Geophysics

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

Tim Munday[1], Aaron Davis[1] , Kevin Cahill[1] and Tania Abdat[1]

[1]CSIRO Earth Sciences and Resource Engineering, Perth

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Important disclaimer

Flinders and Gilbert Agricultural Resource Assessment acknowledgments

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The Assessment was guided by four committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Regional Australia, Local Government, Arts and Sport; CSIRO; and the Queensland Department of Agriculture, Fisheries and Forestry

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Regional Australia, Local Government, Arts and Sport; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government

This report was reviewed by Dr Dave Annetts (CSIRO), Dr Paul Wilkes (CSIRO), and Dr Cuan Petheram (CSIRO).

Some of the interpretations were informed by other activities in the assessment, and we acknowledge the contributions of Ian Jolly, Glenn Harrington, Andrew Taylor, and Cuan Petheram

Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

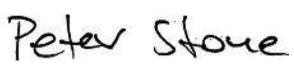
The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.



Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

The Flinders and Gilbert Agricultural Resource Assessment team

Project Director	Peter Stone
Project Leaders	Cuan Petheram, Ian Watson
Reporting Team	Heinz Buettikofer, Becky Schmidt, Maryam Ahmad, Simon Gallant, Frances Marston, Greg Rinder, Audrey Wallbrink
Project Support	Ruth Palmer, Daniel Aramini, Michael Kehoe, Scott Podger
Communications	Leane Regan, Claire Bobinskas, Dianne Flett[2], Rebecca Jennings
Data Management	Mick Hartcher

Activities

Agricultural productivity	Tony Webster, Brett Cocks, Jo Gentle[6], Dean Jones, Di Mayberry, Perry Poulton, Stephen Yeates, Ainsleigh Wixon
Aquatic and riparian ecology	Damien Burrows[1], Jon Brodie[1], Barry Butler[1], Cassandra James[1], Colette Thomas[1], Nathan Waltham[1]
Climate	Cuan Petheram, Ang Yang
Instream waterholes	David McJannet, Anne Henderson, Jim Wallace[1]
Flood mapping	Dushmanta Dutta, Fazlul Karim, Steve Marvanek, Cate Ticehurst
Geophysics	Tim Munday, Tania Abdat, Kevin Cahill, Aaron Davis
Groundwater	Ian Jolly, Andrew Taylor, Phil Davies, Glenn Harrington, John Knight, David Rassam
Indigenous water values	Marcus Barber, Fenella Atkinson[5], Michele Bird[2], Susan McIntyre-Tamwoy[5]
Water storage	Cuan Petheram, Geoff Eades[2], John Gallant, Paul Harding[3], Ahrim Lee[3], Sylvia Ng[3], Arthur Read, Lee Rogers, Brad Sherman, Kerrie Tomkins, Sanne Voogt[3]
Irrigation infrastructure	John Hornbuckle
Land suitability	Rebecca Bartley, Daniel Brough[3], Charlie Chen, David Clifford, Angela Esterberg[3], Neil Enderlin[3], Lauren Eyres[3], Mark Glover, Linda Gregory, Mike Grundy, Ben Harms[3], Warren Hicks, Joseph Kemei, Jeremy Manders[3], Keith Moody[3], Dave Morrison[3], Seonaid Philip, Bernie Powell[3], Liz Stower, Mark Sugars[3], Mark Thomas, Seija Tuomi, Reanna Willis[3], Peter R Wilson[2]
River modelling	Linda Holz, Julien Lerat, Chas Egan[3], Matthew Gooda[3], Justin Hughes, Shaun Kim, Alex Loy[3], Jean-Michel Perraud, Geoff Podger

Socio-economics

Lisa Brennan McKellar, Neville Crossman, Onil Banerjee, Rosalind Bark, Andrew Higgins, Luis Laredo, Neil MacLeod, Marta Monjardino, Carmel Pollino, Di Prestwidge, Stuart Whitten, Glyn Wittwer[4]

