwater lakes in the WA Wheatbelt. Here, the saline watertable is controlled by intensive groundwater pumping.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

- Bedrock structural highs and buried rock masses: can act as barriers to the passage of water.
- Geological faults and dykes: may act either as underground channels that encourage the movement of water or as barriers to the passage of water.
- Vegetation: is most important because the roots of vegetation take up water through a process known as transpiration. Different vegetation types of varying ages and densities transpire different amounts of water. Moreover different vegetation types have differing abilities to tolerate salt when it comes in contact with their roots.
- Groundwater itself: its present location, depth, extent, rate of lateral movement and salt content.

These factors govern the rate, location and destination of groundwater. In order to predict salinity risks the behaviour of each of these factors needs to be understood and described. Ultimately the combined interpretation of the role of these factors can be used to prepare maps of salinity risk that show the extent, severity and timing of the threat of dryland salinity in relation to the class of assets being considered. A 'risk map' has higher inherent value (and is more likely to be acted on) if it is targeted at the particular asset for which management decisions need to be made. Modelling techniques are normally used to forecast risk.

Both the hazard map and the risk assessment can be regarded as information products, each of which can be prepared in a user-friendly format for immediate use by the decision maker who has the responsibility for considering management options. The confidence in the assessment will be directly influenced by the knowledge of the scale of the processes driving the hazard or risk, and this knowledge will be determined largely by the scale of the data available. The people making the decisions need to know the level of risk and uncertainty that is associated with their decisions.

3. SALINITY AND HYDROGEOLOGY

This chapter considers the interplay between salt, water movement and landscape processes. It looks at why hydrogeology and soil type are important in increasing our understanding of how the distribution and dynamics of both salt and water influence the estimates of current dryland salinity and the prediction of future salinity. If we can understand what is happening in the landscape we can undertake management actions to prevent, reduce or remedy the effect of dryland salinity.

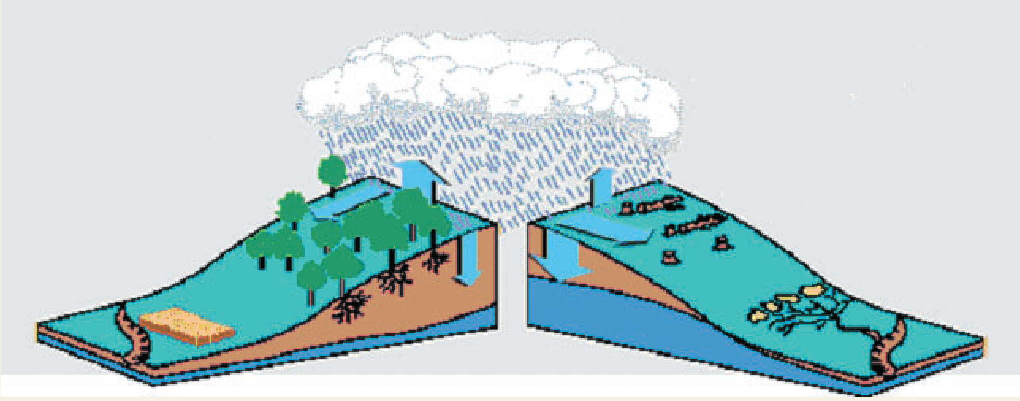
DRYLAND SALINITY

Dryland salinity is described in publications such as those of the National Dryland Salinity Program (e.g. Martin & Metcalfe 1998). Dryland salinity is the salinisation of land and water resources caused by land use, in particular agricultural dryland management systems, which result in rising watertables and the movement of salt to locations where it poses a problem for people or the environment. Rising groundwater occurs when the recharge of water is greater than the rate at which it can drain away, either horizontally or vertically. This leads to either salt being concentrated at the surface by evaporation or to saline discharges onto adjacent land, or into drainage systems, rivers and surface water bodies. Although dryland salinity specifically excludes salinity that results from rising watertable caused by irrigation systems (termed irrigation salinity), the geological processes and mapping techniques used to detect the salinisation, are similar. The main difference between dryland and irrigation salinity is in the management options available to address the salinity risk.

SALINITY IN THE MURRAY–DARLING BASIN

Dryland salinity in the Murray–Darling Basin has arisen from changes in the water balance following removal of native vegetation and introduction of European agricultural practices, most significantly the adoption of shallow-rooted annual crops and pastures (MDBC 1999b). Native vegetation, adapted, through evolution over millennia, to the environs of the dryland basin has a great capacity to optimise water use. Their extensive root systems draw water from deep within soils during dry times resulting in an increased soil water deficit and providing 'room' for the next season's rainfall (Figure 1). This reduces the tendency for waterlogging in the root zone.

Figure 1. The salinisation process in a dryland catchment. The native deep-rooted vegetation keeps watertables low; when the land is cleared, the watertable rises and mobilises salt. Drawing by Salt Action NSW.



Another type of salinity known as 'dry saline land' is not hydrologically connected to a saline watertable, and often occurs in upland, winter-rainfall zones such as semi-arid regions of New South Wales, Western Australia and South Australia (Fitzpatrick et al. 2003a). Two forms of dry saline land are recognised:

- 'surface expressed' where the salinity is very high at the surface; and
- 'subsurface expressed' where high levels of salinity occur in the root zone or subsoil (0.3 to 1.0 m) with salinity trends increasing from the surface to the subsoil.

Dry saline land can exist in both primary (natural) and secondary (induced) forms.

The first step in mapping the extent of dryland salinity and being able to predict changes is to understand the interplay of salt, landscapes, soils and water movement.

Mapping techniques (see Chapter 5) can be used to reveal the static and dynamic operation of the landscape, and to map and determine salt loads and pathways for preferential water movement. The integrated interpretation of these factors can then be used to 'map' and 'predict' salinity hazard and assess risks to assets from increasing salinity caused by changes in land use or other factors.

SOIL SALINITY

The broad categories of soil salinity (primary, secondary, dryland and irrigation) relate to the causes of salinity rather than to its chemical or physical character. For measuring soil salinity, it is more appropriate to consider the chemical composition that is directly related to physical and chemical properties on which most mapping techniques are based.

Soil salinity refers to the presence of salt in solution (plus readily dissolvable salts) in the soil, usually as measured in an aqueous extract of a soil sample. Soils naturally contain a broad range of solutes, the most common being sodium chloride (NaCl), but lesser amounts of potassium and sulphates are common. Ideally, it would be desirable to know the concentrations of individual solutes in the soil over the entire range of field water conditions, particularly when soil sodicity or toxicity of specific ions are to

Salinised swampland where rising saline groundwater has resulted in mortality of ancient *Eucalyptus camaldulensis* – Downes Swamp, near Broken River, VIC.

be assessed, but these measurements are usually restricted to laboratory studies.

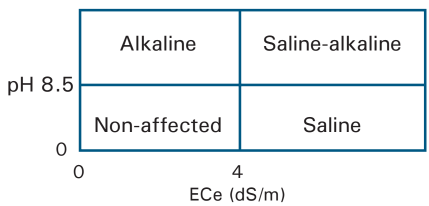
Direct or quantitative measurements of salinity are most often based on laboratory analyses of soil samples (with care taken to preserve water content) and the identification of ion concentration. Sometimes a simplified measure of soil salinity is made by laboratory or field measurements of the electrical conductivity of the extract of a saturated soil-paste sample (EC_e), or solutions of that paste, that bear a simple relation to solute concentration given assumptions about solute type. As the water/soil ratio approaches that of in situ (field) soil, the concentration and composition of the extract approaches that of soil water. Soil salinity can also be determined by measuring the electrical conductivity of a soil-water sample (EC_w), or by measuring a saturated soil-paste (EC_p), or from bulk electrical conductivity of the soil (EC_a). However, electrical conductivity (EC) of soil also depends on moisture levels and clay content. 'Measurement' of soil salinity based on electrical conductivity is thus an **indirect** or **inferred measurement**.

Soil salinity classes

Various descriptors are used to describe the amount of salinity[1] and sodicity in soils. These earlier classifications were expanded to include the relative amount of exchangeable sodium in the soil, measured as the sodium adsorption ratio (SAR), the proportion of sodium ions compared to the concentration of calcium plus magnesium (Table 2). A SAR value of 15 or greater indicates that an excess of sodium will be adsorbed by the soil clay particles, causing the soil to be hard and cloddy and slow to absorb water.

In reality, soils vary in a gradual manner, both horizontally and vertically, and the rigid classification schemes imposed by these classes are sometimes unnecessarily restrictive. Some users (e.g. Metternicht & Zinck 2003) advocate fuzzy or gradational classifications as being more applicable to mapping using remote sensing techniques.

Table 1. Traditional classification into saline, alkaline and saline-alkaline (US Salinity Laboratory 1954).



[1] It is interesting to compare these values with guidelines for drinking water. The Australian (NHMRC 2004) guidelines are total dissolved solids (TDS) < 180 mg/L, or EC < 30 mS/m. This guideline is based on taste rather than health factors, and is consistent with both the WHO and US EPA. The 'palatability' of drinking water rated according to total dissolved solids (TDS) concentrations (in mg/L) are <80 excellent, 80 – 500 good, 500 – 800 fair, 800 – 1000 poor and >1000 unacceptable. Water with extremely low total dissolved solids (TDS) may taste flat and insipid. Typical values of Australian drinking water in major reticulated supplies are TDS values from about 45 mg/L to 750 mg/L (EC 7 to 120 mS/m).

Table 2. Soil salinity and acidity classifications (after Brady & Weil 2002).

Soil	pH	ECe (dS/m)	ECe (mS/m)	SAR*
Normal or non-affected	6.5 – 7.2	<4	<400	<13 – 15
Acidic	<6.5	<4	<400	<13 – 15
Saline	<8.5	>4	>400	<13 – 15
Saline-sodic (saline-alkali)	<8.5	>4	>400	>13 – 15
Sodic (alkali)	>8.5	<4	<400	>13 – 15

* SAR is the sodium adsorption ratio = comparative concentrations of $[Na^{+1}] / [Ca^{+2}] + [Mg^{+2}]$ in the soil solution

Table 3. Soil salinity classifications used by the Western Australia Department of Agriculture (consistent with Chhabra 1996).

Soil	ECe (dS/m)	ECe (mS/m)	ECa (mS/m)
Non-saline	<2	<200	<50
Slightly saline	2 – 4	200 – 400	50 – 100
Moderately saline	4 – 8	400 – 800	100 – 150
Very saline	8 – 16	800 – 1600	150 – 200
Extremely	>16	>1600	>200

(after WA Department of Agriculture). See 'Conversion of soil electrical conductivity to salinity—calibration', p. 40, for descriptions of EC_e and EC_a

Units of measurement of salinity

Salinity refers to the presence of salt, either in solution or in solid form. When salts are in solution, salinity is often quantified in terms of the electrical conductivity of the solution. For example, the *CRC Handbook of Chemistry & Physics* (Lide 2004) defines salinity of seawater in terms of the electrical conductivity of the seawater sample, derived from a simple equation with coefficients based on the ionic concentration of constituents in normal seawater. The average salinity of seawater is S=35 parts per thousand (‰,) or 35 000 mg/L, which equates to conductivities of 3.8 S/m , 4.7 S/m and 5.8 S/m at 10 ºC, 20 ºC and 30 ºC, respectively.

The science of soil chemistry comprises a vast, detailed discipline underpinned by extensive background literature. A full coverage goes well beyond the scope of this ook, but we will discuss the key aspects of measurement of soil salinity as they affect measurement and mapping techniques. A comprehensive description of soil salinity is given by Rhoades, Chanduvi and Lesch (2002), from which much of the material in this section is drawn. While the text deals primarily with irrigation salinity, the discussion that follows is also applicable to other types of salinity. Other primary references are Geonics technical notes TN 5 and TN 6 (McNeill 1980a, b; Geonics 1998). A further description of units commonly used to measure salinity and electrical conductivity is given in 'Measurement of soil salinity by electrical conductivity', p. 39 (see discussion on units inside back cover).

SOME SYMBOLS USED IN SALINITY STUDIES

ρ_b	bulk density of soil
Θ_e	volumetric content of soil water of a saturated paste
Θ_f	volumetric content of soil water of a 'field capacity'
Θ_w	volumetric content of total soil water
Θ_m	mean volumetric content of soil water averaged over depth z
Θ_{wc}	volumetric content of soil water in the continuous-liquid pathway ('mobile water')
Θ_{ws}	volumetric content of soil water in series-coupled pathways ('immobile water')
ΔS_{sw}	change in soil solution salinity within the root zone
C_{dw}	concentration of salt in drainage water flowing from the root zone
C_{gw}	concentration of salt in shallow groundwater
EC_a	electrical conductivity of bulk soil
EC_{4P}	electrical conductivity of bulk soil measured with the 4-electrode method
EC_t	electrical conductivity measured at the temperature of the sample
EC_{25}	electrical conductivity referenced to a temperature of 25°C
EC_e	electrical conductivity of an extract of saturated soil-paste (EC_p)
$EC_{1:5}$	electrical conductivity of a mixture of 1 part by weight (g) dried soil to 5 parts by volume (ml) distilled water.
EC_w	electrical conductivity of soil water
EC_{wc}	electrical conductivity of Q_{wc}
EC_{ws}	electrical conductivity of Q_{ws}
EM	electromagnetic induction
EM_H	EM measurement with horizontal coils
EM_V	EM measurement with vertical coils
S_p	amount of salt removed from solution by precipitation of salt-minerals
SAR	Sodium absorption ration
SP	saturation percentage; the gravimetric water content of a saturated soil-paste
OP	osmotic pressure
z	depth in soil profile

THE INTERPLAY OF SALT, WATER AND THE LANDSCAPE

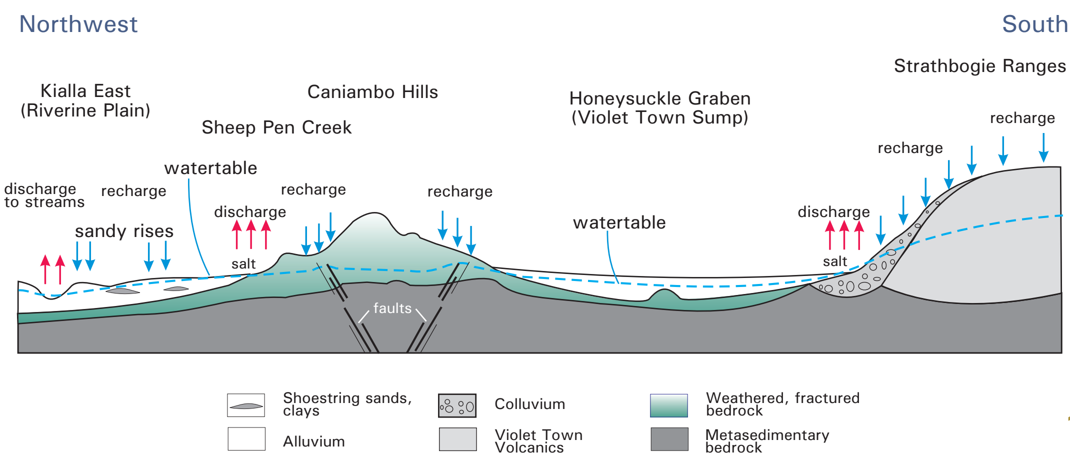
The well-known relation between solute content and electrical conductivity forms the basis for classification schemes of soil salinity and also for the measurement of soil salinity (see Appendix 1.3: Field measurement of conductivity of soil pastes and extracts and Appendix 1.5: Measurement of soil salinity by electrical conductivity).

Salinity as 'hazard' cannot be measured or mapped without due consideration of its spatial distribution and variability (both vertically and horizontally), and the degree and variation of water saturation and soil types. Salinity risk cannot be determined without an understanding of the movement of groundwater since this controls the mobility and transfer of salt stores, among other landscape factors.

Techniques commonly used to 'map' salinity hazards such as remote sensing, and airborne and ground electromagnetics actually measure other quantities such as optical reflectance at a fixed wavelength, natural gamma radiation, and electrical conductivity from which the presence of salt or salinity is inferred or interpreted. In many cases, water plays an equally important role in determining the response of a system; indeed the same 'salinity mapping' techniques have been applied successfully to mapping groundwater or variations in moisture content or identification of soil type.

In the context of salinity management and risk assessment, it is often equally or more important to accurately map water content, flow pathways and soil type, as it is to map salt itself. Salt may not be a problem to agriculture or the environment as long as it is immobile; some agricultural studies have shown that waterlogging has a greater impact on the production levels of certain crops than does moderate salt content. Preferred pathways for subsurface water movement through buried palaeochannels can often have a major influence on the movement of salt through the landscape and thus affect salinity prediction and management.

Figure 2. Schematic representation of the main groundwater processes in the Honeysuckle Creek Catchment, Victoria (drawing modified from Cheng & Reid 2001).



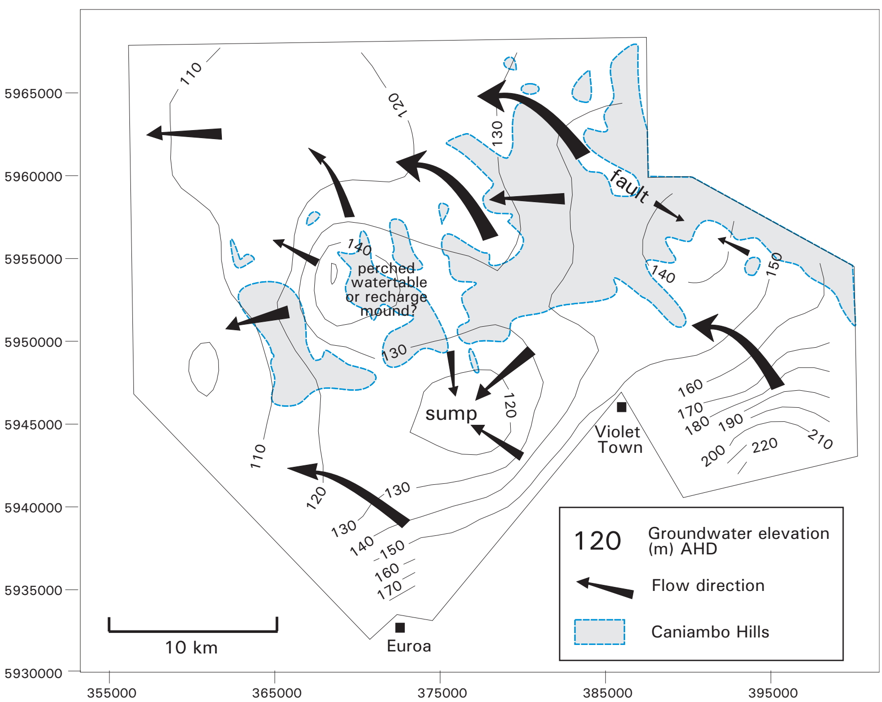
HYDROGEOLOGY AND GROUNDWATER FLOW SYSTEMS

The characterisation of groundwater movement vertically and horizontally at different scales is an important component of salinity studies. The catchment characterisation/groundwater flow systems (CC/GFS) approach described in the National Land and Water Resources Audit (NLWRA 2001; Coram 1998; Coram, Dyson & Evans 2001) is a hydrogeological framework that groups catchments of similar landscape and groundwater processes that contribute to salinity. It is a systematic approach that uses regional datasets (topography, geology and climate) to provide spatially consistent units that define groundwater provinces in which salinity-related processes and management can be grouped and analysed.

As described in the Salinity Audit and the NDSP 'Tools' project <www.ndsp.gov.au/salinity/tools>, groundwater flow systems can be conveniently categorised by scale as follows.

- Local groundwater flow systems (<5 km in length) respond rapidly to increased groundwater recharge. Watertables rise rapidly and saline discharge typically occurs within 30 to 50 years of clearing native vegetation. Examples are the deeply weathered granitic terrain in small catchments in south-western Western Australia, and the large regional alluvial aquifer system such as the riverine plains of the Murray–Darling Basin
- Intermediate groundwater flow systems (5 – 50 km) operate at a scale that may transcend local catchment boundaries. They have a greater storage capacity and generally higher permeability than local systems, and take longer to 'fill'

Figure 3. Groundwater flow direction inferred from watertable levels. From English et al. 2004.



following increased recharge. Increased discharge typically occurs within 50 to 100 years of clearing of native vegetation. Several subcatchments may share a common groundwater system operating over 10 to 20 km or more, yet may not comprise the entire region of a river basin.

- Regional groundwater flow systems (>50 km) are associated with large groundwater aquifers operating on a scale comparable with that of major river or groundwater basins. Regional groundwater flow systems have a much higher storage capacity and permeability than local or intermediate systems, and take much longer to develop increased groundwater discharge—probably more than 100 years after clearing of native vegetation. The full extent of change may take thousands of years. Examples of regional flows include the Murray–Darling Basin in Queensland; the Macquarie, Bogan, Castlereagh, Lachlan and Murrumbidgee catchments in New South Wales; the North East, North Central, Wimmera and Mallee regions in Victoria; and the Murray–Darling Basin in South Australia.

While a map of groundwater flow systems alone is not sufficient to assess dryland salinity risk or hazard, it provides an indication at the broadest level of potential exposure to risk from removing deep-rooted, perennial vegetation without further knowledge of catchment characteristics, such as the location of salt stores. Risk ratings can also be assigned to the various attributes that characterise a particular groundwater flow system (e.g. aquifer transmissivity, specific yield, catchment size), resulting in overall risk ratings for dryland salinisation, water salinity and salt load.

Salinity provinces can also be defined on the basis of other geological and geomorphic factors (e.g. regional groundwater flows that occur within the Riverine Plains of the southern portion of the Murray–Darling Basin where buried river valleys are in-filled with vast quantities of alluvial gravel. Regional systems also occur more westerly in the marine sediments of the basin. These two regional systems have inherent characteristics that make them function in different ways.

George et al. (2003) argue that an integrated geoscience (systems) methodology is the next step to the catchment characterisation/groundwater flow systems (CC/GFS) approach for extending the conceptual approach to the explicit mapping of landscape, salinity and groundwater elements.

CC/GFS maps are at present mainly used for broad, regional analyses due to the paucity of detailed three-dimensional geoscience data and a lack of data inputs at the subcatchment level. However, they are increasingly being used at the scale of subcatchments and farms. In moving from a broader-scale to subcatchment and farm scale GFS frameworks, the amount of data required increases dramatically because greater levels of landscape definition are required to understand local aquifer conditions and local variations in regolith and soils. The subsurface mapping techniques described in this report are well suited to the construction of three-dimensional images of the subsurface, at any scale if applied appropriately.

Areas of saline discharge, either at the surface or as groundwater seepage into streams, represent the surface expression of groundwater systems operating within the groundwater catchment; the manifestation of salinity is the result of the flow of saline water down an hydraulic gradient from the catchment. Once salinity has developed it is sustained by the groundwater flow regime. Understanding this concept provides the basis for remediation and management strategies.

It is worth emphasising that dryland salinity is a problem associated with increased water supply in salty landscapes. This additional water is associated with land use change from native vegetation to crops and pastures that use less water from deep in the soil. Climate, land cover, soil characteristics, salt stores and the hydrogeology and geomorphology of the landscape determine whether this increase in water is enough to cause dryland salinity (Coram et al. 2000a, 2001). Care must be taken to distinguish between seasonal and long-term trends (Ferdowsian et al. 2001). Mapping techniques described in the Chapter 5 are the means by which groundwater flow systems and landscapes are characterised and constructed, and can be applied at any scale.

Isotopic geochemistry

The age and isotopic composition of groundwater can be used to give information on the source of the groundwater, the aquifers through which it has flowed and the rate of its movement through a groundwater flow system. Since higher rates of movement have a greater potential to mobilise salt, isotopic geochemistry is a useful specialist technique in salinity studies. Stable isotopes such as strontium-87/86 are particularly good as groundwater tracers, because different aquifer lithologies have different strontium-87/86 compositions, and impart this signature to the groundwater as it flows through the aquifer. The isotopes oxygen-18 and deuterium (or H-2) can be used to indicate whether groundwaters have undergone open water evaporation (i.e. been recharged from a lake or river), and can also study old groundwaters that were recharged under different climates.

The radiometric carbon isotope C-14 is used to date water that has been in the ground for up to 40 000 years, and the groundwater ages obtained using this technique (also known as radiocarbon) can then be used to calculate rates of groundwater movement. Bennetts et al. (2005) describe the use of radiocarbon (C-14), oxygen and hydrogen isotopes to give insight into sources of groundwater salinity, the rate of groundwater movement and the time period over which salinisation has developed in the Willaura Catchment, western Victoria, which is badly affected by dryland salinity. English et al. (2004) describe the use of radiocarbon dating in the Honeysuckle Creek Catchment in Victoria to assess the degree of mobilisation of subsurface salt.

Chlorine-36 (half life 301 000 years) has been used to date water—for instance in the Great Artesian Basin up to 1 million years or more (Torgerson et al. 1991). Detailed interpretation of the chlorine-36/chlorine (Cl-36/Cl) ratios require an understanding of the sources of chloride and are potentially a valuable tool in salinity studies. For instance chlorine-36 has been used to trace salinity sources in the dry valleys of Victoria land, Antarctica (Carlson et al. 1990). Applications are also being made to solute balances in the Rio Grande in the USA where preliminary results indicate that, for example, low Cl-36/Cl and high strontium 87/86 ratios fingerprint a saline groundwater source (Phillips at al. 2005).

THE ROLE OF MODELLING

The dryland salinity mapping methods described in Chapter 5 provide a primary picture of the extent of a salinity hazard at some place in the landscape at a given point in time. The salt content is also known as the salt store. In order for this hazard to be assessed in terms of its potential to change through time (i.e. pose a risk to assets) it is necessary to understand the fundamental factors that govern the movement of salt in the landscape (see 'The interplay of salt, water and the landscape', p. 19). In broad terms these factors are:

- infiltration pathways of rainwater;
- groundwater and pathways for its movement;
- gross features at the surface and in the regolith such as basement highs, faults and dykes (geology and geomorphology);
- regolith permeability;
- land use;
- climate and weather; and
- vegetation.

These factors provide the framework to which the modelling techniques can be applied to predict salinity movement. They can be used as inputs to systems such as the groundwater flow system which builds on a comprehensive suite of around 14 factors including landform, aquifer transmissivity, temporal and spatial distribution of recharge, and responsiveness to land management. In 2003, the NDSP produced a CD on salinity models called PRISM (Practical Index of Salinity Models) that contains over 90 tools, models and frameworks to assist in natural resource management and planning at the regional scale.

Modelling systems such as FLOWTUBE (Clarke et al. 2001) produce a two-dimensional picture of the rate of flow of groundwater down through the catchment from point to point. FLOWTUBE requires knowledge of the hydraulic gradients, surface drainage features and the permeability of the regolith and soil. Unfortunately these later parameters are usually not well known and models rarely incorporate the variability inherent in most regolith materials.

The combination of modelling systems operating at different scales enables planners to predict the likely location of dryland salinity with greater accuracy. These predictive models are only as good as the data that are put in, the quality of the understanding of the complex interactions of the factors of the landscape and the validity of the decision rules that are applied to drive the model.

Many of the mapping techniques described in Chapter 5 can also be used to derive attributes that can serve as inputs to the models. These data can be referred to as framework data because they help build the holistic picture required for robust forecasting and planning.

4. RISK MANAGEMENT

The purpose of this chapter is to explain the fundamental concepts of hazard and risk and to relate them to salinity management. The terms hazard and risk have evolved over time and, in some cases, vary between States/Territories. The risk management process that is outlined below is based on the Australian and New Zealand Risk Management Standard AS/NZS 4360:2004 (Standards Australia 2004). It is useful first to revisit the formal definitions used in risk management, adopted from the standard for the purposes of salinity management.

DEFINITIONS

Asset: a natural or human-made physical entity. Typically, three classes of assets are recognised: land fertility (which accounts for agricultural productivity), built infrastructure (such as roads and buildings) and biodiversity (the natural environment).

Hazard: anything that can potentially cause harm to an asset. Salt is a hazard as it has the potential to cause harm to an asset if mobilised by water and transported to the asset.

Imminence: the expression of how soon within a specific time period a benchmark level of salinity is expected to be reached.

Impact: the degree of severity or the consequences of an occurrence of the hazard (e.g. increasing salinity) on an asset (e.g. land fertility, infrastructure or the environment). Impact can be expressed in a number of ways (e.g. as a level or concentration of salinity, as the effect of that salinity on an asset, as the financial effect on a relevant person or organisation or as the political effect). The benchmark level of salinity—defined as harmful to an asset—will depend on the nature of the asset, and also on how the results of any particular investigation are to be used.

Likelihood: the probability that a defined impact will occur within a specific time period.

Risk: the chance of something occurring that will affect the achievement of objectives (Australian Standard AS/NZS 4360:1999). In the context of salinity we can define the level of risk as the degree of severity of a hazard as it adversely affects a defined asset (e.g. agricultural productivity) multiplied by the probability of occurrence of that hazard at a specific time in the future. Thus the level of risk that is assessed in this way gives a measure of the level of unwanted consequences.

In effect, it is a way of weighting possible unwanted events by their likelihood. So a highly unlikely event that has serious consequences may be regarded as presenting the same risk as a likely event with minor consequences. Thus, classically,

$$\text{Level of risk} = \text{Impact of hazard} \times \text{Likelihood of occurrence of hazard at a specific time}$$

For example, where a risk can be expressed in monetary terms, a risk of losing \$10 000 where the probability is 1 in 10 per year can be expressed as a risk of \$1000 per year. A potential loss of \$100 000 with a probability of 1 in 100 per year carries the same risk.

However, in the case of salinity risk, multiplying the concentration by the likelihood has no meaning. Therefore it is necessary to express risk in a way that specifies both the impact level and the likelihood, without combining them. Thus it may be said of a particular asset that:

> *The risk of a concentration of C mg/litre being exceeded at a defined vulnerable target within 20 years is 90%.*

In this example, the impact is specified as the concentration of C mg/L, and the probability is specified as a time frame of 20 years with a probability of 90%.

Another view of risk, not covered in the standard, is that it is governed by the **vulnerability** of the asset coupled with the degree of expected or actual **exposure**, as depicted in Figure 2. The size of the triangle, or the size of the risk, is governed by the degree of separation of each of the apices. In this context vulnerability refers to the susceptibility of stakeholders, communities and the environment to the consequences of exposure to the hazard. Thus the vulnerability of a salt-tolerant pasture is much less than a salt-sensitive crop in the same location subject to the same level of salinity at the same time.

It is for this reason that maps that show the level of risk at a specific time are best prepared in relation to the perceived vulnerability of a *specific asset*. As different assets are likely to suffer different levels of consequences as a result of being exposed to the same concentration of salinity, ubiquitous maps of future risk are open to misinterpretation and may be misleading.

Risk management: the systematic process of identifying, analysing and responding to potential project risk. Risk management includes maximising the probability and impact of positive events and minimising the probability and consequences of events adverse to project objectives (ANAO 2003).

Figure 2. Risk diagram.

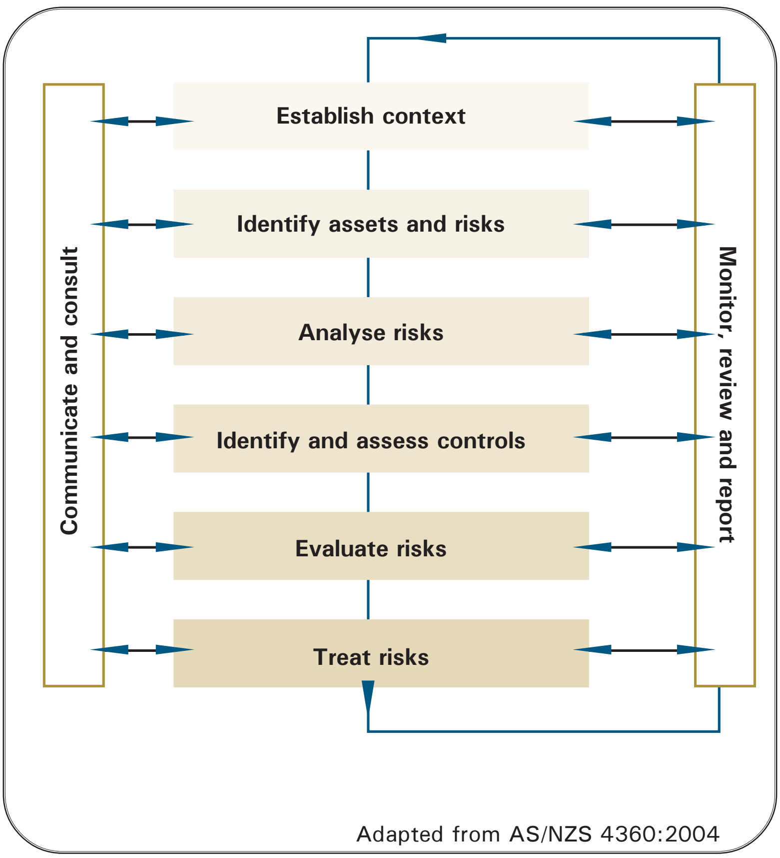
SALINITY RISK MANAGEMENT PROCESS

A systematic and robust process for risk management is described below and summarised in Figure 3.

The methodology of the process of risk management involves eight basic steps.

- **Establish the context.** Examine the physical, political and organisational environment in which the risk identification, analysis and treatment options will be considered.
- **Identify the assets.** Consider the range of things of value to the landowner and wider-scale community (economic, social, environmental) that should be protected.
- **Identify the risks.** Understand the typical problems and concerns that might adversely affect the assets under review.
- **Analyse the risks.** Rank the risks in order of importance based on likelihood of occurrence of a given hazard, consequence or impact of occurrence, and the degree of risk certainty for a specified asset.
- **Identify and assess controls.** Analyse risk mitigation alternatives, measure the effectiveness of controls and develop or modify the relevant plans to incorporate the control strategy.

Figure 3. Risk management process.



- **Evaluate risks.** Prioritise risks and continue to revisit the risk profile, re-evaluate major risks and update the risk profile with actions taken. It is important to identify the time scale of the risk at this point.
- **Treat risks.** Put mechanisms in place to reduce risk. Respond to events by implementing risk treatments. There are a range of options for treatment including: preventing the potential impacts; delaying the onset of potential impacts; limiting the extent of any impacts; responding or adapting to the increase in salinity (e.g. changing the nature of the activities in the areas affected, or increasing the resistance of the assets); or accepting the risk.
- **Communicate and consult.** Work with specialists, experts and stakeholders throughout the risk management process throughout all salinity risk activities. The stakeholders who are important in the management of the risk, in particular, the decision makers should be identified.
- **Monitor, review and report.** Provide regular reporting on risk and risk treatments.

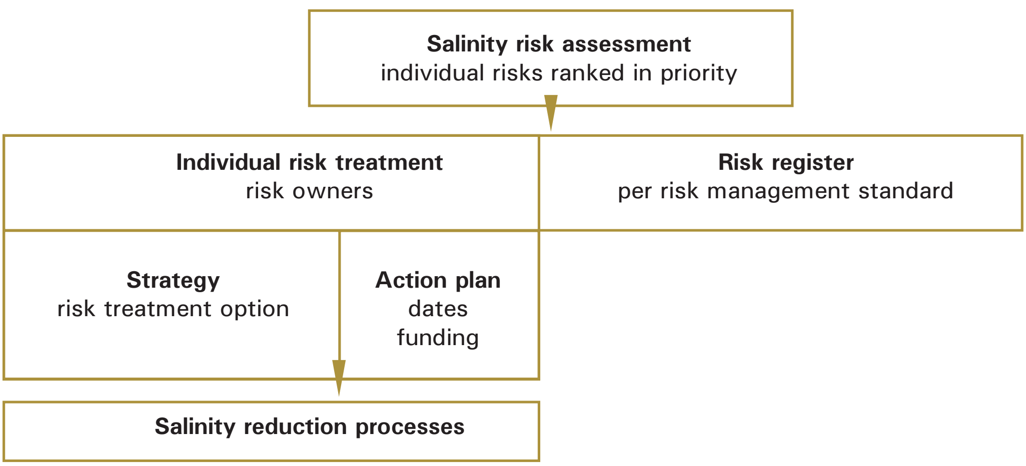
RISK MITIGATION

The overall focus in addressing risk is to use a formalised risk assessment process to determine priorities and timing. When addressing salinity risks, use the formalised process outlined in Figure 4.

The priorities will be determined by the level of risk, based upon Table 4, which has been developed using the related impact and likelihood Tables 5&6.

The focus for risk management is then on drawing up strategies and action plans to mitigate or reduce salinity risk.

Figure 4. Formalised process to address salinity risks.



RISK MATRIX AND RATING TABLES

The following risk definitions and rating tables are suggested for use when conducting salinity risk assessments. A separate estimate is made for each class of asset at risk.

Table 4. Impact or consequence table.

LEVEL	DESCRIPTOR	CONSEQUENCE – DESCRIPTION
1	Insignificant	Low socioeconomic loss, w percent of benchmark salinity level
2	Minor	Small socioeconomic loss, x percent of benchmark salinity level
3	Moderate	Higher socioeconomic loss, benchmark salinity level
4	Major	Major socioeconomic loss, y percent in excess of benchmark salinity level
5	Catastrophic	Huge socioeconomic loss, z percent in excess of benchmark salinity, level

Table 5. Likelihood or probability table.

LEVEL	DESCRIPTOR	PROBABILITY – DESCRIPTION
1	Rare	May occur only in exceptional circumstances
2	Unlikely	May occur at some time, but unlikely
3	Possible	Might possibly occur at some time
4	Likely	Will probably occur in most circumstances
5	Almost certain	Is expected to occur in most circumstances

Table 6. Risk matrix.

LIKELIHOOD	CONSEQUENCE Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
(5) Almost certain	S	S	H	H	H
(4) Likely	M	S	S	H	H
(3) Possible	L	M	S	H	H
(2) Unlikely	L	L	M	S	H
(1) Rare	L	L	M	S	S

H High risk	– immediate action required
S Significant risk	– high-level management attention needed
M Moderate risk	– management responsibility must be specified
L Low risk	– manage by routine procedures

Care should be taken when applying this table to ensure that the interval between the various steps on both the consequence and likelihood scales are commensurate, as mathematical rigour must be employed when multiplying out the table to determine risk. In practice, the ratings are often assumed to be logarithmically spaced, so that risk = impact + likelihood.

A SYSTEMATIC APPROACH TO SALINITY RISK MANAGEMENT

The remainder of this chapter provides a framework within which the applicability and limitations of various salinity mapping and mitigation methods can be assessed.

For any investigation to be effective, and to be economical in its use of limited resources of time and money, it should be undertaken in a systematic manner.

The generic flowchart at the start of this chapter, Figure 3, can be tailored to meet particular classes of risk. However, a universally accepted first step is to define the 'context' within which the risk management process is to be undertaken.

Defining the questions to be answered by the investigation

The following questions illustrate the types that may be asked at the level of an individual farm by the landowner. Similar questions are also relevant at the level of local council, catchment, region or State/Territory, as explained later.

- *What assets (e.g. crop, pasture, forest, water supply, structures, etc.) do I have that could be threatened by salinity?*
- *Do I have a salinity problem at present, or might I have one in the foreseeable future?*
- *What levels of salt would be critical for each of my threatened assets?*
- *What is the extent of my problem now? Will it get worse, stay the same or improve by itself?*

- *Is there any combination of salt source and water which could lead to critical levels of salt being exceeded for my assets at some future time?*
- *Might a critical level of salt be reached in five years, ten years, twenty years, my lifetime?*
- *What methods or technologies could be helpful in clarifying the nature and extent of my problem now; identifying the extent of any potential impacts; and determining the rate (i.e. how soon this may occur)?*
- *How confident can I be in any prediction made by these methods or technologies?*
- *What types of action may be feasible to prevent the potential impacts; delay the onset of potential impacts; limit the extent of any impacts; and respond or adapt to the increase in salinity (e.g. change the nature of the activities in the areas affected)?*
- *How much benefit could I potentially derive from those actions, and what might those actions cost?*
- *Which methods or technologies should I select?*
- *Where can I go for help or advice in selecting methods or technologies?*
- *What impact may any of my actions have on the salinity problems of others? With whom should I discuss this?*

When the context has been studied, the objectives and scope of the risk management task can be defined.

It should be noted that assets at risk from dryland salinity are often located some distance from the human activity that causes dryland salinity. For example, increasing salinity may affect adjacent farms or assets located far downstream. A study by the Murray-Darling Commission, *Determining the full costs of dryland salinity across the Murray-Darling Basin* (Wilson 2003) concluded that non-agricultural stakeholders such as urban, retail and industrial business, local governments and utilities bear two-thirds of the costs of the impact of dryland and urban salinity across the landscape. This excludes salinity damage to natural environmental and cultural heritage. Less than 33% of the costs of salinity directly affects farm income or the capital value of farmland. As concluded by the NDSP:

> *The results highlight the need for local action plans to consider the full costs and benefits of managing salinity in the urban and rural areas of a catchment, and not just focus on the costs and benefits to the agricultural producer.*
>
> Wilson 2003

Thus additional questions that should be added to the list above include:

- *Is the salinity risk on my land arising from land-use practices elsewhere in the catchment?*
- *Could my land-use practices or remediation efforts adversely affect an adjacent landholder?*
- *Where can I go for further information?*
- *How do I become involved in regional groups to tackle this problem more widely?*

In any risk management strategy, there is a need for ongoing monitoring and review to determine as soon as possible any significant change from what was predicted by the investigation, and any notable failure or success of the risk-reduction actions taken.

Excellent examples of risk assessments utilising landscape modelling frameworks are provided in catchment case studies carried out for the National Land & Water Resources Audit (NLWRA 2001). These studies were undertaken in a context in which the most appropriate data for answering the questions of stakeholders were not readily available, and the methods used were adapted to use the best available data and optimal approach. This context is common throughout Australia. Gilfedder and Walker (2001) reviewed dryland salinity risk methods in terms of their ability to predict future salinity levels. Their review, summarised in 'Methods for prediction of salinity risk' (p. 69), outlines composite index methods, strongly inverse methods and trend-based methods, and refers to examples of each. The main difference between these methods is the level of sophistication and data requirements. Composite index methods rely on user experience, strongly inverse methods rely on statistical relationships and trend-based methods incorporate objective data with temporal changes. All of the methods can be applied in a spatial framework using geographic information system (GIS) and used to prepare maps of areas predicted or hypothesised to be at risk of dryland salinity. However the levels of confidence one can have in the outputs of the different methods vary considerably, with trend-based methods generally providing the highest confidence.

A salinity hazard map defines the spatial location (both vertically and horizontally) and concentration of salt load. Salinity hazard maps are normally presented in summary form and do not include whether the salt can or cannot be mobilised.

Salinity risk maps should identify the actual class of asset under threat, the timing of the impact of that threat, the level of anticipated impact should it occur, and the geographic location of both the risk and the asset.

5. MAPPING TECHNIQUES

We are now in a position to describe mapping techniques that can be used to derive physical properties and maps of the landscape, soils, salt content and flow pathways. These mapping methods form the basis of user products that convey higher-level information for non-experts, managers and policy makers. They should be integrated with economic considerations (assets at risk, cost of data acquisition, processing and interpretation, cost of monitoring, consequence of doing nothing) in order to produce a salinity management plan. The techniques are described in detail in Appendix 1.

MAPPING LANDSCAPES, SOILS AND GEOMORPHOLOGY

A wide variety of mapping and measurement techniques is available for use in salinity studies. The technologies are drawn from the disciplines of soil science, hydrology, geology, geomorphology, geophysics and remote sensing, and are summarised in Table 7 (see p. 34). The mapping techniques comprise the twelve 'core datasets' that were described by George et al. (1998) for the NAGP and are needed to understand the landscape processes that govern the distribution of dryland salinity.

High-resolution aeromagnetics can be used to show detailed subsurface geological features.

Image courtesy UTS Geophysics.

It can seen from Table 7 that there is considerable overlap between the capabilities of some of these mapping techniques and thus in their derivative datasets. For instance, gamma-ray spectrometry can be used to derive both soil and geological maps. The actual mapping products with corresponding techniques used to make them are summarised in Table 8.

For catchment management purposes, the NAGP (George & Woodgate 2002) suggested that the twelve core datasets be compiled into a minimum of five information products to aid the decision-making process. These are:

- salinity risk maps;
- groundwater target maps;
- geological maps;
- regolith/salt store maps; and
- soils maps.

All these maps can be constructed in a variety of ways: the more data that are used the more complete the map will be, and the larger the area that is chosen the lower the cost (per ha) of the resultant product. Technological advances, too, will affect which elements are chosen to make up the suite of optimal techniques to provide each product.

Each mapping technique can be used for different purposes and end products, and a skilled interpreter will always combine as many different types of measurement as possible when producing an interpretation, or mapping, product. The user should also bear in mind the scale at which the data were acquired and the inherent spatial resolution of the technique. For instance, aerial photo may be used for mapping at 1:5000 scale; various satellite products have pixel sizes ranging from 1 to 10 m or coarser resolution. Airborne methods measure average response over a 'footprint' associated with flying height and speed. Ground measurements provide a more accurate measurement at one point, but may not reflect the inherent geological variability unless measurements are taken at a high spatial density.

There is an intimate relationship between the landscape, its geological and climatic history, weathered and transported soil types, groundwater and the hazard posed by salt load within the soil. These factors can be combined using an integrated approach to landscape mapping, as demonstrated by Geoscience Australia and CRC LEME (Lawrie et al. 2000). The integrated approach includes detailed regolith studies and palaeogeographic reconstruction to delineate the subsurface geology, regolith architecture and salt distribution. This multidisciplinary 'geological systems' approach is used to generate a three-dimensional picture of the subsurface and associated saline groundwater, salt stores and flow systems that deliver salts to the discharge site (see 'Hydrogeology and groundwater flow systems', p. 20). Detailed studies of the regolith using airborne geophysics and borehole investigations (Lawrie et al. 2002) demonstrate that the subsurface has much greater variability than that inferred from surface measurements, and at catchment and subcatchment scale the effects of variability in the regolith are likely to be particularly significant in influencing salt store and local groundwater flow.

Table 7. Mapping techniques and capabilities.

MAPPING TECHNIQUE[1]	WHAT IS MEASURED	WHAT IS INFERRED
Digital elevation models[2] (DEM)	Height above sea level, topography	Drainage patterns, rainfall, run-off and seepage.
Air photos	Optical photograph of ground, often in stereo pairs	Land use, vegetation, drainage, salt scalds, changes over time
Hydrology	Watertable depth and quality in boreholes, river gauges	Local and regional flow patterns
Multispectral	Reflected electromagnetic energy at various wavelengths	Moisture content, soil classification, vegetation type and stress, salt scalds, changes over time
Field geology	Exposed rock and soil types and relationships	Regolith landforms and evolution, structure, bedrock, framework, salt scalds
Magnetics	Magnetic field (from magnetic minerals in soil and rock)	Geology and structure below surface, barriers to fluid flow
Gamma-ray spectrometry (radiometrics)[3]	Gamma rays from U, Th, K in surface soil	Soil classification, geomorphology, regolith
Electromagnetics	Secondary magnetic field from induced electric currents, converted to conductivity,	Salinity, depth of weathering, palaeochannels, fresh water
Meteorological data	Past and present temperature rainfall, evaporation	Potential for water movement
Soils	Types and attributes of soils	Land management units etc.
Land use, vegetation cover	Type of crop or vegetation	Soil type, quality, hydrology, biodiversity
Cadastre, roads, farms, dams	Accurate maps of human activities	Planning

1 A number of rarely utilised, ground-based, geophysical techniques have application to particular aspects of hydrology and landscape mapping. Nuclear magnetic resonance (NMR) and seismo-electric techniques measure water content directly, and are thus useful for determining hydrogeological parameters. Ground-probing radar (GPR), seismic refraction and reflection, gravity and magnetics can be used to map soil and bedrock structures. Induced polarisation (IP) and gamma ray spectrometry (radiometrics) are useful in mapping soil types. These methods are summarised in Appendix 1.9. Others methods are described later in this chapter.

2 The recommended accuracy for a digital elevation model (DEM) intended for groundwater modelling is at least ±1% of the elevation range in the area. For modelling within individual paddocks, accuracy of ±a few cm is desirable if possible. DEM data is normally acquired simultaneously with airborne electromagnetics.

3 Airborne gamma-ray spectrometry and aeromagnetics are normally acquired together.

Table 8. Mapping products and techniques.

MAPPING PRODUCT	TECHNIQUES USED
Digital elevation model (DEM)	Airphoto, satellite imagery, airborne radar, laser scanner on airborne geophysical platform, ground measurement.
Geological map	Airphoto, multispectral imagery, hyperspectral imagery, airborne geophysics, ground inspection
Soil map	Ground inspection, satellite, air photo, radiometrics, EM, laboratory analysis
Regolith map	Satellite, air photo, airborne geophysics (radiometrics, airborne EM and magnetics), ground inspection, laboratory analysis
Landscape map	Airphoto, satellite imagery, DEM, regolith – this is not a technique
Land use map	Ground inspection, satellite, air photo,
Hydrological map	Airphoto, airborne and ground geophysics (especially electrical and electromagnetics), radar, borehole measurements, soil types, subsurface water and stream EC measurements
Conductivity profile or map (closely linked to salinity)	Ground electromagnetics (EM), borehole EM, airborne EM, conductivity measurements on pastes and soil samples
Existing (surface) salinity map	Satellite, air photo, remote sensing, radar, land use, ground geophysics, ground inspection
Salinity hazard map	Satellite, air photo, radar, airborne geophysics, ground and borehole geophysics, land use description, hydrology, regolith, soil analysis, field inspection

The following example (courtesy of Richard Lane, Geoscience Australia 2003) shows how two airborne geophysical techniques—airborne electromagnetics (AEM) and aeromagnetics—can be used to map regolith units without consideration of notions of 'conductivity' or 'salt-store'.

The magnetic image on the left of Figure 5 serves as a reminder of how magnetic data are generally used. Magnetic maps are predominantly images of magnetite concentrations, yet aeromagnetic surveys are not commissioned to determine the quantities of magnetic minerals per se. Instead, spatial patterns in the distribution of magnetic susceptibility are used to infer boundaries of geological units. The patterns in this image reveal the superficial watercourses and buried palaeochannels where these coincide with appreciable amounts of magnetic mineral accumulation. The actual magnetite content inside or outside the channels is unimportant—the real interest lies in the existence of a petrophysical contrast (in this case magnetic susceptibility) that allows recognition of the channels.

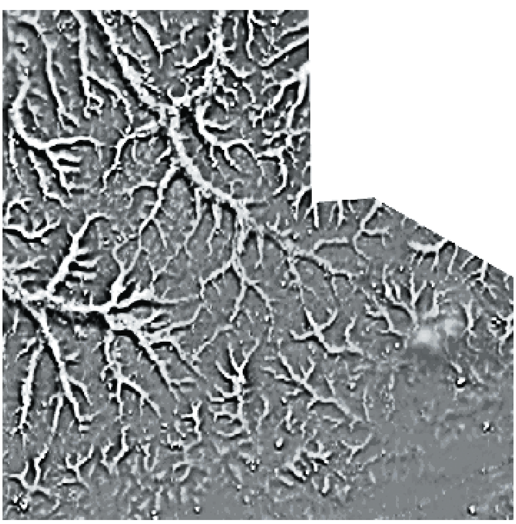
Similarly the use of AEM to determine salt stores may be a secondary goal. AEM is often used to map regolith units through analysis of spatial patterns. In the conductivity image of the same area shown on the right of Figure 5, it is possible to identify buried channels (A), a distinct sub-basin (B), upland areas with thin regolith cover (C) and an east-west break in pattern (D) without considering the possibility of salt stores.

Soil landscape mapping

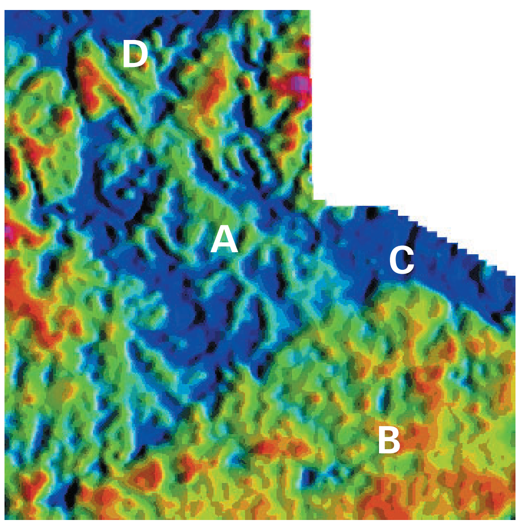
The NSW Department of Infrastructure, Planning and Natural Resources (DIPNR) has carried out a comprehensive soil-landscape mapping exercise for the entire state which delineates areas with relatively uniform soil types and landscape characteristics as a crucial step in assisting land management. Soil mapping methods include geology, remote sensing, geophysics, vegetation, topography air photos, as well as compilation of other maps and reports. Essentially, such studies underpin salinity assessment and management.

Figure 5. Regolith mapping using airborne geophysics. Enhanced magnetic image (left) and conductivity image (right). The magnetic image is first vertical derivative of total magnetic intensity presented as greyscale. The conductivity image is the 10 to 15 m depth slice, where the hotter colours (closer to red and magenta) and indicate higher conductivity values. Images prepared by Richard Lane (CRC LEME /Geoscience Australia) from data provided by the Murray-Darling Basin Commission.

(a)



(b)



The following pages describe 26 mapping techniques for dryland salinity and these are summarised in the table starting on page 56.

DIRECT METHODS FOR MAPPING SALT

'Direct' methods are usually employed to quantify the presence of salt at individual locations. These methods are not, strictly speaking, mapping methods unless sampling is comprehensive enough to extrapolate between sampling sites. 'Salt' is used to describe mineral salts such as sodium, potassium and calcium chlorides and sulphates. Very few mapping techniques measure salt directly. Even traditional electrical conductivity methods require knowledge or assumptions about solute, clay content and moisture levels. Techniques that may be classified as 'direct techniques' are listed in the next few pages. Specific direct and indirect techniques are described in more detail in Appendix 1.