Note: all contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined. [1] TropWATER, James Cook University, [2] Independent consultant, [3] Queensland Government, [4] Monash University, [5] Archaeological Heritage Management Solutions, [6]University of Western Sydney

Shortened forms

AEM	airborne electromagnetics
AHD	Australian Height Datum
APSIM	Agricultural Production Systems Simulator
AWRC	Australian Water Resources Council
CGE	Computable General Equilibrium
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	digital elevation model
GCMs	global climate models
GCM-ES	global climate model output empirically scaled to provide catchment-scale variables
IPCC AR4	the Fourth Assessment Report of the Intergovernmental Panel on Climate Change
IQQM	Integrated Quantity-Quality Model – a river systems model
Landsat TM	Landsat Thematic Mapper
MODIS	Moderate Resolution Imaging Spectroradiometer
NQIAS	North Queensland Irrigated Agriculture Strategy
NRM	natural resource management
ONA	the Australian Government Office of Northern Australia
OWL	the Open Water Likelihood algorithm
PAWC	plant available water capacity
PE	potential evaporation
RCP	representative concentration pathway
Sacramento	a rainfall-runoff model
SALI	the Soil and Land Information System for Queensland
SLAs	statistical local areas
SRTM	shuttle radar topography mission
TRaCK	Tropical Rivers and Coastal Knowledge Research Hub
WRON	CSIRO’s Water Resource Observation Network

Units

MEASUREMENT UNITS	DESCRIPTION
GL	gigalitres, 1,000,000,000 litres
keV	kilo-electronvolts
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	litres
m	metres
mAHD	metres above Australian Height Datum
MeV	mega-electronvolts
mg	milligrams
ML	megalitres, 1,000,000 litres
mS/m	millisiemens per metre

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

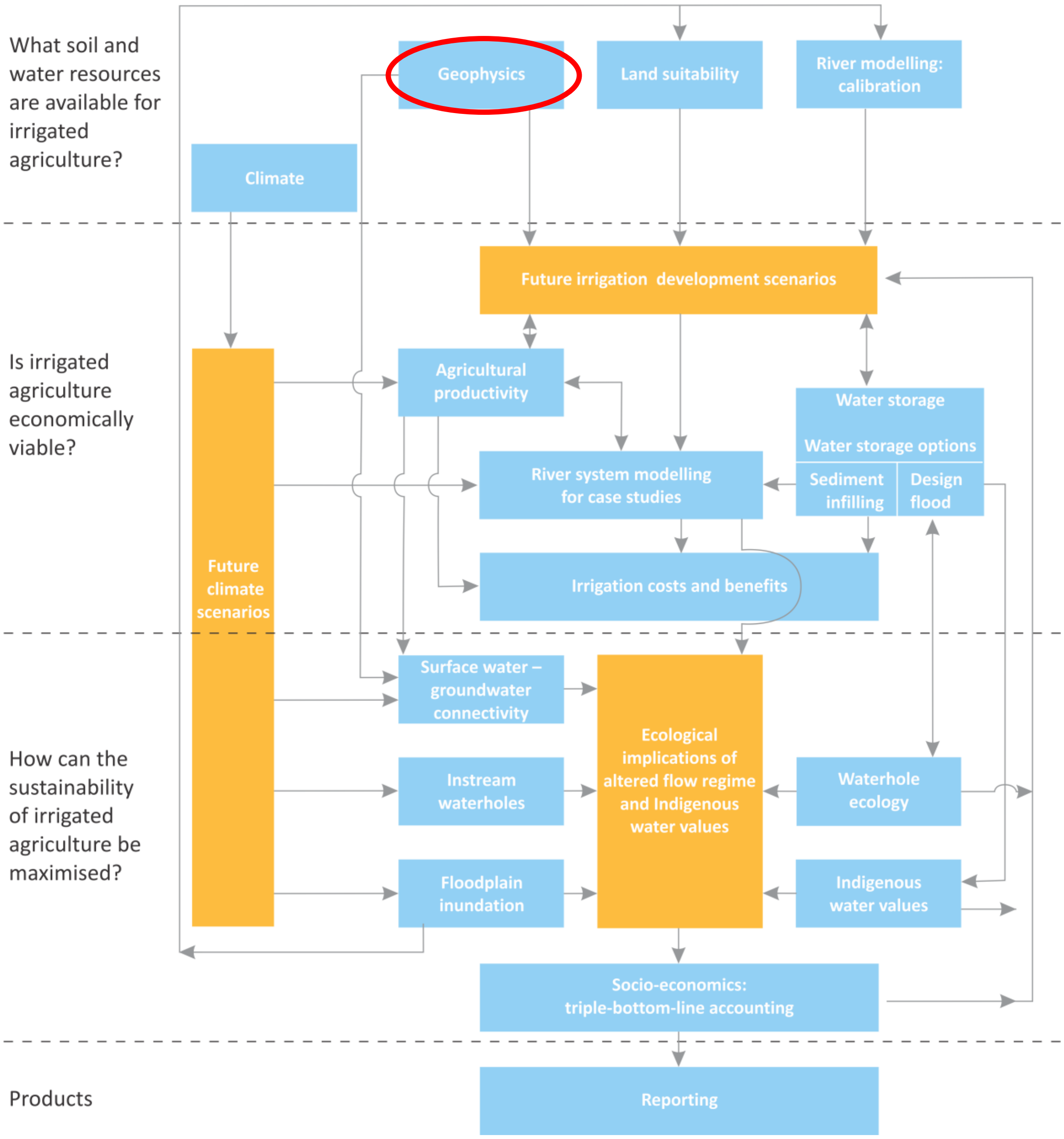
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an 'activity box' links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

Geophysical data are recognised as a key source of information for quantifying groundwater resource potential and salinity risks in priority catchments of northern Australia particularly where new consumptive uses, such as for intensive agriculture, are most prospective. This is particularly so in data-sparse areas, such as Flinders and Gilbert catchments, where they can assist in extending hydrogeological conceptual model development, and confirming and extending our understanding of groundwater and aquifer character and quality. Where they are acquired at finer scales, they can also be useful in linking observed patterns of soil salinity to groundwater characteristics at depth. It is worth noting that the most effective use of geophysical data requires that they be linked to other on –ground investigations to aid their interpretation.

As part of the Assessment, the targeted acquisition of electromagnetic (EM) geophysical data was undertaken across parts of the Flinders and Gilbert catchments using a helicopter EM system. Full coverage of both catchments was not considered as part of this activity, rather a more focussed approach was employed through the acquisition of select traverses along and perpendicular to the main river systems, and in some areas where water storage options were being considered.

Conductivity-depth sections and interval conductivity data were generated for all lines surveyed across the two catchments. While the scope of the data interpretation was limited, the geophysical data provided independent evidence of aquifer architecture and litho-structural features that influence groundwater discharge. Connectivity between the alluvial and deeper aquifers is indicated in the airborne EM data, suggesting that in places base flow from deeper aquifers, may contribute to flows and assist the persistence of pools in the main river systems. In the case of basalts in the Flinders catchment, located adjacent to the Flinders River, inferred processes from the geophysical interpretation indicated why elevated levels of soil salinity occurred on the foot slopes adjacent to the river. The results provide additional constraint on the determination of hydrogeological controls on groundwater variability and discharge to the alluvial aquifer along the Flinders River. In the Flinders catchment the geophysics also contributed to the provision of information pertinent to the water storage sites, including insight into geological structure and stratigraphy.

By mapping near surface conductivity variations, near surface soil salinity distribution was defined in several places in both catchments. The airborne EM data corroborated information obtained by on-ground soil salinity studies in the Maxwelton (Flinders catchment) and Einasleigh (Gilbert catchment) areas and provided additional information on the connection between surface salinity and deeper groundwater. In the former, the geophysics suggested the area was underlain by a thick sequence of alluvial sediments possibly containing fresh groundwater, and these aquifers, in turn, overly deeper systems containing brackish to saline groundwater.