Visual inspection

Visual inspection includes the identification of salt scalds and salt pans where salinity reaches the ground surface, and the observation of vegetation type and health from which the presence of salinity in the root zone is often inferred. Field guides to plants found in saline soil have been published for Victoria, but not for other States.

Field inspection (Appendix 1.1) is an essential component of the calibration and validation process of broadacre mapping and should also be planned for in the initial survey design.

Visual inspection.

Measurement of total soluble salts

Total salt concentration can be determined or estimated from measurements made with a range of in situ or remote sensors (Rhoades & Oster 1986):

- aqueous extracts of soil samples (Appendix 1.3);
- samples of water obtained from streams, the soil or in boreholes (Appendix 1.4);
- in situ, using buried porous salinity sensors that imbibe soil water and measure its electrical conductivity; and
- remote measurements of the electrical conductivity of bulk soil, using 4-electrode galvanic sensors, electromagnetic (EM) induction conductivity meters or time-domain reflectometry (TDR) and insertion parallel-guide electrodes.

EM is the most widely used technique. For the sake of completeness the TDR technique is mentioned here. This technique measures the dielectric constant and electrical conductivity of the soil from attenuation of a voltage pulse and the time it takes to pass through the soil, as guided by two parallel rods inserted into the soil (e.g. Noborio 2001). Such systems have promise as they can measure water content and conductivity simultaneously, but the range is restricted to the immediate vicinity of the sensor.

Research is also being carried out on direct in situ analytical instrumentation suitable for field use, such as ion-specific field-effect transistors (ISFETS) (Hancock & Raine 2001). Such in situ measurements are preferable since they are made in field conditions, without disturbing or disassociating the soil.

Laboratory analysis

Soil sampling with subsequent analytical chemical analysis in the laboratory is the most rigorous method of quantitatively evaluating soil salinity. Samples can be taken at the surface, as well as in the root zone or at greater depths through augering or trenching. Field procedures involve the use of saturated paste extracts of soil samples and soil solution extracts, from which analytic procedures such as the analysis of cations and anions can be performed. Similar techniques can be used for groundwater and water extracted from soil. Complete analyses of multiple chemical species can be obtained from analytical testing at commercial laboratories (see Appendix 1.2).

MEASUREMENT OF SOIL SALINITY BY ELECTRICAL CONDUCTIVITY

Electrical conductivity of an aqueous sample is easily measured and is a practical index of the total concentration of ionised solutes in the sample. For soils, the procedure is more complex and a multitude of techniques have been developed, mostly based on indirect measurements. The most common techniques for measuring (or inferring) salinity in Australia are EC extracts on paste-water samples or measurements of the bulk electrical conductivity of the soil (EC_a) with portable terrain conductivity meters. Borehole and airborne sensors are also used, depending on the level of detail (scale) required.

Factors affecting soil electrical conductivity

Soil is a complex mixture of minerals, organic materials, liquids and gases. The electrical conductivity of soil is controlled by the passage of electrical current through the soil matrix and influenced by a number of factors (McNeill 1980a) including:

- porosity—the shape and volume of pores;
- permeability—the interconnectedness of pores through which fluids can flow;
- moisture content—the extent to which pores are filled with water;
- temperature and phase state (liquid/gas) of the pore water; and
- the amount and composition of colloids such as clays.

The measured electrical conductivity of soil may be greater than, or less than, the conductivity of the pore water. In soils with low salt content the effect of clays usually dominates, and the conductivity of a clay-rich soil can be an order of magnitude higher than the conductivity of the pore water (Emerson & Yang 1997). Conversely, in soils with high salt content the contribution to conductivity from the salt concentration generally outweighs that from cation exchange capacity, and is relatively independent of the clay content. Field studies by Fitzpatrick et al. (2003b) show that EM tools (see 'Shallow electromagnetic conductivity mapping', p. 46) can be used effectively to identify and map areas of 'dry saline land', where salinity is present above the watertable.

Moisture content can markedly affect measured conductivity and, in areas of low and relatively constant salinity levels, EC_a measurements can be used to map moisture content (Job et al. 1998). Thus interpretation of EC_a values in terms of salt content is non-unique and depends on other assumptions about soil properties. However studies in Australia (Baden Williams, pers. comm., 2003) have found that between 75% and 90% of EC_a values can be usually explained by total soluble salt content.

The chemical composition of pore water can also influence the relationship between electrical conductivity and salt content. For example, waters high in sodium bicarbonate ($NaHCO_3$) which occur in some areas of Australia (e.g. the Great Artesian Basin) have electrical conductivities approximately half those of waters with similar concentrations of sodium chloride (Schofield & Jankowski 1998). Carbonate or sodic waters may pose a greater risk to vegetation than saline waters if hazard maps are based on uncalibrated EC values. However chloride concentrations normally dominate bicarbonates in Australian waters in areas of moderate to high salinity, and bicarbonates are rare in the Murray–Darling Basin (Angela Giblin, pers. comm., 2003). The relationship between pore water chemistry, groundwater chemistry and soluble salt content of soils is complex and can only be unravelled by detailed field studies. Field validation procedures described in the next section assist in addressing this issue.

A more detailed discussion of factors affecting conductivity is given in Appendix 1.5.

Conversion of soil electrical conductivity to salinity—calibration

Deriving salinity values from electrical conductivity measurements depends on the establishment of empirical equations that relate depth profiles of soil electrical conductivity of a saturated paste extract (EC_e) or soil water extract ($EC_{1:5}$) to bulk electrical conductivity (EC_a) obtained from EM measurements (see 'Indirect methods for mapping salt in the root zone [10 cm to 2 m depth]', p. 45).

Many calibration approaches have been proposed, based on various types of statistical methods (e.g. Rhoades et al. 2002; Triantafilis et al. 2000). Numerous studies in Australia have derived calibration equations that work reasonably well in particular areas under constant hydrological conditions. However it should be noted that the volume of earth sampled by EC_e measurements on soil samples is much smaller than EC_a values from EM tools. Variations in the salinity profile with increasing, uniform or decreasing depth can be determined by comparing vertical and horizontal orientations of ground EM conductivity tools (McNeill 1980b; see also 'Shallow electromagnetic conductivity mapping', p. 46), from borehole EM logs or from inversion of broadband EM data (see 'Indirect methods for mapping salt in the root zone [10 cm to 2 m depth]', p. 45).

EC_a measurements should only be made in dryland soils during the time of the year when soils are sufficiently moist for the measurable-conduction of electricity. It is inappropriate to try to infer salinity from measurements of EC_a made on dry or nearly dry soil, and also

Conductivity mapping with EM34 electromagnetic induction system.

to include salinity analyses of such soils in the data used to establish EC_a versus EC_e calibrations.

Discussion—biophysical impact of salinity

The deleterious effect of high concentrations of soluble salts in plant growth are mostly related to the increasing difficulty of extracting water from highly concentrated solutions because of increased osmotic pressure (OP), which is quantitatively related to the EC_e of the soil (Chhabra 1996).

However Rhoades et al. (2002) argue that the salinity of soil water (the water that is accessible to plants) may be much lower than that estimated from EC_e. This is because salts will often be present in the saturation-extract that would not be in solution under actual field conditions. Additionally, salts contained within the fine pores of aggregates will contribute to the EC_e value, though it is doubtful that significant amounts of such salts are absorbed by plant roots or affect the availability of most of the water extracted by the plant (which is primarily that present in the larger pores).

In-stream sampling

In-stream sampling is a simple and inexpensive approach for locating salty 'hot spots' in streams and rivers as well as identifying sources of freshwater. The technique is also useful for providing an indication of which parts of the catchment above the stream might be contributing proportionately more salt into the stream. Measurements are made with small portable electrical conductivity (EC) meters to measure point sample, or a towed EC array (Appendix 1.4.) These surveys indicate variations in stream EC at a subcatchment scale and allow definition of those subcatchments that are expelling saline water or which provide fresh water sources for dilution flows.

The method can have the advantage of high community participation by engaging communities to conduct the in-stream sampling and thus to better understand the landscape processes operating in their area.

In-stream conductivity sampling.

INDIRECT METHODS FOR MAPPING SURFACE SALT (0 TO 10 cm DEPTH)

A wide variety of indirect techniques have been applied to map salt at or near the Earth's surface. Many of these methods are, in effect, extensions of visual inspection, where large areas are investigated from aircraft or satellites by the measurement of electromagnetic radiation in either the optical range or at other electromagnetic wavelengths. These techniques include photographs, multispectral and hyperspectral scanning, and measurement of gamma radiation, either from aircraft or satellites. Of the indirect methods, electrical conductivity methods are the most important for mapping salinity below the surface, and can be used at site, local and regional scales with generally increasing depth of penetration. All indirect methods require targeted ground-truthing.

Other methods are based on remote measurements of physical properties of the ground such as near-surface electrical conductivity from which salinity or moisture content can be inferred—inductive electromagnetic techniques that probe deeper than 10 cm are covered later in this section.

Aerial photo interpretation (API)

Aerial photo interpretation (Appendix 1.11) is the oldest remote sensing technique for broadacre mapping and involves the systematic acquisition of photos (traditionally in analogue form) from precision cameras mounted on aircraft. Salinity-related mapping usually involves the detection of visible salt on the surface, or the identification of surrogate measures such as vegetation patterns or water-bodies from which salinity might be inferred. Air photo interpretation can provide an indication of the surface or root-zone expression of salt where it picks up specific vegetation types or patterns that may indicate the presence of salt. It can, therefore, be a reliable mapping technique for existing surface or near-surface salt when interpreted by an experienced operator. It is not, on its own, a useful tool for predicting where salt might occur in the future.

Mapping might also involve detection of drainage lines (hydrology), landform, geology or geomorphology to help with an understanding of landscape processes for the purposes of risk assessment.

A recent development in Australia is the introduction of digital cameras. These cameras acquire digital images as frames which can be subjected to similar photogrammetric correction and analysis as the print (analogue) with the benefit that the initial acquisition in digital form allows for straightforward subsequent digital processing. Digital photography is readily assimilated with other digital data and subsequent computer-based analyses. No significant projects using digital photography to map dryland salinity have been reported in Australia yet.

Modern automated photogrammetric methods can map elevations to an accuracy of tens of centimetres provided adequate ground control exists. Alternative technologies for mapping topography, such as airborne laser scanning (ALS) and airborne laser terrain mapper (ALTM), are fast gaining acceptance and should replace aircraft altimeter radars as they are both more reliable and accurate in vegetated terrains.

Airborne and satellite radar

Radar techniques (Appendices A1.12 and A1.21) measure the complex reflectance of the Earth from electromagnetic radiation in the microwave (5.7 to 68 cm or 5.3 to 430 MHz) range by generating an active pulse transmitted from an aircraft or, more recently, from satellite platforms and reflected off the earth. They have been used in research trials for salinity mapping because they are able to infer the moisture content and, to a lesser extent, the chemical composition of the soil. They do this through a complex property of the ground known as the dielectric constant, which affects the transmission and reflection of the incident radar signal. However most radar systems give very little penetration of the surface and generally do not see lower than the root zone. They require relatively moist ground conditions across the area to be mapped and the radar signal can be confused by the overstorey vegetation. Nevertheless they have been trialled over certain tropical areas in Australia (Bell 2002) and southern Australia with some useful results. The mapping products from the two areas quoted by Bell are yet to be independently validated by ground studies that use other data sources to systematically evaluate the outputs of this mapping.

Light detection and ranging (LIDAR) is a derivative of radar that measures surface material properties as well as elevation information using lasers. Some LIDAR instruments measure laser fluorescence to measure pollutants in shallow water bodies.

Airborne and satellite-based radar systems also have the ability to produce digital elevation models of high quality over large areas. The NASA shuttle-based mapping systems known as the Shuttle Radar Topography Mission used the space shuttle *Endeavour* to acquire radar data over 80% of the Earth's surface in February 2000. The conversion of these data into a DEM is now virtually complete and the data will be released by NASA in due course. The on-ground resolution of the data is 30 m and the vertical accuracy is about 16 m.

Airborne mapping with combined magnetics and radiometrics.

Photo: Fugro Airborne Surveys

Airborne and satellite imaging spectroscopy

The term 'imaging spectroscopy' includes methods that measure reflected sunlight in the visible to short-wave infrared range (0.4 to 2.5 microns in wavelength) and emitted blackbody radiation in the thermal infrared (8 to 12 microns in wavelength) regions of the electromagnetic spectrum, to create images of the surface of the Earth. Such measurements can be made from aircraft or satellites and can cover large areas at high resolution.

By measuring the complex spectra of signals reflected from the Earth's surface it is possible to see vegetation types and infer the effects of stress, particularly for patches of vegetation that are adversely affected by the presence of dryland salinity in the root zone. Under ideal conditions it is also possible to infer mineralogy of iron oxides, sulphate, hydroxyl and carbonate mineral assemblages and, by association, surface salinity. However ground control and local knowledge are important for the accurate interpretation of some properties.

Satellite and airborne systems can now acquire images that resolve objects on the surface of the Earth that may measure just a couple of metres square in size. They can cover tens of thousands of square kilometres in a single pass and repeat that pass every day.

The techniques include multispectral, hyperspectral airborne and satellite systems, and video systems.

These techniques are not fully operational and require some expert user input for reliable interpretation of the data. A good overview of applications for salinity is given by Howari (2003) (see Appendices A1.14, A1.15, A1.19 and A1.20).

Schematic of swath coverage obtained with satellite spectral imaging systems.

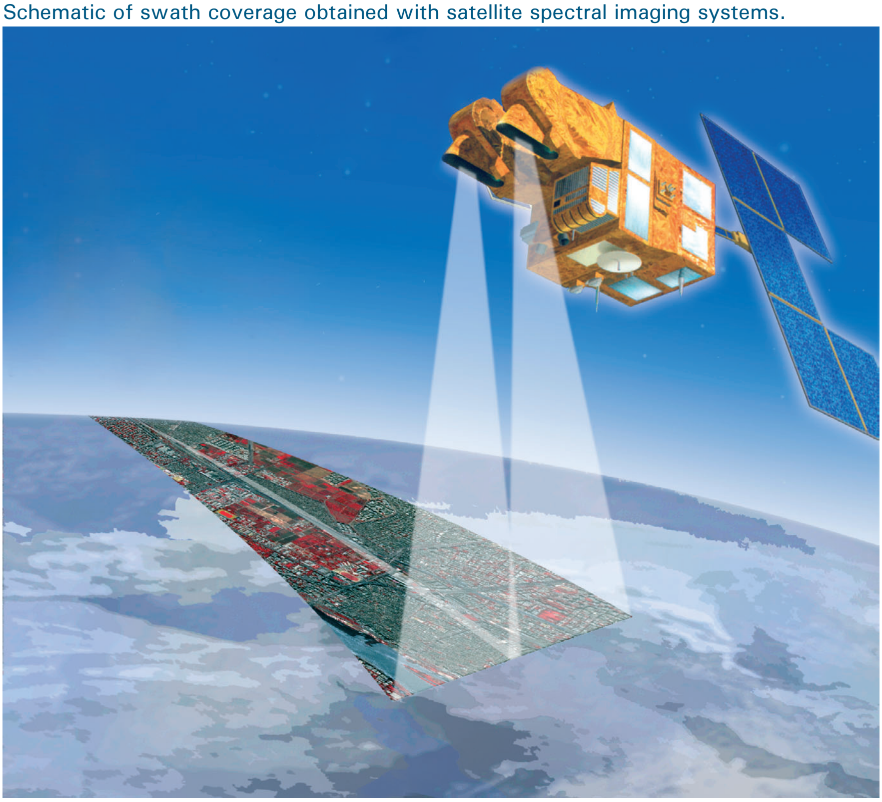


Image courtesy Spot and Raytheon (©CNES 2003)

Airborne and ground gamma-ray spectrometry (radiometrics)

Gamma-ray spectrometry, commonly known as radiometrics, is based on the measurement of naturally occurring gamma rays emanating from materials at the Earth's surface. Gamma-ray spectrometry is widely used for soil mapping and can be measured either from aircraft or, more rarely, from vehicles on the ground. Since surface salinity is often correlated with soil type and landscape characteristics, radiometrics is sometimes used as a tool for (very) indirect mapping of surface salinity and recharge properties (see Appendix 1.16), especially when combined with DEM.

INDIRECT METHODS FOR MAPPING SALT IN THE ROOT ZONE (10 cm TO 2 m DEPTH)

The balance of this section deals with electrical and electromagnetic techniques for measuring conductivity, which are the most widely used methods for inferring and mapping salinity in soil, water and the subsurface. Electromagnetic conductivity methods operate at a variety of scales, from portable conductivity meters (this section), to deeper-probing and airborne methods covered later in the chapter. This section will cover the broad range of techniques and briefly review extensions to current practice in Australia for lowering costs and achieving higher resolutions. Note the discussion in 'Conversion of soil

ELECTROMAGNETIC DEFINITIONS

Frequency domain systems are those that transmit a continuous sinusoidal waveform, and measure the phase and amplitude (or in-phase and quadrature components) of the resultant signal.

Time domain systems transmit a square or half-sine wave pulse, and measure the amplitude of the resultant decaying (or transient) signal at various times after cessation of the transmitter pulse.

Conductivity (electrical) is the ability of material to conduct electrical current. Units are siemens per metre (S/m) or more commonly millisiemens per metre (mS/m).

Resistivity is the reciprocal of conductivity. Resistivity (units in ohm-m) is commonly measured with DC electrical probing devices (see p. 47).

Apparent conductivity, EC_a, is the conductivity of a uniform earth (averaged to the depth of investigation) that would give the same EM response as that measured. Apparent resistivity, ρ_a, is the reciprocal of apparent conductivity.

Skin depth describes the attenuation of electromagnetic fields as they diffuse into a conductive earth. Skin depth is defined as the depth at which an electromagnetic field is attenuated to 37% of its value at the surface of the earth. Skin depth is given by the expression

$$\delta = 500\sqrt{\frac{R}{f}}$$

where R is the resistivity of the earth (equal to 1/EC) and f is the operating frequency. Lower frequencies penetrate to greater depth.

Diffusion depth at time t is an analogous measurement in the time domain, replacing f in the expression by $1/t$. Later sample times penetrate to greater depths.

Low induction-number EM instruments operate over a certain range of transmitter-receiver coil separation and frequency parameters where the depth of investigation is controlled mainly by the separation between the transmitter and receiver coils rather than the operating frequency. Also known as conductivity meters (e.g. EM31, EM38).

Conductance is the product of conductivity and the depth of an electrically thin conductive layer.

electrical conductivity to salinity—calibration' (p. 40) that stressed the need for calibration for soil and moisture conditions.

Rapid indirect techniques based on electrical conductivity measurements are fast becoming the preferred method for inferring salinity in the root zone. Most techniques require either electromagnetic induction ground conductivity meters or DC electrical 4-electrode arrays. Before continuing it is useful to define common terms and concepts used in electromagnetics (see text box on p. 45).

Shallow electromagnetic conductivity mapping

Lightweight, portable, ground conductivity meters have achieved widespread acceptance for salinity mapping in the root zone and are now an important part of land and water management.

These instruments, which are described in detail in Appendix 1.6, are designed for ease-of-use and provide a direct readout of electrical conductivity. They have a focused depth range extending from a fraction of a metre into the root zone to depths of several metres. The instruments can be used in two measurement configurations (horizontal and vertical coils), from which some information can be obtained of the variation of conductivity with depth (e.g. increasing, decreasing or constant through the root zone).

Since single measurements with conductivity meters have a relatively fixed depth of investigation, some users have devised semi-automated systems mounted on a 4-wheel bike or vehicle that employ a combination of coil configurations or systems with different coil spacings to provide better depth information and more rapid coverage of larger areas.

The systems are also used in time-lapse mode to determine soil salinity changes for salinity risk or remediation applications. They have been used in many areas of Australia to determine large-scale, root zone, soil salinity classes.

Electrical conductivity is strongly correlated with salinity however other factors such as soil moisture content, soil texture and composition (in particular the amount and type of clays), and temperature can also affect the readings and corrections should be made for these parameters.

Shallow electromagnetic conductivity profiling with EM31.

Photo: Kate Wilkinson.

DC electrical 4-electrode measurements

Electrical conductivity (or more correctly its reciprocal, resistivity) can also be measured with DC electrode devices that require galvanic (electrical) contact with the ground. Although DC resistivity measurements are slower than those made with inductive conductivity devices, they are capable of improved depth resolution. Measurements are made at a variety of electrode spacings to give information at various depths and automated computer inversion routines can be used to produce depth sections. These methods are further described in the next section and in Appendix 1.8.

INDIRECT METHODS FOR MAPPING SALT IN THE SUB-ROOT ZONE (>2 m INTO THE REGOLITH)

Surface-based electromagnetic and electrical depth sounding

A large number of instruments for measuring electrical conductivity at depths greater than 2 m are available, ranging from larger-spacing terrain conductivity meters, through transient electromagnetic (TEM) and radio-magnetotelluric systems to DC resistivity 4-electrode or array devices. Only a few of these have been used in Australia for groundwater and salinity investigations, and none of the submissions to this review assessed their advantages or efficacy. These techniques, described in more detail in Appendix 1.7, are eminently suitable for mapping salinity and landscape variations within the regolith, and can penetrate down to depths of tens or hundreds of metres.

Mapping products include sections or maps of 'apparent resistivity' at a particular sample time, frequency or electrode spacing, and inverted depth sections showing conductivity or resistivity.

Borehole conductivity logging

Borehole conductivity meters operate on the same principle as surface-based conductivity meters. Output units are in mS/m. Borehole conductivity logging provides excellent 'ground truth' measurements of the true conductivity of the ground versus depth, and should always be used to calibrate airborne electromagnetic soundings and surface-

Down-hole electromagnetic conductivity logging using the EM39.

based electromagnetic and electrical depth soundings.

Each reading gives information for a volume of about 0.5 m radially around the borehole and 0.6 m vertically for successive measurements. Further details are given in Appendix 1.10.

Airborne electromagnetics

Of all the airborne geophysical techniques (aeromagnetics, radiometrics and electromagnetics), only electromagnetics (EM) has a signature closely related to salinity. Airborne EM or AEM systems are similar in many respects to the ground EM systems described above. Fixed-wing AEM systems operate in the time domain, with a transmitter loop strung around the aircraft and a multi-coil receiver housed in a 'bird' towed a hundred metres or so behind and below the aircraft. Helicopter-borne EM (HEM) systems have EM transmitters and receivers suspended below a helicopter. Traditional HEM systems are frequency-domain, with multiple paired coils with various orientations housed inside a torpedo-shaped bird. More recently helicopter-borne TEM systems have been developed. Fixed-wing surveys are generally preferred for larger areas and deeper penetration, while HEM surveys offer finer spatial resolution. Magnetic and digital terrain data are usually obtained at the same time as AEM.

The depth of investigation varies with ground conductivity—at best it is around one skin depth or diffusion depth (see Definitions p. 45)—but can be less depending on signal and noise levels. The footprint (or lateral averaging) of HEM systems is smaller than that of fixed-wing TEM airborne systems, especially in the shallow subsurface, and is discussed in detail in Appendix 1.18.

Because of the fundamental limitations of resolution inherent in inductive electromagnetic techniques (which is related to the volume of soil that contributes to each measurement) airborne EM systems can detect, but usually not resolve, conductivity distribution in the top five to ten metres. The response of EM systems is largely controlled by the integrated conductance from the surface down to a fixed depth, and increases with decreasing frequency (for frequency-domain systems) or increasing time (for time-domain systems).

The main requirements of an AEM mapping system is broad bandwidth and accurate, calibrated data over the entire range of frequencies or sample times, but

High-powered, fixed-wing airborne electromagnetic survey, WA.

especially at high-frequencies or early time. A number of current research projects are directed at improving the near-surface resolution of AEM. Appendix 1.18 contains a more complete description of AEM systems and interpretation procedures.

Interpretation or mapping products include apparent conductivity maps at each frequency or sample time; approximate conductivity-depth image (CDI) sections or depth slices; layered-earth inversion (LEI); and conductance maps. Care should be taken with the application of rapid imaging routines for processing and visualising AEM data, especially with inferred depth values, and estimates of accuracy and uncertainty should always be made. Ground-truthing (through borehole induction conductivity logging (Appendix 1.10) or ground EM or electrical depth sounding ('Indirect methods for mapping salt in the root zone [10 cm to 2 m depth], p. 45) should always be used to calibrate AEM data (e.g. Cresswell et al. 2004). A general discussion of the inversion of AEM data is given in the next section.

Inversion and presentation of geophysical data

Presentation of data from the near-surface mapping techniques described in previous sections of this chapter is reasonably straightforward, with standardised processing and mapping products in routine use.

Depth slices of apparent conductivity, with surface layer draped over topography.

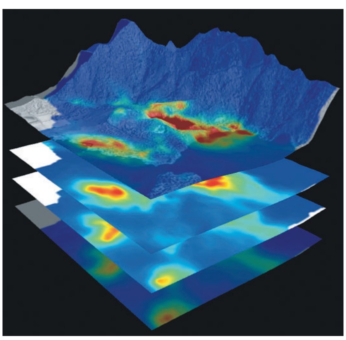


Image courtesy Fugro Airborne Surveys.

Processing and interpretation of geophysical surveys (whether electromagnetic, magnetic, seismic or gravity based) is more complex because the signal originates from a range of depths. The conversion of raw data to a final depth image involves a number of steps, each having specific mathematical and physical assumptions. The purpose of this section is to alert the reader to the key stages in data acquisition, processing and interpretation. We will focus on airborne electromagnetics (AEM) since it is an important tool in mapping subsurface salinity. This material supplements the discussion on AEM given in Appendix 1.18.

Acquisition

The AEM system must be well calibrated with accurate knowledge of transmitted waveform, filter settings, amplifier characteristics, elevation above the ground and the geometric relationship between source and receiver. Deszcz-Pan et al. (1998) describe calibration and error reduction for HEM, and Green and Lane (2003) describes noise sources and acquisition parameters for both HEM and fixed-wing systems. Modern systems such as TEMPEST incorporate advanced processing algorithms that effectively calibrate the data for many of these system parameters.

Basic processing

Standard processing involves correcting for variations in acquisition parameters during the survey, including height corrections, geometric corrections and primary-field corrections. Removal of the primary field (the direct signal arising from causes other than the distribution of the earth's conductivity) remains one of the most difficult tasks in AEM processing, and has been an issue in a number of AEM surveys for salinity mapping over the past few years.

Primary-field removal and system calibration is the subject of active research. The prime objective of basic processing is to obtain accurate data which are independent of both the chosen system and contractor, with a sound knowledge of absolute accuracy (with error estimates) and defined system parameters. This stage is essential if repeat surveys are needed to track the progress of salinisation or its remediation (see 'Survey design, processing and interpretation', p. 78).

Data may be presented as profiles of response at various time or frequency channels along the flight lines, as apparent conductivity (based on a homogenous earth definition) or as principal component (PC) maps (a multivariate statistical technique that extracts key information from the total dataset to display in a single image).

Conversion to conductivity-depth image

The next stage of processing is to convert the corrected data into a cross-section of the earth with conductivity displayed vertically. This procedure is known as inversion. Inversion is a sophisticated, and mathematically and numerically complex procedure with many approaches, each of which has its own assumptions, advantages and disadvantages.

Typical inversion products used for AEM include:

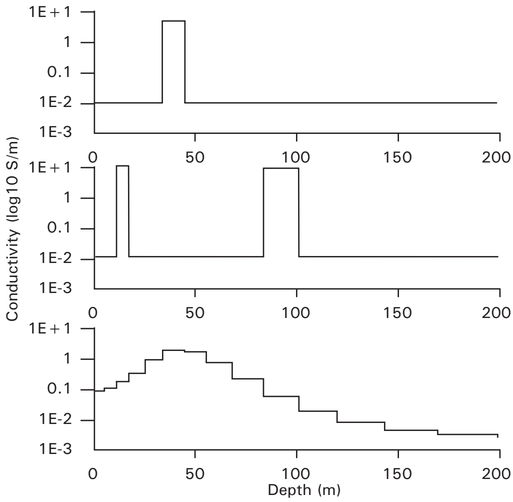
- layered-earth inversion (LEI), where a fixed number of distinct horizontal layers is assumed;
- smooth-model inversion, where the conductivity is assumed to vary smoothly with depth;
- conductance maps and interval conductivity which give the average conductivity over a range of depths; and
- approximate conductivity-depth imaging (CDI) sections are computationally faster than LEI but involve more assumptions (see for example Macnae 2003).

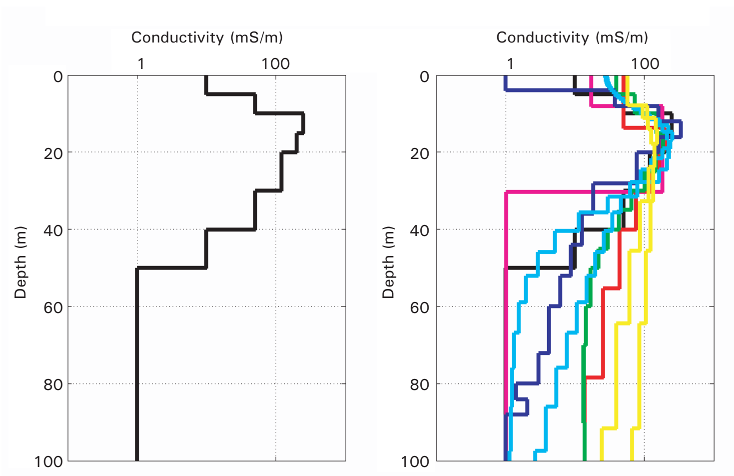
All electromagnetic processing algorithms are constrained by a mathematical principle known as **equivalence—**there are a large number of combinations of layer conductivities and thicknesses that produce the equivalent EM response. The problem of equivalence is ameliorated to some extent with higher bandwidth (frequency or time range) and increased system accuracy, but cannot be eliminated. An example illustrating equivalence, or the non-uniqueness of EM inversion, is given in Figure 6.

Plausible models can be constructed by a careful choice of geological model. For instance, a smoothly varying depth section is typical of many salinity profiles in the regolith. In many cases borehole conductivity data may allow the first and second solutions that include discrete, high conductivity layers in Figure 6 (top) to be rejected as being inconsistent with conductivity profiles in the survey area.

In other words, the problem of non-uniqueness is addressed through **geological constraints** on the solution. Borehole and ground conductivity data ('ground truth') are used to determine the true earth parameters at selected sites, which is then fed into the inversion process. By careful choice of

Figure 6. Top: Example of equivalence in EM inversion. The three synthetic conductivity profiles (depth scale horizontal) all fit equally well to a single TEM decay curve (adapted from Ellis 1998). Lower left: synthetic conductivity-depth profile typical of saline landscapes. Lower right: Eight interpreted conductivity sections (including layered-earth inversion and conductivity-depth imaging with depth scale vertical) obtained from the inversion of the same data. (Inversions courtesy Daniel Sattel, Fugro Airborne Surveys; James Macnae, RMIT; Colin Farquharson, University of British Columbia; Peter Fullagar, Fullagar Geophysics; and Richard Lane, CRC LEME/Geoscience Australia).





geological model (as noted above a smoothly-varying depth section is typical of salinity profiles in the regolith), plausible models can be constructed as long as the model assumptions remain valid. The model usually varies across a survey area. Examples of this variability are bulge profiles (lower left in Figure 6) that may be typical of lower slopes and mid-slopes; monotonic increasing conductivity profiles with an upper bulge that are typical of valleys; and monotonically decreasing or uniform conductivity profiles that are typical of upper slopes. Sufficient borehole and ground control measurements should be used to ensure that the appropriate models are employed in the inversion process.

In many cases, basic processing and conversion to conductivity are very much intertwined. The current trend is towards a more holistic approach to conductivity prediction, and it is not always possible to separate system variables from conductivity variables. In a recent Queensland survey (Lower Balonne—Chapter 8) AEM processing utilised simultaneous solving of geometry (primary field) and ground conductivity influences on the measured data.

Processing and inversion of EM data require skilled and experienced practitioners, and mapping products should always state the procedures used, with clear descriptions of assumptions and confidence limits.

The EM inversion procedures described above assume a one-dimensional earth (i.e. the variations in conductivity are assumed to be in the vertical direction only). These inversions often display unwanted (and potentially misleading) artefacts at sharp lateral boundaries in conductivity. To overcome this limitation, two-dimensional inversion routines have been developed (e.g. Wolfgram et al. 2003) which virtually eliminate artefacts typically seen in one dimensional sections at lateral boundaries. These algorithms are more computationally intensive than one-dimensional interpretation, and hence more expensive, but are much preferable in areas with rapid lateral variability.

A summary of the data processing flow, and recommendations for documentation and archiving is given in 'Data processing flows' (p. 79).

Interpretation

The final stage of processing mapping data is interpretation. In the case of EM, this step involves converting conductivity-depth data to more important parameters such as salt content as a function of depth and lateral position, in addition to the structural interpretation of depth to bedrock and the identification of stratigraphic and structural features. Interpretation requires sound knowledge of the properties of the local geomorphology and landscape, informed by ground and borehole observations.

Some AEM mapping products released over previous years have been affected by insufficient attention to calibration, and the constraints of ground control and geology. The results of the AEM surveys shown in the case studies at Honeysuckle Creek and Lower Balonne (Chapter 8), for instance, underwent successive stages of processing and inversion which incorporated carefully derived geological constraints and corrections to acquisition parameters. Salinity surveys have been instrumental in raising the expectations for system calibration and the ability to incorporate ground control and geological constraints.

Checklist for users

The following questions should be asked in the process of contracting an AEM survey and processing.

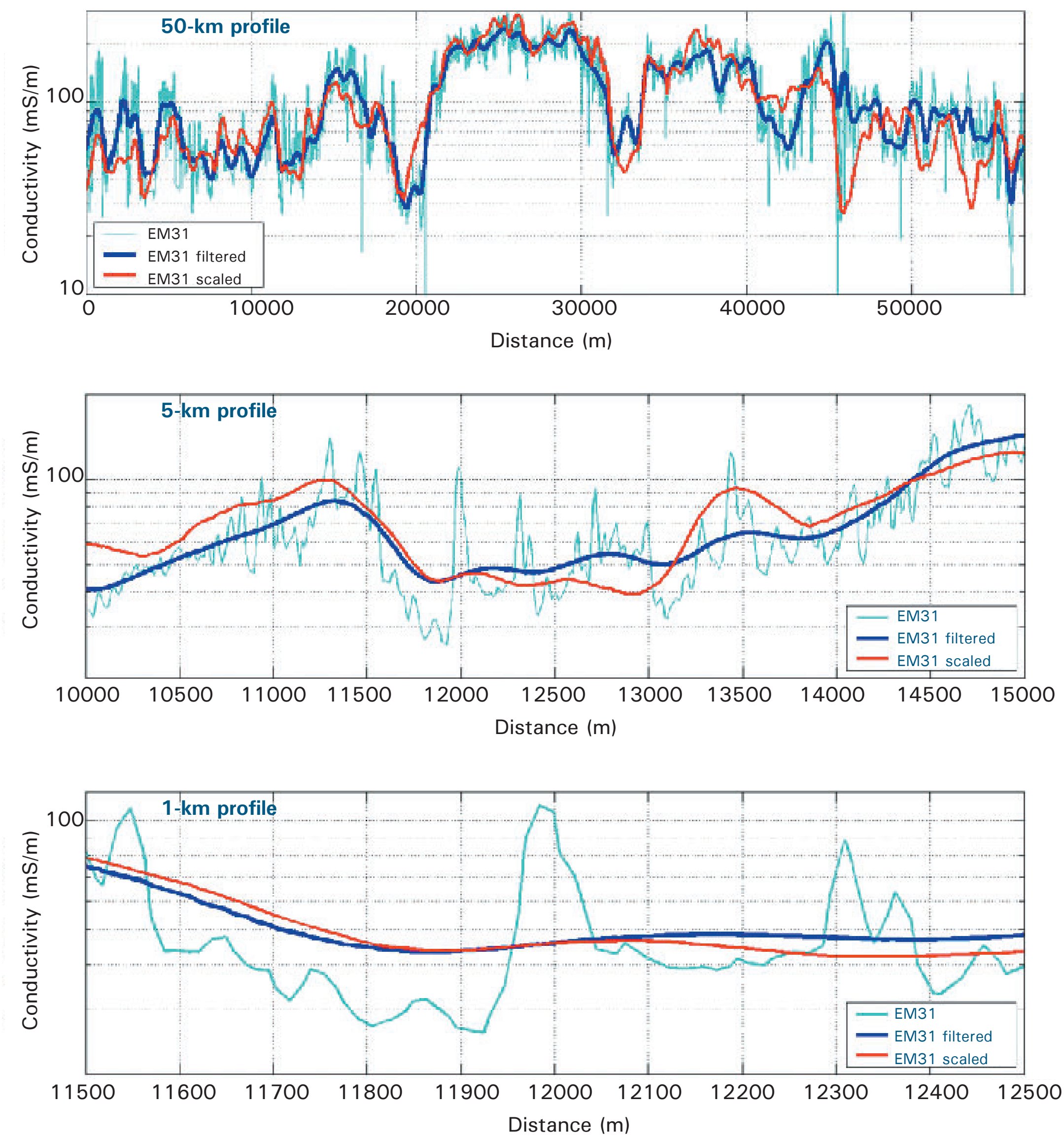
- *Have the target parameters (e.g. lateral extent, depth and conductivity range) been defined?*
- *Has the survey been specifically designed to answer the question at hand, using the most appropriate system and acquisition parameters?*
- *Does the budget incorporate the full cost of the survey including pre-survey planning, data acquisition, preliminary processing, ground-truthing, final processing and interpretation?*
- *Has the client specified clearly what is expected of the contractor? Are these clearly spelt out in a tender specification sheet (such as that issued by Geoscience Australia for NAGP surveys)?*
- *Does the client have access to staff with sufficient expertise to ensure that the survey and processing specifications are met?*
- *Are the mapping products clearly labelled with processing parameters, error estimates and details of the calibration process (if any)?*

Comparison of airborne and ground methods

When comparing the results of airborne, ground and borehole EM it is important to note that each technique has a specific depth of investigation, horizontal footprint, and vertical and horizontal resolution (as shown in Figure A6 on Appendix 1.18, p. 191).

An example from St George in Queensland (Lane et al. 2003), demonstrates the differences in horizontal resolution as measured with ground (EM31) and airborne (TEMPEST) systems over profiles of 50 km, 5 km and 1 km lengths. In Figure 7, raw EM31 measurements are plotted in light blue, TEMPEST AEM conductivity predictions for 0 to 5 m below surface in red, and EM31 measurements, filtered with a rolling average that mimics the lateral sampling of the AEM measurements over several hundred-metre sections, in dark blue. The AEM and averaged EM31 measurements agree fairly well for all profile lengths. At broader scales represented by the 5 and 50 km profiles, the AEM predictions correlate moderately well with the trends in the raw EM31 measurements. However, the bottom panel shows that over profile lengths that are a little more than one kilometre, which is the horizontal resolution of the AEM system, the broad averaging involved in the AEM measurements is unable to capture the local variability detected using an EM31 instrument. The AEM conductivity predictions and the raw EM31 apparent conductivity values would show very low correlation at this local scale.

Figure 7. Profiles of apparent conductivity measured using an EM31 instrument in vertical dipole mode (light blue line), filtered EM31 apparent conductivity (dark blue line) and conductivity predictions for 0 to 5 m depth from TEMPEST AEM data (red line) for a 50 km profile, 5 km profile and 1 km profile. Profiles prepared by Richard Lane (CRC LEME /Geoscience Australia) from data provided by the Queensland Department of Natural Resources and Mines, CRC LEME and the Bureau of Rural Sciences.



Similar issues arise when comparing other types of measurements that sample different volumes (e.g. soil samples extracts, borehole measurements, surface and airborne measurements).

While it is possible to make very accurate measurements of soil properties such as salt content on small samples, such accuracy may be misleading in the light of natural spatial (lateral and vertical) variation. Techniques such as EM that are sensitive to large volumes of ground may not be as accurate or precise as point measurements, but may give a truer representation of average earth properties over a larger area.

TEMPEST airborne EM system being used for salinity mapping in western NSW.

Photo: courtesy Brian Spies, CRC AMET

Drill rig on location to test the depth to watertable and groundwater salinity – Violet Town, VIC.

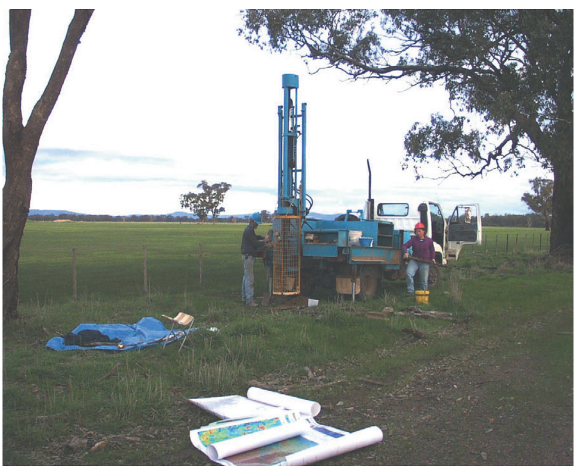


Photo: Pauline English.

MULTI-PHASE AND MULTI-STAGE APPROACHES

No single approach to salinity mapping is suited to all situations. In some cases a paucity of information may mean that approaches such as composite index mapping may be the best way to start before collecting new field-based data. In other situations, knowledge of salinity and landscape processes may be well advanced, and further investigations can be targeted at specific questions.

Regardless of the state of knowledge, it is important to ensure that maximum use is made of existing information, ranging from local knowledge and existing maps to the regional context, before investing in further mapping.

A multi-phase or multi-stage approach, where mapping alternates with ground-truthing and interpretation, ensures that best use is made of the existing and new information, and that data are progressively transformed into information, and then into knowledge of salinity and landscape processes.

One effective mapping design is based on an initial sampling to determine the likely location of salt in the study (field inspection or stream sampling), followed by techniques that map salinity on the surface (air photos, airborne imaging and/or satellites), plus deeper probing techniques (AEM). At each stage, field observation should be used as an essential tool for calibration and interpretation, with borehole measurements as required. The final stage in the loop is post-mapping validation. The cycle is then repeated at the next level of detail, each time targeted to answer specific questions.

This staged approach draws on the best elements of each individual mapping techniques discussed above. It permits the best use of existing information and helps target or prioritise the areas that require new mapping information.

SUMMARY OF METHODS[1] FOR MAPPING DRYLAND SALINITY HAZARD AND RISK ASSESSMENT

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
Analytical and point measurement			
1. LABORATORY ANALYSIS The most rigorous method of quantitatively evaluating soil salinity.	Basic knowledge of the amount and type of salt is an important parameter.	Standard water set of basic anions and cations ~ $100 – 200 per sample.	Laborious—days or weeks needed to obtain results. Salinity often varies substantially laterally and vertically, so samples may not be representative of a larger area unless sampling density is high. Salinity may also vary over time.
2. TOTAL SOLUBLE SALTS MEASURING EC OF SOIL PASTES AND EXTRACTS IN THE FIELD A common and useful field procedure, but ignores soil moisture, content and mobility of salt.	Useful as an adjunct to other techniques.	Around $10 per sample for EC and pH.	Needs to be calibrated for solute type (laboratory) analyses). Not all salt measured on paste extracts affects vegetation or is readily mobilised.
Surface mapping (0 – 10 cm depth)			
3. VISUAL INSPECTION Directly observes salt scalds and stressed vegetation. Applicable to both surface and indirect root zones.	Provides spot checks for some attributes required for risk assessment (e.g. soils, vegetation type, geology and land use).	Subject to the cost of labour.	Useful technique for mapping small areas (paddocks). Essential for checking maps prepared from satellites, aircraft or systematic vehicle-based EM surveys. Ensures that the extensive local knowledge of landholders is used (e.g. changes of salinity outbreaks through time), as well as, observations of causes/effects (e.g. wet seasons, floods).
4. AERIAL PHOTO INTERPRETATION Directly maps salt scalds. Indirectly maps stressed vegetation. Applicable to both surface and indirect root zones.	Substantial contribution as can also map vegetation type, streams, terrain, land use.	Each air photo costs around $50. An experienced interpreter can map 3 to 6 photos per day. Cost is approximately $1/ha (assumes existing air photos and interpretation at a scale of around 1:25 000). New, digital photography costs, $5 to $20/ha scale at, 1:25 000 scale including analysis.	Well-established technique. Can be slow to cover large areas but very reliable for surface mapping. Digital photography is emerging as a replacement for traditional film, at cost per frame from $20 to $50 (minimum purchase often applies – approximately $2000).
5. AIRBORNE VIDEO Applicable although still only experimental Applicable to the surface and indirect root zones.	Potential contribution as can also map vegetation type, streams, terrain and land use.	Cost $10 to $50/ha assuming new acquisitions at a scale of 1:25 000, including analysis.	Competes with the multispectral instruments for applications.
6. DIGITAL ELEVATION MODELS (DEM) (FROM AIR PHOTOS, STEREO MULTISPECTRAL IMAGERY, AIRBORNE LASER, RADAR) Not relevant as DEM do not directly detect salt or groundwater. Applicable to the surface only.	Substantial contribution. Can infer drainage and seepage patterns.	Costs vary substantially depending on scale and level of detail. Large surveys <$0.3/ha.	The landscape context to spatial salinity patterns is invaluable in being able to enhance the final mapping quality and as a very important aid to follow-up management. DEM data is normally acquired simultaneously with airborne electromagnetics and with aeromagnetics.

[1] Mention of a specific vendor or instrument does not imply endorsement.

SUMMARY OF METHODS[1] FOR MAPPING DRYLAND SALINITY HAZARD AND RISK ASSESSMENT continued

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
Surface mapping (0 – 10 cm depth)			
7. AIRBORNE RADAR (AIRSAR)			
Suitable through indirectly mapping surface electrical conductivity for radar wavelengths greater than 6 cm. Applicable from the surface to several metres.	Radar has the ability to map very accurately the terrain surface (DEM) at fine resolution over large areas.	Around \$5 – \$15/ha. Even small areas may cost \$1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	Largely an experimental technique at present with potential application for salinity mapping. Has potential to be used as a tool for creating DEM which could therefore contribute to risk assessments.
8. SATELLITE RADAR (SIR-C & D, JERS -1, SRTM)			
Possibly useful through indirectly mapping electrical conductivity of surface and subsurface where radar wavelengths exceed 6 cm. Applicable to between 10s and 100s of centimetres only.	Has the ability to map the terrain surface (digital elevation models) at fine resolution over large areas very accurately.	Not meaningful to quote cost per hectare. Even small areas will cost \$1000s due to the cost of acquiring the imagery and the software required to process it.	Satellite radar has no proven operational use for salinity hazard mapping at present although it does offer potential. However it will make a solid contribution to the mapping of topography which helps understanding of risk assessment. NASA will be releasing over the next couple of years the Shuttle Radar Topographic Mission mapping that will produce a worldwide DEM and topographic maps for the first time.
9. AIRBORNE IMAGING: MULTISPECTROMETRY (CASI)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. Applicable to the top few centimetres and the indirect root zone.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	\$10 to \$50/ha (assuming new acquisitions at a scale of 1:25 000) including analysis. Even small areas will cost \$1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	Little used due to the substantial cost of acquiring the imagery and processing it to produce maps. Has potential.
10. AIRBORNE IMAGING: HYPERSPECTROMETRY (HYMAP, AVIRIS)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. May also infer salt by known association with specific mineralogies. Applicable to the top few centimetres and indirect root zone.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	\$10 to \$50/ha (assuming new acquisitions at a scale of 1:25 000) including analysis. Even small areas will cost \$1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	New technology still in the research phase; resolving ability higher than multispectral imagery.
11. SATELLITE IMAGING: MULTISPECTROMETRY (LANDSAT, SPOT, IKONOS, EARTHWATCH, ETC.)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. May also infer salt by known association with with specific mineralogies Applicable to the surface and indirect root zones.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	Usually much less than one cent per hectare. Minimum area purchases usually apply so costs can typically run to \$100s plus processing and interpretation.	Proven technique for near-surface salinity hazard mapping in the hands of skilled interpreters in some regions. Well developed for its contribution to risk assessment (e.g. Western Australia Land Monitor).
12. SATELLITE IMAGING: HYPERSPECTROMETRY (HYPERION)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation Experimental only at this stage. Offers potentially greater mapping accuracy than the multispectral instruments. Applicable to the surface and indirect root zones.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	Minimum purchase of 42 km x 30 km for approximately \$3000. Cost \$5 to \$50/ha including processing.	Represents a new and significant improvement in technology (cf multispectral sensors). Requires substantial research before it develops proven applications. Likely to have broader applications than the multispectral instruments. Price set by vendors will in part determine the degree of uptake by users.

[1] Mention of a specific vendor or instrument does not imply endorsement.

SUMMARY OF METHODS[1] FOR MAPPING DRYLAND SALINITY HAZARD AND RISK ASSESSMENT continued

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
Surface mapping (0 – 10 cm depth)			
13. AIRBORNE AND GROUND GAMMA-RAY SPECTROMETRY (RADIOMETRICS)			
Provides mapping of soil types that sometimes correlate with salinity. Applicable to the top tens of centimetres only.	Able to produce quality soil mapping.	Airborne: <$1/ha depending on area. Ground: $10 to $20/ha.	Airborne or ground. demonstrated technique for broad area soil mapping that is showing great promise operationally especially when combined with DEM. Requires specialist analysts for interpretation. Claims about its ability to directly map near surface salinity do not have scientific foundation.
14. SHALLOW ELECTROMAGNETIC CONDUCTIVITY MAPPING (GEONICS EM31, EM38, ETC.)			
Strong correlation with salinity. A popular inexpensive method for mapping spatial variations in conductivity in the root zone at farm scale. Applicable to the root zone only.	Useful in mapping near-surface variability and salt load.	Starts at approximately $1500 per day. Coverage is between 50 ha/day (detailed grid) to 500 ha/day (>100 m lines) at roughly $1 to $30/ha.	Some depth information from varying coil orientation. Moisture variations and clay content are second-order effects. Should be calibrated at key locations.
Mapping below the root zone (>2 m depth)			
15. SURFACE-BASED ELECTROMAGNETIC AND ELECTRICAL DEPTH SOUNDING: DEEPER-PROBING EM (GEONICS EM31, EM34-3, PROTEM, SMARTEM, TINYTEM)			
Useful in mapping salt stores beneath root zone to the regolith.	Can be used at broader scales. Also to map groundwater pathways and bedrock topography.	More expensive than shallow mapping. $2000 per day for 30 to 40 soundings. Profiling 20 to 30 line-km per day, processed data $300 per line-km. Assuming a line spacing of 200 to 400 m gives a cost of $6 to $15/ha.	Cannot resolve conductivity changes in root zone (with exception of EM31). Use in conjunction with shallow-probing EM.
16. SURFACE-BASED ELECTROMAGNETIC AND ELECTRICAL DEPTH SOUNDING: ELECTRICAL RESISTIVITY PROBING (ABEM TERRAMETER, GEOMETRICS OHMMAPPER)			
Capable of resolving vertical and horizontal variations in conductivity from surface to bedrock. Applicable from the surface to the bedrock.	Useful for detailed mapping of groundwater pathways and bedrock topography.	$1400 for several km profiling per day. Resistivity imaging: 1 to several line-km per day; $3000 to $5000 per processed line-km. Assuming line spacing of 200 to 400 m gives a cost of $60 to $250/ha.	Requires use of grounded electrodes and towed arrays. Robust automated inversion software available to produce conductivity depth section. Higher resolution than deep EM.
17. BOREHOLE CONDUCTIVITY LOGGING (GEONICS EM39)			
Ideal method for measuring conductivity versus depth in situ for salt store versus depth. Applicable below the root zone.	Useful for understanding changes with depth.	Usually charged on daily basis; most instruments owned by consultants or government agencies. Approximately $2000 per day for up to 10 bores per day.	Boreholes should be logged as a matter of routine. Important to map salinity profile and for calibration of surface and airborne systems.
18. AIRBORNE ELECTROMAGNETICS			
AEM is the only regional technique that maps salinity through the regolith and can also map total salt store. Applicable from the root zone through to bedrock.	Useful for mapping palaeochannels basement topography and other pathways for groundwater flow.	From less than $1/ha to more than $10/ha depending on line spacing, size and location of area.	Cannot resolve vertical variations within the root zone. Depth range depends on ground conductivity. Must be calibrated with ground and borehole data. Care must be taken with processing and interpretation products.
19. AIRBORNE MAGNETICS [2, 3]			
Used for geological mapping especially through soil cover. Applicable from the surface through to bedrock.	Useful for its ability to map gross features (such as palaeochannels faults, dykes, and basements highs) in the landscape that strongly influence groundwater movement.	Less than a $1/ha.	Excellent method for mapping factors that contribute to better risk assessment; well proven in most landscapes. Requires specialist interpretation. Cost-effective contribution to risk assessment and salinity management.

1 Mention of a specific vendor or instrument does not imply endorsement.

2 Techniques for detailed measurement, such as stream sampling, can also be applied at a regional scale if a sufficient number of measurements are made over a regional area.

3 Auxiliary systems often included in airborne surveys include flight video to map vegetation stress, radar/laser altimeter, GPS (for approximate DEM) and laser scanner (detailed DEM).