The longitudinal lines following the main river systems indicated that the recent alluvium and bedsands were relatively shallow or thin – and that the presence of a fresh water resource maybe relatively limited. In both catchments the recent alluvial sediments appear to overly an irregular surface of weathered and unweathered basement rocks. This characteristic was noted along the Flinders River, but was particularly well developed in the Gilbert catchment. Irregular thicknesses of bedsands were noted in the river sections south east of Einasleigh, adjacent to Georgetown and in reaches of the Gilbert River further west.

Results from the targeted approach to data acquisition that, specifically the acquisition of high resolution helicopter EM data along select longitudinal river traverses and selected perpendicular lines that crossed the main river systems, have demonstrated and reinforced the effectiveness and value of this approach in data poor areas on northern Australia. The information obtained has corroborated existing knowledge and that derived in other activities undertaken as part of the Assessment.

Contents

Figures

Tables

1 Introduction

1.1 Background

Geophysical data are recognised as a key source of information for quantifying groundwater resource potential and salinity risks in priority catchments of northern Australia particularly where new consumptive uses, such as for intensive agriculture, are most prospective (Northern Australia Land and Water Taskforce 2009). This is particularly so in data-sparse areas, such as Flinders and Gilbert catchments, where they can assist in confirming and extending our understanding of groundwater and aquifer character and quality. Where they are acquired at finer scales, they can also be useful in linking observed patterns of soil salinity to groundwater characteristics at depth. It is worth noting that the most effective use of geophysical data requires that they be linked to other on –ground investigations to assist their interpretation.

As part of the Assessment, a targeted set of electromagnetic (EM) data were acquired across parts of the Flinders and Gilbert catchments using a helicopter system. Full coverage of both catchments was not considered as part of this activity, rather a more targeted approach was employed through the acquisition of high resolution helicopter EM data for select traverses along and perpendicular to the main river systems. In some areas, potential water storage sites were also surveyed as were sites where irrigation opportunities may exist.

The value of longitudinal sampling of river systems and the underlying aquifers, particularly when linked to groundwater investigations, helps develop our conceptual understanding of stream–aquifer connections. This has been demonstrated in other northern Australian catchments (see, for example, Harrington et al. 2013). Similar studies, that have addressed the interpretation of AEM data acquired along a stream axis have been reported by Paine et al. (2006 and 2009), and Hatch et al. (2010). However none of these have undertaken an integrated interpretation as attempted by the Assessment (Petheram et al. 2013a; Petheram et al. 2013b, and Jolly et al. 2013).

1.2 Activity links

The geophysics activity and its outputs were employed to inform work being undertaken in the groundwater activity, with contributions to the land capability and water storage activities.

1.3 Activity scope and objectives

This report focuses on a summary of key results obtained from the targeted acquisition of airborne electromagnetic (AEM) data across the two catchments and specifically addressed:

- Task 1: A determination of surface water-groundwater interactions by providing additional constraint on the determination of hydrogeological controls on groundwater variability and discharge. This will inform water resource planners and managers about the potential for current and future groundwater development to impact on the hydrology and associated ecosystem health of permanent in-stream pools through the provision of baseline data on groundwater quality, the geometry of the alluvial aquifer and relationships with underlying aquifer systems;
- Task 2: The provision of information pertinent to the water storage sites, including insight into geological structure and stratigraphy;

- Task 3: The definition of near surface soil salinity distribution from AEM data, particularly in areas that may be favourable for irrigation development. The results will define spatial patterns of both groundwater and surface salinity which can be employed to understand salinity hazard/risk.

The activity targeted river reaches being considered for detailed groundwater study and areas previously identified as having potential irrigation development. The targeted areas and the extent of coverage were defined in consultation with other activities.

Table 1.1 summarises the key science questions, inputs, scale, methods and outputs for the geophysics activity, although this report addresses a sub-set of those questions.

The geophysics activity focussed primarily on surface water-groundwater connectivity and groundwater quality. The scope of the interpretation was also limited; hence the opportunity remains to further investigate the results linked to soil salinity studies and groundwater resource assessment.