SUMMARY OF METHODS[1] FOR MAPPING DRYLAND SALINITY HAZARD AND RISK ASSESSMENT continued

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
Other ground-based subsurface mapping methods			
20. STREAM SAMPLING Provides an indication of salt stores that have entered the catchment upstream of the sampling location. Applicable to indirect surface and subsurface.	Provides evidence of mobilisation of salt.	An EC meter: $100 to $2000. Thousands of hectares can be covered relatively quickly depending on road access and density of streams and rivers.	This method is an indirect indication of land salinity but provides a useful trace-back mechanism to salt store and lateral flow into streams. Continuous profile can also be made in streams with towed EC arrays. The method is easily applied by land managers and community groups.
21. NUCLEAR MAGNETIC RESONANCE (NMR) Detects water content in soil profile versus depth. Applicable to the top 10s to 100s of metres.	May be useful in specialised studies when detailed knowledge of hydrology is required.	$3000 per day for 5 to 8 soundings at specific locations. Cost per hectare not meaningful.	Also known as magnetic resonance imaging. One sounding per hour, alternative to drilling and flow testing stratigraphic layers.
22. SEISMIC REFRACTION AND REFLECTION Maps subsurface stratigraphy. Applicable to the surface to sub-bedrock.	May be useful in specialised studies to map soil thickness, palaeochannels, flow paths, barriers, etc.	$2000/day for 1 – 3 km profile. Refraction 10 spreads/day around 100 m each. $3000 processed line-km. Cost per hectare not meaningful.	Common tool in engineering and geotechnical studies. Not recommended for general use for salinity studies.
23. SEISMO-ELECTRIC Detects hydraulic conductivity (moveable pore water) in sediments. Applicable to the top 10s of metres.	Potential for research tool such as when detailed knowledge of hydrology is required.	Research mode costs $2000 to $3000/day. Cost per hectare not meaningful.	Very much experimental and not recommended for routine use.
24. GROUND MAGNETICS Used for geological mapping, especially through soil cover. Applicable from the surface through to bedrock.	Can be used to map features in the landscape (e.g. faults, dykes and basement highs) that influence groundwater movement.	Reasonably inexpensive: up to $1500/day or $10 to $200/ha depending on line spacing. Rental plus operator: $100 + $200/day ~ 15 to 20 km per day.	Ground variant of common airborne technique. Can be carried or mounted on 4-wheel bike with EM31.
25. GRAVITY Maps variation in bulk density of soil and rock in the subsurface.	Can be used to map features (e.g. faults dykes and basement highs) that influence groundwater movement.	Moderately expensive: at 20 m spacing microgravity 100 stations cost $2000. $1000s/ha.	For specialist use only.
Multi-stage and multi-phase mapping			
26. MULTI-STAGE AND MULTI-PHASE MAPPING[2] Suitable. Methods include mapping of surface salt and the deeper subsurface followed by post hazard mapping verification.	Useful. Risk data sources and systems could include: GIS-based hydro-geology and geoscience data, natural resource data, land-use data, groundwater flow systems, Flowtube and DEM.	Variable depending on size of area to be covered, resolution of mapping and combination of systems used.	A combination approach should always to be considered particularly after reviewing existing data.

1 Mention of a specific vendor or instrument does not imply endorsement.

2 Techniques for detailed measurement, such as stream sampling, can also be applied at a regional scale if a sufficient number of measurements are made over a regional area.

Commonly used mapping methods

A broad assessment of the current level of usage of the methods mentioned above is given in the following summary table (Table 9, see next page). The purpose of Table 9 is to give guidance to the potential user of which techniques are most widely used in Australia.

THINGS TO LOOK FOR IN A GOOD MAP

Maps have traditionally been presented on paper. Over the last decade the increasingly wide availability of geographic information systems (GIS) has meant that high-quality maps (at least from a presentation perspective) are easy to generate and distribute in electronic form. Whichever media are used to present data and interpretations, there are a number of features that characterise good maps:

- informative heading or title;
- prominent statement indicating the status of the map (typically—draft, published or restricted internal use);
- technical description of the technique or techniques used to generate data for the map, and assumptions underlying the presentation used;
- data source and processing history (including processing parameters and software used);
- statement indicating the original purpose of the map and warnings about appropriate use and limitations (may include statements of accuracy);
- acknowledgment of the owner of the data and the owner of the map;
- scale, north point, date of creation, legend; and
- name and contact details of those responsible for the map.

Table 9. Summary of mapping methods available in Australia and their relative level of use[1].

Method	Use in mapping dryland salinity	Use in mapping salt store	Use in mapping regolith & hydrology	Paddock scale	Farm scale	Catchment scale	Regional scale	National scale
Surface								
Visual	***	–	***					
Laboratory	**	–	–					
Radiometrics – ground	–	–	*					
Radiometrics – airborne	–	–	**					
Air photo interpretation	***	–	**					
DEM	–	–	***					
Multi spect (CASI etc.)	–	–	–					
Hyperspectral airborne	–	–	–					
Video	–	–	–					
Satellite imagery	***	–	*					
Hyperspectral satellite	–	–	–					
Root zone (< 2 m)								
Shallow EM	**	***	–					
Resistivity (Wenner, etc.)	–	–	–					
Field/drilling, etc.	–	***	***					
Airborne radar	–	–	–					
Satellite radar	–	–	–					
Deeper (> 2 m)								
Deeper EM31/34 etc.	*	**	*					
Elect resist probing	–	*	–					
Stream sampling	–	**	–					
GPR	–	–	–					
NMR, seismo-electric	–	–	–					
Magnetics	–	–	***					
Gravity	–	–	–					
Borehole logging	–	*	–					
AEM	*	***	***					

*** commonly used

** less often used

* some use

– not applicable

1 Based on a table prepared by Richard George, WA Department of Agriculture

6. MAPPING THE LANDSCAPE TO DETERMINE SALINITY RISK

This chapter ties together the understanding of landscape, soils, hydrology, salt and mapping techniques to generate mapping products such as those generated for hazard and risk assessment, which form the basis of sound management practices and investment decisions.

INTEGRATION OF MAPPING TECHNIQUES

Previous sections of this report demonstrate the wide range of techniques available for mapping the earth at a variety of scales and focusing on a variety of features—the landscape, soils, land use, subsurface features, groundwater and flow pathways, salt expression at the surface and salt store at depth. Any geological interpretation, map or prediction, relies on combining as much quantitative and qualitative information as possible. It is clear that in many areas there is a paucity of firm data that has adversely affected predictions, economic decisions and management responses to salinity risk.

Many submissions to this review emphasised the need for multiple techniques. Integrated interpretation, geological systems approaches, catchment characterisation and modelling techniques all require multiple, accurate datasets and maps as their foundations. No one (or two) mapping techniques are sufficient to provide sound interpretations. Ground-truthing and calibration are essential steps in generating reliable and accurate mapping products.

RISK AND HAZARD MAPPING

The development of robust predictions and the assessment of salinity risk involves a sophisticated integration of many factors. It brings the salt hazard mapping of Chapter 5 within the framework of hydrological and landscape processes of Chapter 3, underpinned by the risk management framework described in Chapter 4. It adds a dimension of analyses designed to support decision making that quantify the vulnerability of assets—agricultural, infrastructure and environmental—in the landscape through time.

Salt hazard maps are traditionally defined as maps of salt content or salt load present in the landscape. As described in the glossary and in Chapter 4, a hazard is defined as anything that can potentially cause harm to an asset. Salt in the regolith is generally regarded as a hazard because it has the potential to be mobilised and move to a location where it threatens an asset. The terms ‘salt content’, ‘salt load’ and ‘salt hazard’ are often used interchangeably. Strictly speaking, salt content refers to the percentage (by weight) of salts contained in a sample of soil. Salt load is normally used in the context of the total amount of salt in the soil profile that can be potentially mobilised by water. Salt hazard refers to salt that can be moved to threaten an asset.

Hazard maps can be made for a wide variety of natural or human-induced phenomena. Maps can be made for flood hazard, bushfire hazard, earthquake hazard, and even political and economic stability hazard.

Risk describes the expected harm to an asset from an identified hazard. Any estimation of salinity risk must include:

- the identification of the asset at risk (e.g. crops, native vegetation, local infrastructure, water quality in adjacent rivers);
- an assessment of the hazard (e.g. salt content in rising watertables reaching 1000 mg/L within 5 years within 1 m of the surface);
- an assessment of the likelihood of this occurrence given a scenario which accounts for land use, climate etc.; and
- an assessment of the economic, social or environmental (often grouped as socioeconomic) impacts on the asset if the event happened.

Thus, **salinity risk** maps need to take into account the particular asset (crops, native vegetation or groundwater quality) as well as a firm understanding of the ability of salt to be mobilised by water flow within a certain time scale. Knowledge of hydrology, flow pathways and soil permeability are just as important as knowledge of salt load.

Risk prediction techniques range from interpretation approaches based largely on human estimation and limited input data (geology, land use change, soils mapping at a continental scale and potential excess rainfall and the absence of salinity hazard data), to approaches that incorporate the groundwater flow system and its fourteen detailed input factors. This chapter will examine the application of these risk assessment techniques and indicate the reliance of each on the salinity mapping methods of Chapter 5. The efficacy of each technique will be discussed so that potential users can properly assess the effort required to apply the technique and the expected reliability of the outcome.

Break-of-slope soil erosion caused by excess infiltration of rainfall from the cleared hillslope and discharge at the base of the slope. This results in evaporative concentration of solutes, salt scalding and soil degradation – Strathbogie Ranges, VIC.

Issues

- The best form of risk assessment relies on input from many sources. At the continental scale some of these inputs are far from complete (including the gross distribution of salt load and the characteristics of vegetation on the 100 million hectares of private native forests). At the paddock scale there is a serious scarcity of data (including soil fertility information). It is critically important that Australia makes the improvement of these sources a priority commensurate with limited resources, the calculated need on a catchment-by-catchment basis and the assessment of the relative value of the assets at risk.
- Comprehensive salinity risk mapping at the regional scale is substantially more reliable if it is based on quantifiable maps of salinity hazard. Lack of quantification of the existing salt load at a regional scale is the single most limiting factor at present.
- Risk modelling systems that rely disproportionately on historic trends in piezometric data without knowledge of permeability, microclimate trends and the impact of future changes in land use should be treated with caution.
- Integrated mapping methods and modelling systems offer the best approach to risk mapping.
- Many of the mapping systems are suitable for commissioning by small groups or individuals, such as farm advisors or farmers, to produce maps of salinity hazard. However some of the framework datasets that are needed to usefully determine maps of risk are too complex to be produced by individuals or small groups in isolation. Examples of these datasets are the digital terrain models (DTMs), regional maps of geology (that show basement highs, faults and dykes). These types of datasets should be coordinated nationally in a consistent format so that they can be merged into larger-scale products for both public and private land.
- The impact of climate change on risk assessment is likely to be even more significant in the future than in the past.
- There appears to be a substantial degree of disconnection between the various mapping systems and the landscape process models. A coordinated approach is necessary to achieve more integration.

METHODS FOR PREDICTION OF SALINITY RISK

In a review of the range of methods used to predict salinity occurrence in various states, Gilfedder and Walker (2001) identified three categories of salinity assessment approaches: composite index methods, strongly inverse methods and trend-based methods.

Composite index methods

Composite index methods used for salinity prediction are based on expert knowledge to integrate existing data, experience and other relevant information into a spatial representation of the key landscape attributes associated with salinity. In the absence of more detailed primary data components that are known to reflect salinity hazard, composite index approaches provide an objective spatial representation of those parts of the landscape with potential for salt mobilisation. In Queensland, for instance (Gordon et al. 2002), the key components of the landscape that are represented within a composite index approach to salinity assessment (as indicators of potential for salt mobilisation) are:

- regolith salt store: this component has been developed from available data and spatial frameworks for soil, groundwater and geological salt stores, and represents the spatial distribution of landscape salt stores;
- recharge potential: this component has been developed from data on soil permeability, excess water (utilising daily rainfall and evaporation data) and depth of weathering information, and represents the spatial distribution of 'leaky' landscapes, based on their inherent characteristics; and
- discharge sensitivity: this component has been developed from data on landscape drainage (soils), landscape features (from digital elevation models) and attributes of groundwater flow systems, and represents the spatial distribution of 'sensitive' landscapes (i.e. components of the landscape that are most responsive to changes in landscape management).

Although conceptual models and scientific data enable the evaluation of different approaches to risk and hazard assessment in the southern and western parts of Australia, in much of northern Australia there are significant gaps in the data coverage. Given these limitations, the composite index approach is the only current credible alternative for regional scale assessment of salinity hazard in these areas.

The composite index mapping approach is usually applied at a coarse scale (say 1:250 000). The outputs can be used to target areas for follow-up with more quantitative approaches based on mapping techniques that collect information that is more directly related to the actual salt load.

Strongly inverse methods

Strongly inverse methods incorporate information on currently salinised areas as one of the spatial datasets (Gilfedder & Walker 2001). These methods statistically determine the relative weights of the risk factors based on available datasets. Examples include the 'weights of evidence' approach (Bradd et al. 1997) and the decision tree approach of Tassell (1995). The main difficulty in statistical approaches is their inability to predict salinisation for processes not included in the risk factors. For example, salinity risk from rising groundwater in regional groundwater systems will not be predicted if the risk factors in the 'training set' all relate to topographic position, climate and geology. Such approaches cannot predict the rate of change of salinity.

Trend-based methods

Trend-based methods are based on mapping changes over time and extrapolating into the future (Gilfedder & Walker 2001). These methods are more reliable in evaluating management impacts. Trend-based approaches have been used for measuring trends in salinisation of land (especially useful in predicting salinity increases under the same climate and land-use conditions), streams (give an integrated result in changes in hydrology and salt movement for a catchment) and groundwater (based on systematic networks of sensors and stratified on the basis of groundwater type, landscape element and the aquifer being monitored). However, it should be remembered that historical trends give a good indication of what has happened and what is happening now, but may not reliably indicate changes in regional groundwater systems that may have a major impact later.

Based on their review Gilfedder and Walker (2001) concluded that 'there is still no readily accepted and adopted approach for the consistent prediction of dryland salinity at a regional scale'. They stated that suitable approaches required:

- appropriate and consistent landscape disaggregation;
- robust methods for assessing salinity risk within each landscape element; and
- an ability to provide long-term predictions of salinity risk.

These elements have been incorporated into a number of recent salinity risk assessments carried out at regional and catchment scales across southern Australia (Coram et al. 2001, NLWRA 2001). In their overview of the case studies carried out for the NLWRA,

Former ephemeral freshwater creek bed overtaken by rising saline groundwater. Efflorescent salt has crystallised in response to evaporative concentration of solutes in the capillary fringe above the watertable – Arthur River valley, WA.

Coram et al. concluded that the modelling approach used

> *… provided a useful technique for comparing the time frames and realistic management options for catchments at risk of dryland salinity in a range of groundwater flow systems across Australia.*

In their opinion the approach provided information to underpin regional salinity management decisions. The approach demands a minimum set of biophysical data on surface hydrology and groundwater, landscape and regolith attributes, land use, climate etc. The mapping methods reviewed in this report provide the means to acquire the basic input data for salinity risk assessments at catchment and regional scales.

DEFINING THE PROBLEM AND CHOOSING THE SOLUTION—THE FOUR CLASSES OF USERS REVISITED

It is instructive to revisit the four classes of users described in Chapter 2 and discuss management options to address the specific questions raised. The next step, described later in this section, is to conduct an economic analysis that forms the basis of a decision of whether to engage in additional mapping, or remediation, or other action.

1. Farmers—paddock scale

Mapping method	Comment or alternative
1. *Are there any indicators of salinity on my land?*	
▮ Visual inspection ▮ Ground EM ▮ Airphotos (if farm is large)	The farmer probably knows of salt scalds, but not whether saline water is approaching the root zone.
2. *If so, how much more salinity am I likely to get, and when?*	
▮ Drill holes – watertable depth and quality ▮ Ground EM ▮ Risk modelling	Investigate what has happened to neighbours and understand activities occurring elsewhere that could mobilise water on farm.
3. *Are my land management activities contributing to the problem?*	
▮ Risk modelling	Understand the influence of land management practices on watertable.
4. *Is this salinity currently damaging any of my assets?*	
▮ Visual inspection – crops, machinery, pumps, fences, etc.	Annual stocktake and assessment. How much damage will the salinity cause?
5. *If not, are there risks to any of my assets in the future?*	
▮ Ground EM ▮ Drill holes – watertable depth and quality (measuring changes over time) ▮ Risk modelling	Education and training may be needed to answer this question. Sustainability is the key question.
6. *What can I do to stop it?,*	
▮ Further mapping (deeper EM) may delineate pathways of water flow	Investigate possible remediation actions before investing in further mapping. Review land and water use and practices. Talk to neighbours or catchment authority.

Quad-mounted and towed EM conductivity systems provide rapid coverage at farm scale).

Photo: Geoforce

2. Local community—subcatchment scale

Mapping method	Comment or alternative
1. *How much salinity are we likely to get, and when?*	
2. *How serious is it now and how serious will it become in the future?* ▮ Soil mapping, vegetation mapping ▮ Airborne and ground EM ▮ Borehole measurements are important. Regional studies from adjacent areas. ▮ Hydrology and watertable trends ▮ Time-lapse satellite or aircraft remote sensing images ▮ Risk assessment	Understanding the relationship of the subcatchment to surrounding areas is crucial. Also changes in land use.
3. *What can we do to stop it?* ▮ More detailed analysis of mapping products as well as modelling for prediction needs.	Prevention and remediation measures require sound understanding of landscape and hydrological processes before action is taken.
4. *Is there anything we need our neighbours to do to stop it?*	
5. *Is there anything we can do to prevent us making it worse for our neighbours?* ▮ Same as 3.	The causes of salinity and its economic impact rarely remain confined within farm boundaries, and the costs and benefits of remediation cross boundaries. Social and policy considerations are important.

Saline groundwater discharge, salt scalding, eucalypt mortality and replacement by salt-tolerant vegetation in topographic lows. Revegetation of surrounding higher ground is aimed at lowering the watertable to ameliorate salinisation of the valley floor – WA Wheat belt.

3. Catchment management groups—regional catchment scale

Mapping method	Comment or alternative
1. *What is the overall level of the problem in the region?*	
▮ Visual inspection ▮ Hydrology and watertable trends ▮ Borehole measurements ▮ Airborne and ground geophysics ▮ Remote sensing (repeated over time) ▮ Vegetation, soil & flow unit mapping	An integrated approach is required for the entire region, to understand landscape dynamics and controls on water movement. Detailed borehole and ground control is essential.
2. *How do managers get that right mix of actions that tackle prevention, recovery, containment and adaptation?*	
▮ Modelling (for prediction) requires good ground (and borehole) control.	Robust assessment of risks and benefits using risk management approaches. Modelling. Socioeconomic considerations may extend outside the regional catchment planning area into adjacent areas.
3. *Where are the best locations to put in salinity management options (e.g. drainage, revegetation works, salt interception schemes) that will deliver the salinity target (e.g. mg/L in the river or a lowered watertable) in the most cost-effective fashion?,*	
▮ More extensive mapping using a suite of techniques is required. Survey design should focus on clear definition of the question to be addressed, and suite of methods chosen, accordingly.	An even higher level of expertise is required to ensure benefits are maximised.
4. *What information is needed to make sound investment decisions at this level?,*	
▮ Full risk assessment and modelling. This might be expressed in terms of an investment framework of where is it best to invest funds to maximise benefit (e.g. into mapping, modelling, new R&D or into salt interception works)?	Socioeconomic modelling (triple bottom line) and sustainability considerations.

4. State/Territory and national—regional catchment scale

Mapping method	Comment or alternative
1. *How much salinity is present, what is its distribution (both in land and rivers) and what are the trends (e.g. mg/L of salt, hectares affected or depth to watertable)?*	
▮ Visual inspection ▮ Hydrology and watertable trends ▮ Borehole measurements ▮ Stream surveys ▮ Airborne and ground geophysics ▮ Remote sensing, essential. ▮ Vegetation, soil & flow unit mapping	An integrated approach is required for the entire region, to understand landscape dynamics and controls on water movement. Detailed borehole and ground control is essential Many of the techniques can be repeated over time to detect trends (taking climatic and seasonal variations into account).
2. *What is the impact likely to be on various classes of assets, and what are the priorities for management?*	
▮ Economic analysis of asset classes ▮ Risk assessment	Primarily socioeconomic considerations at this scale
3. *What are the management options (e.g. where to locate interception schemes to achieve a target of a certain concentration measured in mg/L at Morgan)?*	
▮ More extensive mapping using a suite of techniques is required. Survey design should focus on clear definition of the question to, be addressed, and suite of methods, chosen accordingly.	An even higher level of expertise is required to ensure benefits are maximised.
4. *Which environmental asset is of greatest priority, is at greatest risk and can be viably managed?*	
5. *What will the impact be on other areas if funds are insufficient for management? What resource sharing is required for investments outside the asset to manage the long-term ecological function and use of the asset?*	
6. *What are the overall effects of management options on whole communities through time?*	
7. *What are the priorities for management of other forms of land degradation and the opportunities for synergies for actions to tackle them together?*	
▮ Full risk assessment ▮ Modelling, and assessment of benefits of additional surveys or more detailed interpretation. Mapping using an extended suite of techniques.	Considerations are largely based on socioeconomic and political considerations. Socioeconomic modelling (triple bottom line) and sustainability assessment.
8. *Which initiatives should Australian governments invest to generate the best outcomes in relation to sustainability and profitability?*	
▮ Large scale regional and catchment mapping by State/Territory and Australian Government agencies and catchment authorities.	Improved understanding of the landscape and the human activities (e.g. land use) and natural variations (e.g. climatic and seasonal changes).

CHOICE OF TECHNIQUES AND COST–BENEFIT CONSIDERATIONS

How does a user determine which mapping techniques to use? Is there any point in paying for further mapping if remediation is not feasible, either from an economic or technical point of view? How does a user choose between competing vendors and evaluate claims for a particular product? Is 'knowledge for its own sake' worthwhile, or should investments be confined to targeted problems?

The answers to these questions depend to a large extent on who is asking the question. Certainly the increasing impact of dryland salinity could have been predicted decades ago had adequate basic scientific studies been conducted at the time and prevention measures put in place or had the social and economic costs been evaluated and remediation or prevention measures been politically acceptable and economically feasible.

The decision as to which mapping techniques to use depends to a large extent on social and economic considerations as much as the technical merits of a particular technique. While this book focuses on technical and scientific aspects, investment in mapping techniques depends on a clear evaluation of the costs (which are generally short-term and normally borne by an identifiable group) and benefits (spread over a wide range of time scales and available to a broad range of stakeholders). As an aid to catchment managers, Martin and Metcalfe (1998) compared remote sensing methods (satellite and airborne systems) and ground-based methods used to map dryland salinity in a catchment in terms of aspects such as scale at which it might be used, preferred time of capture, how it is best used, key advantages and limitations of the methods, and their cost effectiveness. While the estimates of costs are not current, their relativities are probably still similar.

The use of mapping techniques requires skill and knowledge by the practitioners—for the selection of the most appropriate method and vendor, for optimum survey design, as well as for data processing and interpretation. It is clear that there is an urgent need within Australia for additional training and education in the use of mapping techniques. The NAGP and other projects have gone a long way to assist in this regard, as have the regular publications and workshops of the NDSP and PUR$L (Productive Use and Rehabilitation of Saline Lands).

George et al. (2000, 2003) describe a set of logical processes that underpin management decisions when investment in mapping methods is being considered. The following example for airborne geophysics is adapted from their papers and updated to reflect the current review.

New map-based information acquired at catchment and regional scales is likely to be cost-effective where:

- the existing natural resource data available to assess the risks and options for management are relatively poor;
- the hydrogeological and landscape processes are not well known;
- the relative importance of the knowledge to making management decisions is high;
- assets of considerable value will be at risk with increasing salinity;

- the options for salinity management are understood and are likely to be cost-effective;
- specific management actions can follow from mapping; and
- off-site and on-site benefits are high, and can be quantified.

The motivation for mapping is likely to be highest where:

- there is a likely net positive cash flow from the agricultural activity of the catchment;
- there is a relatively low level of existing knowledge of the catchments processes; and
- there is a good potential for other off-farm benefits to be realised (e.g. maintenance of infrastructure, management of the public estate, development and maintenance of groundwater resources, management of water quality, protection of biodiversity and provision of government planning and advisory services).

However, the constraint of net positive cash flow from agricultural activity in the catchment cannot be disassociated from issues of equity, benefit and cost sharing. As mentioned previously, the financial impact of dryland salinity may degrade assets located large distances away from the human activity that causes it. In the Murray–Darling Basin it is estimated that less than 33% of the costs of salinity directly affects farm income and the capital value of farmland.

These issues can only be addressed by broader policy decisions made by communities, government authorities or their delegates. Recent moves towards water trading and salt trading demonstrate that solutions are possible, and in some cases may require financial incentives combined with changes to the regulatory framework, to affect land use decisions and reductions in salinity positively.

The situation is further complicated by the fact that, even with inappropriate land management, salinisation may take 50 to 100 years to appear, and remediation measures may take just as long to reverse the process. Considerations of inter-generational equity, user-pays, triple bottom line accounting and sustainability all have key roles in the decision-making process.

Salt scald in pasture land, eastern Riverine Plain – Simmons Creek, NSW.

7. SURVEY DESIGN AND DATA MANAGEMENT

This book provides broad guidelines and descriptions of methods for mapping salinity and other landscape processes targeted at a range of users. The mapping methods are current at the date of publication, but new and innovative technologies continue to evolve rapidly.

Specialists should always be consulted in all phases of mapping—from design of the survey, through processing and integrated interpretation.

SURVEY DESIGN, PROCESSING AND INTERPRETATION

Most of the mapping techniques described in this book were developed for applications other than environmental or land use management. For instance, airborne electromagnetic methods were first developed for submarine detection, then later applied to mineral exploration for the detection of conductive ore bodies, and only recently have been applied to salinity and landscape mapping. Many techniques are not designed to map the near surface in detail, nor are they designed to deliver well-calibrated and repeatable values for the subsurface parameters. To extract maximum information from these methods, care should be taken in the choice of a system of calibration procedures. This is especially important in salinity applications where surveys may be repeated at different times (so called 4-D or time-lapse surveys) to determine progress in salinisation or its remediation. Various submissions to this review reported research projects into refining techniques to improve resolution in the top ten metres and it is expected that advances will continue to be made.

Numerical modelling is routinely used by those involved in the exploration industry to determine the optimum airborne system and survey parameters, and should also be employed in salinity studies by environmental managers. The cost of acquisition can vary widely depending on the scale and level of detail (see for example the discussion of cost of AEM in Appendix A1.18).

To gain maximum value from natural resource management (NRM) surveys, they should be collected to a rigorous set of specifications and procedures, with processing flows and interpretation steps clearly documented.

COSTS

Mapping costs usually comprise:

- cost of initial survey design;
- cost of data acquisition (for ground and airborne surveys includes mobilisation/demobilisation, and sometimes a standby cost in the event of bad weather);
- costs of data preliminary processing, ground-truthing and field calibration, final processing and interpretation; and
- cost of data verification to confirm the quality of the results).

The cost of mapping using various techniques included in the tables on the following pages relate to acquisition costs and in some cases preliminary processing. Total survey costs, including survey design, calibration and ground-truthing, and interpretation can often double these indicated costs.

DATA MANAGEMENT

Data processing flows

The data from airborne surveys go through a number of stages in the standard processing stream.

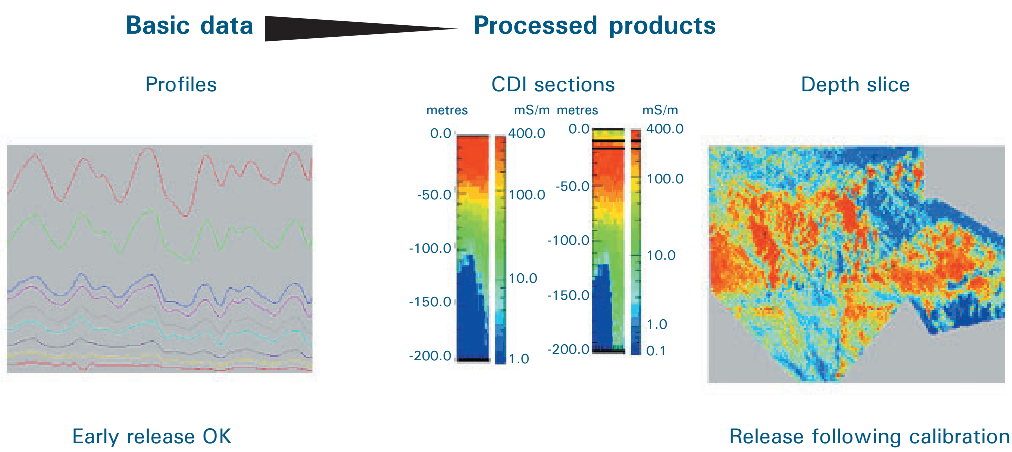
'Basic' data can be classed as raw data collected during the survey that is subject to standard quality control procedures, with standard corrections for elevation, temperature and self-calibration.

'Processed products' are derived from the basic data. For AEM they include computer-generated, conductivity-depth, slice maps and conductivity-depth image (CDI) sections. These products are interpretations of the data, involving various underlying assumptions about the earth model and data accuracy. The inversion of basic geophysical data to earth parameters depends upon assumptions about the earth model. Individual users of software interpretation products will often derive different interpretation images, so it is important that the settings and description of the computer programs are carefully documented.

Ground validation (or calibration) is an essential component of processing many types of geophysical data. For AEM, a program of drilling and borehole conductivity logging undertaken in conjunction with the survey usually results in significant improvement in the processed product. For instance, AEM data from Honeysuckle Creek in Victoria showed significant differences between the calibrated and uncalibrated data (Christensen 2004).

It is recommended that raw data with basic processing be released as soon as practical after collection. Processed

Figure 8. Various stages of data flow (courtesy Alan Willocks, Victorian Department of Primary Industries, October 2003).



depth maps and CDI sections should not be released until they have been calibrated and had ground validation carried out. All data and interpretations that are released need to be well documented with relevant assumptions, processing parameters, caveats and error estimates.

Custodianship

Mapping data collected for NRM applications should be properly archived with associated metadata, including calibration data, processing streams and interpretation products[2]. NRM data requires careful attention to quality control and standardisation of processing procedures.

A vast amount of NRM data, particularly airborne geophysics, has been collected over the last decade for catchment management groups and various agencies, yet much still remains confidential and many of these surveys have yet to be interpreted. Unfortunately access to data collected for NRM purposes is much more restrictive than geoscience data collected by government agencies and industry for mineral and petroleum exploration. Exploration data is legally obliged to be lodged with State/Territory (and Australian) government agencies and, after a confidentiality period, is freely available to the public. Basic geoscientific data collected by State/Territory and Australian Geological Surveys is also freely, or at the incremental cost of copying, available to the public.

A number of submissions received by this review suggested that there should be a policy of open availability for NRM data across all jurisdictions in Australia. A logical repository for such data is with the various State/Territory geological surveys as they already have procedures in place for the appropriate distribution, storage and archiving of geoscientific data. Ideally, all data (e.g. on geology, geophysical details and regolith attributes) should be made accessible to researchers and to the public, so that new processing and interpretation techniques can be applied as they become available.

Data from airborne surveys can be categorised as either basic or processed data, as described above. These data types should be treated as separate products when considering data for release and its timing. The basic data, including located data with standard corrections and in-flight calibrations, should be released as soon as possible. Various processed products including depth slice maps and CDI sections can be released as they become available. At each step, appropriate explanations of the processing flow should be included with the data.

Investments in data management

A balance needs to be struck between the need to collect and use data at fine resolution at paddock scale and the broader benefits that are possible when data are combined to produce a bigger picture at catchment, State/Territory and national levels.

The technologies that are suitable for mapping dryland salinity risk and hazard are evolving rapidly. Australia is particularly fortunate to have an excellent science community that continues to improve our ability to

2 ANZLIC policy and guidelines for standardising spatial data management can be found at <www.anzlic.org.au/policies.html>.

usefully deploy new mapping methods. This review is current because it has been very well supported by this community. For this currency to be maintained the review should itself be periodically updated.

Substantial investments have been made, and will continue to be made, in the collection of data for salinity management. These data require systematic coordination, storage and management in order to optimise their use. Such coordination can ensure the appropriate application of standards as well as helping to identify properly credentialed specialists.

SOURCES OF GEOSPATIAL DATA AND INFORMATION

The Australian and State/Territory governments are custodians of large quantities of geospatial data, which have been acquired through numerous mapping campaigns over a period of decades. Available data include those acquired by or on behalf of government, as well as mapping data acquired by resource companies in the course of exploration programs and subsequently provided to government under appropriate legislation.

The Australian Government introduced a policy in 2001 of making its geospatial data available to the public without charge if it could be accessed on website or for the marginal cost of supply if the data were stored elsewhere. As a result a large range of types of mapping data, at a variety of scales and types, are available free of charge or for the marginal cost of distribution.

State and Territory jurisdictions variously offer different policies on data availability, pricing and permitted use.

The various Australian and State/Territory sites can be accessed through the Australian Government's Geoscience Portal <www.geoscience.gov.au/> and the Australian Spatial Data Directory <asdd.ga.gov.au/asdd/>. Much of the data is at a regional scale, but selected areas have been mapped at finer scales.

At present, much data acquired by government agencies or catchment authorities for NRM applications are not readily available to the public.

Specialist expertise and knowledge of mapping systems can be obtained from government and industry sources, in particular:

- Professional geophysical societies that deal with environment applications
    - Australian Society of Exploration Geophysicists (ASEG) <www.aseg.org.au/>
    - The Environmental and Engineering Geophysical Society (EEGS) (US-based) <www.eegs.org />
    - European Association of Geoscientists & Engineers (EAGE) (European-based) <www.eage.org/>

- Government-funded groups and agencies working in the field of natural resource mapping[3]:
  - Bureau of Rural Sciences <www.brs.gov.au/>
  - CRC-LEME <leme.anu.edu.au/>
  - Geoscience Australia <www.ga.gov.au>
  - public Sector Mapping Agency <www.psma.com.au/>
  - NLW<http://audit.deh.gov.au/ANRA/atlas_home.cfm>
  - NDSP <www.ndsp.gov.au/>
  - State/Territory NRM agencies
  - CSIRO

A GENERIC APPROACH

'The four classes of users' (p. 7) examined the steps required to help decide if new information is needed to better understand the salinity problem in a catchment or at other scales. The following discussion serves as a general template for those wishing to improve their knowledge of salinity in a catchment. This discussion is based on a synthesis of the techniques reviewed by this study. It is also assumed that all existing information has been assembled, including that involving geology, air photos, borehole and land use.

A robust first step in determining if a catchment is likely to have a problem with salt discharging into local streams is to undertake systematic in-stream sampling of salt concentrations across the catchment. This approach can be readily applied to catchments of many hundreds of thousands of hectares in size down to small catchments of just a few thousand hectares.

The outcomes of in-stream sampling help target the subcatchments that have higher areas of transportation of salt load and therefore areas that require further investigation. This can be done using EM techniques (typically airborne electromagnetics) that can then give a measure of salt load at depth, its location and approximate concentrations. Airborne EM and magnetics may also provide crucial information on structural and permeability factors that control subsurface groundwater flow. Most importantly the EM acquired must be systematically calibrated to ensure that its mapped outcomes are accurate and stable. This can be done using existing borehole data or ground-based EM. In this way only that part of the catchment that has an indicated salt load is mapped for EM, saving on costs. EM mapping is the only broadacre mapping technique currently available for remote sensing of salt load below the surface.

Satellite imagery, air photos and field sampling can help map the surface expression of salinity in the form of salt scalds to complete the picture of salt hazard in the catchment.

It may be desirable to acquire aeromagnetics and an accurate DEM over a larger part of the catchment in order to better understand the forces that govern groundwater movement. At this point it is most useful to have a more detailed understanding of soil types

[3] Many service providers for specific products are not listed here but can be identified through web searches and telephone books, or by contacting the agencies listed above.

(e.g. Isbell 1996; Stace et al. 1998) to help identify those that have a predisposition to salinisation. Soils types can be mapped using a variety of techniques that may include radiometrics, satellite imagery, air photo interpretation, combined with field sampling. In future hyperspectral techniques may also be useful for mapping soil types.

With better understanding of the forces that govern ground water movement (see Chapter 3) combined with predictive approaches, modelling and GIS, it may be possible to begin to predict where the salt will occur or may be at risk of mobilisation, permitting a picture to evolve of the risk of exposure to salinity at some point in the future.

8. CASE STUDIES

OVERVIEW OF CASE STUDIES

The case studies are intended to help guide those who are thinking of commissioning studies to collect information to help manage dryland salinity. They emphasise how the information collected (the outputs of the studies that come in the form of information products) can be used to improve management practices and create better outcomes for land managers.

These case studies illustrate a few of the various techniques listed in the technical review of salinity mapping methods in the Australian context and are good examples of what is involved in mapping dryland salinity or implementing risk assessment analyses.

The following case studies demonstrate how various mapping methods can be applied in the study of dryland salinity. The examples have been drawn from studies made over the last few years at a variety of scales and in different States/ Territories and regions. In some cases little was known previously about the hydrogeological systems or landscape of an area, and regional mapping applied to set a consistent framework for more detailed investigations. In other examples the mapping techniques were carefully selected to address specific questions in salinity management.

The case studies demonstrate a number of approaches that have been used to map salinity and should be read in the context of methods available at the time. The methods and approaches are not necessarily what would be used today or will be used tomorrow. The range of case studies does not represent all of the salinity mapping methods available today.

The presentation of the case studies in this report does not imply an endorsement of these methods and potential users of the methods covered here are well advised to seek current professional advice before embarking on similar studies.

Satellite methods

Arguably the largest and best known example of salinity mapping and monitoring is the Land Monitor Project carried out for the Western Australian Government in the agricultural zone of south-west Western Australia (Case Study 1). It is based on the use of LANDSAT multi spectral data combined with rigorous evaluation through ground-truthing. It demonstrates very well the use of satellite remote sensing in identification of current salinisation and monitoring trends through time. One of the impressive strengths of this project has been the effort put into the validation of the estimates of salinisation, and the utility of the resultant products to assist in planning management responses. This project benefited considerably from research and development undertaken through the NDSP by CSIRO and the WA Department of Agriculture. The approach has been shown to be very useful in the subdued landscapes and Mediterranean climate of south-western

Western Australia. One big advantage is the depth of experience in this approach that this has developed in Western Australia.

Airborne geophysics

The two projects using airborne EM to map clay layers in South Australia (Case Studies 2 and 3) are good examples of the application of this technique and highlight the value of preliminary analyses to identify appropriate methodology.

The Bengworden case study (Case Study 9) is not a salinity mapping exercise per se, but an example of how airborne geophysics can be integrated with prior knowledge of geomorphology and soils and limited information of groundwater to define landscape units that might be contributing to groundwater recharge. This was used to make a more detailed examination of hydraulic properties in the field and, presumably, to guide evaluation of land management options.

Case Study 10 in Trayning, Western Australia is another example of the use of airborne geophysical data at a property scale to map soils, areas of low salt storage, regolith depth and geological structures as a basis for the location of trees for production and reduction of groundwater recharge.

The Upper Kent catchment case study in Western Australia (Case Study 11) is an example of the use of airborne geophysics to develop a hydrogeological model of the catchment basement and, in particular, to assess the role of palaeochannels in catchment drainage and the implications for salinity management options. It introduces another level of rigour to the deliberations in the Kent catchment.

Case Study 12 demonstrates very effectively the benefits obtained through the use of airborne EM to supplement previous geophysics and land surveys in the Lake Toolibin and Towerrinning catchments of Western Australia. The extra information gained on the palaeochannels in both catchments has led to better investment outcomes for environmental values in one catchment, and for a rural community and rural enterprises in the other.

Ground-based systems

Case Study 6 used ground-based EM to define the causes of salinity outbreaks at a small catchment scale, and to provide some objective basis for the development of salinity management options. It is typical of the type of approach to salinity mapping that might be undertaken by or for landholders.

Ground-based salinity mapping using EM systems was applied to map and evaluate the impacts of soil and subsoil salinity stores on pasture production in the Swan coastal plain in Western Australia (Case Study 12). This study is an excellent example of the application at farm scale over a subregional area to answer a series of questions raised by farmers about causes, impacts, risks and management options and layouts. The study highlights the value of the EM38 and EM31 systems in salinity management activities.

Stream and groundwater monitoring

Case Study 7 set in the mid-Macquarie region of New South Wales is an example of field-based measurement and monitoring of groundwater and streams to identify the location of areas contributing salt to streams as a basis for targeting more detailed salinity risk assessment and the development of management responses. The project demonstrates:

- the value of a stream and groundwater monitoring network to evaluate the size of the salinity problem and the rates at which change is occurring; and
- the way more detailed (more costly) mapping of likely salt stores which could contribute to stream salinity can be targeted.

Combination of systems

The Billabong catchment case study (Case Study 4) is an example of the use of a suite of techniques to assess salinity risks particularly to water resources and to identify appropriate salinity management objectives. It demonstrates the level of technical expertise, groundwater and landscape information that is required to carry out a salinity risk assessment.

The Simmons Creek case study (Case Study 8) is an excellent example of the integrated or combined use of techniques and skills to define the causes of salinity changes in a stream, the biophysical processes controlling salt movement in the landscape and the development of a landscape framework within which management options could be evaluated. This case study highlights the range of disciplinary skills required to assess salinity risks, and to develop and evaluate management options.

The Lower Balonne airborne geophysics project (Case Study 13) combines a range of airborne geophysical methods with ground and borehole data to obtain a three-dimensional understanding of regolith architecture and groundwater movement in the area. This project demonstrates the importance of community engagement for uptake of recommendations.

Comment

No attempt has been made to 'evaluate' the approaches taken or the results obtained in the case studies. It is not appropriate for this book to make that level of evaluation. It is sufficient to say that in general the circumstances or context of any study determines the overall approach taken and the level of integration of skills possible and desirable. The main determinants are the specific objectives and the available resources (time, funds and skills).

Most of the case studies exemplify the value of developing an overall approach that focuses on a specific set of objectives as against taking an approach of 'try the techniques and see what we can find'.

A common feature of the case studies that use indirect methods of mapping is the associated field studies required to provide validation of the assessments. All demonstrate the need for specialist skills often across a number of aspects.

Nationally there is a strong body of experience available in the application of ground-based EM38 and EM31 systems. The case studies demonstrate some focused applications where the questions being asked by landholders have been specifically addressed.

Experience in the application of the airborne systems is growing slowly in the eastern States; there appear to be some difficulties in getting the range of discipline skills together (costs and availability) to apply these systems as widely as desired.

The thirteen case studies are:

1. Land Monitor Project in south-west WA (Landsat) – Jeremy Wallace, CSIRO;
2. Riverland, Murray Basin, SA (HEM) – Steve Barnett, SA Department of Water, Land and Biodiversity Conservation; and Tim Munday, CRC LEME;
3. Tintinara, Murray Basin, SA (HEM) – Steve Barnett, SA Department of Water, Land and Biodiversity Conservation; and Tim Munday, CRC LEME;
4. Billabung Creek catchment Upper Murrumbidgee, NSW (fixed-wing AEM and radiometrics) – Michele Barson, BRS;
5. Soil Landscapes of the Liverpool Plains, NSW (soil landscape mapping) – Robert Banks and Greg Chapman, DIPNR;
6. Woods Flat Creek (EM31 and geology) – Nik Henry, DIPNR;
7. Mid-Macquarie community salinity prioritisation and strategic direction project (groundwater levels, stream salinity and GFS) – Michele Barson, BRS;
8. Simmons Creek, Billabong Creek catchment, NSW (ground EM, soils, stream sampling, magnetics) – John Gallant and Pauline English, CSIRO Land and Water;
9. Bengworden, VIC (GIS with multiple data including radiometrics) – Greg Street (GeoAg Pty Ltd) and Andrew Harrison, SKM for Department of Natural Resources and Environment, Victoria (DNRE);
10. Trayning, WA (GIS with multiple data) – Simon Abbott (Australia Dryland Salinity Consultants) and Greg Street (GeoAg Pty Ltd) ;
11. Toolibin – Towerrinning catchments, WA (AEM) – Richard George and Don Bennett, WA Department of Agriculture;
12. Salinity mapping in high rainfall agricultural areas of south-west WA (ground EM) – Richard George and Don Bennett, WA Department of Agriculture; and
13. Lower Balonne airborne geophysics project, QLD – Kate Wilkinson, QLD DNRM.

CASE STUDY 1: LAND MONITOR PROJECT IN SOUTH-WEST WA

Submitted by: Jeremy Wallace, CSIRO Mathematical and Information Sciences

Location: The south-west agricultural area of WA

Area: 240 000 sq km (24 million ha)

Scale: Regional, with coverage at fine resolution – 25 m pixels (<0.1 ha)

Rainfall: 700 to 350 mm/annum

Land use: WA's SW 'Mediterranean' agriculture crops, pasture, grazing

Soil classification[4]: Various

Groundwater system: Mainly local

Evidence of salinity: Well-documented extensive dryland salinity, saline streams etc.

Description of problem or concern

Despite the long-recognised importance of the salinity problem in the region, there was a lack of mapping, monitoring and prediction information. There was no consistent, spatially detailed, accurate map of the extent of dryland salinity (other than for small catchments), rates of change on affected land nor any spatially explicit prediction of the area at risk. Similarly, there was a lack of information on the changes in the remnant perennial vegetation in the region. Traditional mapping and modelling methods could not effectively meet this information need.

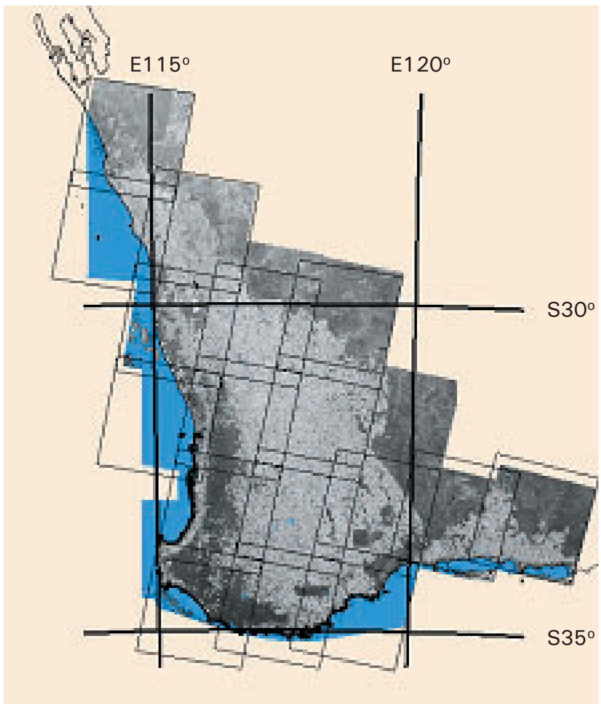


Figure 9. Area covered by Land Monitor data (thematic mapper sequences, DEM, etc.) and products (salinity mapping, monitoring, prediction and perennial vegetation change) in the entire south-west agricultural region of Western Australia. Area shown is approximately 800 km E–W; the area covered for detailed processing is 24 million hectares.

4 For definitions of soil types referred to in the case studies, refer to Isbell (1996).

What was done to study the problem

The Land Monitor Project, 1998 – 2001, supported by Western Australian agencies, through the Salinity Action Plan (1996 – 2000) and the National Heritage Trust, set out to produce accurate and validated maps of:

- the current extent of salt-affected land and the extent of change since 1989;
- prediction of the extent of land at risk; and
- maps of change in perennial vegetation (including clearing, revegetation and more subtle changes) over the period 1988 – 2000.

The approach was to develop and apply statistical methods to available data (principally Landsat image sequences and DEM, as well as ground information) to produce the information products. The principal steps were:

- identification of best datasets (including ground data) and basic processing;
- analysis of individual data layers to produce maps along with confidence estimates (commission/omission statements);
- appropriate integration of processed data layers to produce best maps incorporating uncertainty; and
- validation, product distribution and reporting.

Results

Basic datasets for the entire south-western region (24 million ha) were produced and widely distributed. These included:

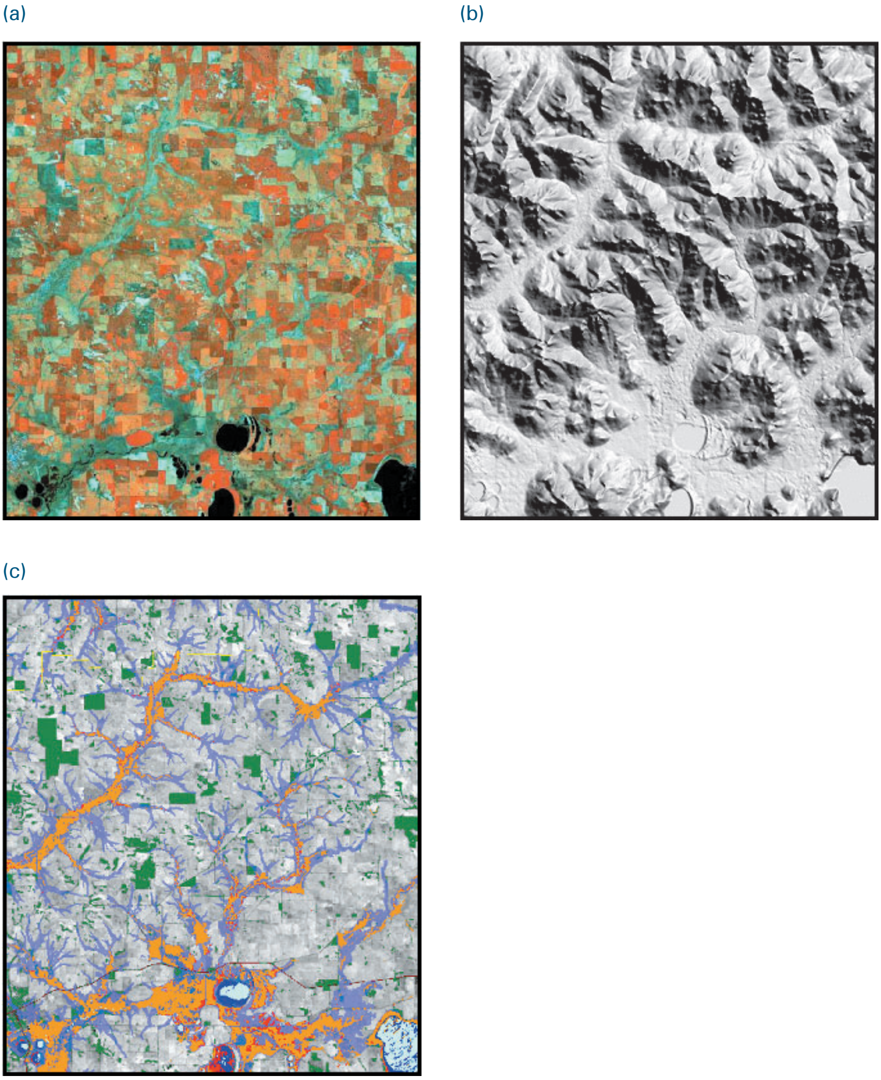
- calibrated Landsat sequences 1988 to 2003;
- an accurate new digital elevation model for the entire region with accuracy for height of +/-1 m at 10 m spatial resolution as research had shown that existing DEM was inadequate for accurate mapping and prediction; and
- ortho-photo mosaics for the region.

Maps and statistical products at 25 m scale for the entire region for:

- salt-affected land;
- change in saline land over the decade;
- statistical summaries of area affected and change;
- vegetation change, clearing and revegetation; and
- generalised hazard maps for more detailed analyses at a local scale (accurate risk mapping was not possible).

All salinity maps were validated for accuracy by ground sampling of points within representative areas of each zone. Typically, several hundred points were checked by ground experts within each satellite scene, with points selected systematically from a grid to minimise bias. Error estimates (commission and omission) were determined and reported for each scene (available on website and provided with each product).

Figure 10. Land Monitor data and products: Detail 30 km by 26 km from Kellerberrin area: (a) Landsat image, spring 1998 (bands 4,5,7 in red, green, blue); (b) Sunshaded DEM of same area—vertical displacement exaggerated; (c) Products: perennial vegetation (green); salinity 1989 (orange), salinity increase (red); hazard areas for follow-up assessment (purple). Background grey is Landsat image.



Cost/benefits (economic, environmental, social)

Land Monitor Project costs are well-documented. The entire project cost $7 million over three years (which equates to approximately 30 cents per hectare). Cost breakdown was approximately:

- new DEM for south-western WA ~ $4 million (more than half project cost);
- data processing, integration and product generation ~ $1.5 million (core scientific activity); and
- satellite data acquisition 1998 – 2002, other data, project management, ground data costs, distribution ~ $1.5 million.

It should be noted that prices of DEM and satellite data are now considerably lower.

The core datasets such as the DEM and the image archive have ongoing value for many users including those concerned with salinity management. The scale of the project resulted in significant economies for data processing and, particularly, for the DEM generation—at approximately 20 cents per hectare for the high quality DEM the price was about one-fifth of the price at the time for catchment-scale DEM. Ongoing monitoring costs would be much less—for instance the update of ongoing vegetation monitoring in the region costs approximately 25 cents per sq km (or ¼ cent per hectare). Ongoing salinity monitoring is not supported at present but a proposed five-year update cycle was costed at ~ $3/sqkm (or 3c/ha).

The study has provided fundamental information infrastructure for managing and communicating salinity and vegetation issues across a wide region.

Direct benefits are difficult to quantify in this summary. The data and products have achieved widespread use by agencies and the public.

For the first time, spatially accurate and consistent data on salinity and change over the region is available to underpin action, planning and funding which previously had no such consistent basis. As the data are distributed to agencies, other groups and individuals, the total effect is not centrally summarised—in fact it would take a major study to collate and value the impacts of access to these data and mapping products.

It should be noted that for many of the users no alternative usable information is available.

Examples of use and users who have accessed information from the Land Monitor Project include:

- data used to identify, plan and inform action in priority catchments (CALM, Department of Agriculture, community);
- salinity maps and hazard data used to provide information about threats to road infrastructure, remnant vegetation and conservation planning (CALM, CSIRO, community groups);
- underpinning funding applications and action by regional groups and conservation planning and lobbying by rural groups (e.g. South Coast Region, Mallee Fowl Group, Gondwana Link);

- salinity and prediction data were crucial to the Department of Agriculture's Rapid Catchment Appraisal Program (a follow-up program which would have been impossible without consistent data);
- vegetation change data used for monitoring rates of clearing and for policy development and conservation management research and the setting of priorities (Greening Australia, CSIRO, CALM) and also for assessment of new forest plantations (CALM, industry);
- data used extensively to identify priority areas for purchase/ conservation; and
- DEM used for information on hydrology, drainage etc. (many and ongoing users).

As well as the specific uses specified above, hundreds of 'individual' users of and customers for specific datasets have been recorded in the Land Monitor Project records—including farm consultants, groups, engineering consultants and the Australian Conservation Foundation.

Other comments

Land Monitor has been a landmark project in working back from a clear objective (the information needs) to identifying the data, methods and costs to meet the objective. It was conducted collaboratively by six Western Australia State agencies and the CSIRO. The study demonstrated a capacity to provide spatially explicit information over broad areas about salinity and the prediction of salinisation. The approach (of data identification, analysis and integration) can be tested and adapted to other region and land information questions. Presently data are being analysed for a test area in Victoria. The Australian Greenhouse Office supports a very large-scale project based on this technology for monitoring vegetation change (not salinity) for the entire continent. Sample images of data and products from Land Monitor are shown in the Figures 9 and 10.

Key references

The methods, project details and products are thoroughly described on the website <www.landmonitor.wa.gov.au>. This site contains a full set of product reports, technical documentation, publications and links in downloadable form. It also contains information on the project and example of the products (see also <www.cmis.csiro.au/rsm> for technical information on data processing methods).

CASE STUDY 2: RIVERLAND IN MURRAY BASIN, SA

Submitted by: Steve Barnett, SA Department of Water, Land and Biodiversity Conservation; and Tim Munday, CRC LEME

Location: Riverland, SA

Area: 1650 km^2 (0.16 million ha)

Scale: Regional

Rainfall: 250 mm/annum

Land use: Dryland farming, irrigation (using River Murray water)

Soil classification: Various

Groundwater system: Regional

Evidence of salinity: Saline groundwater discharge to River Murray

Description of problem or concern

The problem concerns the need to minimise saline drainage from future irrigation adjacent to the Murray River and find areas of higher recharge for improved water management and possible revegetation to reduce the impacts of clearing.

What was done to study the problem

The shallow Blanchetown Clay unit in the Riverland acts as a barrier to recharge in the area. By delineating the location, extent and thickness of this clay unit, it could be possible to reduce recharge, and hence manage future saline groundwater inflows to the Murray River by appropriate remediation and prevention measures. AEM was chosen as the most appropriate tool to map the Blanchetown Clay unit which had been confirmed as a good conductor by conductive borehole logging.

An airborne EM survey was designed based on knowledge of the hydrogeological framework and the results of pre-survey borehole induction conductivity logging. This enabled modelling of the likely EM response of the target given a particular AEM system and survey parameters. This process determined that a helicopter-mounted, frequency-domain EM system was best suited to determining the distribution and thickness of the clay in the region at an adequate resolution for planning purposes. A total of 11 476 line-km of data were acquired with the RESOLVE HEM system (Appendix 1.18) at a line spacing of 150 m. The highest frequency (106 kHz) of this system helped resolve conductors very close to the surface which might represent the Blanchetown Clay units in the Riverland area.

Results

Figure 11 shows the location of boreholes and the interpolate thickness of the clay unit. The interpreted thickness of the clay layer obtained from the AEM survey, constrained by borehole data, is shown on the right. The AEM-derived map provides a much higher definition of clays and buried sand dunes than had been previously known and will be used as a basis of salinity management, including providing information for planning salt interception schemes.

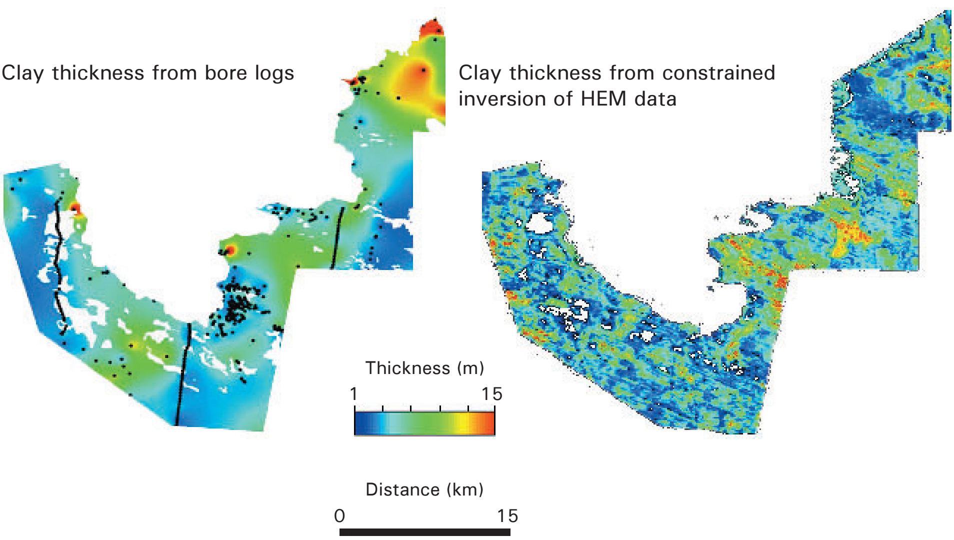
Cost/benefits (economic, environmental, social)

The cost of the survey, including processing, was $470 000. The benefits are still being determined, but include reduction of in the salt load entering the River Murray.

Other comments

Investigations into salinity issues in the Murray Basin carried out over the last twenty years have provided a good understanding of the hydrogeological framework. Considerable thought went into defining useful targets for the AEM survey, rather than a simplistic 'salinity mapping' approach ('let's fly it and see what turns up') that would not have provided the level of detail and understanding required.

Figure 11. Thickness maps of Blanchetown Clay unit derived from boreholes (left) and helicopter electromagnetics (HEM) data (right). The HEM data shows much higher resolution.



CASE STUDY 3: TINTINARA, MURRAY BASIN, SA

Submitted by: Steve Barnett, SA Department of Water, Land and Biodiversity Conservation, and Tim Munday, CRC LEME

Location: Tintinara, SA

Area: 590 km^2

Scale: Regional

Rainfall: 450 mm/annum

Land use: Dryland farming, irrigation (using groundwater)

Soil classification: Various

Groundwater system: Regional unconfined limestone aquifer

Evidence of salinity: Dryland salinity and groundwater salinisation

Description of problem or concern

The problem concerns the need to locate areas of high salinity in the watertable. There are also old bores with uncemented steel casings which corrode where there are saline watertables. It is necessary to ensure that as a result of corrosion they do not contaminate the underlying fresh confined aquifer. There was also the need to map areas of declining health in vegetation (trees) to define areas with saline watertables close to the surface.

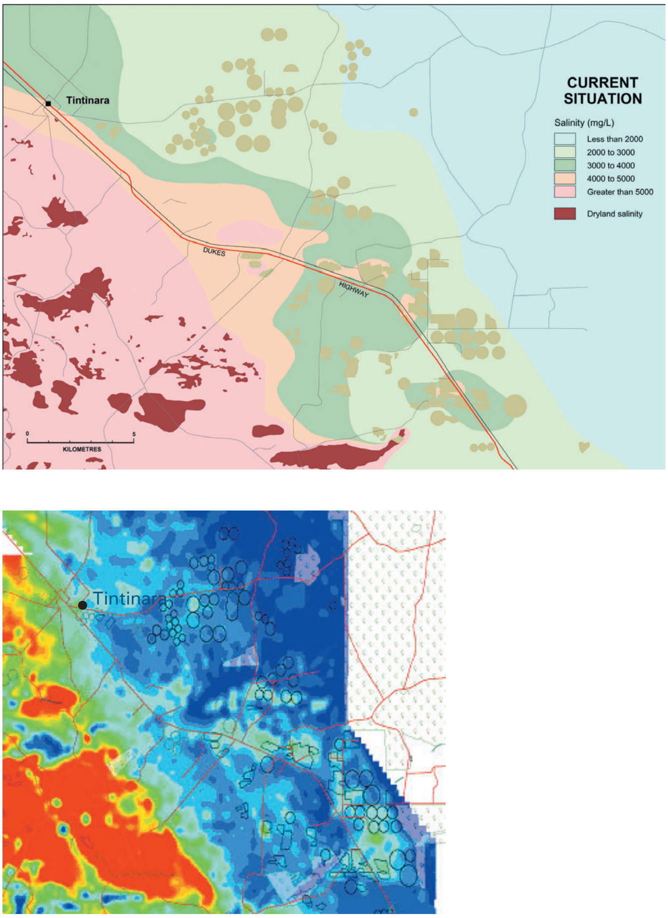
What was done to study the problem

A helicopter-mounted, frequency-domain EM survey was used to map the salinity of the shallow aquifer (depth to watertable 0 to 20 m, aquifer 50 m thick). A total of 2133 line-km was flown with the RESOLVE system (Appendix 1.18) at a line spacing of 300 m.

Results

A salinity map obtained from boreholes in the area (Figure 12) shows known areas of high salinity occurring in the south west. The image on the right is a map of the ground conductivity (red = high conductivity, blue = low conductivity) measured by the RESOLVE HEM system for the top 10 m. It shows a very good correlation with groundwater salinity determined from bores in the uniform limestone aquifer, and suggests that the distribution of saline groundwater close to the surface is more extensive than previously known. In this area the aquifer does not have any clay layers to complicate interpretation of the EM response.

Figure 12. Salinity maps of the Tintinara area of the Murray Basin obtained from boreholes (top) and HEM data (bottom). Salinity in this area is more extensive than previously thought.



Cost/benefits (economic, environmental, social)

The cost of the survey, including processing, was $250 000. The benefits are still being determined, but include improved location of hazards for more detailed assessment. The preservation of biodiversity in the area, particularly where native vegetation is threatened by a rising saline watertable, is a goal of the survey.

Other comments

As shown in Figure 12 (bottom right) the EM picks up localised increases in salinity beneath irrigation areas caused by recycling of salt in the shallow aquifer. This has also been verified by groundwater sampling.

CASE STUDY 4: BILLABUNG CREEK CATCHMENT, UPPER MURRUMBIDGEE, NSW

Submitted by: Michele Barson, Bureau of Rural Sciences (BRS)

Location: Between Cootamundra and Junee, southern NSW

Area: 93 000 ha

Scale: Catchment

Rainfall: Varies from 500 mm/annum in the west to over 700 mm/annum in the east

Land use: Annual and perennial pastures on plains and undulating hills, annual and perennial pastures and remnant native vegetation in highlands

Soil classification: Range of soil types

Groundwater system: Billabung Creek catchment is dominated by local groundwater flow systems, with the alluvial sequences comprising a local to intermediate flow system

Evidence of salinity: Visible salt outbreaks (ponded water EC >800 μS/cm) mapped over 0.5% of catchment, stream salinities vary from fresh (<100 μS/cm) to saline (>6500 μS/cm), modelled stream (surface water) salt exports to the Murrumbidgee of 6600 tonnes/year.

Description of problem or concern

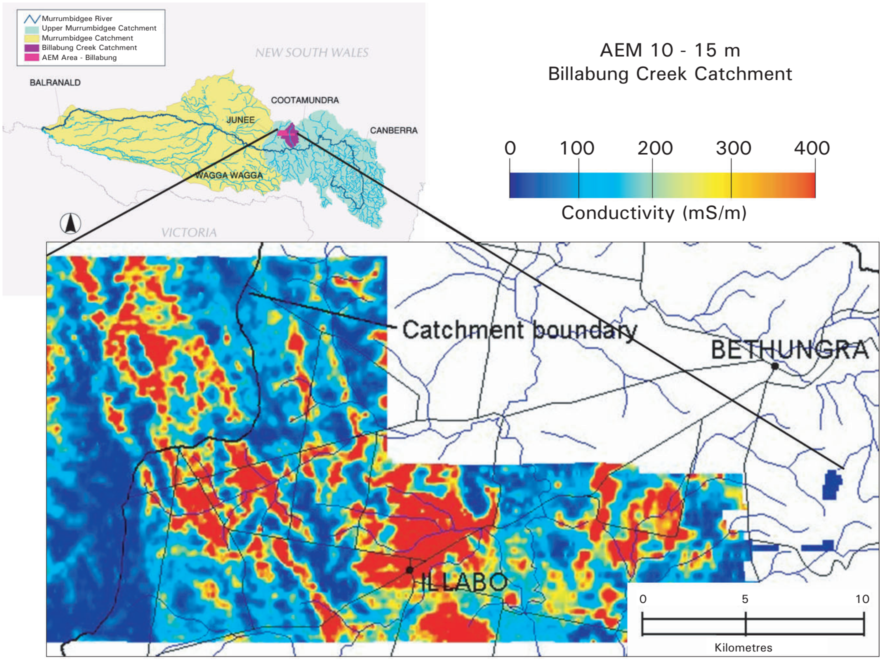
High but variable spot EC readings in ephemeral Billabung Creek were of little local concern but groundwater flow salinity contribution to the Murrumbidgee River was unknown.

What was done to study the problem

The Billabung Creek catchment was chosen by the Bureau of Rural Sciences (BRS) to demonstrate how new methods for salinity mapping and management could be applied in the NAP. BRS worked with regional staff from the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR), and consulted local landholders to establish salinity management objectives. The primary objective was to reduce the amount of salt entering the Murrumbidgee from the Billabung Creek catchment.

AEM was used to map the salt stores and pathways on the plain. The AEM system used was the fixed-wing TEMPEST system with a 150 m line spacing and flying height of 120 m. The data were processed with CDI to a calculated depth of 150 m, producing the map shown in Figure 13. The AEM data showed that the salt stores in thick clay soils are larger and deeper than in soils with more sand or gravel, with a maximum salt content of water in the soil of 9000 μS/cm (900 mS/m). Coarser, less clayey soils associated with the drainage lines (see Figure 30 Braaten et al. 2003) act as a conduit for groundwater carrying salt to the Murrumbidgee River. In the highlands region, airborne gamma radiometrics was used to delineate the thick clay soils from which salt is more likely to be leached to the streams. Bore drilling and surveys of stream salinity were used to validate the information provided by the

Figure 13. AEM image for part of the Billabung catchment.



airborne radiometrics. It was found that in the highlands, salt stores are small, localised and close to the surface.

Analysis of bore water levels, stream flow and the ability of the alluvial aquifer to transmit water, suggested that most water and salt exports from the catchment take place as underground water flow. In addition, salt is exported from highland areas in a winter stream flow through the alluvial aquifer or directly into the Murrumbidgee River. It is estimated that approximately 10 000 tonnes of salt from the highlands and 20 000 tonnes of salt from the plain are exported from the catchment each year (Figure 14).

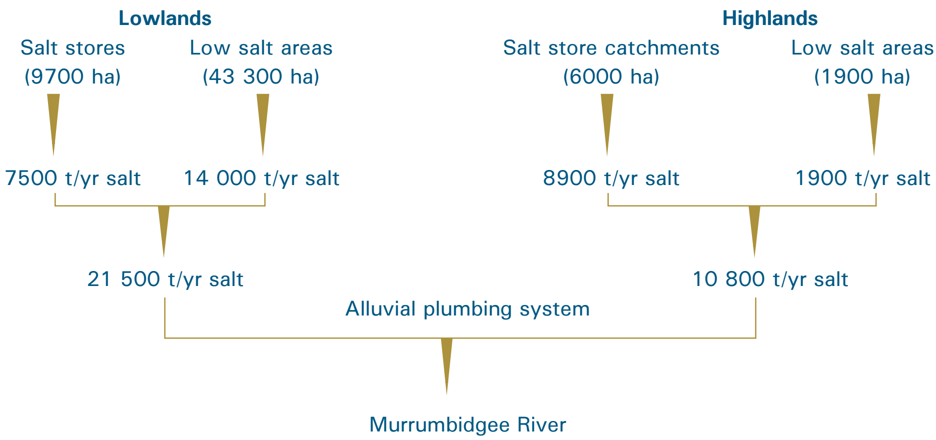
AEM data were available for only 10% of the Billabung catchment. These data were extended by establishing relationships between salt stores and landforms using existing regolith data and thus, indirectly, to subsurface materials across the whole area. Information on salt stores, landforms, regolith and soil types was combined with hydrogeological modelling to estimate deep drainage and salt flows through the landscape under different land use scenarios, including cropping, annual and perennial pastures and tree planting (Doorenbos & Pruitt 1992). This provided a picture of areas at risk, identifying where reducing recharge would have the biggest impact on salinity. The FLOWTUBE groundwater model (Argent 2001) was used to investigate the discharge capacity of the alluvial aquifer. This work indicated that rising watertables are not likely to be a serious issue for the lowlands region, as the catchment appears to be well-drained (see Figure 23, Braaten et al. 2003). However, salt will be leached from the extensive salt stores in the lowland clay soils into the underground flow system, and then to the Murrumbidgee River.

Results

Lowland salt stores occupy only 10% of the catchment's area, but contribute almost one quarter of its salt load. Highland salt stores contribute nearly a third of total salt exports although they represent only 6% of catchment area. Conversion of critical areas from annual crops and pastures to perennial pastures in the plains, as well as some targeted re-afforestation in the highlands, will significantly reduce recharge and subsequent salt export from the catchment. These priority areas for intervention (16 000 ha) total 17% of the Billabung catchment (or 3% of the area of the Upper Murrumbidgee). Reducing recharge over these areas through land use change could achieve a 50% reduction in salt export from Billabung Creek catchment to the Murrumbidgee River, with limited impact on agricultural profitability. Achieving this change would deliver half the salinity reduction target of 30 000 tonnes per year of salt which has been set for the Murrumbidgee River at Wagga Wagga.

Assessing the effectiveness of the proposed action plan for the Billabung catchment will require monitoring groundwater levels at selected sites, changes in the extent of salt outbreaks and in the conductivity of Murrumbidgee waters up and downstream of its confluence with Billabung Creek. Monitoring over a period of five to ten years will be needed to ascertain that observed changes are due to the impact of the new

Figure 14. Sources and volumes of salt delivered from the Billabung catchment to the Murrumbidgee.



management rather than climatic variability. Tracking changes over this time will establish whether further modifications to land use are needed to meet salinity management objectives.

Cost/benefits

Depending on the size of the area surveyed, the current commercial costs of airborne survey range from $50 to $80 per line-km for AEM, and $8 to $12 per line-km for combined magnetics and radiometrics. This translates to a cost of $3 to $5 per hectare. The detailed information collected through airborne mapping can be extended to the whole catchment using other information. For the Billabung Creek catchment, projection of the AEM information from a key area of 9000 ha to the whole catchment, using air photo interpretation of landforms, field reconnaissance and airborne radiometrics over the highlands, reduced the cost per hectare to about 60 cents, including staff time. The results provide information suitable for developing land use options at the farm (1:25 000) scale.

This, and other studies in the Mid-Broken (VIC), Billabong Creek (NSW) and Lower Balonne (QLD), demonstrate that salt is localised in the landscape. Large areas are essentially free of salt, and even large salt stores may not present a salinity risk if the salt is not going to be mobilised. This means that management intervention can be focused on those areas that present real risk and specific interventions can be tailored to individual situations, reducing the level of disruption to agriculture. Therefore, the cost of effective management of salinity will be an order of magnitude less than some earlier predictions.

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CASE STUDY 5: SOIL LANDSCAPES OF THE LIVERPOOL PLAINS, NSW

Submitted by: Robert Banks, NSW Department of Infrastructure, Planning & Natural Resources (DIPNR)

Location: Liverpool Plains, north-west NSW (see Figure 15)

Area: 12 432 km^2 (1 243 263 ha) plus and an additional 3 400 km^2 outside the Liverpool Plains

Scale: Catchment scale – 1:100 000 (minimum mapping area 10 ha unless unit has special properties)

Rainfall: 550 – 1200 mm/annum (mostly in the range 580 – 640 mm/annum)

Land use: Summer and winter cropping (irrigated and dryland), native and improved pasture, grazing, feedlots and minor forestry

Soil classification: About 50% dominated by vertosols (mostly black or grey). The hills with sedimentary rocks and the outwash from these hills have a fairly typical rudosol, tenosol, chromosol and sodosol sequence, with some of the higher sections of the Liverpool Ranges having ferrosols and organosols (peats).

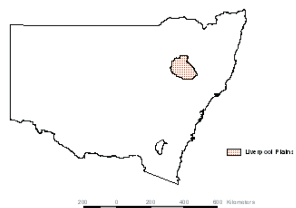
Groundwater system: Local and intermediate groundwater flow systems

Evidence of salinity: Saline seeps and locally extensive crop and pasture death for many of the flat vertosol landscapes and the erosional sedimentary and basaltic landscapes. Visual assessment of salinity in the Liverpool Plains is hampered somewhat by the fact that many of the vertosols on which salinity occurs, simply form a finer mulch and grow nothing, rather than develop salty crusts as are found with other soil types. Saline groundwater close to the surface is extensive in many areas of the Liverpool Plains during wetter years, with salinities exceeding half that of seawater being the norm (i.e. TDS > 20 000 mg/L and EC > 2000 mS/m).

Description of problem or concern

Dryland salinity on a large scale was first recognised as a serious problem on the Liverpool Plains in the late 1980s, with the sudden death of several sorghum crops. Investigation of this issue at the time revealed that salinity was widespread in the Liverpool Plains, one of the most fertile production systems in Australia. Several activities were undertaken to determine the extent of the salinity and to investigate cropping and pasture systems that would minimise deep drainage while maintaining profitable agricultural enterprise. Mostly, this has been successful, with some of the original salinity areas of the 1990s being returned to productive dryland cropping systems.

Figure 15. Location of the Liverpool Plains catchment in New South Wales.



Despite these findings, there has been little in the way of spatial investigation/ survey work by which to extend this information, assess the risks and show where an activity is appropriate or sustainable in terms of salinity (and many other desirable environmental and production issues). The consideration of costs of implementation of changed management regimes, either to the community or individual landholders, could not be addressed without appropriate soil and landscape information. Traditional or even new and technical modelling and mapping procedures—such as AEM survey, showed salt stores and shallow groundwater bodies, or areas where salt may surface without answering the questions of what needed to be done in each part of the landscape to avoid or minimise the mobilisation of salt. To achieve this and understand how the many components of the whole landscape function, further work was needed.

What was done to study the problem

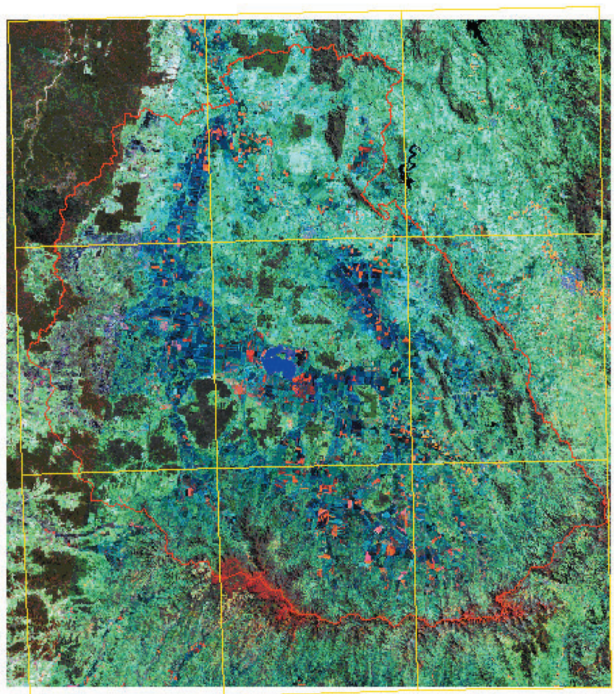
Soil landscape mapping was initiated in the Liverpool Plains to identify and map soil and landscape characteristics and distributions. Soil is the basic building block of all of our production and ecological systems and, as such, without an understanding of the distribution of our soils systems, no reasonable and coordinated approach to comprehensively address natural resource management issues can be initiated on a broad regional basis.

Soil landscapes combine soil and geomorphic information to provide a framework for understanding management issues and surface processes that drive salinity. Hundreds of soil profile attributes are collected which provide detail on factors such as soil type, salt store, permeability, effect of land use and hazards associated with different activities. The geomorphic framework provides a way to extend this information spatially so that it can be used by landholders, planners and scientists, without necessarily having to understand the science behind the mapping.

The Liverpool Plains soil landscape mapping program ran from 1995 to 2003 and was supported by DIPNR, Natural Heritage Trust (NHT) funding and various other State/Territory and Australian Government agencies which contributed or shared datasets to produce accurate and validated maps of soils and landscapes. The maps have since been used to:

- define all of the soil landscapes in the Liverpool Plains, presenting and collating information on soil distribution, geology, vegetation, hydrology and soil and landscape

Figure 16. An overview of the Liverpool Plains catchment on a Landsat TM image. The catchment boundary is outlined in red.



qualities and limitations (which range from agronomic to engineering and general land management);

- provide a base for the extension for all salinity research findings, to determine where new practices are appropriate and viable in the broad region of the Liverpool Plains. This base has proved technical enough for broad planning and comprehensive cost–benefit analyses, as well as simple enough for individual landholders and Landcare groups to use;
- stratify the Liverpool Plains into land management units (LMUs) that are defined by soil and landscape characteristics as well as land capability. These LMUs can then be used to calculate what changes need to occur in specific areas of the landscape to achieve sustainable outcomes. In short, the LMUs define where a land use needs to change, how much it will cost and what are the benefits of change both to the individual landholder and the community (see derivative map delineating LMUs, Figure 17);
- produce derivative maps such as those indicating agroforestry potential, showing where trees can be grown to offset recharge. This is important as there are some soils where recharge can be addressed through changed cropping practice but this map only identifies areas where it is economically feasible to grow trees (Figure 18); and
- communicate information about land use change and salinity to individuals who are experiencing salinity and other NRM problems in their farming and grazing systems.

Examples of individual outcomes for landholders

The Liverpool Plains Land Management Committee (LPLMC), an umbrella group representing nearly fifty Landcare groups in the Liverpool Plains, has used the soil landscape mapping for economic, social and environmental analyses, which has led to the recognition that at least $170 million needs to be spent on land use change in the Liverpool Plains over the next 25 years. To encourage and augment private expenditure on environmental and economic sustainability, the LPLMC are granting funds by tender to individual landholders who submit a property plan with their tender explaining how their proposed changes will affect NRM issues, particularly salinity. Landholders involved in the tender process must complete a TAFE course (including fieldwork) that introduces them to the soils and hydrology of their locality, and how land use systems affect salinity and other NRM issues. Soil landscape maps are used as the basis for these courses.

Tenders are judged on the way they will impact on NRM problems by using products derived from soil landscape mapping that indicate characteristics such as available water holding capacity (Figure 19), soil store (Figure 20) and what land management unit(s) or soil landscape suite(s) the proposal falls into. Successful tenderers are those who clearly demonstrate how the proposed change will affect water balance, and enhance or sustain production and ecological systems on individual properties.

Figure 17. Land management units of the Liverpool Plains.

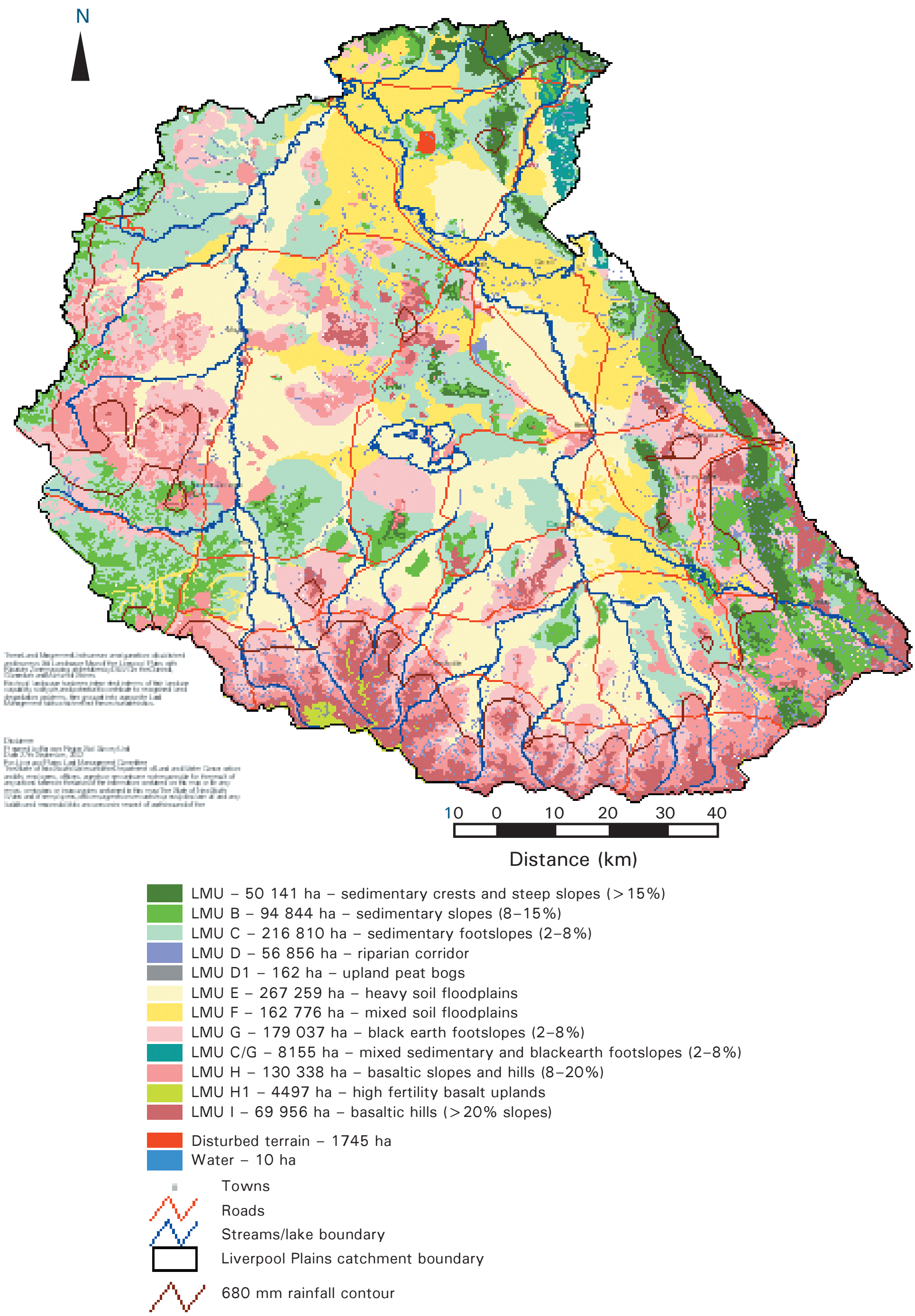


Figure 18. Forest plantation suitability for salinity recharge control.

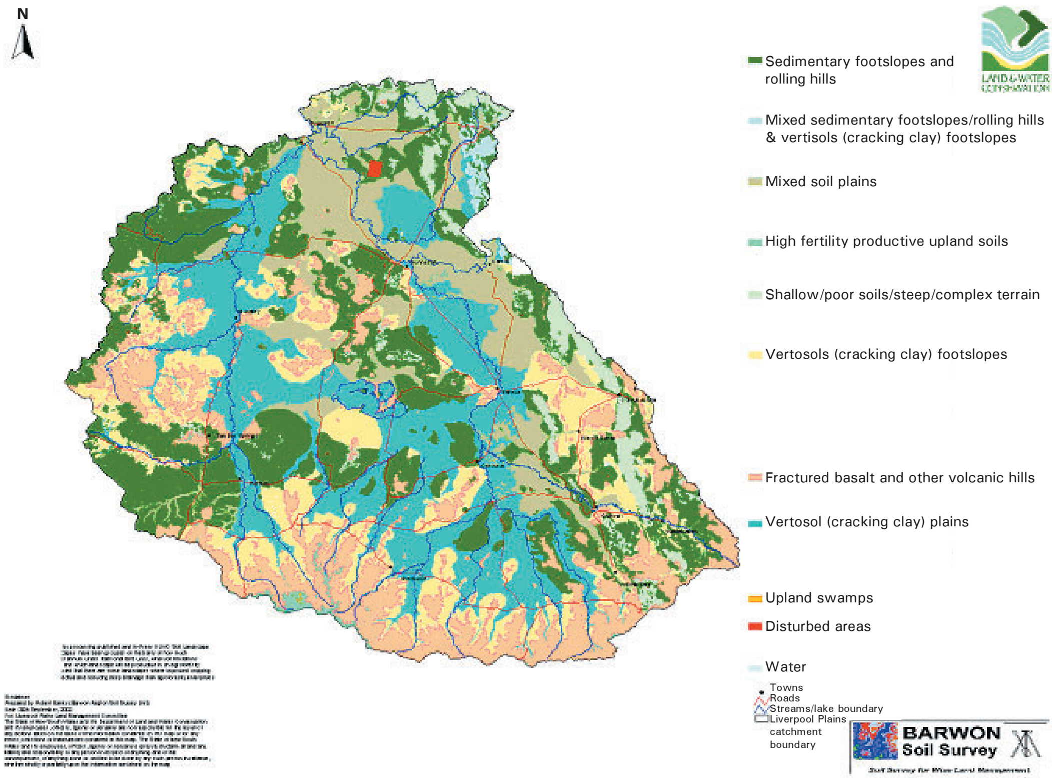


Figure 19. Available water holding capacity.

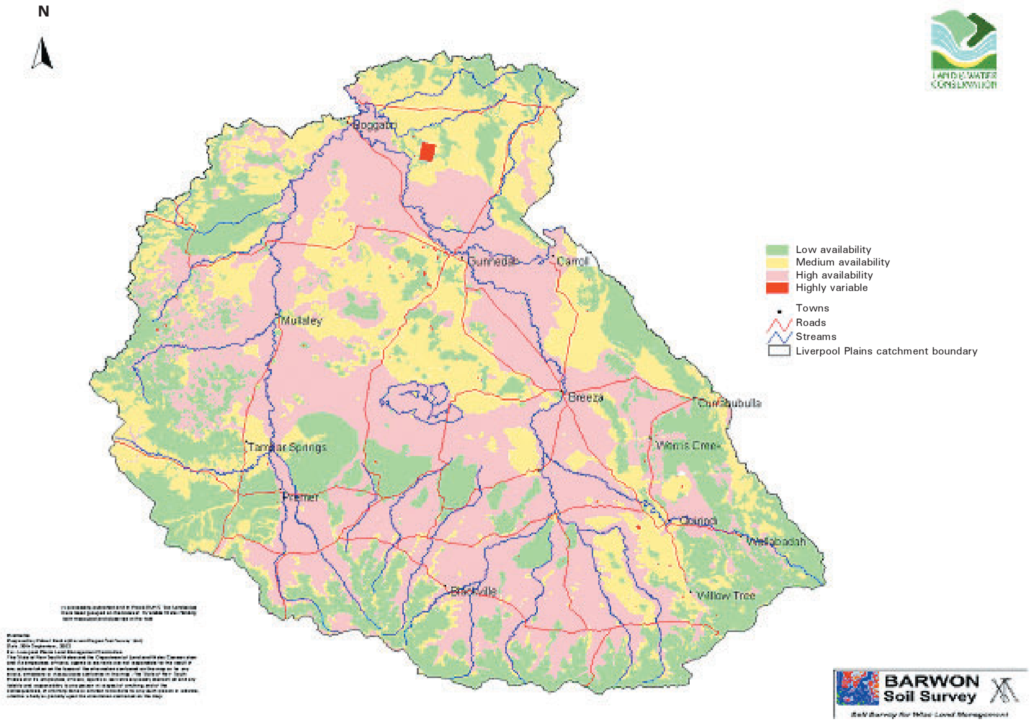
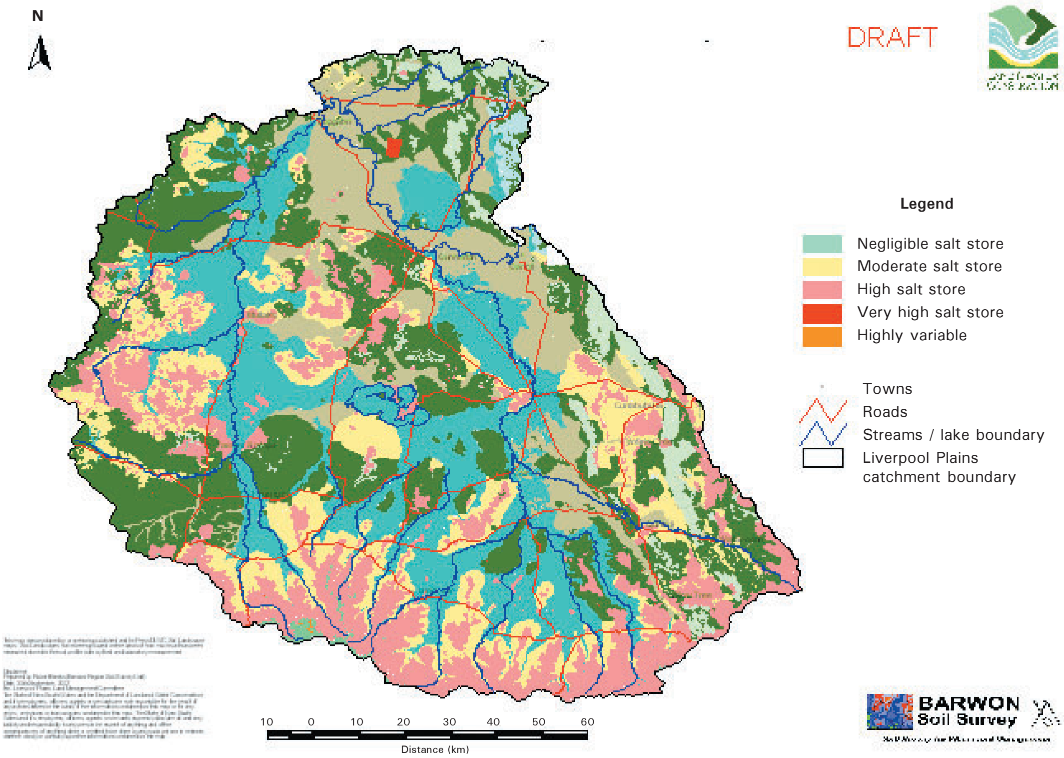


Figure 20. Soil salt stores.



Andrew and Liz Higham, 'Collygra', Emerald Hill, northern Liverpool Plains

Andrew and Liz Higham submitted a tender to the LPLMC to:

- return much of the old cropping land on chromosols and ferrosols on their property, 'Collygra', to pasture;
- fence off waterways; and
- reintroduce native trees to strategic points on their property.

By checking their proposal against soil landscape attributes such as soil salt store, soil permeability, expected community outcomes in terms of reduced salt and sediment delivery to streams, and potential productivity gains or losses, LPLMC staff were able to determine that 'Collygra' was a prime place in which to invest for community gain. Soil landscape attributes were used to determine environmental and economical viability.

As successful tenderers, the Highams will spend the next few years changing their land use to predominantly permanent pastures thus virtually eliminating any deep drainage through high salt store soils into shallow aquifers. At the same time as achieving these environmental benefits, the economic sustainability of the property will increase as management becomes more responsive through the development of an understanding of new management techniques for the combined purposes of NRM and agricultural production.

Hugh Price, Manager, 'Windy Station', Pine Ridge, southern Liverpool Plains

Windy Station encompasses some 20 000 ha in the southern Liverpool Plains. It has had a recent history of a very large decline in production in some areas caused by salinity in the early 1990s. The locality is renowned for having an annual turnover of $1 to $1.5 million per 100 ha. Located largely on a broad floodplain with a constricted outlet, highly saline (>20 dS/m) watertables are often within one metre of the surface in wet years, which can either cause crop failure when plants forage to this level for moisture or can result in localised salinity outbreaks.

Following the publication of the soil landscapes of the Blackville 1:100 000 sheet (Banks 1998), which clearly delineated areas most susceptible to this type of salinity, the manager of 'Windy Station', Hugh Price, took a large risk and decide to rotate his at-risk, high value, cropping land through long, deep-rooted pasture fallows. This has resulted in salts being re-partitioned to a deeper level in the cropping soils of 'Windy Station' and increased organic matter and improved soil structure. When areas with three to five year pasture rotations are cropped again, the production gains are significant.

Managing salinity through pasture rotations in the flat vertosol landscapes of the Pine Ridge district and careful management of the soil profile can be done profitably both through pasture rotations, as in the case of 'Windy Station', or shorter crop fallow sequences employing response cropping methods in fallows.

Cost/benefits (economic, environmental, social)

The economic and environmental benefits from soil surveys are clear in the Liverpool Plains, as many of the salinity management strategies for cropping lands actually lead to greater production as well as better soil health. Mapping is a way of showing where changes such as these can occur without the need of incentives for change. Due to high personal economic benefit to individual landholders, this is good for the social fabric of the small communities of the Liverpool Plains that rely heavily on servicing agricultural enterprises. The mapping also identifies areas where the cost of change is higher than returns in the short term (five years). These are the areas where government or community expenditure can be targeted to assist with developing sustainable enterprise, such as in the case of the Higham property, 'Collygra'.

As indicated by ACIL Economics Pty Ltd (1996), soil landscape mapping is a long-standing and fundamental layer of information with a benefit/cost ratio that exceeds 40 in the first five years. The Liverpool Plains soil landscape mapping cost approximately $1.3 million, but also includes an area of an extra 3500 km^2 outside the Liverpool Plains. This is a total cost of about $0.85/ha. Given the long-lasting nature of the data (soils and landscapes tend not to change in human time frames) and a projected useful lifespan of fifty years, soil landscape mapping in the Liverpool Plains has provided a fundamental tool for land managers and planners and will be used well into the mid–twenty-first century for salinity and other NRM management issues.

Other comments

The Liverpool Plains soil landscape mapping project has been an essential in identifying landscapes that are at risk of salinity and in targeting investment to change the long-term projections for land salinisation in the Liverpool Plains. The project has set new standards for mapping and incorporated all available technologies from airborne gamma radiometrics to electromagnetic induction (where available) as well as more traditional LANDSAT and aerial photograph interpretation. More importantly, the community, through the LPLMC and its subsidiary Landcare groups, have been involved and consulted throughout the process so that community outcomes for the project have been maximised. The result is a technically robust dataset, which can be used for salinity planning at many levels, from strategic catchment scale planning to on-farm works.

The advantage of soil landscape mapping over some other common salinity investigation tools such as EM surveys is that it has many more applications than simply identifying salt sources and can be used to extend best management practice to the community (and more technical users) for a wide range of NRM issues. On-ground works based on soil landscape map findings and derivative products are now relatively commonplace in the Liverpool Plains, which is testament to the utility of the information.

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CASE STUDY 6: WOODS FLAT CREEK SALINITY INVESTIGATION, NSW

Submitted by: Nik Henry, DIPNR

Location: Woods Flat Creek, Woodstock, central west NSW

Area: 5000 ha

Scale: Subcatchment/catchment

Rainfall: 650 to 675 mm/annum

Land use: Mixed farming country – cropping and grazing with some forestry

Soil classification: Euchrozems, red podzolics, non-calcic brown and siliceous sands

Groundwater system: Local and regional (fault related)

Evidence of salinity: Related to geological structures with calcium-chloride-bicarbonate as the dominant salt

Description of problem or concern

Watertables had risen close to the surface causing reductions in crop yields and preventing the growth of palatable grasses.

What was done to study the problem

Ground-based EM31 survey to define boundaries and location of saline areas, combined with a local geological survey to define location of geological structures and map local geology.

Results

The catchment area was divided into three zones where management options could be focused.

Zone 1. Upper part of the Woods Flat Creek catchment with high EC levels and watertables. A geological fault (Wyangala Fault) appears to be acting as a barrier to groundwater flow causing waterlogging just downstream.

Zone 2. On the western side of the area the Woodstock fault controls the groundwater movement and saline outbreaks appear along this fault. Anecdotal evidence indicates that local recharge systems operate in addition to regional influences.

Zone 3. The rest of the area where local recharge systems cause saline seeps at the break of slopes and the low-lying areas of the Woods Flat Creek catchment. Saline outbreaks are also found at changes in geology.

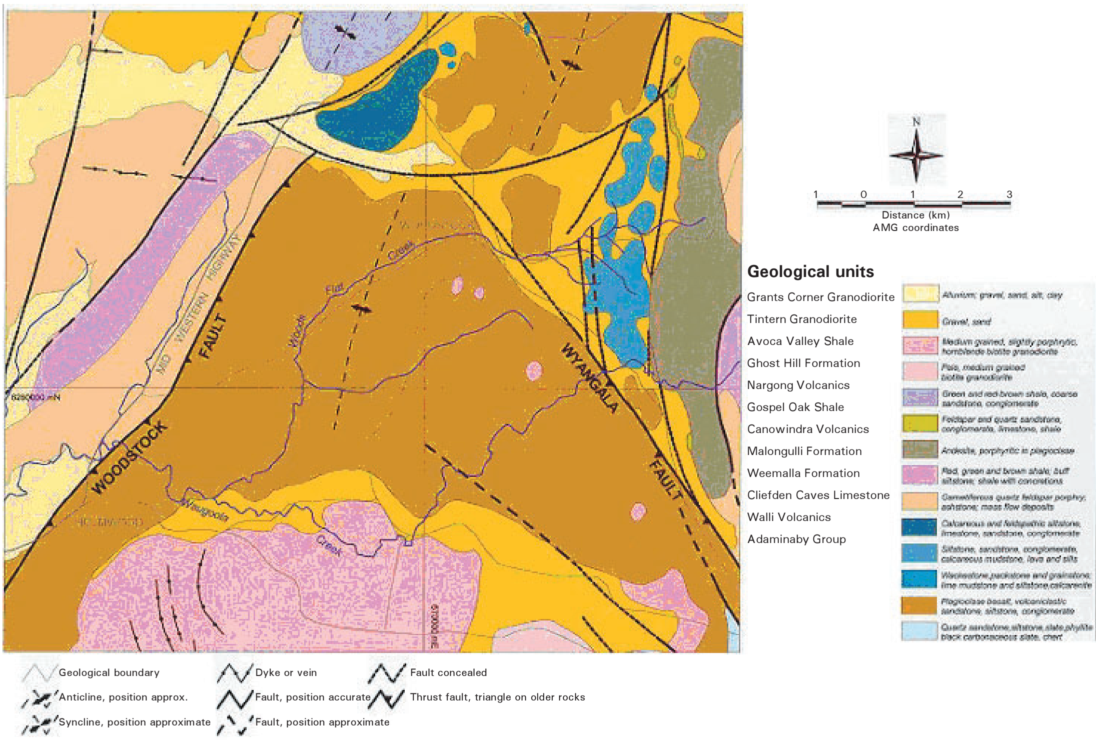
Cost/benefits

N/A

References

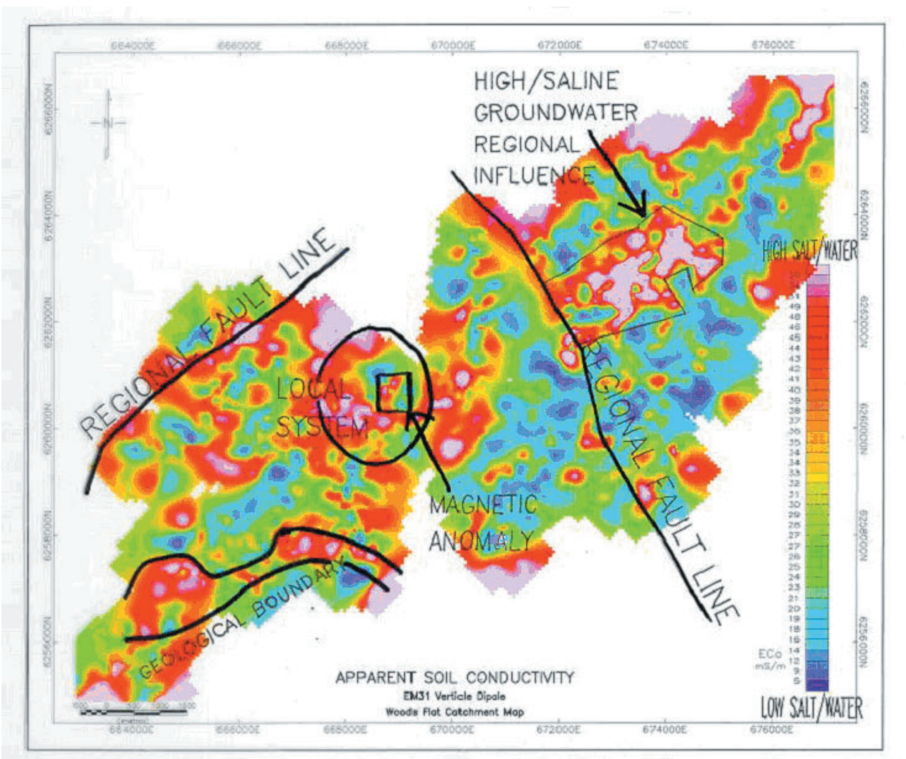
The report is available for public viewing and copies can be obtained by contacting Rob Muller or Nik Henry at <www.dipnr.nsw.gov.au/>.

Figure 21. Woods Flat Creek surface geology.



(after Raymond et al. 1997)

Figure 22. Apparent soil conductivity.



CASE STUDY 7: MID-MACQUARIE COMMUNITY SALINITY PRIORITISATION AND STRATEGIC DIRECTION PROJECT, NSW

Submitted by: Michele Barson, Bureau of Rural Sciences (BRS)

Location: The mid-Macquarie region is in the central west of New South Wales between Burrendong Dam and Dubbo, stretching from Coolah in the east to Molong in the south, and encompassing the Bell, Little, Macquarie and Talbragar catchments.

Area: 1 101 000 ha

Scale: Regional

Rainfall: Less than 650 mm/annum over approximately three-quarters of the area; the north-east and south-east parts of the region receive up to 900 mm/annum

Land use: Primarily cropping and grazing with irrigation development towards Dubbo

Soil classification: Various

Groundwater system: Numerous local and one intermediate groundwater flow system

Evidence of salinity: Up to 50 000 ha of salinised land had been mapped by DIPNR in the late 1990s. rapid stream EC survey in 1994 indicated that a number of streams in the region were highly saline.

Description of problem or concern

The region was considered to be at major risk of both land and stream salinity. The Central West Catchment Management Committee ranked dryland salinity as the second highest NRM priority issue. The study was undertaken to quantify and predict the long-term movement of salt in the Mid-Macquarie catchment for the development of catchment management plans such as the Central West Catchment Blueprint.

What was done to study the problem

Data from about 100 boreholes with three or more groundwater level measurements were analysed to estimate the rate of change in water level from the date of drilling to the most recent measurement. This information helped establish whether groundwater levels were rising or falling in a particular region or groundwater flow system (GFS) of the mid-Macquarie. Where time series data over a number of years were available, fluctuations in groundwater levels were corrected for climatic influence using the HARTT method (Ferdowsian et al. 2001).

Rapid stream surveys were undertaken to identify likely sources of salinity. The results of these surveys were plotted spatially to determine areas of high or low salinity and to prioritise locations for the installation of electrical conductivity loggers to quantify variations in salinity over time. Salinity exceedence curves were constructed for all loggers. These curves defined, in this case, the probability of a stream having an EC above a designated value.

Rainfall data were also converted to residual mass curves (graphs of the cumulative departures from the arithmetic mean) to show periods of below or above average rainfall. Changes in the residual mass curve were compared with changes in bore water levels to examine links between long-term rainfall trends and fluctuations of groundwater level.

An analysis of stream flow for selected creeks was undertaken to determine if any increase in groundwater discharge was discernible. Flow duration curves show the percent of time a particular flow occurred at a gauging station during the available period of record. Curves were constructed for gauging stations within the mid-Macquarie region to analyse the effect of groundwater base flow on stream flow. Flows recorded at the gauging station at the catchment outlet were plotted in three-year increments to determine the changes in stream flow over time.

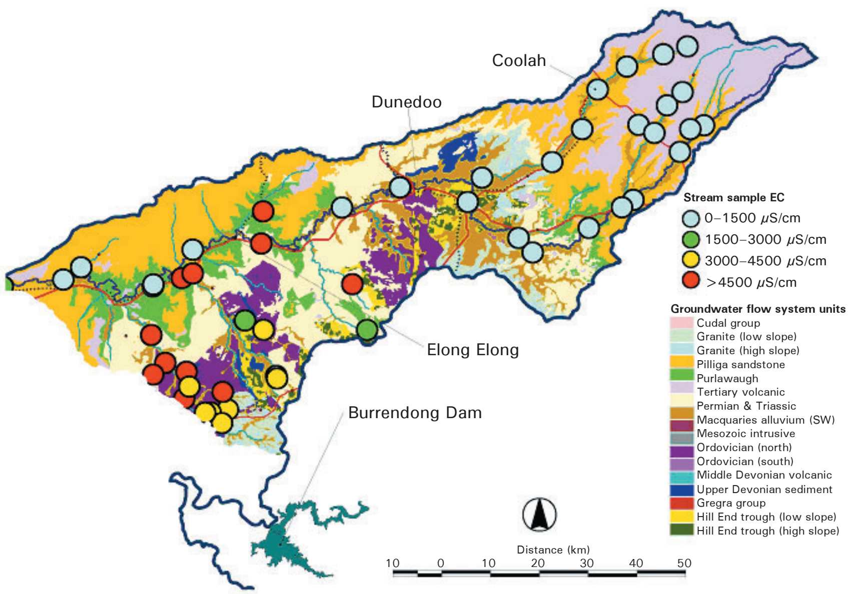
Seventeen GFS classes were delineated in the study region using a combination of slope and geology. For each GFS class, consideration was given to its biophysical parameters and the applicability of each land management practice in terms of, for example, the reduction in recharge.

Results

The results demonstrated that salinity was not a problem throughout the entire mid-Macquarie region, but that most of the salt stores were located in less than half of the Talbragar catchment (Figure 23) and less than one-third of the Little River catchment respectively.

Importantly, stream flow and salinity data indicated that, during the study period, 50% of the salinity exported from the mid-Macquarie region was generated upstream of Burrendong Dam, outside the region. In addition, the Bell River catchment and the Little River, where it flows through granite country, provide the main freshwater contribution for the region. This understanding has important consequences for the development of management regimes, particularly in ensuring that such dilution flows remain available. For example, it has been decided that extensive tree plantings proposed for this locality should not now proceed as the trees would reduce the quantity of baseflow.

Figure 23. Talbragar River Catchment (mid-Macquarie region). Stream EC survey overlain on groundwater flow systems.