Table 1.1 Input, scale, methods and outputs for geophysics (Activity 5)

KEY SCIENCE QUESTION	INPUT	SCALE	METHODS	OUTPUTS AND LINKS TO OTHER ACTIVITIES
What is the nature of the deeper regional aquifer systems at catchment scales?	• Regional geophysics • Regional Geological mapping	Catchment	• Interp of magnetics and literature review of regional geology	Regional understanding of deep aquifer systems Define the spatial extent of basalt aquifers beneath the alluvials in the upper Einasleigh River
What is the nature and variability of Flinders and Gilbert alluvial aquifer systems, and what are the spatial patterns associated with deeper aquifers and the quality of water they contain?	• AEM data acquired in longitudinal sections • Bore data/geophysical logs	Significant river lengths or just smaller sections of river systems – 100-150kms?	• Acquisition of Helicopter EM data • Inversion of AEM data and interpretation against available bores	• Physical structure of aquifer systems and the groundwater depth and quality variation.
What are the catchment scale variations in alluvial/soil type?	• Regional geophysics - radiometrics •	Catchment scale	Analysis of radiometrics	• Maps of surface/soil material variations
What are the soil salinity variations in key areas?	• AEM data • Soils data	1:50,000	Constrained interpretation of AEM data using available soils data Analysis of near surface responses of AEM data	• Maps of near surface soils salinity in target areas

2 Methods

2.1 Airborne electromagnetics (AEM)

The geophysics activity employed an airborne electromagnetic (AEM) method to better understand the nature and variability soils, the alluvial aquifer systems and their geometry and variability for parts of the Flinders and Gilbert catchments. Full coverage of both catchments was not possible; hence a more targeted approach was taken for critical sections.

2.1.1 PRINCIPLES OF AEM DATA ACQUISITION AND INTERPRETATION

AEM surveying techniques involve the measurement of the varying response of the ground due to the propagation of electromagnetic fields. Primary fields are generated by passing a current through a loop or coil positioned in the air, referred to as the transmitter loop (see Figure 2.1). A secondary field is induced in the ground and these fields are detected by the alternating currents that are induced to flow in a receiver coil, by a process known as electromagnetic induction. As the induction of current flow results from the magnetic component of the electromagnetic field there is no need to have physical contact between transmitter or receiver and the ground. Consequently, electromagnetic (EM) surveys can proceed effectively both on the ground, and in the air.

The primary field travels from the transmitter to the receiver via paths above and below the ground surface (Figure 2.1). In the presence of a conducting body (for example a conductive sediments), the magnetic component of the electromagnetic field penetrating the ground induces eddy or alternating currents to flow in the conductor. These eddy currents generate the secondary electromagnetic field which is measured by the receiver (Peters 2001). The receiver coils record the response of a decaying signal in the ground at various times after the transmitter pulse has been switched off.

The difference between the transmitted (primary) and received (secondary) electromagnetic fields will be determined by the geometry and electrical properties of conductors in the ground. Materials that are highly conductive produce strong secondary electromagnetic fields. Sediments (alluvium), soils or other regolith materials that contain saline pore water generate such fields. The shape of the decaying signal provides information about the conductivity structure of the subsurface.

AEM systems map contrasts in ground conductivity that are then interpreted on the basis of experience and with the support of ancillary data, including surface and bore water EC, downhole conductivity measurements, lithology logs from drilling, surface geophysical investigations and other observations. AEM systems have the capability to map conductivity to depths of several hundreds of metres. With some systems near surface (soil) conductivities can be mapped in conjunction with those at greater depths. Therefore appropriate AEM systems have the potential to provide a three dimension picture of aquifers, and groundwater, in addition to providing information relevant to salinity investigations.

2.1.2 GROUND CONDUCTIVITY

The influence of particular petrophysical characteristics of the alluvial aquifers and underlying sediments on the observed geophysical response follows.