Further work is required to delineate the location and size of the Talbragar and Little River catchments' salt stores more closely. This could be undertaken most effectively using airborne geophysics. The area now has top priority for the collection of airborne geophysics data in New South Wales under the National Action Plan for Salinity and Water Quality (NAP).

Cost/benefits

Major benefits from this project include the development of a strong community understanding of the nature and extent of the salinity issue in their region and identification of the areas where further work is required. NAP-funded work is now focusing on more detailed identification of the sources of salt. Work is currently being conducted by BRS in the Gundy Creek catchment (part of the Little River catchment) and, in collaboration with DIPNR, on the sources of salt upstream of Burrendong Dam.

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CASE STUDY 8: SIMMONS CREEK, NSW

Submitted by: John Gallant and Pauline English, CSIRO Land and Water

Location: Simmons Creek, subcatchment of Billabong Creek near Walbundrie, southern NSW

Area: 171 km^2

Scale: Subcatchment

Rainfall: 570 mm/annum, winter dominant

Land use: Cropping (wheat, triticale, canola, barley), pasture

Soil classification: Red, yellow and brown chromosols, red kandosols, brown and yellow sermosols, yellow and brown sodosols, developed on granite, metasediments and alluvial deposits with aeolian overlay (parna)

Groundwater system: Local to intermediate

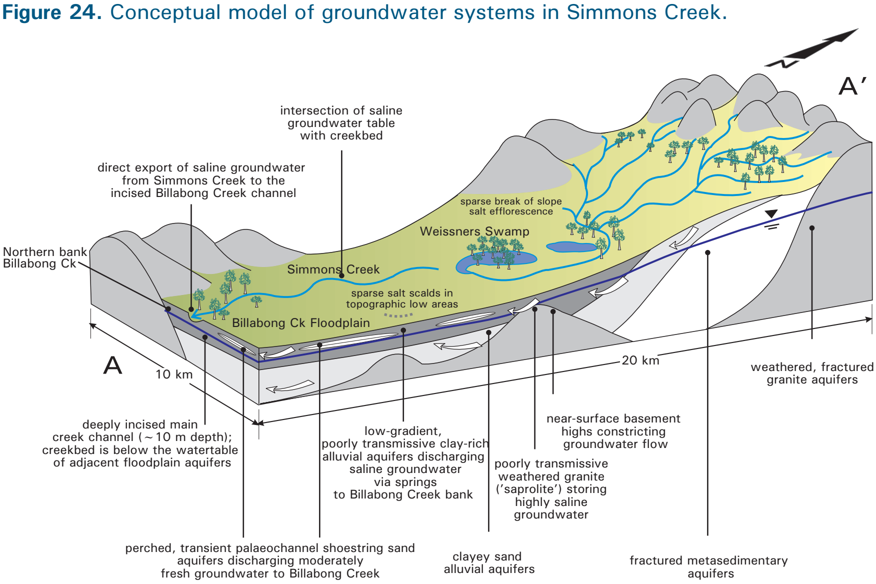
Evidence of salinity: Small area of land surface salinisation; saline groundwater discharges into Simmons Creek; increasing salinity in Billabong Creek as it flows past Simmons Creek catchment; ephemeral to seasonal break-of-slope saline outbreaks.

Description of problem or concern

The dominant problems were a rising trend in stream salinity in Billabong Creek and high salinity in Simmons Creek. The study aimed to understand:

- the relative importance of salt transport via surface washoff processes and baseflow;
- groundwater dynamics in the shallow aquifer system, specifically the patterns and processes of recharge, pathways of salt transport and groundwater discharge;
- the mechanisms controlling the generation and delivery of streams in riverine plain landscapes generally; and
- the impact of changes in land use on the export of salt from the catchment.

Figure 24. Conceptual model of groundwater systems in Simmons Creek.



What was done to study the problem

A number of initiatives were set in motion including:

- discussions with landholders to establish historical behaviour of the catchment;
- investigation of groundwater processes using logged piezometers to determine piezometric surface, hydraulic conductivities and temporal trends;
- ground electromagnetic survey (surface and down-hole) to study flow pathways;
- EC monitoring in streams to identify salinity trends;
- survey of soil landscapes to determine soil properties and salt stores, based on field survey, airborne gamma radiometrics and high resolution digital elevation data from airborne laser mapping;
- modelling of farming systems and water flows to assess salt and water movements;
- airborne magnetic imagery to identify bedrock structures; and
- system understanding and process understanding were both exploited to interpret the behaviour of the catchment.

Results

A conceptual groundwater model was developed for the catchment. Baseflow was established as the dominant mechanism of salt export from the catchment due to raised groundwater levels resulting from clearing. The catchment appears to have established a new hydrologic equilibrium with recharge and discharge approximately equal in the shallow groundwater system, with the incised drainage network now functioning as outlets for the shallow aquifer. A large salt disequilibrium currently exists with exports of salt being much larger than imports.

Detailed conceptualisations were developed for various discharge scenarios, and organic and inorganic processes operating in discharged saline groundwaters. The role of parna as a source of salt and as the primary material for heavy clay soils was highlighted. The modelling predicted that modest changes of land use from cropping and annual pasture to trees (10% of the catchment) and perennial pasture (20%) would have little impact on groundwater levels and salt export. A CD 'Billabong Land Information System' was produced and distributed to the local Landcare groups and to landholders.

Cost/benefits (economic, environmental, social)

Not quantified.

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CASE STUDY 9: BENGWORDEN, VIC

Submitted by: Greg Street (GeoAg Pty Ltd) and Andrew Harrison, SKM for Department of Natural Resources and Environment, Victoria (DNRE)

Location: South-west of Bairnsdale, Victoria

Area: Upstream catchment 17 700 ha. Study site area approximately 900 ha

Rainfall: Variable; 584 mm/annum at Bengworden township

Land use: Mixed grazing of sheep and cattle; minor cropping

Evidence of salinity: Secondary land salinisation has been perceived as a problem by both landholders and the Department of Conservation and Environment since the early 1990s.

Description of problem or concern

Possible deleterious effects on Ramsar wetlands; shallow watertables below 6600 ha of grazing land could inhibit the growth of palatable grasses.

What was done to study the problem

Using GIS, areas of higher potential recharge that might contribute to the identified salinity were mapped.

Previous investigations provided the following data:

- airborne geophysics including radiometric and magnetic data collected by Australian Geological Survey Organisation (AGSO);
- DEM from airborne geophysical survey;
- bore hydrographs;
- previous studies of geomorphology (Ward 1977) and land use systems (Aldrick et al. 1992); and
- field sampling of soil texture.

Only the DEM and the geophysical data were available over the entire project area. Bores were present only for the area south of Bengworden Road and provided only point measurements. Previous geomorphological studies were regional and did not focus on groundwater recharge.

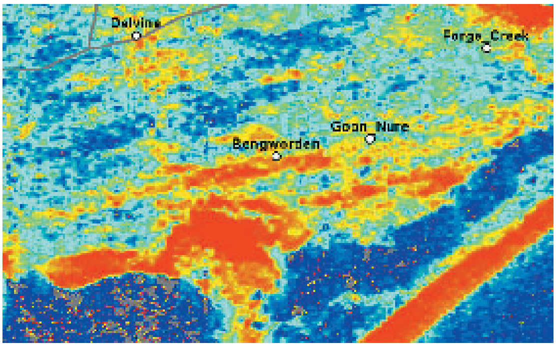
GIS maps were produced which incorporated all available data plus images of radiometrics (Figure 25), magnetics (Figure 26) and digital terrain models (DTM) (Figures 26 – 27).

The recharge mapping was primarily based upon on an interpretation of soil permeability using the airborne radiometrics data and the DEM. The interpretation of the radiometrics data was supplemented where possible by information from bore hydrographs, soil mapping conducted by Ward (1977) and field observation of soils.

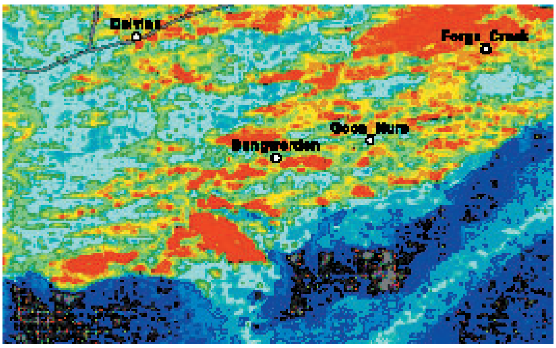
The purpose of the study was to map units with high, medium and low recharge potential. Airborne gamma radiometric data is a measure of the radioactive mineral content of the top 0.5 to 1 m of the soil profile. The distribution of this material is strongly related to the processes of soil formation and it is unaffected by vegetation. Terrain slope and elevation are also related to soils and recharge potential and thus were also used in the classification. The variables used in the classification are shown in Table 8.

Figure 25. Classification of radiometric and slope data into 20 classes with possible soil types (a – e).

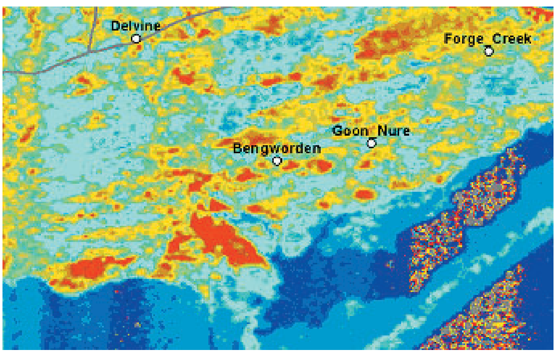
(a) Potassium



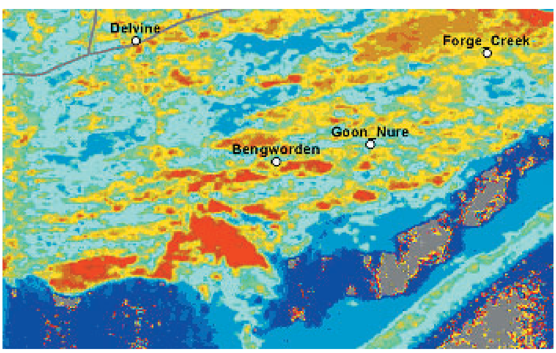
(b) Thorium



(c) Uranium



(d) Total count



(e) Radiometric ternary

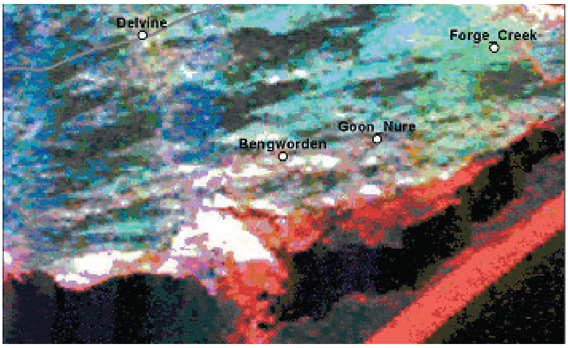


Figure 26. Areas of loamy sand to sand with higher potential recharge interpreted from geophysical data. Magnetic 1st V derivative.

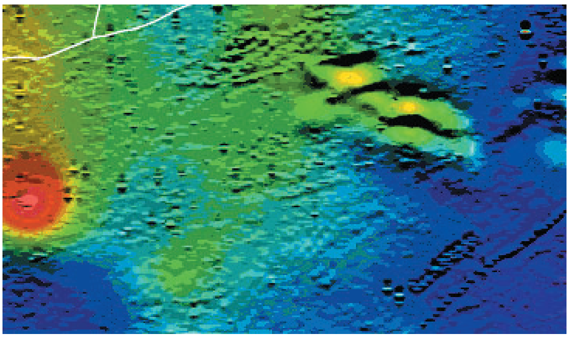
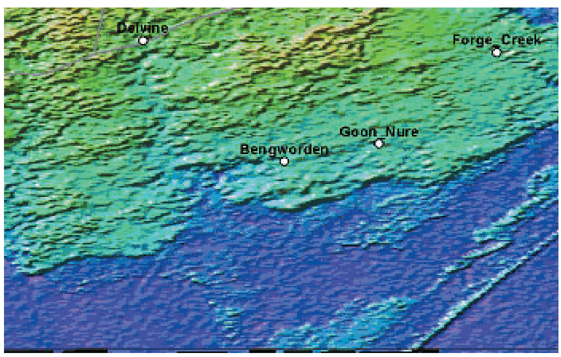
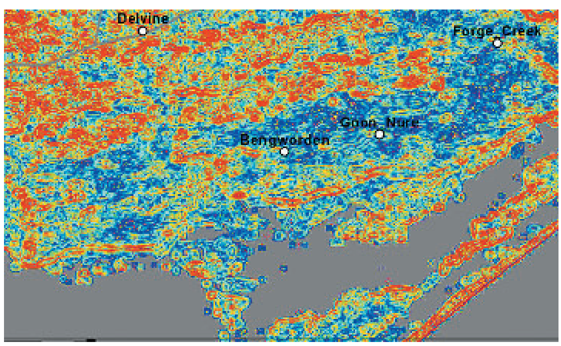


Figure 27. Areas of highest interpreted recharge. These areas were then field checked and recharge rates measured.

(a) Topography from DTM



(b) Slope from DTM



The advantage of using the unsupervised classification process is that such systematic spatial analysis can reveal patterns in the data that may not be visible to the naked eye or by manual interpretation techniques. The classes obtained can then be assigned a possible soil type and assigned different relative recharge rates. Fieldwork and laboratory measurement can then be used to quantify recharge.

Table 8. Data used in classification and codes (after Anderson-Mayes 1999).

Data variable	Code
Potassium	K
Uranium	U
Thorium	T
Total count	X
Slope	S
Elevation	E

Figure 28. Classification of radiometric and slope data into 20 classes with possible soil types.

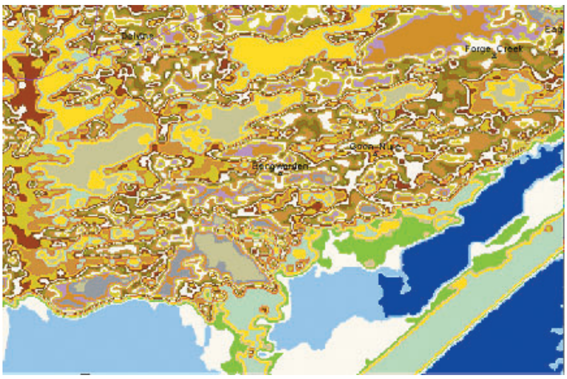
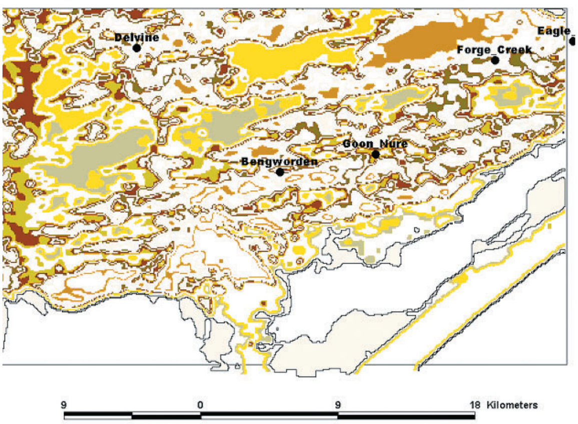


Figure 29. Areas of loamy sand to sand with higher potential recharge interpreted from geophysical data.



The unsupervised classification applied in this study was a three-step process.

Step 1: Clustering algorithm applied to a subset of cells.

Step 2: Clusters derived in Step 1 were used to classify all the data.

Step 3: The characteristics of the derived classes were checked to ensure a valid classification had resulted from Steps 1 and 2.

The radiometric data was classified into twenty classes using the potassium, uranium, thorium, total count, elevation and slope data. The radiometric classes derived have been assigned divisions largely adopted from Ward (1977) who divided the study area into three main geomorphic units:

- the river terraces and floodplains;
- the Munro Plain; and
- the coastal lowlands.

Within each geomorphic area there are further soil classes. Where Ward's soil mapping closely coincides with a class that name has been used. Elsewhere more detailed mapping by the radiometric classification has been interpreted to various soil units based on the elements that make up each class.

Finally the regional radiometric, magnetic and DTM images were used to better separate various geomorphic units with varying recharge. For example an in situ beach sand deposit recognised by a heavy mineral deposit in magnetic data was considered to have a relatively higher recharge potential than a wind-blown sand.

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CASE STUDY 10: FARMER'S PADDOCK, TRAYNING, WA

Submitted by: Simon Abbott (Australia Dryland Salinity Consultants) and Greg Street (GeoAg Pty Ltd)

Location: Approximately 250 km by road north-east of Perth (Figure 30)

Area: Upstream catchment 17 700 ha; study site area approximately 900 ha

Scale: Paddock

Rainfall: 300 mm/annum

Land use: Cropping and sheep grazing

Evidence of salinity: Farmer's observation of expanding bare scald areas.

Description of problem or concern

The concern was that of water erosion on slopes with waterlogging and salinity around the creek, and that scalds were expanding on areas away from the scald-free creek bed despite conventional best practice management strategies.

What was done to study the problem

Previous studies had involved the installation of piezometers where the creek enters and leaves the property. Both showed average piezometric heads within 2 m of the surface. Surface water management earthworks were designed (Figure 31) and constructed according to best practice guidelines to address the erosion on the slopes and the waterlogging on the flats. Belts of native trees and shrubs and belts of saltbush were planted across the lower parts of the paddock to form an alley farming area in an effort to draw down the watertable. However, scald areas continued to spread and killed some of the alley plantings. The farmer felt that he had exhausted all sources of information and advice.

The new investigation involved assembling all available data, including airborne geophysics as recommended by Nulsen et al. (1996) and George et al. (1998) into a comprehensive GIS.

A regional interpretation of the data was undertaken prior to fieldwork. This included analysis of the data for indications of potential for relatively fresh groundwater within the root zone of woody perennials. The 'Agraria Line' identifies that part of the landscape where woody perennial vegetation is

Figure 30. Location of study area.

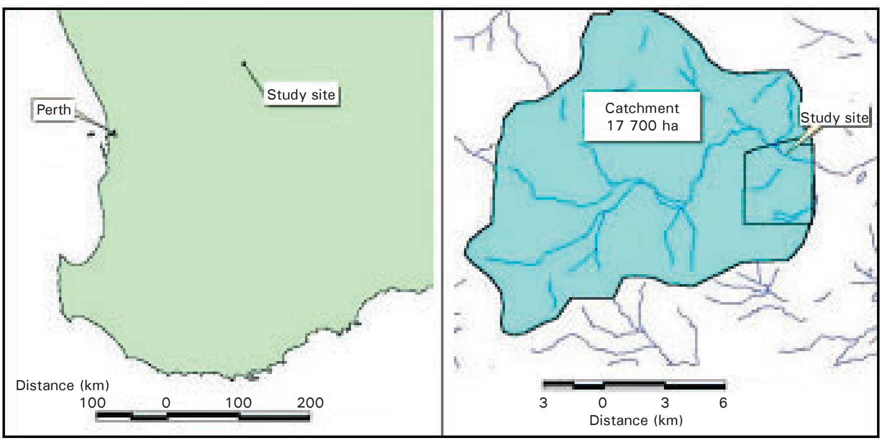


Figure 31. Original plan on air photo.

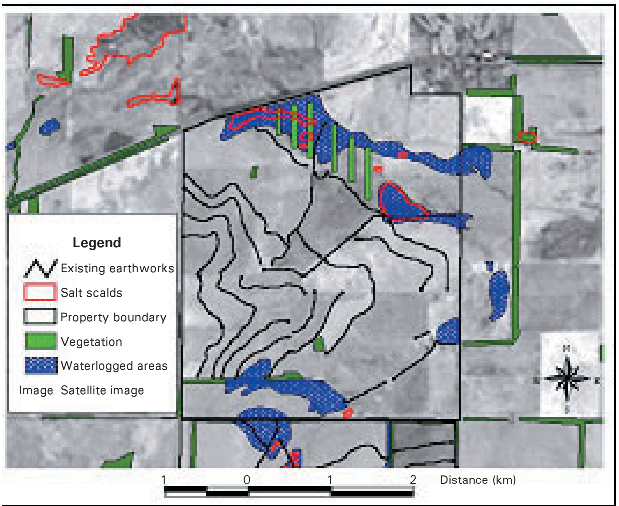
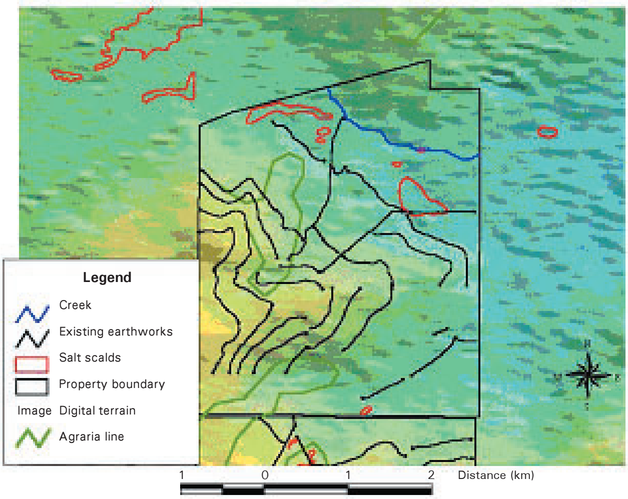
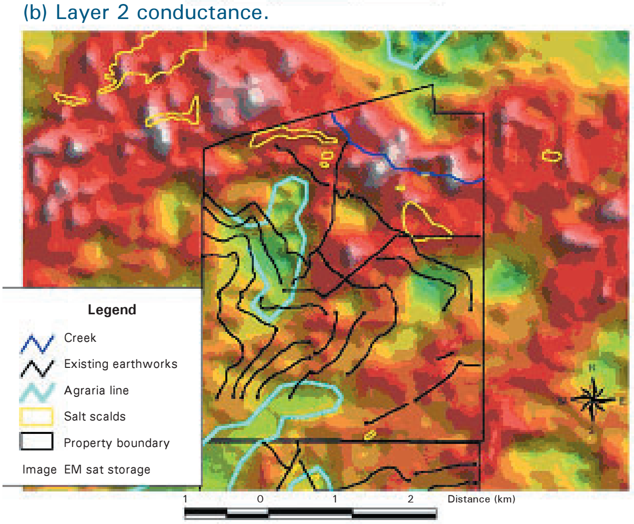


Figure 32.

(a) Plan on topography.



(b) Layer 2 conductance.



most likely to survive and produce and to affect groundwater levels (Street et al. 1996). Interpretation criteria and data used to establish the 'Agraria Line' were:

- downslope edges of sandy soil areas (radiometrics);
- downslope edges of low salt storage areas (EM);
- regolith thickness less than 25 m (EM and drilling records) and downslope of areas satisfying criteria above (EM);
- areas as defined by criteria above but also confirmed by basement topography (EM);
- soil texture contrast zones where texture increases in downslope direction (radiometrics); and
- areas where interpreted dykes confirmed on the surface in the field are located within or downslope of areas defined by criteria above (magnetics).

The data were used to compile the 'Agraria Line' (Figure 32). Field mapping of all surface features was done in the company of the landholder. This produced accurate mapping of features at 1:10 000 scale.

The magnetic image (Figure 33) shows a magnetic high (interpreted as a dolerite dyke) aligned east–west in the north of the paddock. This dyke and a possible associated basement high could have been expected to have a damming effect and to cause groundwater discharge right across the valley (Engel et al. 1987). However, this is not occurring and the presence of the dyke does not explain the limited size of the scalds or their location.

Figure 33. Magnetics.

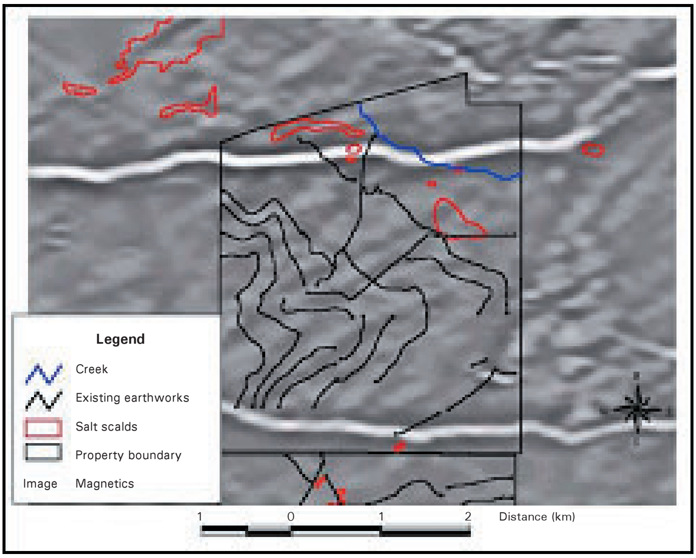


Figure 34. Basement topography.

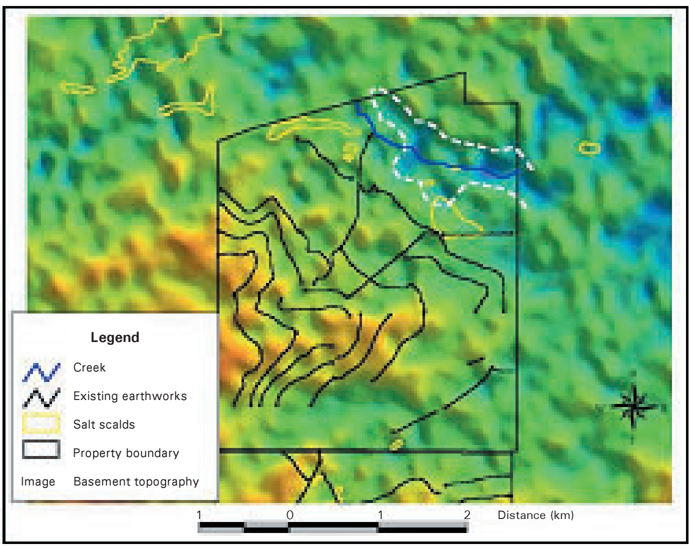


Figure 35. Conductance of layer 2.

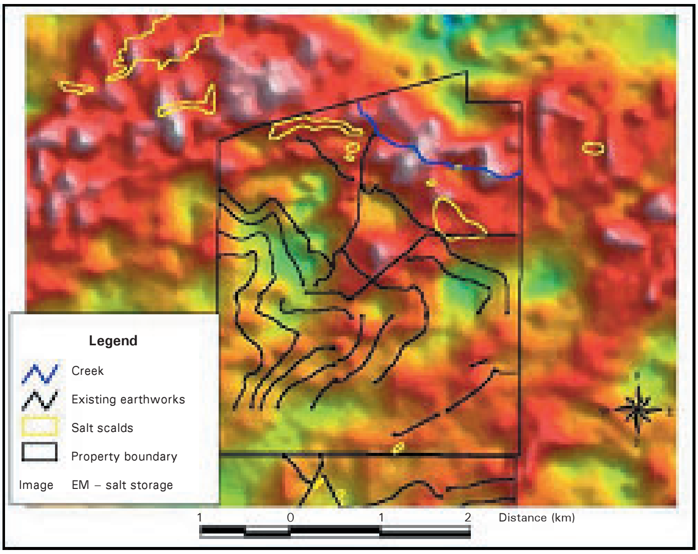
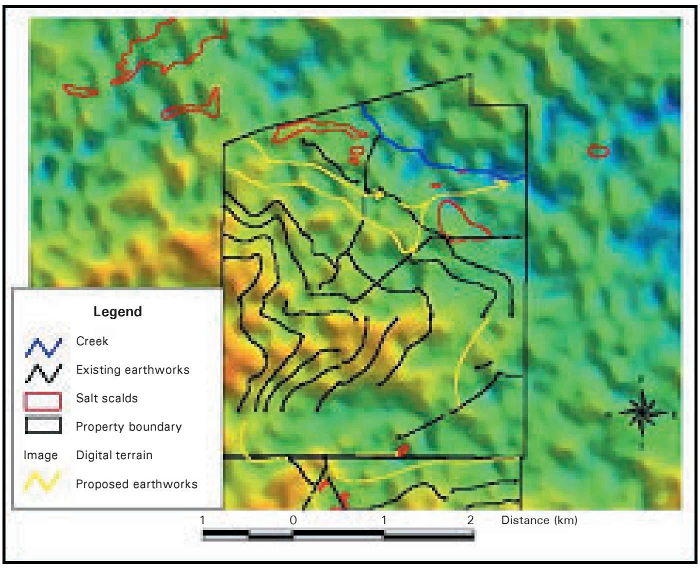


Figure 36. New plan on basement topography.



The basement topography image (Figure 34) shows a basement trough running parallel to the surface creek bed and crossing the dyke. The basement surface (including the dyke) has been eroded down and the regolith over this trough is probably sedimentary.

The salt scald sites have relatively shallow basements (see basement topography map Figure 34) and high salt storage (Figure 35). The existing surface water management earthworks discharge water onto these sites, saturate the regolith and cause scalding.

The deeper sedimentary regolith further downstream has a greater capacity to absorb and transmit water and this explains the reduced occurrence of groundwater discharge and scalding in this location. The dashed white line indicates the boundary of the basement trough.

This new knowledge facilitated an amended design for the surface water management earthworks so that their intended benefits are obtained without causing further degradation (Figure 36). In addition, the 'Agraria Line' provided a site-specific guide to the farm planner for the most effective placement of woody perennial vegetation in this paddock. Prior to acquiring this knowledge, land management strategies in this paddock were based on techniques that had worked elsewhere but they failed in this location.

Cost/benefit

The farmer had invested an estimated $30 000 in surface water management earthworks and $12 000 on tree establishment to develop a farm plan that was not working. The cost of additional information from geophysics including interpretation and farm planning was $7 per hectare or $6300. The expenditure of 15% on information and an extra 10% on earthworks has produced a plan (Figure 36) which is addressing the physical characteristics of this particular site and thus is more likely to be successful.

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Nulsen RA, Beeston G, Smith R & Street GJ 1996, *Delivering a Technically Sound Basis for Catchment and Farm Planning*, paper presented to the WALIS Forum, Perth, Western Australia.

Street GJ, Abbott S, Pracilio G & Tedesco K 1996, *Farm and Catchment Planning Reports*, unpublished report to the World Geoscience Corporation.

CASE STUDY 11: TOOLIBIN AND TOWERRINNING CATCHMENTS, WA

Submitted by: Richard George and Don Bennett, WA Department of Agriculture

Location: Toolibin and Towerrinning catchments, 200 – 250 km ESE and SE of Perth, WA

Area: Two catchment-based AEM surveys of approx. 30 000 ha each

Scale: Catchment

Rainfall: 400 – 550 mm/annum

Land use: Dryland agriculture crops, pasture, grazing and developing specialised industries

Soil classification: Deeply weathered upland soils and valley sediments

Groundwater system: Local to intermediate

Evidence of salinity: Well-documented for the south-west of WA– extensive dryland salinity, saline streams and brackish to highly saline groundwaters in weathered granite terrain. Saline areas are typically bare, or covered with salt tolerant vegetation. Groundwaters are typically rising in upland (Towerrinning) and valley (Toolibin) landforms. Salinity expansion is active, especially in lower rainfall areas. Lakes, wetland and valley floor remnant vegetation is particularly vulnerable.

Description of problem or concern

Lakes Toolibin and Towerrinning are located approximately 100 km apart, 200 to 250 km east-south-east and south-east of Perth. Both lakes and their catchments are actively salinising and interventions are being developed as part of major salinity management planning programs.

Areas of dryland salinity have been well-mapped using satellite-based, remote sensing systems. Airborne geophysics systems (SALTMAP, TEMPEST) were evaluated to determine the reasons for the salinity, the nature of the aquifers and options for management.

At Toolibin Lake, a 300 ha Ramsar wetland was becoming saline as a result of shallow watertables and saline inflows. AEM was flown to assist in choosing the best locations for groundwater wells used to lower watertables. The survey built on previous, locally targeted surveys of airborne magnetics acquired to define areas of low permeability and highly magnetic dykes. At Towerrinning, similar problems had been experienced with increasing areas of land salinity, farm water resources being abandoned and two large nature reserves (Capercup and Dingo Swamp) being threatened.

What was done to study the problem

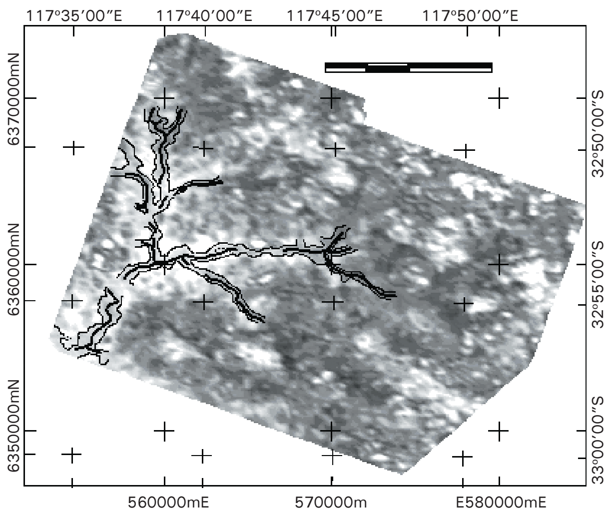
Industry standard SALTMAP AEM surveys (150 m line spacing) were flown to map the degree and extent of salinity and controls on subsurface water movement, complemented by major drilling programs (see George et al. 1996; 1999).

Results

AEM surveys (Figures 37 & 38) revealed previously unmapped palaeochannels in both catchments. At Toolibin Lake, as a result, pumping bores were specifically targeted to the palaeochannel and yielded large flows (500 k/day) of highly saline water (50 000 mg/L). The impact was pronounced and as a result, piezometric levels have declined over much of the 300 ha of the Toolibin Lake and some recovery of native vegetation has commenced. Without the AEM the palaeochannel would not have been located and the existing pumping would have been less effective and/or more expensive.

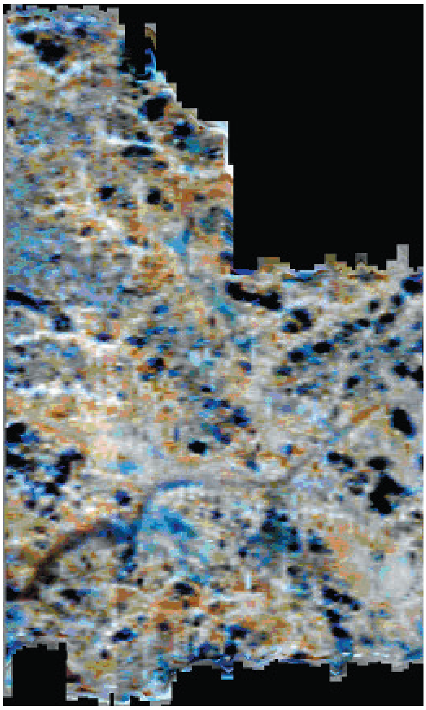
At Towerrinning, the AEM revealed a palaeochannel that contained low salinity groundwater (< 2000 mg/L). This contrasted markedly with the saline groundwaters (>10 000 mg/L) that occurred in the surrounding weathered granite soils of the catchment. Further analysis of the data and drilling indicated several areas where the groundwater was potable. As a result production wells were installed to provide water for Duranillin, a small township which previously had no water supply scheme. In addition, several small on-farm water supplies were established for the 'Wandoo Farm' vineyard. At Dingo Swamp Nature Reserve, modelling also suggests groundwater pumping targeted to the palaeochannel will prevent loss of biodiversity and enable the development of beneficial uses of the pumped water.

Figure 37. Principal component[5] greyscale image of SALTMAP AEM data at Toolibin. The palaeochannel pattern (sketched in black) is clearly delineated by the dark central line within the white (valley floor) areas. Lake Toolibin is located in the south-western corner, just south of the break in the interpreted lines (image courtesy of Gabby Pracilio). Interpreted channels in the upper catchment area were found to represent a combination of shallow sediments and a leached regolith beneath them.



[5] Principal component (PC) analysis is a convenient technique for optimising the display of multiband data to emphasise differences across the image (see Appendix 1.18)

Figure 38. Principal-component ternary image of SALTMAP AEM data at Towerrinning. A palaeochannel is recognised as the dark trench running NE-SW across the area. Bluer colours are fresh groundwater (analysis courtesy Andy Green).



Cost/benefits

Cost–benefit analysis of the catchment-based acquisition of the datasets for Toolibin and Towerrinning (>30 000 ha) has proved to have a low benefit–cost ratio (George & Woodgate 2002). However, when the benefits were scaled to the specific target (Toolibin Lake) the imputed value increased significantly. Economic benefits in this case depend on the value assigned to the Ramsar wetland. At Towerrinning, water was provided to a small community, a new vineyard was developed and a catchment made less vulnerable to drought. However, no exact dollar value has been placed on these benefits.

Other comments

Airborne geophysics (magnetics, radiometrics and AEM) were acquired in both catchments. Data provided unparalleled insights in catchment hydrogeology and allowed more effective investigations and salinity management planning. However, without the implementation of cost-effective treatments that rely on the spatial data, the value of the datasets would have been greatly diminished. Only the groundwater resource elements and soil mapping can be clearly shown to have short-term benefits.

AEM could be targeted to locate similar palaeochannels in other areas if the benefits of salinity management could be shown to exceed the costs of acquisition. For broadacre uses, the evidence suggests that this would be cost-effective where high value assets are targeted and other benefits are derived (e.g. soils maps from radiometrics).

As expected, no spatial relationship was determined between any of the systems and the surface expression of dryland salinity; rather AEM was effective in mapping salt stores in the subsurface.

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CASE STUDY 12: SALINITY MAPPING IN HIGH RAINFALL AGRICULTURAL AREAS OF SOUTH-WEST WA

Submitted by: Richard George and Don Bennett, WA Department of Agriculture

Location: Swan Coastal Plain, south-west Western Australia

Area: Approximately 8000 ha

Scale: Paddock to subcatchment

Rainfall: 1000 mm/annum

Land use: Irrigated and dryland agriculture pasture, viticulture and other specialised industries

Soil classification: Deep sedimentary

Groundwater system: Local to regional

Evidence of salinity: Dryland and irrigation-based salinity affects large areas of the Swan Coastal Plain. Salinity is usually disguised beneath actively growing, salt-tolerant pastures and is, therefore, often poorly recognised when compared with the more obvious signs of salinity in the wheatbelt. Nonetheless, large production losses are attributed to salinity in this landscape. Traditional mapping was based on air photo, visual and 'expert' systems, leaving limited opportunity for objective analysis, restricting remediation and not being targeted in terms of government planning.

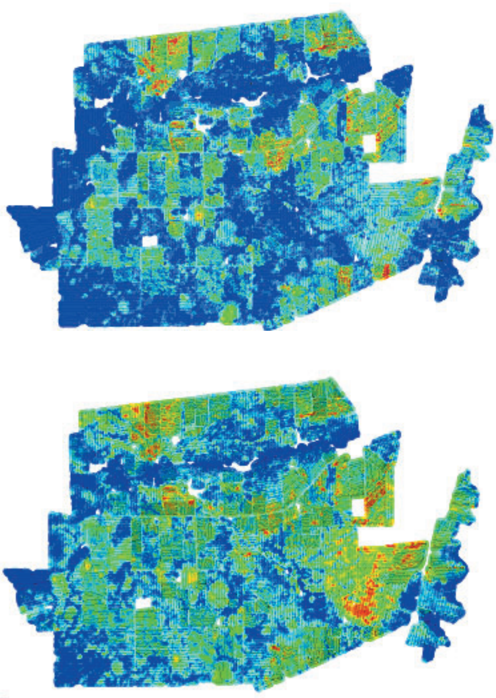
Description of problem or concern

Stored winter run-off is used to flood irrigate perennial pastures with about 91 700 ML of water in the south-west irrigation area (SWIA). It would be possible to water about 34 000 ha of land although only approximately 40% of this area is presently irrigated. Dairy farmers (170 farms) are the major water users (64% of water used), while beef farmers (120 farms, 30%), horticulturists (20 farms, ~1%) and 140 small farms (5%) account for the remainder. In addition, a further 200 000 ha of the Coastal Plain is non-irrigated but still subject to dryland salinity (5%).

What was done to study the problem

A large area near Brunswick, on the Swan Coastal Plain, was surveyed with EM38 and EM31 portable electromagnetic conductivity meters (Appendix 1.6) to map root zone and subsoil salinity, and radiometrics was used to map soils. The EM38 instrument has a depth range of less than one metre, while the EM31 probes to between four and six metres. EM38-derived conductivity and pasture yield relationships were determined for major pasture species and EM38 maps converted to production impact maps (Figure 39).

Figure 40. EM38 and EM31 maps of the Brunswick area. Tracks (dots) indicate the location of the surveys and their density (<50 line spacing common). EM38 (top): Blue areas are low conductivity (< 50 mS/m) and grow pastures at potential rates, while conductive (>100 mS/m) areas (yellow/red) perform poorly (<25% potential). Most green and yellow areas are irrigated. Dark red areas occur in areas of poor surface drainage or where deeper groundwater may be discharging. EM31 patterns (bottom) show greater conductivity at depth over much of the eastern area. They also indicate the influence of deeper alluvial soils associated with the river (elongate pattern to the north).

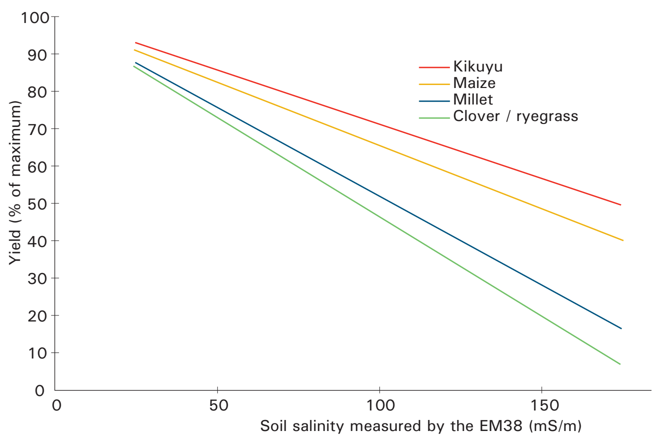


Results

EM38 maps correlate closely with elevated soil salinity levels in the root zones of pastures in the area mapped (depth <1.0 m). EM31 images, while they show consistent spatial relationships, indicate salt stores to a depth of at least 4 to 5 m.

In the survey area (approximately 8000 ha, Figure 40), saline areas (EC>100 mS/m) occur on approximately 20 to 25% of the region's farming area. Results of surveys on a subset of seven irrigation farms (1220 ha) indicated that 64% of the area surveyed has root-zone salinity levels exceeding 50 mS/m, 20.7% exceeds 100 mS/m and 1.3% exceeds 200 mS/m. Subsoil salinity levels exceed 100 mS/m over 40 to 60% of the area, while extreme subsoil salinity occurs over 10% of the area.

Figure 39. Common regressions between pasture yield and EM38-derived salinity. At 100 mS/m, the production of most pastures and crops is reduced by 50%.



Cost–benefits

Formal cost–benefit analysis has not been undertaken. However the information has been disseminated through numerous field days and one-on-one sessions answering questions (see below for examples). Interpreted maps provide answers in both formal and spatially explicit ways. Interpretation is provided by experienced agricultural hydrologists.

Why do some of my paddocks have consistently low pasture yields despite the application of adequate water, fertiliser and management?

This is a common question for farmers in the SWIA as salinity is often at 'subclinical' levels. Salinity mapping quickly identifies where soil salinity is the limiting factor to pasture production.

On which areas should I concentrate my inputs?

High production pasture and fodder systems which require high levels of input (e.g. reseeding, high rates of fertiliser) can be reserved for soils where salinity is not the limiting factor to production. Lower input, lower production systems (e.g. paspalum/ kikuyu dominant pastures) could be maintained with lower inputs on higher salinity areas. In the near future differential-GPS–controlled fertiliser spreading equipment will able to be directly coupled to maps.

What areas are at risk?

Subsoil (EM31) salinity maps and root zone (EM38) maps can be combined (EM31 > EM38) to provide an assessment of salinity hazard. In areas where there is a greater salt store at depth, farmers are encouraged to review subsoils (watertable depth) and irrigation practices. In addition, when moving from shallow-rooted species (tolerant grasses) to less tolerant crops with deeper roots (e.g. fruit trees), growers are encouraged to seek low root zone and deeper conductivity targets.

Where do I begin to redevelop my existing farm?

It is difficult to decide where to begin to invest in further development or salinity management. EM mapping systems can be used to determine which paddocks could be laser-levelled (by selecting low EM areas), drained, or sown to alternative crop and pastures species.

If I choose to reduce salinity, how do I do it?

One option may be to dry off the saline area and commit funds to irrigate a new part of the farm. By doing this, long rotation irrigation systems may be feasible, allowing land previously irrigated to leach its salt. Other management options include installing drains, and planting new pastures and trees.

Where do I put my drain?

Main surface drainage systems may be located to bisect saline areas, or target parts of the farm where salt or waterlogging are severe. The more intensive and expensive subsurface drainage systems may be accurately designed (spacing and depth) and located in the paddock for maximum effect in rehabilitating areas that are saline or waterlogged.

Do I fence off the salinity areas?

EM maps provide boundaries along which to fence. In flat areas where topography is less important, EM boundaries may be the main biophysical factor needing consideration for management

Which tree species grows best in which EM zone?

EM maps indicate salinity 'hot spots' which have poor prospects of short-term production so may be best planted to salt-tolerant trees which will provide watertable and shelter benefits to other parts of the farm. Lists of salt tolerant tree species suitable for different salinity classes are available and continue to be developed. The best tree species can be matched to soil salinity for general shelter-belt or commercial timber plantings, avoiding costly failures.

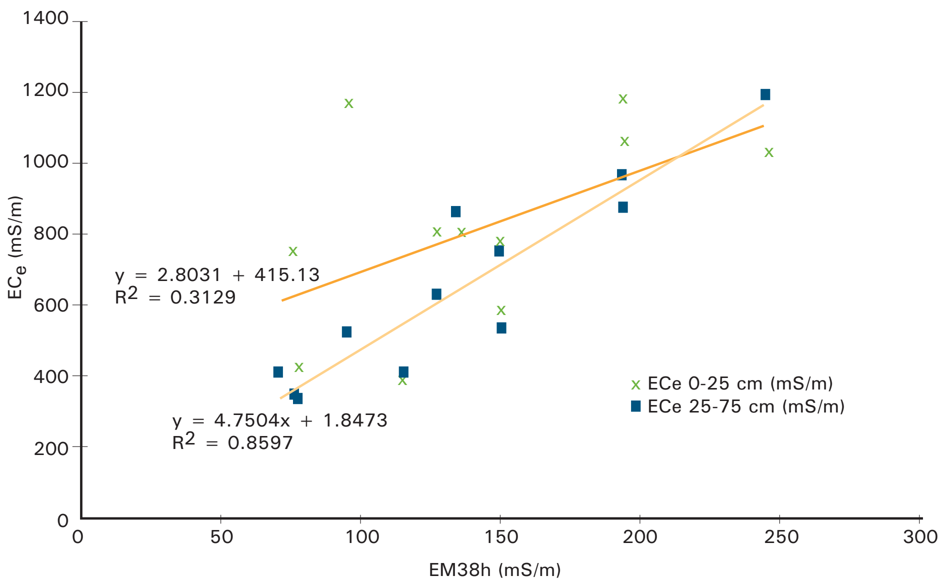
Other comments

The EM38 and EM31 maps are extremely valuable tools to help farmers decide where the salt-affected areas are on their farms, how salty the soils are and how their preferred salinity management systems are working. Recently, a much larger survey of the irrigation district has been completed. This map is being used by irrigation managers to review the distribution targets, tackle channel leakage and assist individual growers assess questions such as those posed above.

Weaknesses and potential improvements to the EM system

For agricultural or forestry the main end uses of the EM38 has been to characterise land according to likely growth response of a particular plant species being grown or contemplated to salinity. It is the most appropriate tool for this purpose because of its shallow depth of penetration. However for very shallow-rooted species such as pastures, even the EM38 may read too deeply to give the resolution required at for example < 0.25 m. Where the instrument has been used for this purpose and calibrated with soil salinity, calibrations are often relatively poor (Bennett et al. 2000). This can be seen in the calibrations in the horizontal mode undertaken with soil EC_e at the Norton test site (Figure 41) located in the Brunswick survey area. The instrument is very well calibrated with EC_e between 0.25 m and 0.75 m but quite poorly calibrated above 0.25 m. This is likely to be because most of the signal is penetrating below this zone rather than any signal or calibration errors within this zone.

Figure 41. Calibration of EM38 with soil EC_e at different depth intervals at the Norton test site.



Soil type affects calibration. For example, the EM38 surveys give a good estimation of salinity (and its effect on shallow-rooted species) for gradational textured soils such as in the SWIA. The greatest problem occurs in strongly duplex soil profiles where the clay content and salt storages are likely to be very different between horizons. An improved EM method of accurately measuring salinity in the surface 0.25 m would be an advantage in salinity mapping. All of the calibrations presented in Bennett et al. (2000) show very good correlations between EM31 and deeper salt stores from the surface to between 3 and 6 m.

Clearly, an EM technique that enables either accurate measurement of salinity at shallow (0 – 0.25 m, 0 – 1 m) and deep (2 – 5 m) locations, or the determination of a salinity boundary layer would be of great advantage to agricultural, environmental or forestry managers. Preliminary results on developing and testing a multi-coil, multi-frequency system, termed the 'EMU', are reported in Bennett et al. (2001).

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CASE STUDY 13: LOWER BALONNE AIRBORNE GEOPHYSICS PROJECT, WA

Submitted by: Kate Wilkinson, Queensland Department of Natural Resources and Mines

Location: Lower Balonne, south-western QLD

Area: 900 000 ha (9000 sq km)

Scale: Regional

Rainfall: 450 – 520 mm per year

Land Use: Mostly dryland cropping and grazing, some irrigated cotton

Soil classification: Various – majority vertosols, sodosols and dermosols

Groundwater system: Mixture of local, intermediate and regional response systems

Evidence of salinity? Three local expressions of secondary salinity have been documented. Dryland salinity is evident at Goondoola Basin with saline seeps and near-surface saline groundwater up to 5000 mS/m (50 000 μS/cm), as well as two sites with irrigation salinity.

Description of problem or concern

The Lower Balonne area, located just north of the New South Wales border in south-central Queensland, is highly productive with diverse agriculture. The local community is concerned about the impact of potential salinity on sustainable land management.

What was done to study problem

Airborne geophysics was used to map salt and landscape structures beneath the surface, and extrapolate between locations with in situ measurements of salt and regolith materials.

Airborne geophysical data (EM, magnetic and gamma radiometric) were combined with ancillary investigations of hydrological data from borehole investigations, soil site data and surface regolith data to provide a better understanding of the nature of regolith materials and groundwater in the project area. These data enabled the construction of a three-dimensional framework of salt stores and regolith characteristics influencing water and salt movement, as well as an overview assessment of areas (land and water) at risk from salinity.

The project is a collaborative scientific activity involving scientists from Natural Resources and Mines, the Bureau of Rural Sciences and the Cooperative Research Centre for Landscape, Environments and Mineral Exploration. A community steering group was formed from land management interests in the area, as community engagement is critical to the uptake of the report recommendations.

Results

Prior to this project, knowledge of the regolith of the Lower Balonne area was generally limited to regional datasets. Major geomorphic units identified in the project provided a valuable framework for exploring land management issues. Radiometric data provided more detailed mapping of the surficial distribution of regolith materials and soil attributes.

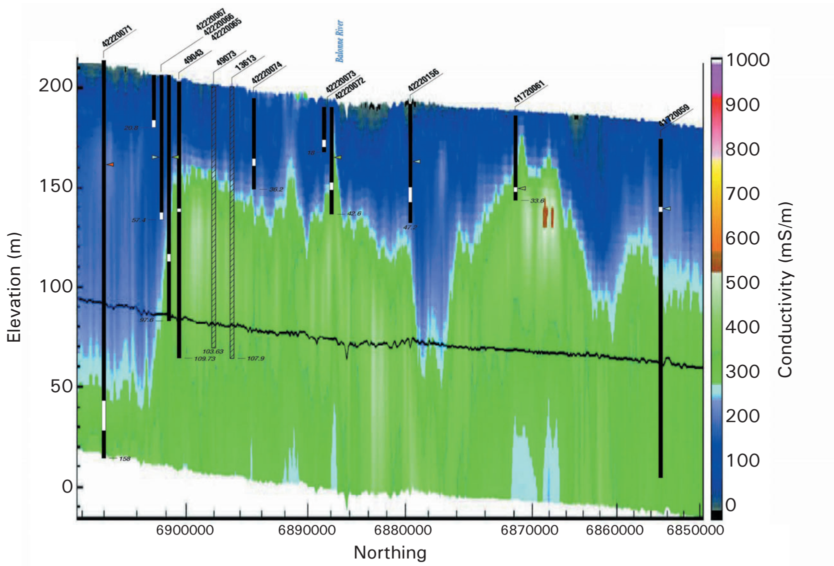
The study of geological and geophysical bore logs, in conjunction with interpretation of the AEM dataset, provided a valuable insight into the architecture of the regolith at depths up to approximately 100 m. The AEM data proved to be useful in extrapolating material information between bores as well as highlighting anomalous regions where further investigation is needed. A previously unmapped palaeochannel cross-cutting the Griman Creek Formation was discriminated in the AEM data. McAlister (2000) investigated the regional subartesian groundwater systems, and showed that the pre-existing bore network provided a large body of data relating to the alluvial groundwater systems. The current project provided the resources for further targeted drilling as well as the development of a more robust conceptual hydrogeological model, although understanding of the dynamics of the groundwater systems was limited by the lack of pump test data. Monitoring throughout much of the study area outside of the established irrigation areas has only recently commenced.

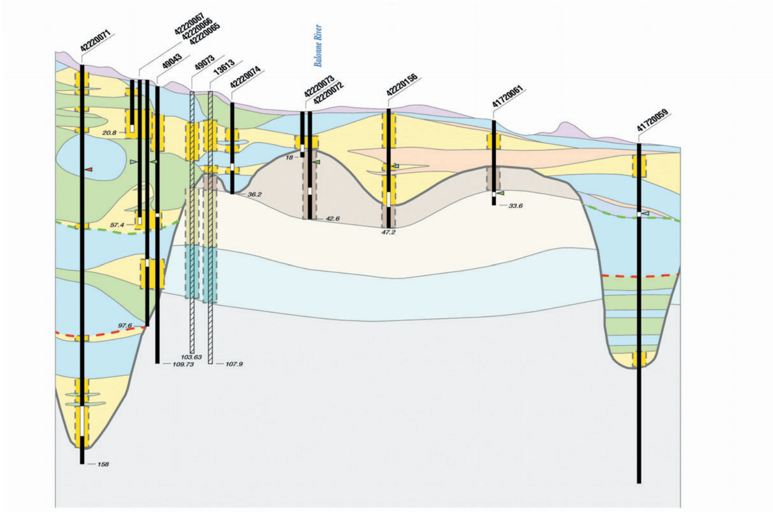
The three-dimensional distribution of regolith materials was represented by depth surfaces and lithological cross-sections based on the bore network (Figure 42) and also visualised using 3-D vrml (virtual reality) package. Interpretive regolith salt load maps were derived using a linear relationship between salt content and AEM bulk conductivity. High salt loads within the regolith were highlighted, some near assets such as river systems and groundwater resources.

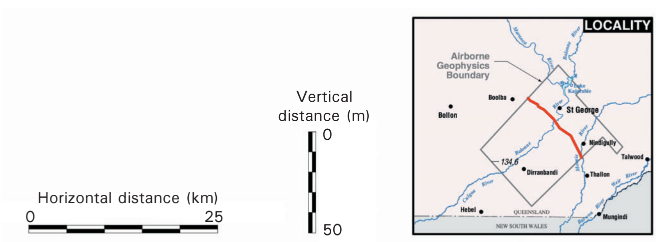
The study improved the spatial knowledge of current saline expressions and, by comparing salt load maps with land use data, also highlighted areas at risk of salinisation. To summarise the findings, the landscape was divided into three categories based around the depth to salty weathered bedrock. The three regions have varying responses to land use impacts, and recommendations for monitoring were made on the basis of this framework.

The combination of better surface and subsurface information derived from geophysics, ground-truthing and flow tube modelling allowed the dynamics of groundwater rise to be investigated. While the modelling used high-end water use (and therefore was a worst-case scenario), it showed the dependence of salinity outcomes on the distribution of regolith materials. Detailed numerical groundwater and catchment process models which can simulate the behaviour in the various aquifers in response to land management are planned after continued monitoring of the new and existing bores improves the parameter sets.

Figure 42. Comparison of drill interpretation and AEM conductivity-depth section of line 10 running north west (left) to south east (right).

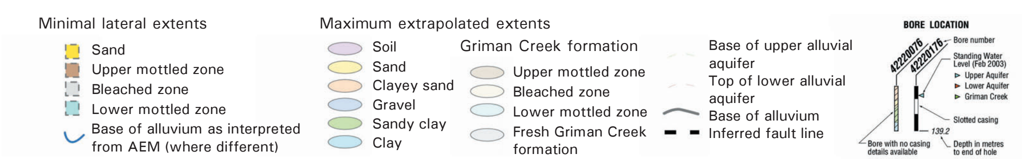






National Action Plan on Salinity and Water Quality
Lower Balonne airborne geophysics area hydrogeological cross section no. 10

24 June 2002 A3-507139



Cost/benefits

The total project expenditure is $3.3 million. The largest portion of funds was spent in the acquisition and processing of the airborne geophysical data ($2 million) and remaining funds used for a number of ground-based studies, drilling, sampling and chemical analysis to extend the existing soil, regolith and groundwater studies to refine the data and develop interpretations, and in project management. The project also used a substantial quantity of data and information which were not paid for directly within the project and which in most cases were collected for other purposes. While these data were not paid for within the project, they were crucial in understanding and using the project data.

The project captured most of the key datasets identified in George and Woodgate (2002) needed to adequately plan for salinity management in a catchment with the exception of orthophotos. These data are now available for further application in land management. In addition, the airborne data led to improvement in aspects of hydrological data, field geology and soils; and provided more detail on infrastructure and its effects. The one area that the project was not able to materially improve on key information was in a better understanding of groundwater trends. New monitoring bores were installed, however, and the project provides improved context for siting new bores or for rationalising the existing network.

This is not the first use of this technology for salinity and there has been evaluation processes established in the past. Nonetheless, this has been the largest use of airborne electromagnetics for this purpose and advances in capture and processing have been made. Additionally during the project, potential efficiencies were highlighted and increased reliability in sensing salt load was achieved through adaptive processing.

A more formal economic benefit–cost analysis will be undertaken as part of the final project. Further value will be gained as the information is used to guide and assist land management in the area by landholders and those with regional responsibilities. The actual use of the data by the community over the next few years will be the true test its value for land management.

Other comments

The project has developed a range of comprehensive datasets that provide information on geomorphology, hydrogeology, salt store and salinity processes. The project has also identified a number of areas/processes that need further investigation in order to understand the salinity risk and implications for land management. In addition, for much of the area, there is no current program for groundwater monitoring beyond the life of NAP projects. A longer program of targeted monitoring is required to adequately model and predict land management and salinity outcomes.

The airborne geophysical data have made contributions to all aspects of this study. The three geophysical methods trialled within the study area measure different aspects of the physical properties of regolith. Radiometric data were most useful for mapping surface soil and regolith features, and in conjunction with the AEM, for defining areas of potential high recharge and for understanding the distribution of soil salt stores. Magnetic data proved to be of limited value due to a lack of magnetic minerals in the study area.

The AEM dataset provided a way to extrapolate regolith architectural information between boreholes. Where the AEM data did not correspond to known variations in the regolith, they highlighted anomalies which were usually attributed to varying salt content. The AEM data were also shown to account for much of the variation in groundwater quality in the saturated zone.

A notable feature of the data capture in this project was the need to re-model the AEM data received from the contractor to fit the knowledge of the regolith (variably conductive at depth) using a constrained inversion approach. Although this led to pronounced delays in the project, the final 'fit' of remote data to measured ground data was greatly improved.

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9. CONCLUSIONS

Conclusions are grouped into two categories: those of a general nature that relate overall to the issue of mapping the hazard and risk of dryland salinity, and those that are specific to individual systems.

MAPPING HAZARD AND RISK OF DRYLAND SALINITY

1. Dryland salinity is the salinisation of land and water resources caused by the clearing of native vegetation for agriculture, particularly in dryland areas. This land-use change results in a rising of watertables and movement of salt to locations where it poses a problem for people or the environment. Assets at risk from dryland salinity include agriculture, water resources, built infrastructure and the environment.

2. In the context of dryland salinity, a **salinity hazard** is salt that can potentially cause harm to an asset. Salt is only a hazard if it has the potential to move into a location where it can threaten an asset, through mobilisation by surface and groundwater.

   A salinity hazard map defines the spatial location (both vertically and horizontally) and concentration of salt that can potentially be mobilised by water.

3. Water is the main agent that moves salt in the landscape. Mapping has important roles in delineating the location and extent of salt in the ground as well as identifying the hydrological pathways through which it is transported. In order to determine whether salinity has the potential to harm an asset, the suite of mapping systems must include those capable of collecting information about the factors that govern the hydrogeology of the area.

4. **Risk** is the likelihood that a hazard will cause harm to an asset at some defined place and time in the future. Risk is classically defined as an impact (usually an unwanted impact) multiplied by its likelihood of occurrence at some given time in the future. Assets include agriculture, water resources, built infrastructure and environmental attributes such as biodiversity. **Salinity risk maps** should identify the actual class of asset under threat, the timing of the impact of that threat, the level of anticipated impact should it occur, and the geographic location of both the risk and the asset.

5. Preliminary analyses for hazard assessment should first use existing datasets to develop an overview of the landscape and to identify priority areas for detailed mapping. Such an approach can also be used over large areas (multiple catchments or State/Territory level).

6. Salinity risk management should endeavour to prioritise areas, information needs and mapping methods for appropriate levels of detailed investigation. A sieving approach, moving from general overview to specific detail based on progressive investigation and analysis, can identify priority areas for appropriate types of mapping.

7. An integrated geoscience or systems methodology, employing three-dimensional mapping of landscape, salinity and groundwater elements, will increasingly provide valuable insight into salinity processes and salt store distribution. It builds upon the groundwater flow systems approach which to date has mainly been applied at regional scale and in most cases is limited to two-dimensional models. Both techniques can be applied at any scale where three-dimensional information is available.

8. All mapping techniques should be 'ground-truthed' and calibrated through field inspection prior to the finalisation of the mapping program, and in many cases before a mapping program is commenced. Field measurements (including soil sample measurements and borehole logging) should be an integral part of any mapping campaign and take into account the three-dimensional nature of the earth and statistical spatial variations within the subsurface.

9. As a general rule it is advisable to plan to undertake independent assessments of the veracity of all major mapping programs at the conclusion of mapping. Such validations provide sound justification for the subsequent decision-making phase by confirming the accuracy and uncertainty associated with the mapping products. They are also a valuable learning tool.

10. Most mapping systems require a high level of expertise for their sound use. Prior experience and a proven track record in understanding the acquisition, processing and interpretation phases is highly desirable. Users are advised to seek specialist advice before committing resources to mapping programs.

11. A balance needs to be struck between the need for data at fine resolution at paddock scale and the broader benefits that are possible when data are combined to produce a bigger picture at catchment, State/Territory and national levels. Some of the systems reviewed (e.g. radiometrics and electromagnetics) can be used at both an overview and detailed scale.

12. The technologies that are suitable for mapping dryland salinity risk and hazard are evolving rapidly. Australia is particularly fortunate to have an excellent science community that supports the development and deployment of new mapping methods as they continue to evolve.

13. Substantial investments have been made, and will continue to be made, in the collection of data for salinity management. These data require systematic coordination, storage and management in order to maximise their value. Such coordination can ensure the appropriate application of standards as well as help to identify properly credentialed specialists.

CONCLUSIONS ON SPECIFIC MAPPING SYSTEMS

14. The 26 mapping methods covered in this review can be used in some way to map salinity hazard and/or risk. The optimal choice of methods depends on the scale of mapping, the vertical and horizontal resolution required, availability of finances, pre-existing knowledge and complementary datasets.

15. Two techniques (laboratory measurements and measurements of soil paste extracts) are useful as analytical point measurement techniques of salt content.

16. Eleven techniques (visual inspection, satellite [e.g. Landsat and SPOT] and airborne remote sensing, air photos and digital elevation models [DEM]) can be used for surface mapping in the 0 to 10 cm depth range. Some of these methods give direct information on salt at the surface, while others give indirect information on salinity in the root zone through interpretation of vegetation stress. Others, such as radiometrics, are useful for soil mapping. Visual inspection, air photo and DEM interpretation, multispectral satellite imagery, and ground electromagnetics (EM) are well developed operationally.

17. Ground electromagnetic conductivity mapping and ground-penetrating radar can be used to probe to several metres into the Earth to give information on salt load and/or moisture content. Of these, electromagnetic conductivity mapping using instruments such as the EM38 is the most cost-efficient technique and has wide utility at farm, community and subcatchment scale.

18. Eight methods can be used to probe deeper than 2 m into the subsurface and map at high resolution. These include deep EM (such as EM31) and electrical probing methods, borehole conductivity logging and stream sampling, all of which give information on salt load. Several methods (ground magnetics, seismic) can be used to help delineate palaeochannels and barriers to subsurface flow. Two methods (nuclear magnetic resonance and seismo-electric) show promise for groundwater detection but are expensive and only used in research mode at present.

19. Airborne electromagnetics and airborne magnetic methods can be used for deep probing (greater than 2 to 5 m) on a subcatchment to regional scale. Only one system, airborne electromagnetics (AEM), offers a proven approach to broad area mapping of salt store below the root zone using a range of airborne platforms. Although relatively expensive, AEM has been used in dozens of studies over the past decade. It has some limitations at shallow depths (less than 5 m below surface) that are now being addressed through applied research. AEM also has limitations in areas where there are complex variations in vertical patterns of salt store and geology. Careful attention should be paid to all stages of survey design, acquisition, processing interpretation and ground calibration to maximise the utility of AEM.

20. Many mapping methods are used in combination, and some are acquired simultaneously. The skill base in each technique is highly specialised, and there are few users who are expert at more than two or three methods.

21. Some vendors' claims that their techniques directly detect salinity are unsubstantiated (e.g. some radiometric and remote sensing proponents claiming direct detection of salinity). It is good practice for potential users to seek independent advice on claims made by vendors.

APPENDIX 1

Mapping and measurement methods

This section provides a summary of the characteristics of each of the salinity and landscape mapping methods.

FIELD AND LABORATORY

Appendix 1.1 Visual inspection from the ground

Summary of method and description of mapping products

Salt crusts and salt pans are clear indications of salinity at the Earth's surface. The type of vegetation often gives a good indication of the degree of salinity present in the root zone. Various field guides have been prepared over the years to assist with on-ground visual identification and mapping of salt-affected land. Significant areas devoid of vegetation such as salt scalds and salt pans are also included in this technique. This technique is used in the creation of salinity hazard maps.

Prior use and evaluation

Victoria produced its first working field guide to plants associated with saline soils in 1987 (Bozon & Matters 1989) and its first published version in 1989 (Matters & Bozon 1989). Bui and Henderson (2003) provide an analysis of vegetation as a salinity indicator in Queensland.

Scale (level of detail)

The vegetation field guides are intended for on-ground use and so operate at paddock scale.

Survey design

The guides are typically used as part of a systematic survey to calibrate mapping undertaken by one of the broadacre techniques such as airborne or satellite surveying, or to subsequently validate the mapping. They can also be used to undertake isolated surveys of relatively small areas.

Inspecting salt scalding at the base of steep cleared bedrock slope – Boho, Victoria.

Data processing, interpretation and mapping products

The guides include colour photographs of individual plants and plant communities for quick visual identification, summary maps of regions to show the likely localities of occurrence, descriptions that indicate the degree of severity and discussion of the typical soil types.

Limitations

These guides are not complete for all regions of Australia affected by salinity. Subject to confirmation it is believed that the guides do not exist for Queensland, parts of New South Wales, South Australia and Tasmania.

Any mapping technique that relies primarily on field inspection will be slow and expensive. If field inspection is to be the primary source for the construction of the mapping product it is recommended that only relatively small areas, such as individual paddocks be covered this way. On the other hand field inspection is an essential component of the calibration and validation process of broadacre mapping and should also be allowed for in the initial survey design and budget. The time of year and rainfall patterns can also influence vegetation.

Vegetation indicators are a useful, but not definitive, method of detecting salinity. An extensive study of over 2000 field observations in Northern Queensland (Bui & Henderson 2003) showed wide scatter between vegetation type and soil salinity.

Fitness for purpose

There is a certain skill level involved in field identification of vegetation types. Experienced operators should be engaged to conduct the mapping or to ensure an appropriate level of training is made available for less experienced field workers.

Best practice—considerations for users

Field inspection is one of the most immediate forms of confirmation of the surface expression of dryland salinity. It is therefore an excellent tool for hazard mapping.

Field inspections are an essential component of broadacre mapping techniques and are best when integrated with other forms of mapping.

Costs

The costs are made up of the labour costs, transport costs and costs of training (if required). These costs can be determined on a case by case basis. As a rough rule of thumb, calibration and validation cost are generally around 10% of the total cost of the mapping survey.

Research questions

- *Are the field guides complete for the majority of areas affected by salinity in Australia?*
- *Are the field guides being used on a regular basis to assist with the training of interpreters, and the checking and validation of salinity hazard maps?*

Appendix 1.2 Laboratory measurements

Soil sampling with subsequent analytical chemical analysis in the laboratory is the most rigorous method of quantitatively evaluating soil salinity. Samples can be taken at the surface, as well as in the root zone or at greater depths through augering or trenching. Field procedures involve the use of saturated paste extracts of soil samples and soil solution extracts, from which analytic procedures such as cation analysis and anion analysis can be performed. Similar techniques can be used for groundwater and water extracted from soil.

The chemicals and their compounds present in salt-affected soil include soil solution ions of calcium (Ca), magnesium (Mg), sodium (Na), chloride (Cl), sulphate (SO_4), bicarbonate (HCO_3) and carbonate (CO_3); exchangeable cations Ca, Mg, Na and phosphorus (K), and precipitated salts (in solid form), namely calcium carbonate (lime) and calcium sulphate (gypsum) (American Society of Civil Engineers 1990). Other informative measurements include pH, EC_e and the saturation-paste water content. Other parameters that can be calculated from these data include the sodium absorption ration (SAR), the exchangeable sodium percentage (ESP) and the salt mass per unit volume or area. Complete analyses can be obtained from analytical testing at commercial laboratories. Rayment and Higginson (1992) have good descriptions of analytical techniques.

Research is being carried out on direct in situ analytical instrumentation suitable for field use, such as ion-specific field-effect transistors (ISFETS) (Hancock & Raine 2001). Such in situ measurements are preferable as they are made in field conditions, without disturbing or disassociating the soil (no submissions to this review).

As described in Chapter 3, hydrological parameters such as porosity and permeability, and related factors of soil type and fluid pathways, are key factors in understanding the movement of water, and hence salt, through the soil. Isotopic geochemistry is a powerful technique for determining the source of the groundwater, the aquifers through which it has flowed and its rate of movement. Measurement of isotopic composition and isotopic age-dating is carried out at the CSIRO, Australian Nuclear Science & Technology Organisation (ANSTO) and many universities.

Rapid indirect techniques of inferring salinity, such as electrical conductivity mapping, are widely used as an alternative to laboratory measurements and are discussed in detail in Appendix 1.6.

Sampling groundwater for laboratory analysis.

Photo: Lisa Worrall

Measurement of total soluble salts

Total salt concentration can be determined or estimated from measurements made with a range of in situ or remote sensors (Rhoades & Oster 1986) including:

- aqueous extracts of soil samples;
- samples of water obtained from the soil or in boreholes;
- in situ, using buried porous salinity sensors that imbibe soil water and measure its electrical conductivity; and
- remote measurements of the electrical conductivity of bulk soil, using electromagnetic-induction conductivity meters, 4-electrode galvanic sensors or time-domain reflectometry (TDR) and insertion parallel-guide electrodes.

The most common techniques in Australia for measuring (or inferring) salinity in small samples are EC extracts on paste-water samples or measurements of the bulk electrical conductivity of the soil (EC_a) with portable terrain conductivity meters.

Cost (laboratory measurements)

Standard water set of basic anions and cations ~ $100 – 200 per sample.

Research questions

- *How accurate are analytical results from Australian laboratories at high levels of salinity (George Rayment, pers. comm., 2004)?*
- *Have ion-specific field-effect transistors (ISFETS) sensors for in situ chemical analysis been trialled in Australia?*

Black sulphide mud in a saline groundwater discharge zone – Simmons Creek, NSW.

Appendix 1.3 Field measurement of electrical conductivity of soil pastes and extracts

Electrical conductivity of an aqueous sample is an easily measured, practical index of the total concentration of ionised solutes in the sample. The procedure is more complex for soils and a multitude of techniques have been developed to give a measure of salt concentration. The most common methods used for testing individual soil samples are the EC_e paste extract method and $EC_{1:5}$ soil-water extract technique.

EC_e: The electrical conductivity of a saturated soil extract is the most useful and reliable measure of salinity for comparison between soil types. The most accurate measurements of EC_e are laboratory-based.

$EC_{1:5}$: This method is based on the measurement of the electrical conductivity of a mixture of 1 part by weight (g) air-dried soil to 5 parts by volume (ml) distilled water. The results obtained depend on soil texture, particularly on clay content. Volume:volume measurements are unreliable and not recommended.

Typically, conductivities of saturation extracts (EC_e) are between six and 15 times higher than those of $EC_{1:5}$ soil-water extracts, with clayey soils having the higher values. The actual conversion figure can vary quite widely for particular soils. Tables of values for various soil textures are produced by State agencies such as the WA Department Agriculture[A1] .

Costs

Around $10 per sample for EC and pH.

[A1] <http://agspsrv38.agric.wa.gov.au/servlet/page?_pageid=449&_dad=portal30 &_schema=PORTAL30????>

Appendix 1.4 In-stream electrical conductivity sampling

In-stream sampling is a simple and inexpensive approach for locating salty 'hot spots' in streams and rivers as well as identifying sources of freshwater. The method can also have the advantage of high community participation by engaging members of the relevant community to conduct the in-stream sampling and thus to understand better the landscape processes operating in their area.

Summary of method and description of mapping products

In-stream sampling uses small portable electrical conductivity (EC) meters to measure river and stream salinity. These surveys indicate variations in stream EC at a subcatchment scale to allow definition of those subcatchments that are expelling saline water and those which provide fresh water sources for dilution flows.

Such surveys need not be extensive (such as the 'run of the river' surveys in South Australia, described in more detail below) and can take advantage of existing infrastructure features (bridges, roads, etc.) from which to conduct survey measurements. The advantage of community involvement is that in addition to using infrastructure features, local landholders can conduct surveys on private property, thus providing a more comprehensive coverage of the conductivity regime of catchments.

Prior use and evaluation

In-stream sampling has been used in a number of areas to identify sources of salinity. A good reference for the application is Baker and Evans 2002 (see Case Study 7) whose investigative work using in-stream sampling in the mid-Macquarie region in New South Wales demonstrated that over 70% of the catchment does not pose a salinity risk since the salt had either previously been leached from the landscape or was not being mobilised and transported to the river.

Scale (level of detail)

In-stream surveys can be applied at a range of scales. The main criteria are to ensure that all subcatchments have at least one reading preferably taken near the bottom of the subcatchment. Existing infrastructure is usually sufficient for this purpose.

Measuring in-stream electrical conductivity.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

Survey design

Survey design is dependent on the number of people available and the level of community involvement. The latter will determine whether sampling can be conducted on private land. Surveys are planned on topographic or DEM-derived maps. Individual maps can then be provided to the sampling team. Confirmation of the sample location can be readily determined using a GPS instrument.

Readings should be taken monthly and after major rainfall events. After twelve months the data collection is sufficient, in most areas, to delineate which subcatchments are the major sources of salinity and allow the prioritising of investigative projects designed to identify the precise location of the salt store contributing to the stream salinity load. If stream flow data is available this prioritisation could be taken to a finer scale. Communities should continue to take readings on a long-term basis to monitor the success of local remediation work and also any adverse effects of changes in land use or rainfall patterns.

The advantages of a high level of community involvement are that it provides opportunities to motivate on-ground work which will provide strategic information and influence outcomes. Subcatchments that are a source of salt can be identified for further work and appropriate strategies developed, if needed, to improve the management of other areas.

Data processing, interpretation and mapping products

No data processing is required other than transfer into a useable format. For example the data collected can be collated by a web-based system for use at catchment, regional, State/Territory and, where appropriate, national levels. The data is then plotted on maps showing an appropriate scale—a salt tolerance scale is often the most appropriate (e.g. drinking levels for humans and livestock, crop limitations).

The data can then be plotted on a groundwater flow systems (GFS) framework if required but plotting on a topographic map is sufficient to determine the spatial distribution of saline subcatchments. The use of the GFS framework 'value-adds' to the in-stream data and does require some more interpretive work such as the production of the framework.

Limitations

The obvious limitation to in-stream sampling is the requirement that running water be present. However in normal circumstances this is not an issue. Even in dry times, seeps and springs can be sampled. Sampling of the study area should take place in the shortest possible time to provide a 'snap shot' of stream salinity. The size of the area to be covered is therefore limited by the number of available people.

Fitness for purpose

In-stream sampling should be the first new source of data acquisition for any area. It provides a quick and rapid interpretation of where further and more expensive technologies should be applied.

Best practice—considerations for users

The EC meters used should be regularly calibrated and used in conjunction with a GPS to confirm sample locations.

While not required to interpret salinity 'hot spots', linking of the in-stream data to a GFS framework provides a better understanding of the location and maximum extent of the salt source.

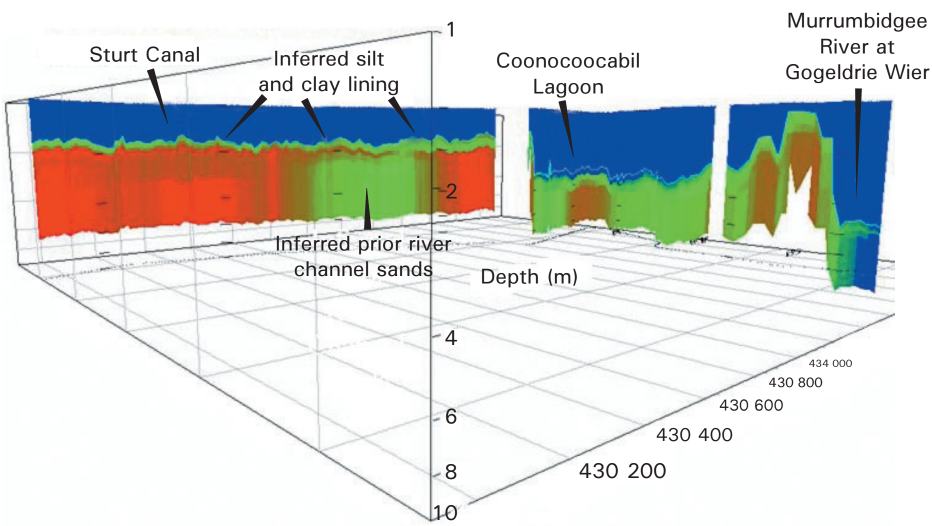
Subcatchments identified as being salt sources can then have more permanent EC meters installed that also measure flow so as to determine salt load.

Another technique being trialled at various locations in Australia is a towed resistivity array (see Appendix 1.8) from a boat along a stream or canal, as shown in the example below. This technique is effective in providing a detailed picture of salinity variations within and along a stream, and pinpointing locations where saline or fresh water is entering (see also Street et al. 2003). Production rates of 60 km in a day have been obtained.

Cost

EC meters cost between $100 and $150. When surveys are conducted by communities members there is little to no acquisition cost. Interpretative costs are limited to GIS production and a limited amount of analysis though this increases if combined with a GFS framework. Continuous profiling is more expensive (~$1k/day) than point sampling and is appropriate when finer detail is required in specific areas.

Figure A1 Top: a towed conductivity streamer on a canal. Bottom: conductivity map showing salinity variations along the Sturt Canal after it exits the Murrumbidgee River at Gogeldrie Weir, NSW (from Allen & Merrick 2003).



Appendix 1.5 Measurement of soil salinity by electrical conductivity

Soil is a complex mixture of minerals, organic materials, liquids and gases. Electrical conductivity of soil containing dissolved electrolytes (salts) in the soil can be represented by the simplified electrical conductivity model (Figure A2). Conductance occurs along three pathways (or elements) acting in parallel:

1. conductance through alternating layers of soil particles and the soil solution that envelopes and separates these particles (a solid-liquid, series-coupled element);
2. conductance through continuous soil solution pathways (a liquid element); and
3. conductance through or along the surfaces of soil particles in direct and continuous contact with one another (a solid element).

Mineral grains are usually insulators, but clay minerals (especially montmorillonite) conduct electricity by the exchange of ions at their surface with those in solution.

The passage of electricity in soils is generally dominated by the movement of ions (electrolytic conduction) through moisture-filled pores. Conductivity is determined by:

- porosity—the shape and volume of pores;
- permeability—the interconnectedness of pores through which fluids can flow;
- moisture content—the extent to which pores are filled with water;
- temperature and phase (solid/liquid/gas) of the pore water; and
- the amount and composition of colloids such as clays.

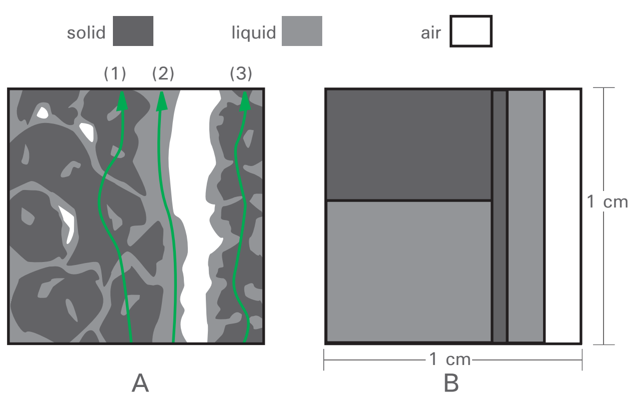
A summary of the most important factors follows.

Moisture content—normally low at the surface but increases with depth until it reaches near 100% at some distance (the capillary head) above the watertable.

Clay type—the cation exchange capacity (CEC) describes the number of negatively charged sites on clay surfaces that can attract positive (usually sodium) ions from the pore fluid. In the presence of water the adsorbed ions can partially disassociate themselves from the clay particle and become available for ionic conductivity; each sodium ion typically carries six clay-bound water molecules. Montmorillonite, vermiculite and halloysite have high CECs, whereas kaolinite and illite have low values.

Electrolytes—the conductivity of an electrolyte (ions in solution) is proportional to both the total number of charge carriers (ions) in the solution as well as their velocity or mobility (which increases with temperature). The most mobile ions (that contribute most to conductivity) are

Figure A2 Simplified electrical conductivity model (after Rhoades et al. 1989).



H^+, OH^-, SO_4^-, Cl^- and K^+; whereas bicarbonate HCO_3^- has about half the mobility of Cl^-. Thus bicarbonate or sodic waters would appear to pose a greater risk to vegetation than saline waters if hazard maps are based solely on EC values without reference to salt type.

The main contribution to conductivity in the $EC_{1:5}$ procedure are ions already in solution and those readily dissolved although some of the exchange ions that are loosely bound to fine-grained materials may also be dislodged and contribute to the conductivity. The $EC_{1:5}$ method does offer some insight into the conductivity of water occupying pore space, but $EC_{1:5}$ values will not match quantitative measurements of the true electrical conductivity of the pore water, or the bulk soil or rock.

The measured electrical conductivity of soil may be greater or less than, the conductivity of the pore water. In low-salinity areas the effect of clays usually dominates, and the conductivity of a clay-rich soil can be an order of magnitude higher than the conductivity of the pore water. Conversely, in high-salinity areas, the contribution to conductivity from the salt concentration generally outweighs that from cation exchange capacity and is relatively independent of the clay content. However moisture content can impact markedly on measured conductivity. Between 75% and 90% of EC_a values can be usually explained by total soluble salt content[A2].

As noted by Rhoades, since dry soil is essentially an insulator, no useful information about salinity, or other soil properties for that matter, can be inferred from EC_a measurements made on dry soils. EC_a measurements should only be made in dryland soils during the time of the year when they are sufficiently moist for the measurable-conduction of electricity. It is inappropriate to try to infer salinity from measurements of EC_a made on dry, or nearly dry, soil and to include salinity analyses of such soils in the data used to establish $EC_a - EC_e$ calibrations .

In addition, Rhoades notes that considering the difficulties of using $EC_{1:5}$ to estimate EC_e, a faster and more accurate method is based on simple measurements of the volume-weight and EC of the saturated-paste itself rather than of its extract. This eliminates much of the work involved in measuring EC_e and saturation (SP) using conventional methods which involve oven-drying for 24 hours without the loss of accuracy that occurs in estimating it from EC measurements made on extracts obtained at higher dilutions. Additionally, one also obtains SP information with this method, which is valuable as an estimator of many soil properties including texture, water-holding and cation-exchange capacity.

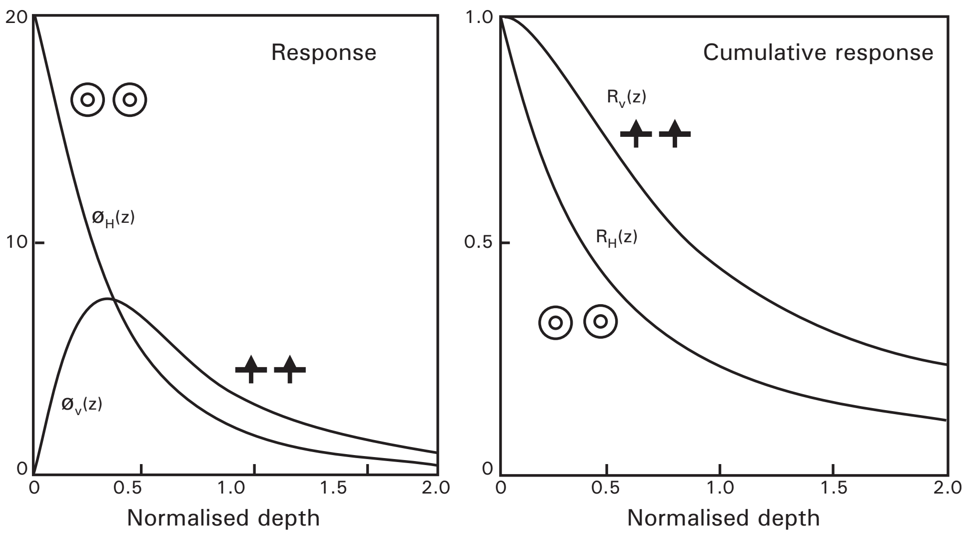
[A2] Job et al. (1998) use EC_a to measure moisture content in areas of low (and relatively constant) salinity.

Appendix 1.6 Shallow-probing electromagnetic conductivity meters

Lightweight portable ground conductivity meters have become very popular for mapping conductivity (and inferring salinity) in the root zone.

These portable ground conductivity meters are frequency-domain electromagnetic instruments that operate in the 'low induction number range', where the depth of investigation is controlled mainly by the separation between the transmitter and receiver coils rather than the operating frequency. The depth of investigation of the two orientations is shown in Figure A2. By making measurements in the horizontal and vertical coil configurations it is possible to gain insight into the variation of conductivity (and hence salinity) with depth. However better depth resolution is gained by using DC electrical techniques described in Appendix 1.8.

Figure A2 Variation of response (vertical axis) with depth for low-induction number conductivity meters. Left: comparison of vertical dipole (ϕ_v) and horizontal dipole (ϕ_h) configurations. Right: cumulative relative contribution, to various depths. H = horizontal coils, V = vertical coils. The horizontal axis on the graphs is the ratio of depth to inter-coil spacing (after McNeill 1980b).



Shallow conductivity measurements with EM38.

Photo: Kate Wilkinson

Table A1 summarises the technical specifications of available low-induction number, hand-held electromagnetic conductivity meters.

Processing—Results are presented directly as values of apparent conductivity, EC_a at one or more frequencies.

Corrections

- Skin depth attenuation. In areas with conductivity greater than 80 mS/m, corrections tables (such as those supplied by Geonics – see McNeill 1980a) are used to adjust the EC_a values for skin-depth attenuation. In newer systems this correction is made automatically in system software.
- Soil texture corrections should also be made.
- Temperature. Soil temperature has a relatively strong effect on the electrical conductivity of soils). Good field practice proscribes that temperature corrections should be made prior to interpretation (Sudduth et al. 2001).

The *depth of investigation* with the EM31 and EM38 ranges from 0.4 to 5 m, depending on conductivity and coil configuration. Figure A2 shows the sensitivity of the EM31 and EM38 as a function of depth in a uniformly conductive earth, which is related to the coil separation. The figure shows that the total signal is an average from a range of depths. For the EM38, for example, 50% of the signal originates from depths above 0.4 m. The GEM2 claims deeper penetration at lower frequencies, but some users report drift problems.

Table A1 Specifications of common ground (and borehole) shallow-probing conductivity meters.

Coil separation	Coil configuration*	Operating frequency	Depth of investigation (50% response)**	Depth of investigation (30% response)**	Drift
Geonics EM38					
1 m	VD, HD	14.8 kHz (or 40.4 kHz)	0.4 m (HD) 0.85 m (VD)	0.8 m (HD) 1.5 m (VD	0.2 mS/m /ºC (temperature compensated)
Geonics EM31					
2 m	VD, HD	9.8 kHz	0.7 m (HD), 1.5 m (VD)	1.3 m (HD), 2.7 m (VD)	< 1 mS/m/ºC
3.7 m			1.4 m (HD), 3.1 m (VD)	2.8 m (HD), 5.6 m (VD)	
Geophex GEM2§					
~ 2 m	VD, HD	90 Hz to 48 kHz	several metres	several metres	?
DUALEM					
2 m (VD) 2.1 m (HD)	VD, HD	9 kHz	several metres	1.5 m (HD) 3.2 m (VD)	?
4 m (VD) 4.2 m (HD)	VD, HD	9 kHz	several metres	3.4 m (HD) 6.4 m (VD)	0.1 mS/m/ºC

* VD = vertical axis dipole (coils horizontal coplanar)
HD = horizontal axis dipole (coils vertical coplanar)

** assuming uniform earth

§ The GEM2 operates over a range of frequencies and claims to obtain depth information. Some users comment that depth resolution may be compromised by drift.

The volume sampled with handheld sensors can be approximated by a half ellipsoid with axes 2, 1 and 1.5 m coil separations for inline, perpendicular and depth axis, respectively.

Interpretation of the data is normally limited to plotting values of EC_a at various locations. It is possible to make measurements with two different orientations with the EM31 and EM38 (see for example Geonics Technical Notes 8 and 11 – McNeill 1980 c, d – to construct an approximate depth section), and different spacings for EM34.

Summary of method and description of mapping products

(See above)

Prior use and evaluation

Very widely used and popular techniques (see Triantafilis et al. 2000; Sudduth et al. 2001 and selected reprints by Geonics – see McNeil references).

Widespread use of these systems has been made in America (Lesch et al. 1992), Canada and Australia. In Victoria, Norman (1990), Norman & Heslop (1990) and Broadfoot et al. (2002) used EM38 systems to map extensive areas of dryland and irrigation salinity on the Tragowel Plain. In New South Wales, Slavich and Read (1994) used similar systems to map the impact on barley crop production. Anon (2001) document evidence of the widespread use of these systems to map salinity, soils and the impact of salinity on crops and pastures. This unpublished proceeding is the most recent and thorough review available of the systems application in Australia.

Scale (level of detail)

Detailed metre-scale mapping suitable for farm scale. Systems often mounted on 4-wheel bikes with GPS and data loggers for continuous operation.

Survey design

No special requirements. Carried or vehicle-mounted operation.

Calibration and drift correction usually necessary.

Conductivity profiling with a towed EM31.

Photo: Kate Wilkinson

Data processing, interpretation and mapping products

These systems measure a volume-weighted, average conductivity of the ground over the volume of investigation, with a direct reading output of EC_a in units of mS/m. However, the relative contributions from different depths depends on the coil configuration and the conductivity profile. For instance a shallow, highly conductive layer may give the same response as a layer twice as deep with four times the conductance, a phenomenon known as 'equivalence'. Some interpretation products are available (e.g. Geonics) to interpret multi-configuration data.

Corrections are required for soil texture, moisture and temperature, and drift and also for magnetic effects (affects in-phase response) and superparamagnetism (viscous magnetisation) effects in lateritic and maghemitic soils. Some instruments (e.g. EM31, EM38) also measure magnetic susceptibility (as an in-phase response).

Limitations

- Soil moisture must be > 20%.
- Response depends on soil texture, although relative patterns usually remain unchanged.
- Need to calibrate (particularly older) instruments.
- Errors due to magnetic lateritic gravels. Some users have modified the EM38 to output in-phase and quadrature so magnetic effects can be corrected.

Fitness for purpose

Suitable for determination of large-scale, root zone, soil salinity classes (irrigated properties in Northern Victoria). Important part of land and water management.

Also in time-lapse mode to determine soil salinity changes (risk or remediation).

Costs

Starts at about $1500 per day. Coverage is between 50 ha/day (detailed grid) to 500 ha/day (>100 m lines) at roughly $1 per hectare at district scale to $30 per hectare for very detailed coverage.

Best practice—rapid data collection

Since single measurements with conductivity meters have a relatively fixed depth of investigation, some users employ a combination of coil configurations or systems with different coil spacings. Corrections should be applied for temperature, sensor height and non-linearity at high conductivity values. Field calibrations should be applied for soil texture, clay content and moisture levels to enable conversion to salinity. Calibration transects are recommended to test areas representative of classes of response.

Research questions

- *How universal are EM corrections for soil texture?*
- *How important are corrections for soil moisture content and magnetic soils in EM?*
- *Should there be national standards for salinity maps?*

Appendix 1.7 Deeper-probing ground electromagnetic conductivity techniques

AND

Appendix 1.8 Electrical resistivity probing

Some ground conductivity mapping systems mentioned above span from the surface to below the root zone. This section covers techniques with investigation depths greater than two metres.

A large number of instruments for measuring electrical conductivity at depths greater than two metres are available, ranging from larger-spacing terrain conductivity meters, through transient electromagnetic (TEM) systems, to DC resistivity 4-electrode or array systems. Only a few of these have been used in Australia for groundwater and salinity investigations, and none of the submissions addressed advantages and efficacy. The use of DC electrical resistivity imaging method for dryland salinity is described by Acworth (1999).

A summary of the technical specifications of these systems is given in Table A2.

Summary of method and description of mapping products

Deep-probing ground EM systems such as the time-domain Sirotem, Geonics EM37 and 47, and Protem, are designed to resolve the conductivity structure over a range of depths and were originally designed for mineral exploration. Modern broad-band systems measure times from several microseconds to tens of milliseconds. Many of these systems have been modified for environmental applications by incorporating accurate early-time measurements to improve near-surface resolution.

The behaviour of the TEM currents that are induced in the earth after cessation of the transmitted pulse has been likened to 'smoke rings' that diffuse down and away from the transmitter loop with time. The currents diffuse more rapidly in a resistive earth. The conductivity structure of the earth can be derived mathematically from the shape of the decay of the secondary fields detected in the receiver coil.

DC electrical (4-electrode) systems measure the resistivity of the earth through pairs of electrodes injecting current into the ground and measuring the resultant potential at the surface. Depth information is obtained by varying the electrode spacing. Modern DC electrical systems use an array of electrodes for more rapid profiling. Systems that use capacitively coupled electrodes that can be dragged along the ground have a smaller depth of investigation (e.g. Christensen & Sørensen 2001).

Conductivity sounding with EM34.

Photo: Kate Wilkinson

Table A2 Specifications of deeper-probing ground EM and electrical resistivity systems.

System description	Horizontal resolution	Depth of investigation	Comments	Manufacturer
CONDUCTIVITY METERS				
EM31 VD and HD coils* 2 m or 3.7 m coil separation 9.8 kHz	Few metres	Between 1 and 6 m; depends on orientation	Simple to operate, boom-mounted coils. Also measures magnetic susceptibility.	Geonics Limited
EM34-3 VD and HD coils 10, 20, 40 m coil separation (6.5, 1.6, 0.4 kHz, respectively)	Tens of m	4 to 60 m; depends on coil orientation.	Cable connected between coils. Slower than EM31.	Geonics Limited
TIME DOMAIN EM				
Protem Wire loop transmitter, side length 5 – 100 m Rigid 60 cm receiver coil, 700 kHz bandwidth Time range 6 μs – 32 ms In-loop or separated loop configurations	Wider than transmitter loop, increases with time	Few to hundreds of metres; depends on conductivity and loop size	More expensive but greater versatility and depth range. Various models for different applications. Time gates can be shifted.	Geonics Limited
Pulse EM Wire loop transmitter, side length 20 – 100 m Receiver coil 500 kHz bandwidth, 4 μs sampling Time range 6 μs – 10s ms In-loop or separated loop configurations	Same as above	Same as above	Same as above	Crone Geophysics (Outer Rim Geophysical Services in Australia)
NanoTEM General features similar to above. 1.2 and 1.6 μs sampling rates	Same as above	Same as above	NanoTEM is a battery-powered, early-time transmitter for the GDP series receivers. Time gates can be shifted	Zonge Engineering and Research Organization

... continued on next page

* VD = vertical axis dipole (coils horizontal coplanar)

HD = horizontal axis dipole (coils vertical coplanar)

** ~1/5 of outer electrode separation

Table A2 Specifications of deeper-probing ground EM and electrical resistivity systems (continued).

System description	Horizontal resolution	Depth of investigation	Comments	Manufacturer
TIME DOMAIN EM (continued)				
SMARTem Digital programmable TEM receiver. Continuous acquisition with10 μs resolution	Same as above	Same as above	Digital programmable TEM receiver, compatible with Zonge, Geonics, Iris and other transmitter systems.	Electro-Magnetic Imaging Technology (EMIT)
TinyTEM Towed coils (1.5 m square coaxial) behind 4-wheel bike, few ms to few 100 μs	Same as above	Few to 20 m	Used with SMARTem, for target detection and semi-quantitative depth profiling Can be towed at 4 km/hr	Geoforce / EMIT
DC RESISTIVITY				
Syscal Automated multi-channel resistivity systems	Approx outer electrode spacing	cm to 100s of m**	Automated electrode switching up to 72 electrodes	Iris Instruments
Terrameter Automated 4-channel resistivity systems	Same as above	Same as above		ABEM Instruments
LUND Roll-along continuous imaging system	Applicable electrode spacing	Same as above	Includes 2-D inversion software	ABEM Instruments
OhmMapper Capacitively coupled system operating at 17 kHz	Applicable electrode spacing	Less than m to few m	Capacitive coupling; can be dragged along ground	Geometrics Inc
CORIM Capacitively coupled system operating at 12 kHz	Applicable electrode spacing	Less than m to few m	Capacitive coupling; can be dragged along ground	Iris Instruments
PACEP Pulled array continuous electrical profiling	Applicable electrode spacing	1 m to tens m	Inductive source and electrodes dragged along ground	Aarhus University, Denmark

* VD = vertical axis dipole (coils horizontal coplanar)

HD = horizontal axis dipole (coils vertical coplanar)

** ~1/5 of outer electrode separation

Mapping products include maps of 'apparent resistivity' at a particular sample time, frequency or electrode spacing, and inverted depth sections showing conductivity or resistivity versus depth (see example in 'best practice', below.)

These deeper-probing, ground EM systems are valuable tools for salinity hazard and risk mapping since they give information on salt store and flow pathways below the root zone.

Prior use and evaluation

Widespread use for environmental and mineral exploration applications (e.g. Fairbairn 2002 describes use of EM31 for salinity studies in Victoria).

Scale (level of detail)

The volume of earth investigated increases with later times, lower frequencies or larger electrode spacings. The vertical depth resolution is at best 10% of the depth to the layer. EM responds to conductive layers better than resistive layers; the inverse holds for DC resistivity.

The *depth of investigation* of TEM depends on the earth conductivity and sample time and, in contrast to frequency-domain techniques, not on the source-receiver separation. In homogeneous earth the depth of investigation increases as the square root of the sample time, and is inversely proportional to the one-fifth power of conductivity. The ultimate limit to penetration depth is the time at which the signal decays to the noise level of the system. The radius of investigation, or 'footprint', also increases with sample time and resistivity. Most modern TEM systems have variable time gates and higher-resolution windows suitable for near-surface investigations.

These techniques can be applied for detailed investigation at farm scale, or as ground control on airborne EM surveys.

Survey design

Although the optimum resolution is obtained with a loop size comparable with depth of investigation, larger loops can be used to average over a greater spatial distance.

Data processing, interpretation and mapping products

Processing. Standard preliminary processing applies system and geometric corrections to the data to provide a value of C_a or R_a for each sample time. Some practitioners use a late-time approximation for ease of calculation, but the values are not representative of actual earth conductivities at early and intermediate times.

Corrections are normally not necessary with standard field procedure. But may have to correct for superparamagnetism effects (viscous magnetisation) in lateritic and maghemitic soils which affects TEM systems with small source-receiver separations (superparamagnetism manifest itself as a 1/t decay at late times). Other users report magnetic soils can affect EM data.

Interpretation. TEM data measured over a range of sample times can be combined mathematically to produce an estimate of the earth's conductivity profile with depth. A variety of schemes are employed, usually based on a one dimensional or horizontal layered-earth assumption.

- *Layered-earth inversion* (LEI) techniques produce a layered-earth interpretation consisting of between two and five discrete layers. Although the interpretation is not unique, the models usually fall within a reasonable range of classes. A three-layer earth model is commonly used in regolith dominated terrains, with a middle conductive layer sandwiched between dry resistive top soil and resistive basement. The conductivity and thickness of a thin conductive layer cannot be separately resolved, but the product of the conductivity and thickness of the layer, or its *conductance*, is a well-resolved parameter. Some computer inversion programs produce a set of equivalent models so that the non-uniqueness can be evaluated though calculation of a multiple suite of forward models.

- *Smooth inversion*, or Occam inversion, is a variation of layered-earth inversion that does not require an assumption of a known number of layers. The method produces a smoothly varying section of conductivity with depth, usually constrained by a most-smooth assumption that penalises sharp conductivity boundaries. Proponents of this method argue that it makes the least number of assumptions, whereas advocates of the layered-earth approach argue that sharp boundaries are often geologically more realistic. Smooth inversion is much more computer-intensive than layered-earth inversion.
- *Thin-sheet inversion* is often more robust than layered-earth inversion, particularly if TEM measurements have been made in a restricted time range. This semi-quantitative procedure interprets the TEM data in terms of conductance of equivalent thin layers as a function of depth. The *apparent conductance* may be calculated from the difference between two time channels to eliminate calibration errors. The technique is normally confined to airborne systems (see below) and cannot readily be interpreted quantitatively.
- *Conductivity depth imaging* (CDI) is a rapid technique to produce an approximate conductivity value as a function of depth. The CDI method (Macnae et al. 1991) is much less computer-intensive than layered-earth inversion, but is usually considered less accurate. Some studies suggest that the method is less subject to edge-effects over non-layered (i.e. 2-D and 3-D) earth structures than the other 1-D techniques listed above.
- *2-D* inversion provides a more accurate image of the subsurface, particularly where there are lateral changes in conductivity (Auken & Christiansen 2004; Møller & Sørensen 1998; Møller et al. 2001). Although not widely used, these techniques are far superior to the approximate imaging algorithms. Free downloads of 2-D DC resistivity inversion programs are available on the ABEM web site at <www.abem.com/Software/demosoft.htm>.

Limitations

TEM systems need to be designed or modified for very early-time operation to be suitable for near-surface salinity studies. Even so, modern systems cannot resolve variations in the top few metres (root zone) as well as portable ground conductivity systems.

The requirements of interpretation tools for environmental applications are much more rigorous than for mineral exploration EM.

Christiansen and Christensen (2003) show that much more accurate results can be obtained if quantitative measures of noise and accuracy are included in non-linear inversion. They show that a good time-domain system is capable of resolving several layers within the few tens of metres.

Fitness for purpose

Ideal for local and regional salinity hazard mapping to depths of tens of metres, as well as risk assessment by delineation of preferential flow pathways. These EM tools cannot resolve variations in the root zone, but DC electrical measurements with smaller electrode spacings can.

Costs

Ground TEM surveys cost around $2000 per day for 30 to 40 soundings. TEM profiling can cover 20 to 30 line-km per day. Processed data costs around $300 per line-km. Assumed line spacing of 200 to 400 m gives a cost of $6 to $15 per hectare.

Electrical resistivity probing costs $1400 for several kilometres of profiling per day. Resistivity imaging—from one to several line-km per day costs $3000 – $5000 per processed line-km. Assuming line spacing of 200 to 400 m gives a cost of $60 to $250 per hectare.

Best practice—considerations for users

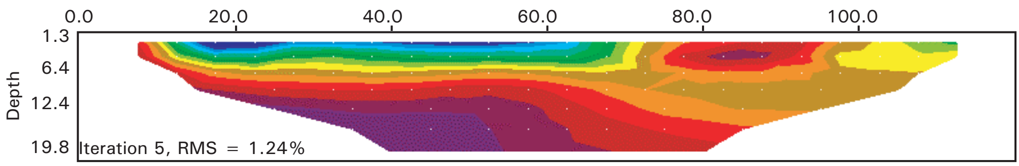
TEM system: lightweight, early-time system with insignificant system response at early times. Some systems can be mounted on a sled or vehicle and profiled continuously.

Interpretation: layered earth inversions are superior to CDIs, although more computer-intensive.

For detailed depth information, DC resistivity systems are usually superior (although slower) and layered-earth inversion programs are readily available.

Electrical sounding systems (such as the 72 electrodes, ten channel Iris Syscal) can be used when better depth resolution is needed. Measurement takes around five minutes per array. These are good for mapping palaeochannels and basement detail. Automated inversion software is readily available (see Acworth 1999 who advocates using electrical imaging as follow-up after EM profiling, to provide better definition and improve the siting of piezometers).

Figure A3 Example of resistivity image in the Liverpool Plains obtained from 2-D inversion of DC resistivity data. The resistivities range from 2 ohm-m (blue colours) to 10 ohm-m (purple colours) (courtesy Ian Acworth, UNSW).



Multichannel DC resistivity system for rapid resisitivity imaging. The cables are connected to electrodes implanted in the ground.

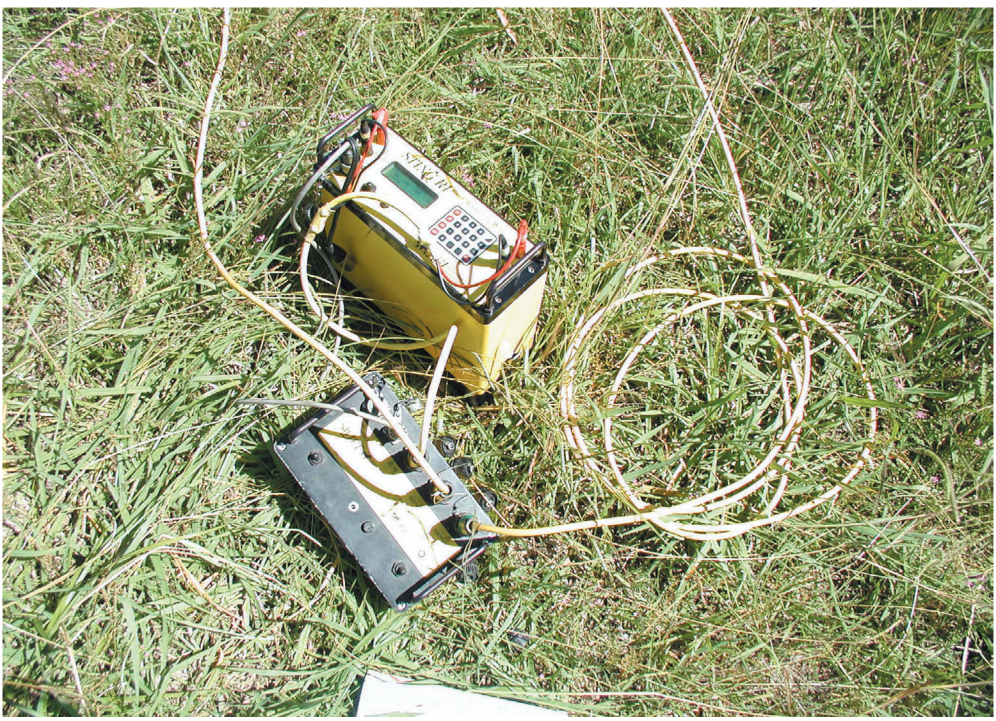


Photo: courtesy Bryce Kelly, National Centre for Groundwater Management, University of Technology, Sydney

Appendix 1.9 Other ground-based systems (ground-probing radar, nuclear magnetic resonance, seismo-electric, refraction seismic, gravity, etc.)