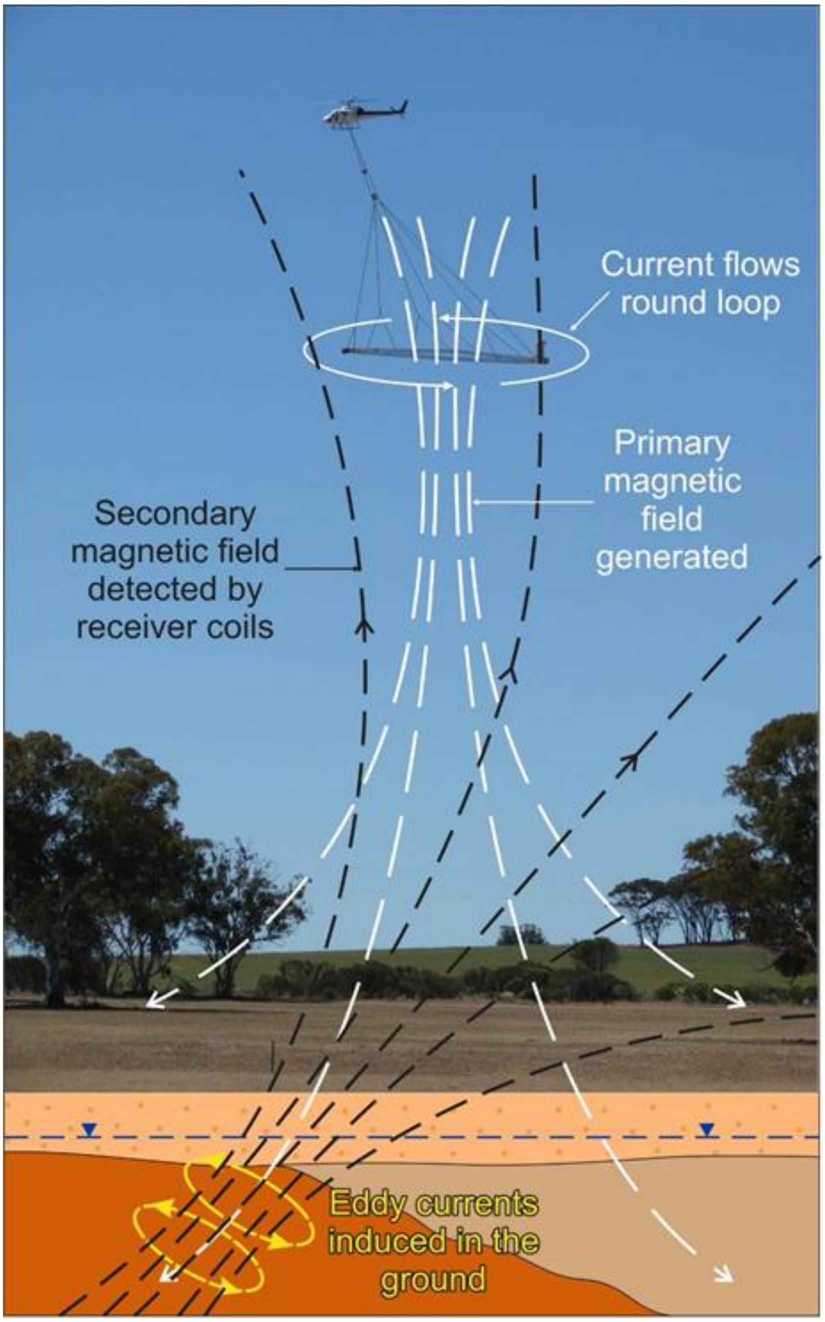


Figure 2.1 Operating principles of an airborne electromagnetic (AEM) system (in this example it is a helicopter-borne time domain EM system)

The measured electrical conductivity (the reciprocal of resistivity) of such materials is a measure of how easily an electrical current can pass through a material. Conductivity itself is a complex function of a number of variables including:

- concentration of dissolved electrolytes - the concentration of ionic conductors in solution;
- amount and composition of clays - particularly those with a moderate to high cation exchange capacity (CEC);
- moisture content - the extent to which the pores are filled by water;
- porosity: shape and size of pores, number, size and shape of interconnecting passages; and
- temperature.

Sedimentary rocks, whether consolidated or unconsolidated are characterised by a range of conductivities (Figure 2.2), but the influence of contained water quality and quantity can also be significant (Palacky,

1987). Generally speaking, it is reasonable to assume that the observed ground conductivity, whether measured by a ground or airborne system, would be non-unique for any given aquifer system. In both consolidated and unconsolidated regolith and sedimentary materials, including alluvial materials and underlying sedimentary rocks, the conductivity will be significantly influenced by the electrolyte (salt) which occurs in moisture-filled pores within an insulating matrix (McNeill, 1980). Whilst the porosity and connectivity of the pores in sediments and in-situ regolith materials play a part in driving conductivity, particularly in the absence of clays, it is the quantity and in particular the quality of the contained pore water that is critical. Clay content and type become important when the concentration of ionic conductors (for, example, salts in solution) is low. Their significance becomes negligible at high ionic concentrations, particularly for clays of low to moderate CEC, such as kaolinite (Emerson and Wang, 1997). Given the quality of the groundwater contained in the alluvial sediments of the catchments studied (see Jolly et al. 2013), it is reasonable to expect that the observed conductivity structure in the AEM data will reflect variations in water quality associated with particular sedimentary packages, rather than factors linked to sedimentary texture (ie grain size, and orientation). Nonetheless, a relationship between sediment type and salinity may occur in some instances.