A wide range of other ground-based, geophysical techniques are available which have application to particular aspects of salinity, hydrology and landscape mapping. Some techniques measure water content directly, and are thus useful for constraining hydrogeological parameters. Others can be used to map soil and bedrock structures. Some of these methods are listed and summarised in Table A4 with key references where the reader can obtain further information.

Table A4 Summary of other geophysical systems.

System	Responds to	Depth of investigation	Constraints
WATER DETECTION			
Nuclear magnetic resonance (NMR)	Moveable water in pores	Up to 50 m	Depth limited in conductive ground
Seismo-electric	Water content, interfaces	Few 10s of m	Mechanisms not well understood
STRUCTURE MAPPING			
Ground-probing radar	Dielectric impedance contrasts	Few m	Depth limited in conductive soils
Seismic refraction and reflection	Acoustic impedance contrast	Tens to 100s of m	
Gravity	Density contrast	No limit	Non-uniqueness
Magnetics	Magnetic material	No limit	Non-uniqueness
SOIL PROPERTIES			
Induced polarisation	Mineralogy and texture of metallic and clay minerals	Tens to 100s of m	Difficult to interpret
Gamma ray spectrometry	Radioactive products of K, Th, U – soil type	Tens of cm	

Nuclear magnetic resonance (NMR)

This technique, also known as magnetic resonance imaging (MRI) or proton magnetic resonance (PMR), is based on induced magnetic resonance of hydrogen protons in water molecules in the soil, following transmission of an electromagnetic signal in a current into a loop laid on the ground. NMR responds to hydraulic permeability and is the only non-invasive technique that measures the presence of groundwater directly. Computer inversion of measurements gives an estimate of the water content and the mean pore size of each layer at depth, and is useful to assess the prospects of a groundwater resource before drilling. In conductive areas the depth of investigation is about 50 m, but can be higher in resistive areas (Valla & Yaramanchi 2002).

Seismo-electric

Also known as electro-seismic and electro-kinetic, this is based on the conversion of seismic energy to electromagnetic energy. In practical implementation, a seismic signal is generated at the earth's surface by a hammer source or similar, and electrodes are used to detect the associated electrical signal caused by oscillation of ions in solution as the seismic wave passes. The method can be used to infer hydraulic conductivity. However the theory underlying seismo-electric behaviour is complex and involves complex coupled hydraulic, interfacial and electromagnetic waves. At present there is only one commercial supplier of equipment, but details of its operation are confidential. A number of research projects to verify the system and explore the potential of this technique in Australia are underway (Butler et al. 1996).

Ground-probing radar (GPR)

GPR has the highest resolution in subsurface imaging of any geophysical method, approaching centimetres in some circumstances. GPR is based on high-frequency (20 MHz to 1 GHz range) electromagnetic wave propagation and scattering to detect changes in electrical properties (particularly the dielectric constant; i.e. water content) in the ground. GPR is highly sensitive to variations in water content and chemistry. It has been widely used to map watertables and the corresponding soil stratigraphy that controls groundwater flow including buried stream channels. The depth of investigation is normally limited to a few metres in conductive saline soils, but can be much higher in dry sandy soils. The technique cannot see through the saline layer (Annan 2003).

Radio-magnetotelluric

An experimental technique that measures electromagnetic signals from radio station transmissions to give information on the conductivity of the top few metres of the ground. Potentially rapid and inexpensive (Chaplot et al. 2001).

Seismic refraction and reflection

The seismic method is based on the detection of reflections or refractions from seismic waves, generated at the surface, from impedance contrasts between differing rock units or materials at depth. These contrasts may arise from either the nature of materials in different layers (density, soil or rock type), or modification of physical properties by, for example, the presence of fluid. The main application of the seismic method in salinity studies, is where the presence of water modifies the physical properties of the regolith. In particular, the top of the watertable can create a sharp contrast between the material above and below this surface, which can be detected. Large volumes of concentrated salt may also change the physical properties of the material. Seismic investigations can provide an additional tool for salinity studies when the objective of the study is to image the regolith/bedrock contact or to map the top of the watertable.

There are two types of seismic methods that can be used to investigate geometrical aspects of salinity problems. The first is the seismic refraction method. In this type of survey, a simple energy source (e.g. sledge hammer, weight drop, small explosive or minivibrator) and a closely spaced geophone array will record shallow refracted energy within the top few metres of the surface. This provides a map of the varying subsurface layers based on seismic velocity variations within the regolith. These layers can include the top of the watertable and the base of the regolith. The second applicable technique is high-resolution seismic reflection imaging. This can be used when additional information is required to map the geometry of the regolith, any lithological variations and velocity anomalies that may indicate the presence of fluid within the salinity-affected landscape (any geophysical textbook is a suitable reference).

Gravity

The gravity method is based on accurate measurements of acceleration due to gravity, usually at the Earth's surface, using a portable gravity meter or gravimeter. The technique is applicable for mapping changes in soil density and thickness, as well as depth to bedrock. Interpretation of gravity and magnetic (potential-field) data are non-unique and require a skilled interpreter (any geophysical textbook is a suitable reference).

Magnetics

Similar to aeromagnetics (Appendix 1.17), but with the sensor carried by a person or non-magnetic vehicle along the ground. Ground magnetics has been successfully used in South Australia to map magnetic susceptibility of soils in transects across the Jamestown valley associated with transient salinity, and correlated well with areas of high conductivity picked out by EM38 (Fitzpatrick et al. 2003b). It is often useful to conduct ground magnetic surveys in conjunction with ground EM surveys, since EM responses may need to be corrected for magnetic soils (Deszcz-Pan et al. 1998).

Gamma ray spectrometry

Similar to airborne gamma ray spectrometry (Appendix 1.16), but with the sensor carried in a vehicle over the ground. Some users mount a gamma ray spectrometer, magnetometer and EM induction meter on 4-wheel bikes for salinity and soil mapping.

Induced polarisation (IP)

A variation of the DC electrical resistivity technique (Appendix 1.8), which measures the time- or frequency-dependence of the received voltage. IP signals are sensitive to metallic and clay minerals in the soil (Ward 1990).

Costs of these techniques are given in 'Summary of methods for mapping dryland salinity hazard and risk assessment' (p. 56).

BOREHOLE METHODS

Appendix 1.10 Borehole conductivity logging

Table A5 Specifications of borehole EM conductivity systems*.

Coil separation (m)	Coil configuration	Operating frequency (kHz)	Radius of investigation** (m)	Measuring range (mS/m)	Drift
Geonics EM39					
0.5	vertical coaxial dipoles	39.2	0.6	0 – 3000	0.1 mS/m/°C
Auslog A634; Envirolog					
0.5	vertical coaxial dipoles	26	0.6	1 – 3000	Noise 3 – 5%

* Mention of a specific vendor or instrument does not imply endorsement.

** 50% response

Summary of method and description of mapping products

Borehole conductivity meters operate on the same principle as surface-based conductivity meters. Output in units of mS/m. Provides ground truth of true conductivity values versus depth.

Prior use and evaluation

Becoming more commonly used. CRC LEME has case studies.

Scale (level of detail)

Probe lowered down borehole (wet or dry, but not steel-cased). Provides a volume average 0.6 m vertically and 0.5 m horizontally (McNeill 1986).

Borehole conductivity logging with EM39.

Photo: Kate Wilkinson

Survey design

Readings should be taken at less than 0.2 m depth intervals or logged continuously. Every borehole drilled should be conductivity logged. Measurements are plotted at the probe centre. Care should be taken to null the probe (drift calibration). Magnetic soils can also cause errors (in-phase response).

Data processing, interpretation and mapping products

Corrections need to be made for borehole diameter.

Limitations

The borehole can be wet or dry, but not steel-cased. The long length (several metres) of the probe prevents readings being obtained near the ground surface or at the very bottom of the borehole.

Fitness for purpose

Ideal tool for measuring EC versus depth when boreholes are available.

Best practice—considerations for users

Ideally, all boreholes should be conductivity logged.

Cost

The cost of a borehole logging tool, data logger and winch is ~$40k – 60k inclusive. A logging system can be operated by one person from a small flatbed truck and shallow holes can be logged in a few minutes. Most instruments are owned by consultants or government agencies and they are usually charged out on a daily basis at an approximate cost of $2000 day, for up to ten bores per day.

AIRBORNE METHODS

Appendix 1.11 Aerial photo interpretation (API)

Summary of method and description of mapping products

Aerial photo interpretation is the oldest remote sensing technique for broadacre mapping. It has been employed in Australia for landscape mapping since the 1940s. The technique involves the systematic acquisition of photos from precision cameras directed vertically down mounted on-board the aircraft. Photos are acquired regularly along flight lines over large areas, typically hundreds or thousands of hectares at a time. The photos usually overlap both within a flight line and between flight lines permitting a contiguous picture of the surface. Because the photos overlap they can be viewed in pairs, producing a stereo view that can show the height of ground objects.

The salinity-related mapping usually involves the detection of visible salt on the surface, or the identification of surrogate measures such as vegetation or water-bodies that might infer salinity. Mapping might also involve detection of drainage lines (hydrology), landform or geology to help develop an understanding of landscape processes. The photos can be acquired in black and white, true colour or colour infrared. Colour infrared photos may produce the best results because they show more clearly the stressed vegetation.

A large archive of air photos exists across Australia variously housed with State/Territory and Commonwealth government agencies or in the archives of various companies. Most photos are readily accessible through well-advertised sources.

A recent development in Australia is the introduction of digital cameras. These cameras acquire digital images as frames which can be subjected to similar photogrammetric correction and analysis as the print (analogue) with the benefit of initial acquisition in digital form and the use of digital processing which permit more ready assimilation with other digital data and subsequent computer-based analyses. No significant projects mapping dryland salinity have been reported as being undertaken in Australia.

Aerial photo of saline land near Williams Creek, NSW.

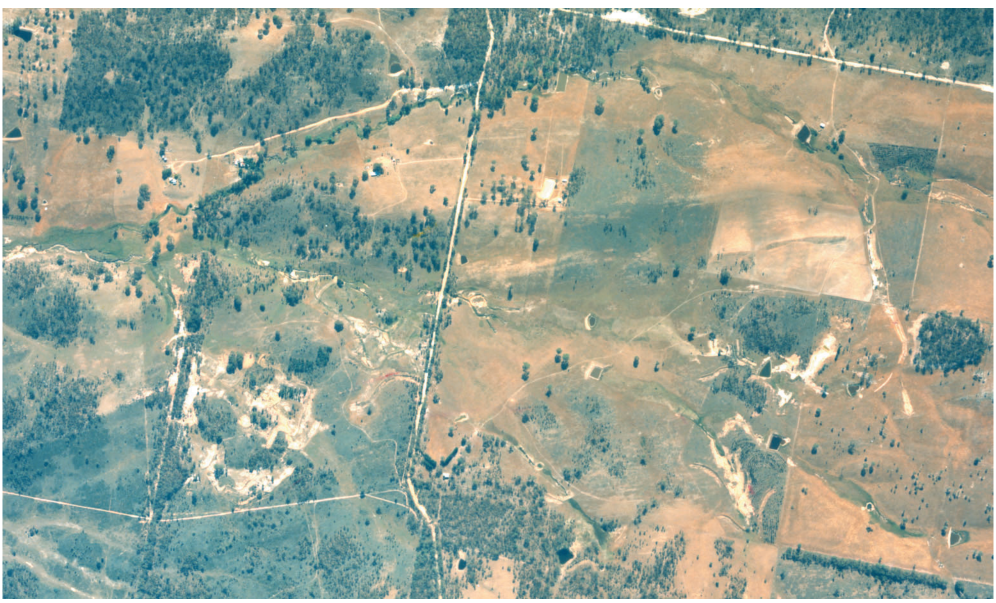


Photo: courtesy DIPNR NSW

Prior use and evaluation

Ferdowsian (1994) evaluated the well-established technique of aerial photo interpretation for identification of saline discharges in Western Australia. He provided costs estimates and comments on the advantages and limitations of the method for farm scale, catchment scale and regional scale applications.

There is no known significant prior use of digital cameras for dryland salinity mapping.

Scale (level of detail)

Typical aerial photo projects are available at two scale ranges: at medium scale (1:20 000 to 1:80 000) and at a larger scale (1:4000 to 1:20 000). For reference purposes at scale 1:50 000 one square centimetre on the photo represents 500 m by 500 m on the ground or 25 hectares. A typical boundary drawn from a 1:50 000 scale air photo will be accurate to within 15 to 25 m of its true location.

Digital photos can be acquired at matching scales to conventional aerial photos.

Survey design

Aerial photo projects are typically carefully planned. Flight diagrams for the area to be flown are drawn up showing the location of the centre of every proposed photo. Global positioning systems are typically used to guide the aircraft to the right location.

Data requirements, processing, interpretation and mapping products

Virtually all photos are still acquired on print film. These are developed and made available to specialist mapping organisations for broadacre mapping. Individual photos may be acquired for small area mapping. Usually a standard map with linework and classes is prepared. Increasingly these may be captured by a digital mapping system (and input into a GIS). Ground checks are an important part of interpretation.

Limitations

Given the wide availability and high quality of existing photos it is recommended that users contact their nearest company or government agency dealing with natural resource management issues and seek advice on the most appropriate photos that cover their area of interest. The user may then wish to engage one of many photo-mapping companies to undertake the mapping.

The technique may give an indication of the surface or root zone expression of salt where it picks up specific vegetation types that infer the presence of salt. It is a reliable salinity hazard mapping technique for existing surface salt, and moderately reliable for inferring near-surface salt, when interpreted by an experienced operator and checked with ground follow-up. It is not, on its own, a useful tool for predicting where salt might occur in the future.

Interpretation of aerial photos can be confused by other factors that can cause vegetation to look stressed including dieback, drought, water-logging and bushfire damage. The black soils of eastern Australia can also cause confusion. Clouds and smoke can reduce the quality of the photos. Terrain shadow is also to be avoided (only a problem in the steeper areas).

Fitness for purpose

Aerial photo interpretation for salinity mapping based on detection of vegetation stressed by salt in the root zone is best undertaken from photos acquired in a ‘normal’ year—note that factors other than salt can stress vegetation.

Aerial photos are suitable for use in most biogeographic regions.

Aerial photos taken at multiple times over a period of years are often useful in tracking the progress of salinisation.

Refer to the statement of limitations.

Best practice—considerations for users

It is a very useful technique for mapping salt scalds. An experienced photo-interpreter can identify vegetation stress (die-back) caused by leaf insects or pathogens, rising salinity levels in the root zone and a range of other factors. Systematic field sampling is used to calibrate identified features (determine the cause of die-back), including root-zone salinity. It is also often used to corroborate other sources of salinity hazard mapping though post-mapping validation.

Costs

Existing photos can usually be purchased for between $30 and $50 depending on whether they are black and white or colour, recent or older and who is supplying them. New photo acquisition projects that involve hundreds of aerial photos usually cost tens of thousands of dollars. Ferdowsian (1994) estimated costs for mapping, monitoring at farm, catchment and regional scale as follows:

- for farm and catchment level, mapping and monitoring estimated costs were $0.9/ha; and
- for regional level application mapping estimated costs were $0.1/ha and for monitoring $0.9/ha.

New digital photography costs $5 to $20/ha at 1:25 000 scale including analysis.

Appendix 1.12 Airborne radar

Summary of method and description of mapping products

Radar is an active sensor and can be mounted on satellites, aircraft and on ground-based vehicles. It operates by producing an active pulse of high-frequency electromagnetic energy that interacts with the objects that it strikes giving a return signal that provides information about those objects.

Radar has a number of properties:

- it can provide information about the shape of objects;
- it can detect the moisture content of the objects;
- it can detect surface conductivity by the measurement of the dielectric constant; and
- it can penetrate through cloud and smoke and therefore has an advantage over passive multispectral and hyperspectral systems whose images are compromised by cloud and smoke.

LIDAR, or '**li**ght **d**etection **a**nd **r**anging', is a derivative of radar that measures surface material properties as well as providing elevation information using lasers. Some LIDAR instruments measure laser fluorescence to measure pollutants in shallow water bodies.

Prior use and evaluation

Airborne radar is a relatively new approach. It is in the market for surface salinity and hydrology mapping. It has been applied at Kakadu National Park in the Northern Territory and at Kerang in Victoria with claims of 80% mapping accuracies in both areas compared with ground data.

One vendor offers an airborne radar system based on an L band synthetic aperture radar (SAR) with a wavelength of 24 cm (a frequency of 1.25 GHz) producing pixel sizes of around 2 m x 2 m that sets out to map surface salinity and hydrology. A good summary of radar and other microwave remote sensing techniques is given by Ulaby et al. (1986).

Scale (level of detail)

By producing maps with a pixel size of 5 m x 5 m, radar has a relatively high spatial resolution capable, for example, of detecting relatively small salt scalds at paddock level. Its ability to cover up to 10 000 square km per day means large areas can be imaged.

Survey design

As with all airborne missions much careful thought needs to be put into the acquisition of the imagery to ensure the best possible coverage and interpretation. The survey design is best undertaken by specialists.

Data processing, interpretation and mapping products

Radar is a highly complex imaging technique that relies on specialist software and interpreters.

Limitations

Radar has a number of well-documented limitations:

- it only penetrates into the top few centimetres of the soil;
- it has a limited ability (depending on wavelength) to penetrate vegetation canopies that are relatively dense;
- in order to infer salt the soil must be moist as it cannot detect dry salt stores—acquisition of imagery therefore is best undertaken after a recent rainfall event and this requirement can add significantly to the cost and also reduces flexibility; and
- its signal is distorted in relatively steep terrain requiring the use of inversion algorithms to correct for the distortion.

Fitness for purpose

Radar's best application is in relatively lightly vegetated, relatively gently undulating terrain where the soil is moist at the time of image acquisition. Radar can also be used as a ground-based method (see 'Ground-probing radar' in Appendix 1.9).

Radar is finding significant application as a technique for creating DEM.

Best practice—considerations for users

Airborne radar is a relatively new salinity hazard mapping tool. Potential users are advised to seek independent validation of the effectiveness. It requires field validation and results from one area cannot automatically be applied to another.

Costs

$5 to $15 per hectare for large surveys (1000s of ha). Even small areas may cost thousands of dollars due to the cost of acquiring the imagery and the software required for processing (one-off cost).

Appendix 1.13 Airborne video

Airborne video is a technique similar to airborne multispectral imaging. It relies on an aircraft-mounted video camera that scans systematically in flight lines. The images can be computer processed. They have properties that are similar to those of colour air photos.

This review received no submissions on using airborne video mapping for dryland salinity. However the technique is being used for vegetation assessment, crop mapping and bushfire monitoring.

Summary of method and description of mapping products

There are no examples of mapping products. In other applications products are very similar to airborne multispectral images.

Prior use and evaluation

None that are known for mapping dryland salinity hazards in Australia.

Scale (level of detail)

Offers pixel sizes of around 1 m x 1 m in size, which theoretically make it suitable for paddock-scale applications.

Survey design

Airborne video is a passive sensing system and must be operated in daylight. Systematic data collection in properly designed flight lines is recommended.

Data processing, interpretation and mapping products

Specialist software and interpretation are required.

Limitations

Limitations are similar to multispectral imagery.

Video interpretation for salinity mapping would be based on the detection of surface salt scalds and on vegetation stressed by salt in the root zone. Acquisition of imagery would be best undertaken in a 'normal' year. Thus it would be best to avoid regions affected by drought. Vegetation suffers from dieback from causes other than salinity, such as recent bushfire damage. Caution should also be exercised on the black soils that occur in some parts of Australia and particularly in Queensland as these soils can confuse the interpretation of woody vegetation.

Fitness for purpose

See limitations. Airborne video can be useful where immediate playback of the imagery is desired.

Best practice—considerations for users

As the technique has yet to be applied any potential users should carefully consider the alternatives first. In addition advice should be sought that is independent of the purveyor of the technique.

Costs

$10 to $50 per hectare assuming new acquisitions at a scale of 1:25 000 including analysis.

Appendix 1.14 Multispectral airborne imagery

Summary of method and description of mapping products

No submissions were received on the use of airborne multispectral imagery. However for the past 15 years these systems have been in regular use during the bushfire season to help locate burning areas and have been used irregularly for other natural resource applications. Experimental datasets have been acquired over the years for vegetation mapping and other purposes. Their operation is similar to that of multispectral satellite systems (Appendix 1.19). Based on our knowledge of multispectral satellite systems it is likely that the airborne multispectral systems are able to map salt scalds and, possibly, vegetation stressed by salinity in the root zone.

Prior use and evaluation

No prior use for operational dryland salinity hazard mapping in Australia.

Scale (level of detail)

Airborne multispectral systems for other natural resource mapping applications are capable of less than 1 m x 1 m pixel resolutions.

Survey design

Survey design is very similar to that of other airborne systems including aerial photos. Systematic survey design is required.

Data processing, interpretation and mapping products

Requires specialist software and interpretation.

Limitations

Refer to aerial photo interpretation for limitations as these are shared with airborne multispectral imaging.

Fitness for purpose

See limitations.

Best practice—considerations for users

As the technique has yet to be applied any potential users should carefully consider the alternatives first. In addition advice should be sought that is independent of the purveyor of the technique.

Costs

Even small areas will cost \$1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost). Cost \$10 to \$50 per hectare assuming new acquisitions at a scale of 1:25 000 including analysis.

Appendix 1.15 Hyperspectral airborne imagery

Summary of method and description of mapping products

Hyperspectral airborne imagery or imaging spectrometry as it may be also known offers the most detailed picture of the surface of the earth of all passive imaging systems (other passive systems include air photos and multispectral imagery). Whilst multispectral systems may use up to a couple of dozen imaging channels across the electromagnetic spectrum, hyperspectral systems may use hundreds, thereby greatly enhancing the fine resolution of the spectral properties (appearance) of the objects in the images. Hyperspectral systems are one of the newest of the imaging systems and have yet to be proven operationally for salinity mapping. Hyperspectral systems have the ability to see in much finer detail the growth habits of plants and possibly the mineralogy of the soil because of the superior coverage of the sensors in the visible, near infrared and middle infrared parts of the spectrum. Their products are likely to be similar to air photo mapping or multispectral systems enhanced by a finer degree of detail.

Its primary application is likely to be for hazard mapping although they will have the ability to collect attributes of value to risk assessment including information on land use and vegetation type and health within the root zone. Their products may include the mapping of salt scalds, saline soils, stressed vegetation through salinity in the root zone and mapping of vegetation types that can be used as surrogates for the presence of salinity.

A hyperspectral (HyMap) image of part of the Coleambally Irrigation Area, NSW. The image shows cut-and-fill from laser levelling of paddocks and different planting dates for summer crops (rice, corn, soy and sorghum). The vegetated paddocks (summer crops) are red; stubble (from the previous season winter crops) is white, and bare soils are green. The image resolution is 5 m, and was acquired on the 12 January 2002. The false-colour image is formed by the 558 nm, 680 nm and 832 nm bands being displayed through the blue, green and red colours respectively.

Source: Courtesy Tim McVicar and Tom Van Niel, CSIRO Land and Water and Cooperative Research Centre for Sustainable Rice Production. The acquisition of the HyMap image was supported by the Hyperspectral Task of the CSIRO Earth Observation Centre.

Prior use and evaluation

Examples of mapping based on hyperspectral systems are few and only very recently published. Dehaan and Taylor (2002, 2003) report that the HyMap system is capable of differentiating disturbed bare ground due to ploughing operations from bare ground due to irrigation-induced salinisation. However hyperspectral imaging is still largely in the experimental stage.

Scale (level of detail)

The usual pixel size is between 2.5 m up to 15 m and is suitable for both paddock and regional level mapping.

Survey design

Survey design is similar to that of any other airborne technique. It involves collection of imagery using systematic flight lines. Large areas can be acquired in this way.

Data processing, interpretation and mapping products

Specialist software and interpretation are required to interpret the imagery. Considerable research is required to develop operational techniques for salinity hazard mapping.

Limitations

The most significant limitation is the lack of knowledge about the properties of hyperspectral imagery and, in particular, the likely spectral indictors that will track changes in salinity levels.

Fitness for purpose

To be determined through appropriate research.

Best practice—considerations for users

As the technique has yet to be applied, potential users should carefully consider the alternatives first. In addition advice should be sought that is independent of the purveyor of the technique.

Costs

Even small areas will cost thousands of dollars due to the cost of acquiring the imagery and the software required to process it (one-off cost). Cost is $10 to $50 per hectare assuming new acquisitions at a scale of 1:25 000 including analysis.

Appendix 1.16 Airborne gamma-ray spectrometry (radiometrics)

Summary of method and description of mapping products

Airborne gamma-ray spectrometry, also known as airborne radiometrics, is the measurement of naturally occurring gamma rays emanating from radioactive materials at the earth's surface using detectors carried in low-flying aircraft. Surveys may be made over small areas with detectors mounted in vehicles on the ground. A gamma-ray spectrometric survey measures the spatial distribution of the three most common radioactive elements (potassium-K, thorium-Th and uranium-U), in the top 30 – 40 cm of the earth's crust.

Radiometric mapping products are valuable in assisting trained practitioners to understand soil, regolith and geomorphological conditions, and are often used in the production of soil maps over large regions. There are no independently verified and proven applications of radiometrics for salinity hazard mapping. Moreover the physics of radiometrics suggests that based on our current understanding there is little likelihood of a technique being found that will do so in the future.

Prior use and evaluation

Aerial gamma-ray survey data has been collected since the 1950s, initially for exploration for radioactive minerals, and from the 1980s for geological mapping. More recently, the method has been applied to mapping soils (e.g. Cook et al. 1996, Dickson & Scott 1998, Slater 1997, and Verboom & Pate 2003) with good results. Gamma-ray survey data can sometimes be used to differentiate soil types with a propensity to store salt in the profile or to map variability in the recharge properties of surface materials. Such correlations must be carefully evaluated and calibrated with detailed ground-truthing for each region,

Scale (level of detail)

Gamma rays recorded in airborne surveys originate from a thin layer at the earth's surface with an elliptical shape approximately twice the flying height wide and a similar distance plus flying time over which the signal is measured (typically one second). The lower the flying height the better the resolution of the data. At 100 m height, about 80% of recorded gamma rays originate from a region below the aircraft several hundred metres wide. Methods have been developed to remove along-line blurring from the data, providing much better resolution.

High-resolution acquisition of airborne magnetic and radiometric data – Western Australia.

Photo: Fugro Airborne Surveys

Survey design

For environmental mapping applications, line spacings between 25 and 400 m are typically used. Flying heights range from 20 to 100 m, depending on topography. Sample spacing is governed by the speed of the aircraft—typically 50 to 70 m for a fixed-wing aircraft and less for helicopter systems. Survey design standards developed by Geoscience Australia are given by Grasty and Minty (1995). Another recommended reference is IAETechnical Report 323 (1991).

Data processing, interpretation and mapping products

Data processing for gamma-ray spectrometry has recently seen several major advances in which Geoscience Australia and CSIRO have both played a role. At least four methods are available for reducing the high noise inherent in radiometrics due to low count rates and short, one second counting times (Dickson & Taylor 2003). All four methods use the multichannel spectrum (usually 256 or 512 channels) to obtain more accurate measurement of the ground concentrations.

Topographic corrections must be applied to data collected in rugged terrain (even small hills appear ‘rugged’ to a low-flying aircraft) to correct for deviations from the assumed exponential altitude attenuation over flat terrain. Other corrections are needed for background radiation, the un-mixing of the K, U and Th window responses (called ‘stripping’) and the sensitivity of the detector.

Data from multiple surveys can now be merged using accurate micro-levelling, as for example shown by the images with almost complete coverage for Victoria and Northern Territory that have recently been completed.

Mapping products are normally ternary images that represent the relative abundances of K, Th and U, but digital data is used for more advanced interpretation.

Signatures in airborne gamma-ray spectrometry are complex, reflecting:

- variations in lithology;
- variation in sediment source;
- topography;
- degree of weathering;
- drainage and water saturation;
- prior stream activity;
- water discharge;
- degree of source rock metamorphism; and
- extent of compaction or cementation.

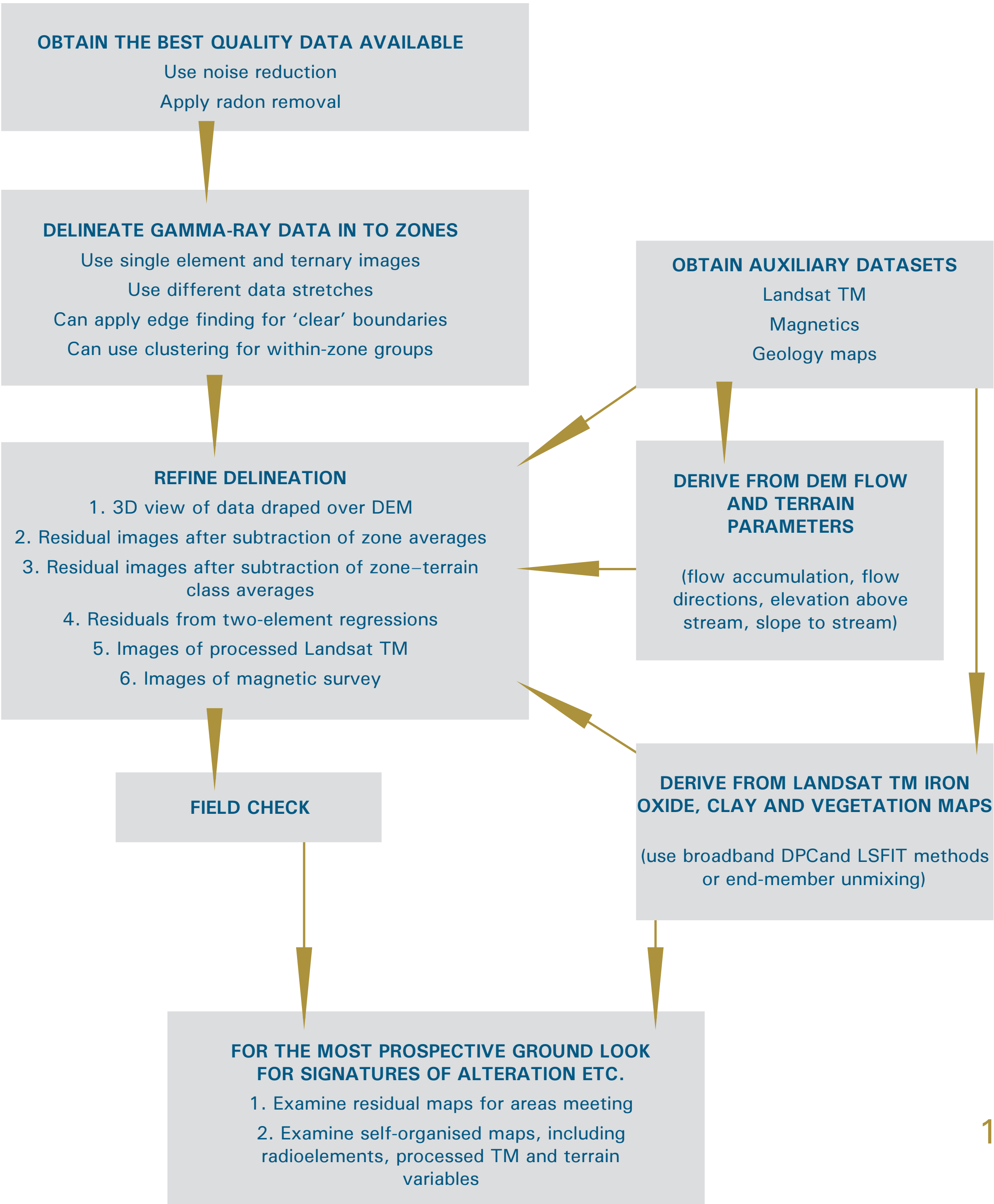
Interpretation is best achieved with access to other information such as DEM, prior geological mapping, Landsat and other remotely sensed imagery and existing soil and land system maps. A schema, shown below, for very detailed interpretation of radiometric data was developed during AMIRA Project 465. An important conclusion from that

Ternary gamma-ray spectrometry (radiometric) image.

Image courtesy UTS Geophysics

study is the need to apply appropriate pre-processing to the auxiliary datasets (DEM, etc.) and the inappropriateness of using conventional statistics in processing radiometrics. A program was developed for automating many of the processes described in the schema but it has not yet been made available to other than the project sponsors.

Figure A5 Schema for detailed interpretation of radiometrics involving pre-processed auxiliary datasets (courtesy Bruce Dickson, CSIRO).



A refinement of the technique is to generate K-residual maps, which have been shown to indicate soils with a high likelihood of storing significant salts in the deep profile (Richard Creswell, Bureau of Rural Sciences, pers. comm., 2004). The observed signal strength is subtracted from the expected signal strength assuming no soil to be present (i.e. the equivalent of bedrock signal). A strong potassium deficiency indicates leaching and commonly represents the surface expression of deeply weathered soil profiles. In regions where salt is not readily leached from the landscape (e.g. south-western slopes of New South Wales and the Adelaide Hills) the salt is preferentially stored in these profiles. A number of caveats apply:

- the signal is strongly attitude dependent, so classification by slope is required;
- the technique is really only applicable in relatively high energy (erosional) environments, where relief is high;
- the technique has not been shown to work in depositional environments, although variability may represent different soil properties that can be used to define recharge zones;
- high rainfall (>650 mm/y) areas are generally leached of salts, even if the environment is right for salt accumulation (e.g. western slopes of the Adelaide Hills);
- the technique is not universally applicable, so rigorous ground-truthing must be carried out; and
- while the aircraft samples every seven metres across the terrain, the footprint is of the order of 10 to 100 m for each spot, so boundaries may not be as well defined as an image may indicate.

The first two dot points mean that the contrast can be subdued in very high relief areas, and self-reinforcing. That is, high slopes may define the expected K signal, so the residual K may merely map the low slopes, rather that the specific soil associations.

Limitations

Limitations of the method are:

- high noise since normal rocks and soils have on average 1% K, 2 ppm U and 8 ppm Th which gives a very low gamma-ray emission;
- the signal from any one lithology is not unique;
- since the signal comes from the upper 30 cm, weathering, soil transport and other pedological processes play a large part in responses;
- varying moisture levels affect repeatability;
- naturally occurring airborne radon can degrade surveys; and
- interpretation is a skilled task but the apparent simplicity of the data may trap the unwary into inappropriate treatment of the data.

We note here some unjustifiable claims regarding radiometrics. Firstly, extrapolations from ground concentrations of K, U and Th to other soil properties (pH, salinity and conductivity) involve correlations that may only be valid locally and have not been generally proven as fundamental properties of soils. Potassium as measured by aerial surveying is not the same as ‘available K’ as often required for agricultural mapping.

Claims for measurement of Na-24 for salinity mapping

Claims have been made by some vendors that airborne radiometrics can be used to directly map salinity, through neutron activation of Na-23 in saline groundwater to produce Na-24. This claim has been the subject of intense scrutiny, including a detailed scientific review commissioned by the NSW Department of Infrastructure, Planning and Natural Resources (Baddeley et al. 2003), which concluded that Na-24 count rates are undetectable (at least 6000 times lower than background) with modern airborne gamma-ray detectors. In addition, claims for mapping salinity using gamma-ray spectrometric map data is based on an inferred association between mapped salinity and the distribution of K, U and Th in soil. Any relationship between salinity mapped using this methodology and the distribution of the radioelements cannot be generalised from one survey to the next, and in each instance the validity of any such association can only be tested by ground-truthing. The claims were also examined by experts at two workshops run jointly by the Australian Academy of Sciences and the Australian Academy of Technological Sciences and Engineering in Canberra on 1 September and 17 October 2003 with similar conclusions[A3].

Fitness for purpose

Radiometrics is readily applicable for soil mapping, with signals emanating from the top 10 to 40 cm of the earth surface, in the upper part of the root zone. A major advantage for soil mapping is that it gives complete ground coverage and so could be used to extrapolate more detailed field measurements of soil properties over wider areas. Radiometrics can also be used as a ground-based method (see Appendix 1.9).

Costs

Less than $1 per hectare, depending on area.

Best practice—considerations for users

Best practice requires that:

- data is collected in line with recommendations concerning calibration and daily data quality controls;
- data is processed with the most appropriate noise reduction method (tests may be necessary), radon stripped and micro-levelled;
- interpretation follows the schema above; and
- field testing is carried out as a fundamental part of the interpretation.

Guidelines and standards for airborne gamma-ray surveys are given by IAE(1991) and Grasty & Minty (1995).

[A3] Dr Bruce Dickson, CSIRO, said in respect to the measurement of cosmogenic sodium in airborne gamma-ray surveys: ‘The estimated count from 24Na with a level of 1% NaCl in the soil would be that you would get one count in 50 km of flying, and I think that is a very conservative estimate. In the same time the aircraft would see a quarter of a million counts from potassium, which has an energy of 1.46 MeV, almost coincident with the 1.37 MeV from sodium, and 55 000 counts from thorium, which is 2.61 MeV, almost coincident with the 2.75 MeV from sodium. Essentially, you cannot measure sodium via cosmic ray activation using an aerial gamma-ray survey.’ <www.science.org.au/conferences/salinity/dickson.htm>

Appendix 1.17 Airborne magnetics

Airborne magnetics, commonly known as aeromagnetics, is the most widely used airborne geophysical technique, primarily for geological mapping and mineral exploration. It is relatively inexpensive and magnetic maps are often used as a high-resolution geological base map in areas of unconsolidated sediment cover. Aeromagnetics is usually collected in conjunction with radiometrics. A useful by-product of detailed aeromagnetic survey is a good DEM ('Mapping landscapes, soils and geomorphology, p. 32). Note that magnetics can also be collected on the ground (Appendix 1.9).

Summary of method and description of mapping products

Aeromagnetics is the measurement of the earth's natural magnetic field measured from aircraft or helicopters. Usually the total magnetic field is measured, with various processing methods used to highlight short- or long-wavelength features of interest. Maps consist of coloured shaded-relief images of magnetic field. For salinity and landscape mapping purposes, the primary source of magnetic signals are magnetic detrital minerals such as magnetite and maghemite in the soil, often concentrated in stream-beds and palaeochannels. The technique is excellent in mapping the location of faults as well as dykes and other intrusions. Basement depths can be estimated when magnetic minerals are present in bedrock.

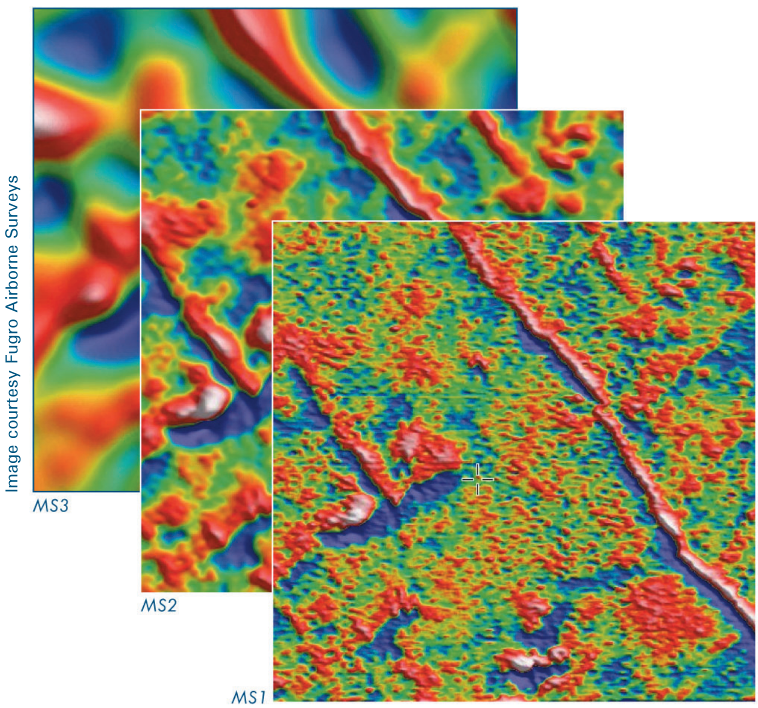
Prior use and evaluation

Widely used for geological mapping for over fifty years. A good overall reference is Gunn (1997).

Scale (level of detail)

The level of detail is related to the flying height above the ground. Normally the shortest wavelength that can be resolved is the order of the flying height. Data can be acquired with a caesium-vapour magnetometers at 0.1-s sampling rates which corresponds to samples every few metres over the ground. This is of the same order as GPS (global positioning system) navigational accuracies.

Frequency filtering of aeromagnetics, showing magnetic sources from deep (MS3) to shallow (MS1) depths.



Survey design

Survey design for radiometrics is in many ways similar to aeromagnetics; in fact the two methods are usually flown together. A trade-off exists between the level of detail (flying height and line spacing), and cost (line-km) of flying. Typical line spacing is 400 m at 80 m flying height, but may be decreased to less than 100 (flying heights 60 m) if high levels of detail are required.

For paddock-scale surveys, ground magnetic surveys are often cost-effective and can be run together with ground conductivity measurements.

Data processing, interpretation and mapping products

Corrections are routinely performed for:

- drift of the natural field (diurnal correction obtained from a base station);
- compensation for magnetic effects of aircraft;
- tie-line and micro-levelling to remove variations between adjacent flight lines; and
- removal of outliers caused by powerlines, fences, etc.

Maps can be presented in the form of stacked profiles, contour maps, coloured shaded-relief images and pseudo-coloured images of magnetic intensity superimposed on DEM. Image enhancement is also used to highlight various rock properties. A wide range of other processes can also be performed, such as directional filtering, upward and downward continuation, statistical filtering, forward modelling and inversion to magnetic depth.

A skilled interpreter takes into account other geophysical datasets and knowledge of the magnetic signatures of the area.

Limitations

Aeromagnetics measures signals from magnetic minerals. Thus an aeromagnetic map will not give direct information on materials or structures that are not magnetic. In addition, because magnetism is a potential field, there are many subsurface distributions of magnetic material that will cause the same observed response. The skill of the interpreter is important in choosing between various scenarios.

In mountainous terrains helicopter magnetics can follow topography better than fixed-wing aircraft.

Fitness for purpose

Magnetic data, when in the hands of a skilled interpreter, can reveal variations in regolith thickness, lateritic surfaces, palaeochannels that may be conduits for subsurface fluid flow and buried features such as dykes and faults that may act as lateral barriers to subsurface flow.

Best practice—considerations for users

Aeromagnetics is a mature technique offered by a wide range of contractors. Aeromagnetic data, though, is best used as part of an integrated package by a skilled interpreter. It is normally not recommended for use by individual landowners.

Guidelines and standards for airborne magnetic surveys are given by Teskey et al. (1991).

Cost

Magnetics costs around 60 cents a hectare to acquire and 20 cents a hectare to process to a map stage. The cost depends to a large extent on the level of detail needed and the scale of survey—the larger the survey the lower the cost.

Appendix 1.18 Airborne electromagnetics

Of the airborne geophysical techniques, only airborne electromagnetics (AEM) has a signature closely related to the presence or absence of salinity.

Airborne EM, or AEM, systems are similar in some respects to the ground EM systems described previously, but the technology is much more advanced.

Airborne electromagnetic systems are the only airborne systems that are capable of mapping salinity hazard below the root zone. There are no analogous satellite-based electromagnetic systems.

There are several classes of airborne EM systems.

Fixed-wing TEM systems (e.g. TEMPEST, GEOTEM) operate in the time-domain, with a transmitter loop strung around the aircraft and a multi-coil receiver housed in a 'bird' towed a hundred metres or so behind and below the aircraft. They have a large footprint and deep penetration. These systems tend to be used for regional surveys.

Helicopter-borne EM (HEM) systems (e.g. DIGHEM, RESOLVE, SKYTEM) are mounted on or underneath a helicopter—they have a smaller footprint, less depth penetration and usually provide more detail near the surface than fixed-wing systems. Traditional HEM systems have multiple pairs of transmitter-receiver coils of various orientations operating at a range of frequencies and housed inside a torpedo-shaped bird that is suspended from a helicopter. Older systems tend to have calibration and stability problems, and they generally have too few, widely spaced frequencies to provide a good depth section. A number of TEM systems are now being developed for helicopter operation, for instance SKYTEM being built specifically for groundwater applications. HEM is suitable for detailed surveys over small areas.

A summary of current AEM systems is given in Table A5.

Airborne electromagnetics (AEM) with large fixed-wing system for deeper penetration (left), and helicopter-mounted AEM system (right) for higher resolution surveys.

Photo: Fugro Airborne Surveys

Table A5 Specifications of common airborne EM systems*.

System** description	Horizontal resolution§	Depth of investigation##	Comments	Contact (service provider)
HELICOPTER SYSTEMS				
DIGHEM-V 30 m altitude, 8 m coil separation, HCP and VCA, 380 – 56 kHz	20 m	few m to 100 m	Traditional HEM frequency-domain system	Fugro Airborne Surveys
RESOLVE 30 m altitude, 8 m coil separation, HCP and VCA, 385 – 106 kHz	20 m	few m to 150 m	Digital with internal calibration coils for automatic phase and gain	Fugro Airborne Surveys
GEM2A HCP 90 Hz - 48 kHz			Programmable synthesised signal. Not presently available in Australia	Geophex
SKYTEM 30 m altitude, in-loop TEM, 10 μs – 10 ms	20 m	few m to 150 m	Designed in Denmark for groundwater studies	Fugro Airborne Surveys
HOISTEM 30 m altitude, in-loop TEM 25 μs – 14 ms	20 m	few m to 150 m	Symmetric geometry, small footprint	GPX Airborne Geophysical Services
FIXED-WING SYSTEMS				
TEMPEST TEM, bird towed behind aircraft TX @ 120 m altitude, RX @ 45 m below and 120 m behind, 20 μs – 20 ms	50 m	few m to several 100 m	Designed for broad bandwidth	Fugro Airborne Surveys
GEOTEM TEM, bird towed behind aircraft TX @ 105 m altitude, RX @ 45 m below and 120 m behind, 0.1 ms – 40 ms	50 m	20 m to many 100 m	Deep penetration	Fugro Airborne Surveys

* System names are trademarks of the company listed in the 'Contact' column. Mention of a specific vendor or instrument does not imply endorsement.

§ The term 'footprint' is used to describe the surface projection of the volume sampled below the ground (see below).

Depth of investigation varies with conductivity and noise levels. See discussion below.

** HCP = horizontal coplanar (vertical axis) coils

VC = vertical coaxial coils (horizontal axis) coils

Summary of method and description of mapping products

There are two basic types of AEM systems—helicopter-borne frequency-domain and fixed-wing time-domain systems. Helicopter systems have greater lateral resolution than fixed-wing systems but an inferior depth of investigation.

The *depth of investigation* varies with ground conductivity—at best it is around one skin depth or diffusion depth (see 'Definitions', p. 45)—but can be less depending on signal and noise levels.

The *footprint* (or lateral averaging) of HEM systems is smaller than that of fixed-wing TEM airborne systems, especially in the shallow subsurface (see discussion under 'Scale' below).

Interpretation (mapping) products include:

- apparent conductivity maps at each frequency or sample time;
- approximate conductivity-depth image (CDI) sections or depth slices;
- layered-earth inversion (LEI);
- conductance maps; and
- principal component (PC) maps[A4] .

AEM interval conductivity maps give a good qualitative understanding of lateral variations in conductivity, and that conductance is well-resolved (see also 'Indirect methods for mapping salt in the root zone (10 cm to 2 m depth]', p. 45).

Prior use and evaluation

AEM was initially trialled nationally for NRM applications under the auspices of the National Airborne Geophysics Project in 1997 to 1998 (NAGP 1998). While the NAGP reports provide some useful information they are largely out of date due to rapid advances in technology. A good summary of AEM is given by Lane (2002), and recent salinity applications are published in the ASEG's Special Issue on Salinity and Land Management (Street 2002).

Scale (level of detail)

The resolution of AEM systems varies with the system, with sample time or frequency, with ground conductivity, and is different in the horizontal and vertical directions. Usually, scale or resolution is considered in terms of the volume of the ground that contributes most of the response for each measurement.

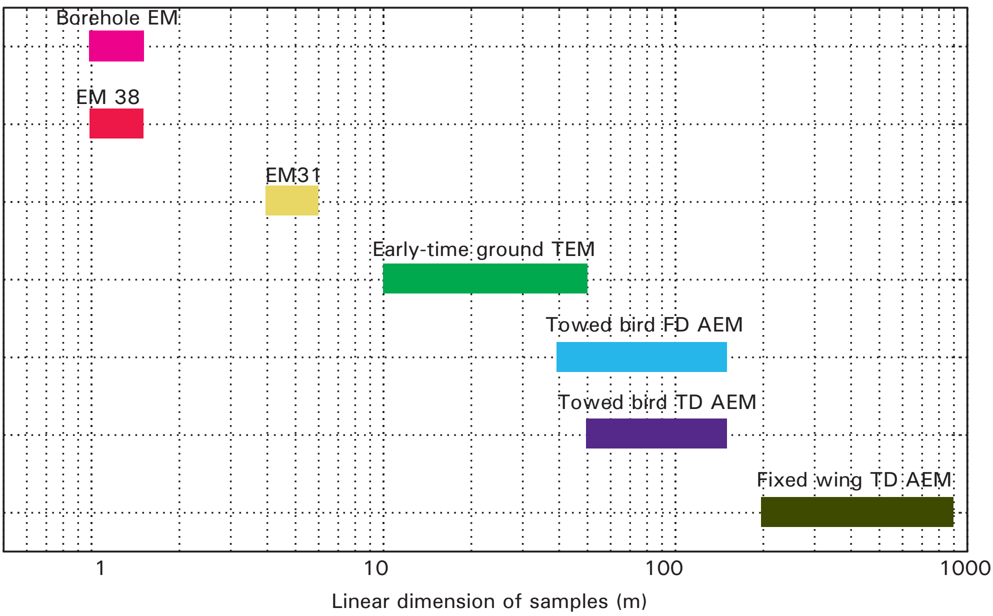
The AEM 'footprint' is the area below the transmitter-receiver system that contributes to the response, and the depth of investigation is the total depth (from the surface down) that contributes to the response. Figure A6 shows a comparison of the horizontal scales (footprint sizes) for a number of EM systems. For example, an EM31 system returns a weighted average of conductivity at lateral scales around 4 to 8 m. In contrast, a fixed wing time domain AEM system such as TEMPEST returns a weighted average over lateral scales of several hundred metres. Unless the ground is laterally completely homogeneous over this distance, the two instruments will return different conductivity predictions for the same point.

[A4] Principal component (PC) analysis is a coordinate transformation typically associated with multiband imagery. PC analysis reduces the redundancy contained within the data by creating a new series of images (components) composed of linear combinations of raw data channels. This compresses the information content and enables an optimised display of differences across the image (see Green 1998)

Besides the volume sampled by an AEM measurement, along-line processing algorithms used to improve the signal-to-noise ratio also increase the size of the effective sample volume for processed data and hence decrease the horizontal resolution (e.g. Sattel 2003). In theory, AEM systems can resolve much smaller features along the flight line than is normally quoted as the size of their footprint, especially where those features present a good conductivity contrast such as a narrow channel containing saline water[A5]. Perpendicular to the flight lines, the resolution is determined by the line spacing. The smallest features that can be resolved near the surface are around 20 to 40 m for helicopter systems and 50 m for fixed-wing systems and these figures increase with depth.

For AEM systems, good near-surface vertical resolution depends on accurate high frequency or early time measurements and accurate knowledge of the system geometry. It is enhanced if a system has a wide range of high frequencies or time delays (termed a 'broad band' system), and if the system can be flown close to the ground. As with horizontal resolution, it is difficult to generalise about the vertical resolution of AEM systems, but the best documented level of performance is somewhere between an average over the top 10 m and the top 4 m. Any statement about vertical resolution must still carry the caveat of lateral averaging over the horizontal scale of the system.

Figure A6 Representative horizontal linear dimensions for near-surface sampling using different EM instruments. Figure prepared by Richard Lane (CRC LEME /Geoscience Australia).



[A5] Sattel (2003) defines three terms—'anomaly detectable', '1-D detectable' and '1-D resolvable'—and determines values for fixed wing TD and helicopter FD AEM systems in scenarios relevant to salinity mapping applications. '1-D resolvable' equates to a situation where the target occupies a very significant portion of the sample volume. Features that occupy just a fraction of the sample volume can be detected (i.e. 'anomaly detectable') given a suitable conductivity contrast and signal-to-noise ratio.

Survey design

AEM data are acquired along pre-determined parallel flight lines spaced a sufficient distance apart to give the required level of detail. Traditionally, flight lines are spaced several hundred metres apart. Flight lines are sometimes increased to reduce cost per hectare in regional surveys, at the expense of detailed resolution. Care must be applied to gridding and interpolation algorithms. Modern systems should have excellent calibration and negligible drift. Magnetic and DEM data are usually measured at the same time as AEM.

Data processing, interpretation and mapping products

The raw data from AEM for frequency-domain systems are in-phase and quadrature components, and for time domains systems the transient response as a function of time.

Corrections: a variety of corrections are applied, such as variations in transmitter-receiver coupling and flying height, aircraft compensation, and deconvolution of the transmitted waveform. Sometimes data are transformed into the 'step response' domain to assist with computer processing. In high-resolution surveys it may sometimes be necessary to correct for the effect of magnetic soils (e.g. Deszcz-Pan et al. 1998).

The *depth of investigation* varies with ground conductivity—at best it is around one skin depth or diffusion depth (see Definitions p. 45)—but can be less depending on signal and noise levels.

Interpretation (mapping) products include:

- apparent conductivity maps at each frequency or sample time;
- approximate conductivity-depth image (CDI) sections or depth slices;
- layered-earth inversion (LEI) and smooth-model inversion;
- conductance maps; and
- principal component (PC) maps.

AEM conductivity data draped on topography, with depth slices.

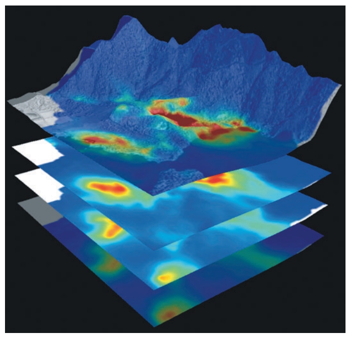


Image courtesy Fugro Airborne Surveys

Limitations

Many older AEM systems, developed for mineral exploration, are not calibrated well enough for environmental applications. However the main limitation of AEM for salinity mapping is the inability to resolve conductivity variations in the top few metres of the ground—a conductive layer a few centimetres under the surface is indistinguishable from one 5 to 10 m in depth. In addition, EM systems are unable to resolve thin individual layers, and some processing and interpretation packages may give the user an over-optimistic impression of the vertical resolution obtained (see discussion in 'Interpretation' in 'Indirect methods for mapping salt in the sub-root zone [>2 m into the regolith], p. 47).

AEM technology is improving rapidly. Research is underway at universities, government agencies and service companies to broaden the bandwidth, accuracy and resolution of AEM systems and associated processing and interpretation tools.

Issues of techniques and limitation of AEM processing and interpretation are further discussed in 'Inversion and presentation of geophysical data' (p. 49).

Fitness for purpose

AEM is an ideal tool for regional mapping of conductivity variations and is normally well correlated with salinity. It is also an important tool for mapping spatial patterns within the regolith associated with palaeochannels and subsurface drainage flow. It is also applicable for mapping groundwater in non-saline areas (e.g. Auken et al. 2003).

AEM is unlikely to be cost-effective in upland landscapes, where the surface exposures give a good indication of salinity hazard. A range of surface and shallow mapping methods will most likely be more effective and cheaper in these landscapes (e.g. Wilford et al. (2001).

In contrast, AEM should be seriously considered in areas of subdued topographic relief where the presence of transported material limits the usefulness of inferences that can be made using surface observations, for instance the northern block of the Gilmore survey area (Lawrie et al. 2000) and at Honeysuckle Creek (Dent 2003).

Costs

As with other geophysical surveys, costs for AEM can be broken down into mobilisation/ demobilisation, survey costs (cost per line-km), and processing and interpretation costs.

The mobilisation/demobilisation charge generally makes acquisition of data over small survey areas expensive on a $/ha basis. Survey costs on a $/ha basis for larger surveys will principally depend on the survey area and line spacing (hence, the total number of line-km) and the system used. Line-km rates typically vary between $50 and $100 depending on the system and the total number of km. For NRM applications, contractors provide quotations on a $/ha basis.

The number of line-km will be determined by the size of the survey area and the spacing between lines. Survey costs can be reduced if the survey objectives allow the line spacing to be increased (Lawrie et al. 2003). At $75/km, the line-km charge at line spacing of 200 m equates to $3.75/ha. If the survey objectives can be achieved with lines spaced at 2 km intervals, then the line-km charge is equivalent to the much lower figure of $0.37/ha. However, such an increase in line spacing precludes interpretation at a farm or paddock scale and may limit the application of AEM for on-ground remediation. If mobilisation charges are fully borne by one user, total survey costs may reach $25 – $40/ha for small surveys, but be substantially lower for larger surveys. Survey costs can often be reduced by negotiating the survey date well in advance with the contractor, so that mobilisation costs are shared with other surveys.

Processing, ground calibration and interpretation are essential to effective use of AEM, and should be part of the total budget. The cost of this phase may be 20% or higher of the survey costs.

Best practice—considerations for users

The main requirements of an AEM mapping system is broad bandwidth, and accurate, calibrated data over the entire range of frequencies or times, but especially at high-frequencies or early time. Assistance should be obtained from experts in AEM methods who can help with technical aspects such as the evaluation of options prior to a survey, design of the survey and management of the survey process. This is especially important when using contractors who do not offer these services or do not have in-house experts in AEM available for their clients. Users should obtain independent information to evaluate the accuracy of the delivered products. AEM survey is not a stand-alone salinity mapping solution and must be integrated with other methods.

Ground truth and validation using surface and borehole logging is important for all AEM surveys.

SATELLITE METHODS

Appendix 1.19 Multispectral satellite imagery

Synoptic (that is world-wide coverage) of earth-observing satellites for relatively high-resolution imaging commenced in 1972 with the first of the Landsat series of satellites. This series, and others like it since, have a number of common properties:

- typically a repeat cycle of less than four weeks;
- passive sensors that produce pictures simultaneously in several parts of the electromagnetic spectrum (the visible, near infrared and middle infrared regions thus giving a 'multispectral' image);
- pixel sizes of less than 100 m by 100 m and in some cases now around 1 m x 1 m;
- coverage for each scene that is usually at least one hundred thousands of hectares in size;
- images that are fully digital;
- public availability of data for a competitive price; and
- well-researched capabilities and uses.

In addition to the Landsat series (US) there are a number of other routinely available satellites such as the SPOT series (French), the IRS series (Indian), IKONOS (US), EARTHWATCH (US) and MODIS (US), among others, that have land-related applications.

These satellites have several advantages:

- they 'see' the photosynthetic activity of vegetation that gives a reasonable measure of its health;
- they allow analysis of very large areas relatively quickly;
- they permit the same site to be compared periodically to monitor change; and
- because they are ubiquitous different sites across a whole continent can be compared from a common perspective.

False-colour 2.5 m resolution SPOT5 image near Boorowa, NSW, November 2003 (©CNES 2003).

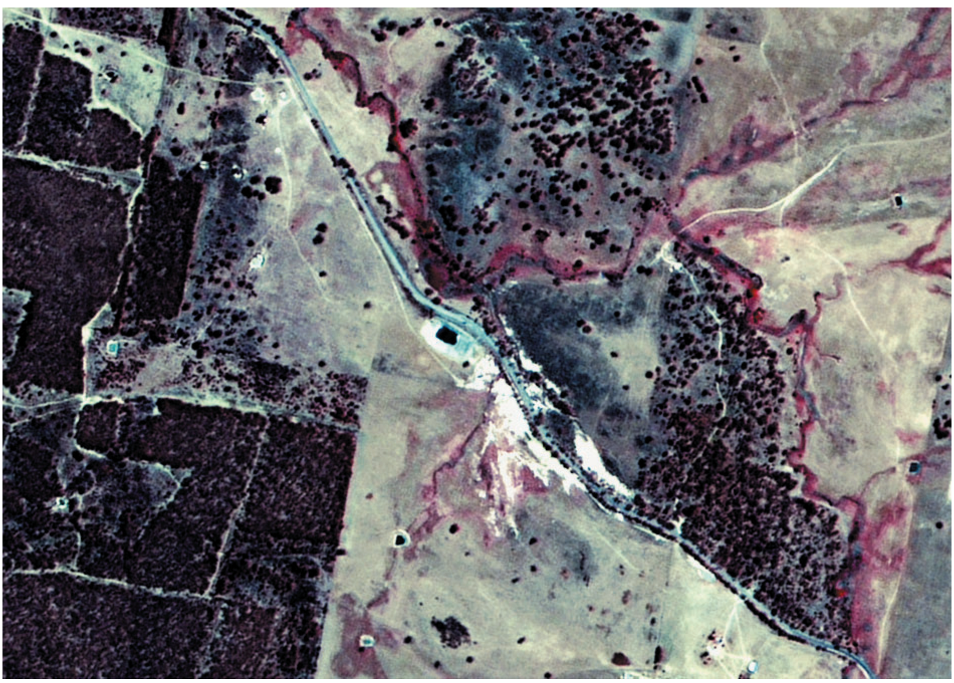


Image courtesy Spot and Raytheon

In relation to salinity specifically, these satellites have useful properties. Their spectral (colours) and spatial context (patterning) may actually detect salt where it is present and exposed at the surface. They can also monitor vegetation as a surrogate for salinity by measuring the decline in photosynthetic activity as a result of salt stress and by helping detect the type and phenology (seasonal changes) of the vegetation that is present, and relating this to the likely presence or absence of salt in the root zone. They are, therefore, useful for salinity hazard mapping.

In addition these satellites have proven abilities to map attributes of value to salinity risk assessment. These attributes include vegetation type (particularly woody vegetation monitoring over large areas), land use, hydrology and land systems (a combination of lithology, geology and vegetation).

Summary of method and description of mapping products

There are two typical mapping products: those in digital form and those in hard copy form. The scale of mapping depends on the input scale of the imagery and the preferred output scale. Usually the scales range from 1:10 000 (for paddock scales) up to 1:1 000 000 for regional mapping. The mapping classes (or units in the legend of the map) usually indicate the presence or absence of salt or salt scalds when mapping salt directly. When mapping vegetation type as a surrogate of salinity the type of vegetation will be noted (e.g. barley grass, mallee eucalypts, red gum woodland) and then this type will be related to the likely presence of salt in the root zone.

Prior use and evaluation

There are many examples of prior use. One of the best examples of prior use is the Western Australian Land Monitor <www.landmonitor.wa.gov.au/index.html>.

Scale (level of detail)

High spatial resolution satellites such as SPOT, IKONOS and EARTHWATCH with pixel sizes of around 2 m can produce useful maps at scales of between 1:1000 and 1:10 000. SPOT and Landsat can produce maps at scale of around 1:10 000 to 1:40 000 or smaller.

Survey design

Synoptic satellites such as Landsat, SPOT, IRS, IKONOS and EARTHWATCH can be asked ('tasked') to image the same area on a regular basis at the same solar time because they are in a regular orbit (known as sun synchronous). Tasking the satellite can be organised through the distributors of the imagery who are usually franchised by the operators of the satellite. Distributors are found in all States/Territories.

Moreover most of the satellites have extensive archives of existing imagery that can be located by reference to the catalogues, again through the distributors.

The preference for a given image will depend on a number of factors including the area to be covered, the value of the existing archive, difficulty of the mapping task and the cost.

Data processing, interpretation and mapping products

Mapping can be done by supervised or automated computer-based techniques usually with some form of human interpretation. Experienced analysts are recommended and these can be found in many companies or in government organisations. Specialist software packages are needed for the analysis. Most processing can be performed on standard personal computers. Processing usually takes a few days for a standard satellite scene but may take longer if larger areas are involved.

Field checking of the mapping is highly recommended.

Limitations

Satellite data can be acquired over any part of Australia. Cloud cover is the single most restrictive factor and should be checked prior to any purchase. Steep slopes, typically over 15 degrees, can produce terrain shadowing that can mask features. Significant recent events such as flooding, severe drought effects and bushfires may produce local effects that mask the effect of salinity.

It should be remembered that satellite imagery when used for mapping salinity is only detecting the salinity as it occurs at the surface or in the root zone. It is not used to draw any direct inferences about the deeper location of salt load or the deeper processes that govern the movement of salt.

Best practice—considerations for users

Satellite images can also be used to detect and map drainage lines, land use, terrain, and geological and lithological features that help build a picture of the landscape processes. When used in this way the imagery is making a contribution to the framework of risk analysis so that, when combined with forecasting techniques, risk scenarios can be developed.

The use of satellite images for mapping salt classes is a technique for inferring salinity as a hazard.

Satellite imagery is frequently used in combination with other data sources for mapping salinity.

Costs

Some of the typical costs are given below. It is recommended that users check with data distributors for accurate and up-to-date prices and product offerings and minimum purchases.

Landsat 7 ETM: $1500 per scene, equivalent to 4 cents per square km.

Landsat 5 TM: $1500 per scene, equivalent to 4 cents per square km.

Landsat 2 to 5 MSS: $595 per scene, equivalent to 1.7 cents per square km.

Schematic of swath coverage obtained with satellite spectral imaging systems.

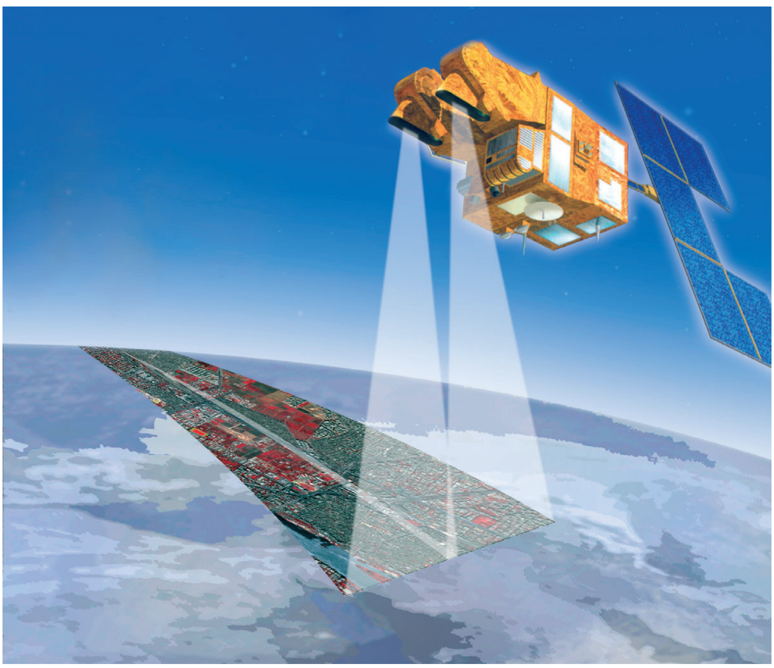


Image courtesy Spot and Raytheon (©CNES 2003)

Appendix 1.20 Hyperspectral satellite imagery

Summary of method and description of mapping products

The first readily available, hyperspectral, satellite sensor is Hyperion which is on board the EC-1 mission that was launched in November 2000 as a research mission. Still very much in research mode there are no published or reported studies of its use for describing salinity hazards. Nevertheless, because the specifications of the Hyperion sensor are significantly better than most of the those of the currently available multispectral satellites it is likely that in time it will find operational use for natural resource applications. It is covered in this review for completeness.

Prior use and evaluation

Very few for dryland salinity mapping. Refer to the discussion on airborne hyperspectral imaging for an indication of its potential.

Scale (level of detail)

The Hyperion sensor has a pixel size of 30 m. It has more than 200 spectral bands (covering the range of wavelengths from 0.4 to 2.5 microns), compared with the multispectral satellites that typically have fewer than ten bands. Because of its greater spectral coverage and spectral resolution, it is possible that Hyperion may have better performance for some natural resource applications, despite its limited signal to noise ratio in the short-wave infrared part of the spectrum (1 to 2.5 micrometers).

Its pixel size is too large to pick up the smaller salt scalds and patches of vegetation that may be salinity-stressed so its use would begin at paddock scale.

Survey design

Subject to the normal systematic acquisition procedures for satellites that routinely orbit the Earth.

Data processing, interpretation and mapping products

Specialist software and interpreters are required for the analysis of the imagery. Further research is required before details of the mapping products can be determined.

Limitations

The limitations of this sensor have yet to be determined.

Fitness for purpose

It is likely to have similar applications to those of the multispectral satellites:

- as a salinity hazard tool in the first instance limited to the root zone but like the multispectral sensors it is likely to also collect information of use in developing risk assessments as well;
- restricted to cloud-free and smoke-free scenes;
- potential confusion in regions that have been subject to a green flush of vegetation;
- potential confusion in areas affected by drought, recent bushfire damage, vegetation dieback not caused by salinity, and recent floods; and
- limited ability to detect small patches affected by salinity (less than 30 m x 30 m).

Best practice—considerations for users

Best practice considerations are yet to be determined.

Costs

Experimental datasets currently cost around $1500 for a 185 km x 42 km area.

Appendix 1.21 Radar satellite

Summary of method and description of mapping products

Satellite radar is similar in operation to airborne radar described in Appendix 1.12. It is an active technique that operates by transmitting a pulse of high-frequency electromagnetic energy that interacts with and reflects from the surface of the earth.

The presence of salt at the earth's surface can be inferred through measured changes in the complex electrical conductivity of the surface as a result of changing dielectric constant, or through physical changes to a surrogate such as vegetation.

The application for salinity hazard mapping using satellites has been tested by a variety of workers over the past decade with mixed results. The primary output is usually a hazard map showing the likely presence of salinity within the root zone.

The ability of satellite radar to be used to develop digital elevation models (DEM) as an input into salinity risk assessment has been recently demonstrated through the Shuttle Radar Topography Mission. This was a space shuttle mission that flew in November 2000 and it acquired radar imagery over the entire terrestrial surface of the earth. This imagery has been used to create a world-wide DEM which should be suitable for use at scales of 1:100 000 and maybe even 1:25 000 (paddock scale) because its vertical accuracy will be around 16 m. This data is to be released over the next year or so.

The potential also exists for radar data to develop DEM with vertical accuracies of just a few centimetres making them useful at subpaddock scales in the most gently undulating terrain. A development like this would have significant implications for accurate mapping at high resolution.

Prior use and evaluation

There have been a small number of experimental users of satellite-based radar imagery in Australia including McNeill et at. (1999) using Radarsat in Western Australia, and Taylor et al. (1995) using SIR-C imagery at Tragowel Plains in Victoria. The results of these studies have generally been inconclusive with respect to the ability of satellite radar to be developed operationally for salinity mapping.

Scale (level of detail)

Pixel sizes vary but are around 25 m x 25 m in size rendering it suitable for paddock scale use. Swathe widths can run up to around 100 km and are of varying lengths permitting large areas to be covered.

Survey design

Commercial satellites such as RADARSAT routinely orbit the earth and systematically acquire their imagery. Images are best acquired when the target area is relatively wet as these conditions optimise the ability of the processing to detect areas that are likely to be salinity affected.

The space shuttle is clearly an irregular source of imagery and should be considered suitable for research purposes only.

Data processing, interpretation and mapping products

Radar data requires specialist software and interpreters. It is one of the more complicated sources of remotely sensed data.

Limitations

There are a number of limitations for hazard mapping, including:

- the imagery is yet to be proven operationally; and
- the imagery is best interpreted when it is near or maximum water-retention capacity.

This presents real limitations with respect to the timing of acquisition because it implies the need to have had a recent rainfall event that also coincides with the overpass of the satellite.

These limitations do not apply to the use of radar for the creation of digital elevation models. Other limitations do:

- The creation of a DEM from radar data requires very specialised skills. Moreover the creation of very high resolution DEM with vertical accuracies measured in centimetres are still in the experimental stage. Operational use is still some years away.

Fitness for purpose

Satellite-based radar mapping for salinity hazard is not robustly proven as yet.

Satellite-based radar mapping for contribution to the DEM for risk assessment is becoming recognised as a useful tool.

Best practice—considerations for users

Satellite-based radar imagery for salinity hazard mapping is not recommended at present.

Satellite-based radar imagery for DEM is certainly worth considering.

Costs

RADARSAT imagery costs around US$3000 for a 100 km x 100 km image. Cost $5 to $50 per hectare including processing.

APPENDIX 2
Scope and governance

Appendix 2.1 Terms of reference and objectives

The terms of reference (TOR) for the review were to evaluate the range of methods available in Australia for mapping the impact and extent of dryland salinity and assessing potential impacts and risks.

These objectives are:

1. collate and review existing evaluations of salinity mapping and risk assessment methods, techniques, models and approaches, adding to these any additional information or alternative methods that has since become available, and prepare a single comprehensive list;
2. assess and review methods not previously evaluated;
3. provide a plain language definition of the difference between risk and hazard assessment for salinity mapping, and the context for their use;
4. for each method, identify and assess the costs and effectiveness, scale, survey design and data requirements, applicability and limitations;
5. with regard to the *Guidelines for Best Practice in the Public Presentation of Salinity Data and Mapping Products* prepared by the Science and Information Working Group of the Natural Resource Management Ministerial Council, identify issues, specific to each method, that need to be considered when releasing mapping products to the public;
6. indicate the limitations for each method for the broadly different geological/geomorphic regions of Australia, using the Catchment Characterisation Map of Australia as a base;
7. provide a draft user-friendly stochastic key to guide users to the best methods to use for their purpose, and identify the information, tools, technical capacity and systems that the user may require to interpret and use the different methods and meet their information requirements; and
8. note the extent to which the various methods could link into existing natural resource management, reporting and evaluation systems and programs.

Objectives

Compile a list of known salinity mapping and risk assessment methods. Indicate the source of existing evaluations for each method. If no known evaluation exists then indicate that this is the case. The full list will be included in the final report and will be used to help compile the user-friendly guide (TORs 1 & 2 and included in Output No. 1)

For each method listed in Objective 1 note whether the method is useful for hazard assessment and /or risk assessment. Do so in plain English (TOR 3 and included in Output No. 1)

For each method listed in Objective 1 indicate (TOR 4 and included in Output No. 1):

- cost;
- scale of application;
- describe the type of survey design required for its use;
- other data required to permit the effective use of the method; and
- the applicability and limitations.

Include a statement of the limitations with respect to geological, geomorphic, and biogeographic regions (TOR 6 and included in Output No. 1).

For each method listed in Objective 1, and for each of the resultant mapping products, prepare a 'fitness-for-purpose' statement that can be used by the public. Have regard to the *Guidelines for Best Practice in the Public Presentation of Salinity Data and Mapping Products* prepared by the Science and Information Working Group of the Natural Resource Management Ministerial Council (TOR 5). Present this as a user-friendly guide that will indicate the likelihood of success of the method (TOR 7 and forms the basis of Output No. 2).

For each method listed in Objective 1 indicate how the method may be relevant to existing natural resource management, reporting and evaluation systems and programs (TOR 8 and included in Output No. 1).

The project will produce several distinct outputs as defined in the terms of reference.

Expected outputs

- **Output No 1** (to be completed by the Mapping Methods project team): A draft project report addressing all project objectives. This report will be considered by a national workshop (a public forum) to be convened jointly by the Academy of Science and the Academy of Technological Science and Engineering in October 2003.
- **Output No 2** (to be completed by the Mapping Methods project team): A draft user-friendly guide (specifically TOR 7). The intended audience for this output is the end-users including regional catchment management authorities, regional councils, salinity management officers within government, and other land management advisors.
- **Output No 3** (to be completed by the academies)**:** The proceedings of the academies' workshop. The workshop will review the draft project report to a standard acceptable for publication by an international journal.
- **Output No 4** (to be completed by the Mapping Methods project team after the national workshop): The revised final report (derived from Outputs 1 & 2).
- **Output No 5** (to be completed by the academies): Final user-friendly guide (derived from Output 2). The Academies may choose to contract the Salinity Methods project team, or to determine some other mechanism for completing this output.

Appendix 2.2 Project governance

The Australian Government Department of Environment and Heritage (DEH), and Department of Agriculture, Fisheries and Forestry (DAFF) jointly commissioned the review on behalf of the Natural Resource Management Standing Committee. Land and Water Australia are their agents for the overall work. The Board of the National Dryland Salinity Program has asked its Operations Committee to oversee the project. A Steering Committee has been selected from the membership of the Operations Committee to provide governance to the project. This Steering Committee is chaired by Dr Sharon Davis with Dr Richard George and Dr Mirko Stauffacher as its other members. The need for an independent review that is transparent in its conduct and outcomes has been stressed by the clients. The joint role of the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering is most important in this regard.

Steering Committee

The project is managed by the Operations Committee of the National Dryland Steering Program. This arrangement is facilitated through a Steering Committee.

The Steering Committee comprises:

Dr Sharon Davis, Murray-Darling Basin Commission (Chair)

Dr Richard George, Department of Agriculture, WA

Dr Mirko Stauffacher, CSIRO Land & Water

Acting as an instrument of the Operations Committee, the role of the Steering Committee is to:

- keep the Operations Committee informed of progress with the study;
- facilitate networking and access by the study team to appropriate sources of information and people; and
- facilitate liaison with the appropriate contact officers in DAFF and DEH.

The role of the Operations Committee is to:

- provide direction in the capacity of project managers in the development of the project brief and methodology; and
- ensure that the project objectives and methodology are adhered to, and that an effective process is run in relation to the conduct of the study.

Neither the Operations Committee nor the Steering Committee is to have a role in reviewing the findings of the study itself.

The Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering will host a national scientific workshop to review the project report. The Academies will jointly review the project outputs to ensure the work is scientifically rigorous and to provide peer review through the conduct of a workshop.

Project Team

The Project Team was led by Peter Woodgate from the Cooperative Research Centre for Spatial Information based at University of Melbourne and by Brian Spies from CSIRO Division of Exploration and Mining. They were responsible for the day-to-day conduct of the study including the delivery of its outcomes.

Appendix 2.3 Method of review

Scope of review (inclusions and exclusions)

The review is designed to concentrate on those methods that can be used to map the existing extent of dryland salinity (hazard mapping) and to consider the usefulness of the mapping methods as inputs to the systems that are used for predicting the future extent of dryland salinity (risk assessment).

The review is not considering mapping methods for detecting irrigation-induced salinity, nor is it reviewing the efficacy of mapping systems for detecting primary (or naturally occurring salinity) although much of the knowledge gained in reviewing dryland salinity applies to these forms of salinity as well.

The review is not considering mapping methods for detecting salinity in open water bodies such as streams, rivers and dams.

In order to predict the likely future extent of salinity it is necessary to understand the fundamental landscape processes that govern the expression of dryland salinity. This review is not intended to cover these landscape processes comprehensively. It will summarise them to provide a context for the discussion on risk assessment. It will also note in passing how the mapping methods can also be used to map and determine many of the attributes that describe landscape processes.

The review notes that the assessment of risk implies the identification of an asset that has an anthropocentric value (e.g. agriculturally productive land, environmental values such as biodiversity, and built assets such as roads and houses). The review does not intend to describe these values in detail. However the review has these values uppermost in mind in describing the usefulness and limitations of each mapping method and the resultant risk assessment techniques.

Call for submissions of expressions of interest

On 5 July 2003, the review called for submissions from all interested organisations and individuals. The call for submissions involved advertisements in the Weekend Australian, the newsletter of the National Dryland Salinity Program and extensive email server lists.

Thirty-six submissions were received and a summary is given in Appendix 3.1. In addition the project team reviewed other relevant sources of information that relate directly to the terms of reference.

Appendix 2.4 Independent review and the academies

The Australian Government has indicated its strong intention to ensure the review has a high degree of independence, transparency and peer review. The joint role of the **Australian Academy of Sciences** and the **Australian Academy of Technological Sciences and Engineering** is to lead this independent review. This process involved a Scoping Workshop on 1 September 2003, a Public Forum on 17 October 2003, and a final technical review (8 – 14 December 2003).

A2.5 Declarations

For those persons responsible for the governance and conduct of the study and in order to ensure:

- a high order of probity;
- the independence of the study;
- absence of bias; and
- transparency in the process of the study and its outcomes.

The Steering Committee and project team members all declared in writing their prior and current interests relevant to the objectives of the study. Those that might be considered a conflict – of interest are to be specifically identified. These declarations were provided to the academies, DAFF and DEH.

The procedure for dealing with conflicts of interest will be:

- a submission in writing of the declaration of potential or actual conflict;
- provision of this declaration to all members of the Project Steering Committee and NDSP Operations Committee and the Project Team leader;
- a determination that the declaration does not constitute a conflict;
- a determination that the declaration does constitute a conflict, but that it is modest in nature and best handled by isolating the person from decisions that involve the issue specified in the declaration;
- a determination that the conflict is significant and that person should cease to be involved in the study; and
- depending on the timing of the declaration with respect to progress on the study, remedial action may need to be undertaken on work completed by that individual to date to ensure the conflict does not have an impact on the study, either in the process of its conduct or in its outcomes.

APPENDIX 3
Contributors

Appendix 3.1 List of submissions

1. BR Senior & Associates Pty. Ltd. Salinity mapping using stereoscopic interpretation of aerial photographs and desk top digital photogrammetry
2. James Patrick Cunneen & Anne Marie Anderson Mayes
3. Victorian Department of Primary Industries, VIC (Kim Broadfoot)
4. Natural Resource Intelligence, (James Moody & Brian Tunstall)
5. Soil Information Systems Unit, NSW Department Infrastructure, Planning and Natural Resources, (Greg Chapman & Jonathan Gray). Also supplementary submissions including a videotape of 'Cross Country' on soil and salinity management and mapping in New South Wales
6. Pelham Group, (Robin Greenwood-Smith, Bob Smith & Allan Bremner)
7. Centre for Natural Resources, NSW Department of Infrastructure, Planning and Natural Resources (Ross Williams)
8. Geoforce, (Justin Anning)
9. Department of Primary Industries, Victoria, (Mark Reid) and Minerals and Petroleum Division, (Alan Willocks)
10. GecOz Pty. Ltd., (Darren Bell)
11. Raytheon, (Philip Tickle)
12. Department Applied Science, RMIT, (James Macnae). Supplementary methodology for substantive improvement in the resolution and accuracy of airborne and ground EM for salinity mapping
13. Geo-Processors, (Aharon Arake)
14. Geophex Ltd. Canada, (IJ Won)
15. Bureau Rural Sciences, (Peter Baker & Michele Barson)

16 UTS Geophysics, (David Abbott)

17. CSIRO Mathematical and Information Sciences, (Jeremy Wallace)
18. Orbtek Pty. Ltd., (Rob Gourlay)
19. Salient Solutions Australia Pty. Ltd. (for NSW NPWS), (P Please, W Evans & W Watson,)
20. CRC LEME/Geoscience Australia, (Ken Lawrie et al.), Executive Summary

20a. CRC LEME/Geoscience Australia, Key datasets for salinity mapping

20b. CRC LEME/Geoscience Australia, (P Please & K Lawrie)

20c. CRC LEME/Geoscience Australia, (Ken Lawrie & Jane Coram), Limitations in using catchment characterisation (GFS) maps as the basis for assessing methods/approaches of salinity mapping in particular landscapes.

20d. CRC LEME/Geoscience Australia, (Ken Lawrie, Matt Gray, Andrew Fitzpatrick, Paul Wilkes, Richard Lane, Colin Pain & Ian Lambert), Assessing cost-effective salinity mapping strategies using a landscape-based approach to methodologies and technology selection (see also Lawrie et al. 2003)

20e. CRC LEME/Geoscience Australia, (Paul Wilkes & Kirsty Becket)

20f. CRC LEME/Geoscience Australia, Regolith logging

20g. CRC LEME/Geoscience Australia, (Ross Brodie, Richard Lane & David Gibson), Data interpretation, correlation and modelling

20h. CRC LEME/Geoscience Australia, (Richard Lane), Ground and airborne electromagnetic methods

20i. CRC LEME/Geoscience Australia, (Roslyn Chan & David Gibson), Regolith Landforms of the Gilmore Project Area

20j. CRC LEME/Geoscience Australia, (Tim Munday, Nerida Reilly, Mark Glover, Kenneth Lawrie, Tenille Scott, Colin Chartres & Ray Evans), Petrophysical characterisation of parna using ground and downhole geophysics at Marinna, central New South Wales

20k. CRC LEME/Geoscience Australia, (Tim Munday, Andy Green, Ross Brodie, Richard Lane, Daniel Sattel, Steve Barnett, Peter Cook & Glen Walker), Developing recharge reduction strategies in the Riverland of South Australia using airborne electromagnetic data - a case study in tailoring airborne geophysics given a particular target and a desired set of outcomes

20l. CRC LEME/Geoscience Australia, (Ross Brodie & Richard Lane), The importance of accurate altimetry in AEM surveys for land management

20m. CRC LEME/Geoscience Australia, (K Lawrie, T Munday, D Dent, D Gibson, R Brodie, J Wilford, N Reilly, R Chan & P Baker), A geological systems approach to understanding the processes involved in land and water salinisation

20n. CRC LEME/Geoscience Australia, (Tim Munday, Glen Walker, Richard Creswell, John Wilford, Steve Barnett & Peter Cook), South Australian salt mapping and management support project - an example of the considered application of airborne geophysics in natural resource management

20o. CRC LEME/Geoscience Australia, (John Wilford), Scientific visualisation and 3-D modelling applications for mineral exploration and environmental management

20p. CRC LEME/Geoscience Australia, (J Wilford, D Dent, T Dowling & R Braaten), Rapid mapping of soils and salt stores

20q. CRC LEME/Geoscience Australia, (Penny Kilgour & Colin Pain), National regolith data - present status and work to be done

20r. CRC LEME/Geoscience Australia, (Ken Lawrie, Colin Pain, David Gibson, Tim Munday, John Wilford & G Jones), Regolith - a missing link in mapping salinity processes and predicting dryland salinity hazards

20s. CRC LEME/Geoscience Australia, David Gibson, John Wilford, Kok Tan & Kenneth Lawrie), Palaeogeography, a predictive tool in environmental studies - applications to the margins of the Murray Basin

20t. CRC LEME/Geoscience Australia, (David Dent, Tim Munday, Ross Brodie & Kenneth Lawrie), Implications for salinity and land management - Honeysuckle Creek, Victoria: a preliminary interpretation of high-resolution airborne geophysical data

20u. CRC LEME/Geoscience Australia, (John Wilford, David Gibson, Kenneth Lawrie & Kok Tan), Extending regolith-landform maps into the third dimension - unravelling the palaeogeography story for mineral exploration and environmental applications

20v. CRC LEME/Geoscience Australia, (Andy Green), Analysis of Hoistem Calibration Data

20w. CRC LEME/Geoscience Australia, (Colin Pain, John Wilford & Ken Lawrie), Geomorphology and salt: what can landforms tell us about salinity prediction in Upland areas)

20x. CRC LEME/Geoscience Australia, ACT, (Ian Lambert, Ken Lawrie & Colin Pain), Mapping and understanding salinity in the landscape

20y. CRC LEME/Geoscience Australia, (Ken Lawrie, Patty Please, Colin Pain, Mike Grundy & Glen Walker), An integrated geoscience approach to reassessing regional groundwater flow systems for salinity mitigation in the Murray–Darling Basin

20z. CRC LEME/Geoscience Australia, (Ken Lawrie, Andrew Fitzpatrick, Toby Payenberg, Kate Wilkinson, Ben Maly, Richard Lane, Dave Gibson & Ross Brodie), Mapping aquifers and salinity systems using an integrated geoscience approach

20aa. CRC LEME/Geoscience Australia/ WA Department Agriculture, (Richard George, Ken Lawrie & Peter Woodgate), Convince me all your bloody data and maps are going to help me manage salinity any better? Remote sensing techniques and their application to salinity assessment and management, PUR$L 2003 paper sent later

20bb. CRC LEME/Geoscience Australia, (Colin Pain, John Wilford & Ken Lawrie), The role of geomorphology in assessing salt and water movement in upland landscapes

20cc CRC LEME/Geoscience Australia, (Ken Lawrie, Patty Please, Andrew Fitzpatrick, Matthew Grey & Colin Pain), An integrated approach to groundwater management and salinity mitigation

20dd CRC LEME/Geoscience Australia, (Ken Lawrie, C Pain, J Wilford & D Gibson), Regolith: a critical component in a holistic systems approach to mapping and assessing dryland salinity hazards

20ee. CRC LEME/Geoscience Australia, (Ken Lawrie, Dave Gibson, John Wilford, K Tan, Colin Pain & Tim Munday), Mapping salinity and groundwater systems - a multi-disciplinary approach integrating geophysics and regolith geoscience

20ff. CRC LEME/Geoscience Australia, (Tim Munday, Don Hunter, Ross Brodie & Ken Lawrie), Spatial resolution and mapping scales - matters pertinent to the application of airborne geophysics in salinity management

21. Australian Cotton CRC, NSW, (John Triantafilis), Ground-based EM induction (Overview of ground EM with extensive reference list)

22. Motorola, (Aled Jones)

23. National Dryland Salinity Program, Occasional paper 20/98, (Lin Martin & Jenni Metcalfe), Assessing the causes, impacts, costs and management of dryland salinity

24. Greening Australia (for NSW NPWS), (Nicki Taws), Woodland remnants and dryland salinity

25. Fugro Airborne Surveys, (Michael Lees)

26. Geonics Limited, Canada, (Miro Bosnar)

27. Baden Williams, Surface-based electromagnetic induction (EM)

28. Bureau Rural Sciences **(**Michele Barson)**,** Steps to solving salinity (Rob Braaten, Peter Baker & David Dent) + four reprints

29. Cambium Land & Water Management Pty. Ltd. (Neil Meadows), Corrections for near-surface EM conductivity meters

30. School of Biological and Environmental Sciences, University of New South Wales, (Geoffrey Taylor), Imaging Spectrometry (Hyperspectral Remote Sensing) – the only way to reliably map salinity

31. University of New South Wales, (Lin Lin Ge), Generation of high accuracy and high resolution digital elevation models using satellite radar interferometry

32. ABARE, (Colin Mues), Targeted reforestation for salinity management (Heany et al.); Salinity management – assessing priorities (Mues & Kemp)

33. QLD Department Natural Resources and Mines, (Mike Grundy), Salinity hazard mapping

34. Phil Dyson and Associates, (Phil Dyson), Salient Solutions, (Ray Evans), A landscape framework for planning and implementing catchment management strategies for dryland salinity management

35. Department of Infrastructure, Planning and Natural Resources, NSW, (Tony Watson)

36. Murray-Darling Basin Commission, (Paul Nanning), Loddon Salinity Management

Appendix 3.2 Other contributors to drafting and review

The authors would like to thank the following people for their significant contributions to the review of this document:

- Peter Baker (stream sampling)
- Darren Bell (remote sensing in general, radar in particular)
- Dennis Clark (for considerable assistance in risk management)
- Bruce Dickson (for assistance in gamma-ray spectrometry)
- Richard George (salinity in WA)
- Jane Inall (for general assistance)
- Richard Lane (for considerable assistance in airborne electromagnetics)
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GLOSSARY[6]

Air photo interpretation (API)
The examination of photographic images for the purpose of identifying objects and patterns and judging their significance (Wolf 1974). API may involve mapping the features of interest from a single photo or from two photos (known as a stereo pair), in which case the interpreter has the benefit of seeing the features in three dimensions. API is both an art and a science, and in general the more experienced the interpreter the better the result. When used for salinity mapping API is seeking to map direct evidence of salt at the surface, or is seeking to infer its presence in the root zone through signs that the vegetation is suffering or through signs that salinity has caused actual changes in the type of vegetation over time.

Asset
A natural or human-made physical entity considered to be of value to humans or future generations, such as land used for cropping, pasture, agricultural produce, built assets, water supplies, and natural entities such as forest, rivers, lakes used for recreation or used to retain wilderness or biodiversity.

Biodiversity
The variety of all life forms—the differing plants, animals and microorganisms, the genes they contain and the ecosystems of which they form a part (CoA 1996). Australia's biodiversity is one of its most precious bequeathed assets and this asset is directly under threat ('at risk') as a result of salinity.

Biophysics
The science that deals with the application of physics to biological processes and phenomena.

Cadastral map
A map showing the parcels of land ownership.

Calibration
1. (Engineering) Adjustments made to an instrument or system so that it reads to the highest possible accuracy. A calibrated instrument should specify error bounds of the measurement.
2. (Geophysical surveys) To adjust processing parameters so that data from one type of survey (e.g. airborne) agree with data from another (e.g. surface and borehole measurements), sometimes by applying constraints in an **inversion** process.
3. (Resource Management) Often used in the sense of 'correlation', where one quantity is numerically related to another quantity. Linear regression is commonly used to derive this calibration relationship.

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6 Many of these definitions draw from the *Encyclopedic Dictionary of Applied Geophysics*, by RE Sheriff: Society of Exploration Geophysics, Tulsa USA, 2002.20d.; CRC LEME/Geoscience Australia, (Ken Lawrie, Matt Gray, Andrew Fitzpatrick, Paul Wilkes, Richard Lane, Colin Pain & Ian Lambert); *Assessing cost-effective salinity mapping strategies using a landscape-based approach to methodologies and technology selection* (see also Lawrie et al. 2003)

Digital elevation models (DEM)

Computer-based representations of the topography of the surface of the Earth. They usually comprise a grid of regularly spaced elevation values that can show the surface in three dimensions. They can be derived from a variety of techniques including:

- aerial photos using photogrammetric techniques;
- multispectral satellite imagery;
- airborne laser scanning; and
- airborne or satellite radar interferometry.

Modern systems can generate DEM with vertical accuracies of 1 to 5 m or better. In future vertical accuracies of around a few millimetres may be possible with new satellite-based radar techniques.

As a rule of thumb the vertical accuracy of a given DEM for any area should be about 1% of the total elevation range of the area. So if the area of interest has a total elevation range of 600 m the vertical accuracy should be approximately 6 m. They may also be known at digital terrain models (DTM).

Dryland salinity

The following description is taken from *Australian Dryland Salinity Assessment 2000* of the National Land and Water Resources Audit, 2001. Two broad forms of salinity are recognised in Australia.

- **Primary** or naturally occurring salinity is part of the Australian landscape, and reflects the development of this landscape over time. Examples are the marine plains found around the coastline of Australia, and the salt lakes in central and western Australia.

  Salts are distributed widely across the Australian landscapes. They originate mainly from depositions of oceanic salt from rain and wind. Salt stored in the soil or groundwater is concentrated through evaporation and transpiration by plants. In a healthy catchment, salt is slowly leached downwards and stored below the root zone, or out of the system.

- **Secondary** salinity is the salinisation of land and water resources due to land use impacts by people. It includes salinity that results from watertable rises from irrigation systems—**irrigation salinity—**and from dryland management systems—**dryland salinity**. Both forms of salinity are due to rising watertables mobilising salt in the soil. There is no fundamental difference in the hydrologic process.

  Where the water balance has been altered due to changing land use (e.g. clearing of native vegetation for broadacre farming or grazing) the excess water entering the watertable mobilises salt which then rises to the land surface. Movement of water drives salinisation processes and may move the stored salt towards the soil surface or into surface water bodies. It is the combination of the effects of salt and its movement by water through the landscape that leads to the creation dryland salinity.

Electrical conductivity (EC)

The ability of electrical current to pass through a substance. EC is commonly used to estimate the amount of soluble salt in solution. EC measurements can be made with a range of devices on ground and stream water, soils, and soil-paste extracts. Units of electrical conductivity are commonly given in mS/m, dS/m or µS/cm; 100 mS/m = 1 dS/m = 1000 µS/cm. Here, *S* is the symbol for siemens, and the prefixes *d* is deci (10^{-1}), *c* is centi (10^{-2}), *m* is milli (10^{-3}) and µ is micro (10^{-6}).

Geographic information system (GIS)

A computer-based mapping system that records information about objects at any point in the landscape. Such information includes the location, type, size, boundaries, neighbours, history, distances to other objects and many more data depending on the amount of information actually collected. The GIS offers an efficient storage, retrieval and analysis approach for any map-based information.

Geophysics

The study of the Earth by quantitative physical methods, such as magnetics, electromagnetics, gamma ray spectrometry (radiometrics), seismology and gravity.

Geophysical interpretation

Determination of the location, size, geometry and depth of bodies in the subsurface from spatial measurements of a geophysical field such as magnetics, electromagnetics, gravity. Multiple interpretations are often made based on different assumptions depending on the type of **model**. Interpretations should be constrained by known information from ground observations or drill hole data, and may use computer-based **inversion** techniques.

Geomorphology

The branch of geology and geography that deals with the study of the evolution and configuration of landforms.

Ground penetrating/probing radar (GPR)

A **radar** system used to map the shallow subsurface using electromagnetics waves, usually in the 10 to 1000 MHz band. The two-way travel times of reflected radar waves give the depths to where changes in electrical properties occur. The antennae of GPR systems are held in close contact with the ground to reduce surface reflections and maximise depth range.

Hazard

For the purposes of this book, a hazard is defined as anything that can potentially cause harm to an asset (NLWRA 2001). Salt becomes a hazard when it has the potential to move into a position where it has the ability to threaten an asset. Water is the means by which salt moves in the landscape. Thus a dryland salinity hazard will mean the combination of salt with the potential for movement by surface or groundwater.

The word threat can be used interchangeably with hazard in the context of this review.

Hydrogeology
The branch of geology that deals with the occurrence, distribution, and effect of groundwater. Groundwater is important in salinity studies, because it controls the mobilisation and movement of salt through the landscape.

Hydrology
The scientific study of the properties, distribution, and effects of water on the Earth's surface, in the soil and underlying rocks, and in the atmosphere.

Hyperspectral imagery
A form of **remote sensing** that involves the acquisition of images at typically tens to hundreds of sensor wavelengths using an airborne or spaceborne imaging spectrometer that collects electromagnetic radiation, typically from visible light to the shortwave infrared (0.4 – 2.5 µm) and less commonly at thermal infrared (8 – 12 µm) wavelengths. Hyperspectral systems have continuous wavelength coverage (i.e. their wavelength channels are contiguous). Interpreted or derived information is usually presented using 'false-colour images' that use colours to show the spatial distribution of different mineral or environmental targets (see *multispectral remote sensing*).

Impact
The consequence of an occurrence (e.g. increasing salinity) on an asset such as a person, entity or the environment.

Information product
A map-based product that provides information of immediate use for decision making. Information products are derived from a range of data that may be in mapped form through a process of expert assessment. A typical information product may be a whole-of-farm map and plan that shows the location of assets such as productive pasture and the presence of salt somewhere below it.

Interpretation
The process of converting data to useable information. In a geoscientific context, interpretation is the derivation of a simple, plausible geological or other **model** that is compatible with all observed data. The model is never unique or complete and should be refined as more data comes to hand. Everything about an area should be considered when formulating an interpretation (see *air photo interpretation*, *geophysical interpretation*)

Inversion
Deriving from field data a geologically plausible **model** of the subsurface that is consistent with observed data (also known as inverse modelling).

Landscape processes
The complex interactions between the natural events of the environment and the impact of human land use. The natural events include the movement of water through gravity and other forces, solar irradiation, climate, weather, plant and animal growth, droughts and floods and so on. Human land

use includes the cultivation of land, construction of built assets such as roads and dwellings, irrigation, management of national parks, forestry, and other activities. It is the interaction of human activities and the natural processes that have led to the occurrence of dryland or secondary salinity in Australia.

Lidar (light detection and ranging)
A **radar** system that operates using visible, near infra-red or ultra-violet light. Lidar systems can measure surface material properties as well as deriving accurate DEM.

Mapping methods
In this book a salinity mapping method is any technique on its own, or in combination with another, that can be used to detect or infer the presence, concentration, location and extent of salinity at the time at which the techniques are applied. The extent is best defined by considering the breadth, width, and depth (the primary axes of an existing feature; the x, y and z axes) of a patch of salinity of consistent concentration. Salinity mapping methods range from soil sampling for salt concentrations to the use of satellite-based techniques for mapping vegetation that is indicative of salt in the root zone. Soils, groundwater, regolith, vegetation and other spatial data can also be mapped using mapping methods.

Model
A concept from which to deduce effects in comparison to observations. The 'model' may be conceptual, physical or mathematical. Models are essential in any **interpretation** or **inversion**.

Modelling
The process of developing a better understanding of observations.
1. The use of interpolating techniques to produce a contiguous picture of the Earth expressed in two and three dimensions from point-based data (put simply, the joining of the dots).
2. Forecasting into the future the likely extent, location and amount of a feature. In this book, modelling is often used in this context; as a forecasting technique for the likely location and concentration of salinity in the future. Therefore modelling introduces the fourth dimension, time.
3. The computer simulation of a mapping method over a particular scenario in order to determine whether that mapping method is suitable for the particular mapping task. Modelling in this sense is often used as a survey planning tool. (see also *numerical modelling*).

Multispectral remote sensing
A form of **remote sensing** that involves the acquisition of images at more than two and typically less than 20 sensor wavelengths using an airborne or spaceborne imaging spectrometer that collects electromagnetic radiation, typically from visible light to the shortwave infrared (0.4 – 2.5 μm) and less commonly at thermal infrared (8 – 12 μm) wavelengths. Multispectral systems do not have continuous wavelength coverage, or necessarily evenly spaced wavelength channels. The precise wavelengths of the channels are generally chosen to sense spectral features of specific targets. Interpreted or derived information is usually presented using 'false-colour images' that use colours to show the

spatial distribution of different mineral or environmental targets (see *hyperspectral imagery*).

Numerical modelling

1. Use of numerical techniques to calculate the theoretical response caused by an assumed set of subsurface parameters (also known as forward modelling).

2. Use of direct or iterative methods for deducing subsurface parameters from geophysical or other data (also known as inverse modelling (see *inversion)*.

Palaeochannel

An ancient water channel or stream bed, which has been covered by materials laid down by subsequent geological processes.

Prediction

A reasoning or statement about the future. The application of a modelling technique in the context of this report produces a prediction of the timing, location, extent, and concentration of future salinity, thereby permitting an analysis of the consequences of the prediction.

Radar

A system in which short-wavelength (radio and microwave) electromagnetic waves are transmitted and the energy scattered back from reflecting objects is detected. Acronym for 'radio detection and ranging'. The radar spectrum ranges from P-band (225 – 390 MHz) to V-band (46 – 56 GHz). Airborne and satellite radar systems employ a narrow beam reflected from the ground from which an image similar to air photos is derived. (see also *Lidar* and *ground probing radar*).

Regolith

The unconsolidated material between the surface and fresh bedrock, consisting of products of weathering, transport and deposition. Regolith often has a complex structure and can vary in thickness from a few centimetres to hundreds of metres.

Remote sensing

Remote sensing is the science and art of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation (Lillesand & Keifer 1979). In common usage, remote sensing refers to measurements made at a large distance, usually from high-flying aircraft or Earth satellites, although it can include ground based measurement systems as well. Especially refers to measurements of either natural electromagnetic radiation (**passive techniques**) or radiation from a source near the sensor (**active techniques**) that has been reflected back from the Earth's surface. While the most common data are available for Landsat, Spot and AVHRR, there are many other remote sensing data sources such as radar, airborne geophysics, and the hyperspectral instruments. The information is usually presented using false-colour imaging to create an image of the target species of interest.

Risk

The chance that a hazard will cause harm to an asset at some defined time in the future. Risk is classically defined as an impact (usually an unwanted impact) multiplied by its likelihood of occurrence at some given time in the future. In effect, it is a way of weighting possible unwanted events by their likelihood. So a highly unlikely but serious impact may be regarded as presenting the same risk as a likely but minor impact (see Chapter 4).

Risk management
The systematic process of identifying, analysing and responding to potential project risk. Risk management includes maximising the probability and impact of positive events and minimising the probability and consequences of events adverse to project objectives (ANAO 2003).

Salinity
The presence of mineral salts such as sodium chloride (NaCl), potassium chloride (KCl), lime (calcium carbonate or $CaCO_3$), gypsum (calcium sulphate or $CaSO_4$), either in solution or as solids (see also *dryland salinity*).

Salt
The general term for mineral salts such as sodium chloride (NaCl), potassium chloride (KCl), lime (calcium carbonate or CaCO3), gypsum (calcium sulphate or $CaSO_4$).

Scale
The ratio of the dimensions of objectives in real life as represented on maps. They are mainly expressed as the following simple ratios.

1:10 000
1 mm on the map is equivalent to 10 m on the ground, and 1 square mm is equivalent to 0.01 ha. This is a useful scale for representing *paddock level* information.

1:50 000
1 mm on the map is equivalent to 50 m on the ground, and 1 square mm is equivalent to 0.25 ha. This is a useful scale for representing *subcatchment level* information.

1:100 000
1 mm on the map is equivalent to 100 m on the ground, and 1 square mm is equivalent to 1 ha. This is a useful scale for representing *subcatchment and catchment level* information.

1:250 000
1 mm on the map is equivalent to 250 m on the ground, and 1 square mm is equivalent to 6.25 ha. This is a useful scale for *regional* representations.

1:500 000
1 mm on the map is equivalent to 500 m on the ground, and 1 square mm is equivalent to 25 ha. This is a useful scale for *regional* and *State/Territory* representations.

1:1 000 000
1 mm on the map is equivalent to 1 km on the ground, and 1 square mm is equivalent to 100 ha. This is a useful scale for *State/Territory* representations. Forty-one 1:1 000 000 map sheets are required to cover Australia.

The larger the scale the closer one gets to the real life object. Thus 1:10 000 is considered to be large scale in relation to 1:1 000 000 which is considered to be small scale. Expressions of local, regional and national scales are also commonly used.

Sodicity
: Measure of the proportion of exchangeable sodium ions in the soil. High sodicity weakens soil structure and increases susceptibility to erosion (erodibility).

Soil chemistry
: The chemical composition, structure, properties, and reactions of a soil.

Soil salinity
: The accumulation of salts in the environment. Saline soil is normally assumed to be non-alkaline. Where pH>8.5 the soil is referred to as saline-alkaline (see also *dryland salinity*).

Threat
: Threat is considered to have the same meaning as hazard for this report.

Validation
: The process used to verify the quality of the outcome of a mapping project. It usually needs to do so by using an independent source of information from that which was used to construct the original map.

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7 See also Glossary on p. 221.

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UNITS

A variety of units are used for measures of salinity and electrical conductivity. The international standard (SI) unit for conductivity is S/m, and common EM instruments are calibrated to read mS/m. EC_e units are commonly quoted in dS/m or μS/cm. For this report, the unit mS/m will be used (100 mS/m = 1 dS/m = 1000 μS/cm).

Salinity is reported in a variety of units, such as parts per thousand (‰), parts per million (ppm), milligrams per litre (mg/L), osmotic potential (OP), and percentage total soluble salts in a 1:5 mix (%TSS 1:5). Various approximate factors exist for relating salinity measures but are based on assumptions about salt and soil type. As a rough guide, water with 15 000 mg/L TDS (total dissolved solids) has EC values around 2300 mS/m (TDS in mg/L $\approx$ 6.4*EC in mS/m).