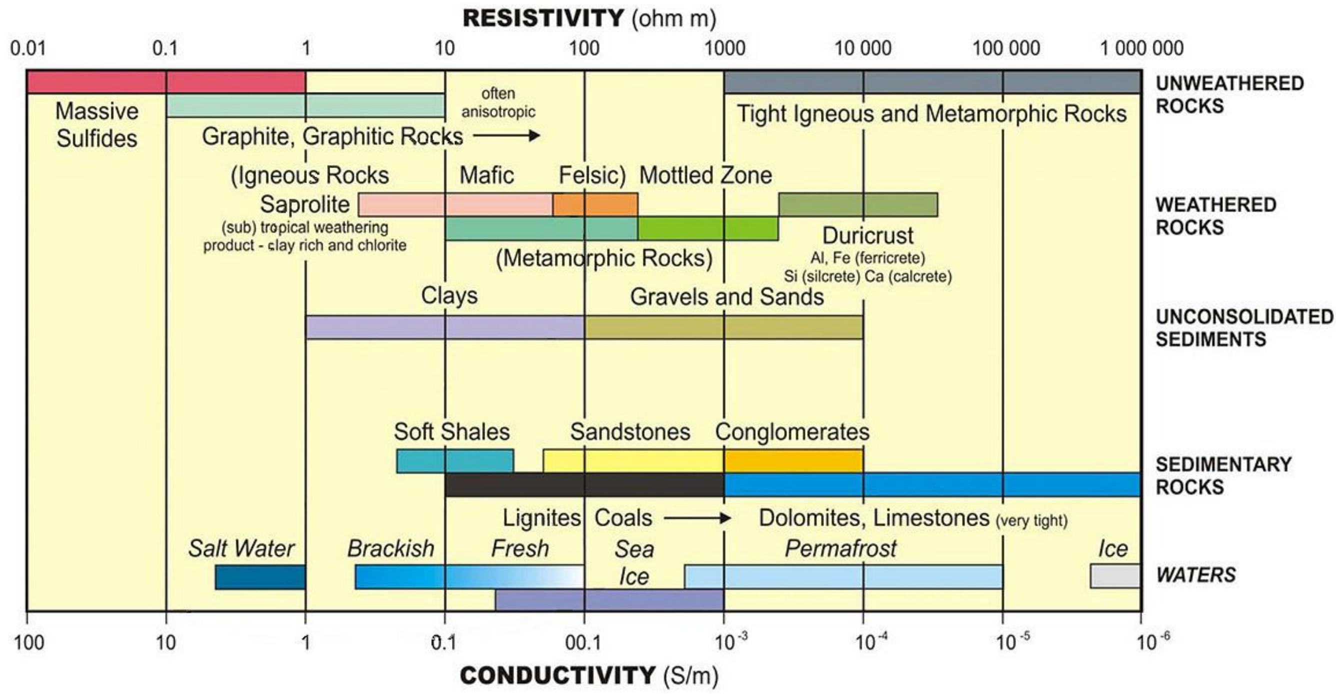


Figure 2.2 A simple schematic that displays the expected conductivity or resistivity of common earth materials. Overlapping values of conductivity show that the inverted conductivity values of the subsurface may not allow for unique determination of material

2.1.3 SPATIAL RESOLUTION

The spatial resolution of an AEM system varies with the system type, sample time or frequency, and with ground conductivity. It is different in the horizontal and vertical direction. Commonly resolution is considered in terms of the volume of the ground that contributes most of the response for each measurement. Helicopter AEM systems return a weighted average response over lateral distances of up to 100 metres or more. The smallest lateral (horizontally orientated) features that can be resolved near surface are around 30-60m for helicopter systems where good conductivity contrasts are present. These figures increase with depth. Normally the highest resolution is measured along a flight line, with the perpendicular resolution being determined by line spacing. These issues should be borne in mind when comparing models of ground conductivity or other products derived from the AEM data to information collected from bore data, individual soil pits, or surface EM surveys undertaken with EM 38, or EM 31 instruments.

2.1.4 AEM SURVEY APPROACH AND SYSTEM REQUIREMENTS

Geophysical system selection for the Flinders and Gilbert catchments was predicated on the need to acquire high resolution AEM data in a longitudinal section down a braided/anastomosing river system. The approach adopted is represented schematically in Figure 2.3, with data acquired along the main channels of the Flinders, Gilbert and Einasleigh Rivers. Lines were also acquired perpendicular to the river system to help understand spatial patterns of groundwater quality and aquifer character across broader sections of the alluvial systems that characterise these catchments. Given the sinuous nature of these river systems a helicopter EM system was deemed most appropriate for data acquisition. A similar rationale was employed with success for a survey along the Fitzroy River in northern Western Australia (Fitzpatrick et al. 2011).

In addition to the above, there was a need to resolve variation in groundwater quality, the characteristics of the aquifer in the near surface and at depth (up to ~100m), and the salinity in soils. Therefore, careful consideration of system bandwidth was required. In an environment where groundwater was known to be brackish to saline in places (Jolly et al. 2013), but where the distribution of salinities are generally poorly understood, the project sought to maximise system depth of investigation while maintaining a near surface mapping capability. System sensitivity to small changes in relative resistivity, particularly at high (more resistive) levels, also formed part of the system assessment/selection.

Another consideration that influenced system choice related to system calibration. In the absence of ground calibration data and the desire to eliminate the use of external calibration procedures as part of the Assessment, we sought to employ a system that did not necessarily require either.

The airborne electromagnetic (AEM) system selected for this study was the SkyTEM[304] Time Domain helicopter EM (TDHEM) system (Sørensen and Auken 2004, Joseph and Williamson, 2013). This system has been successfully applied to the mapping of alluvial and deeper aquifers in northern Australia (e.g., Lawrie et al. 2010; Fitzpatrick et al 2011) and has a demonstrated ability to define both a near surface and deep conductivity structure in environments as was expected for northern Australian catchments. The SkyTEM system is calibrated in the laboratory and verified at the Danish National Reference Site (Forged et al. 2013), hence it offered the opportunity to deliver relatively accurate models of ground conductivity through the employment of appropriate interpretation methods without necessarily resorting to the use of site-specific calibration data.

2.1.5 SKYTEM AEM SYSTEM

The SkyTEM[304] time-domain electromagnetic (EM) system is carried as a sling load towed beneath a helicopter (Figure 2.4). A full technical description of the SkyTEM is given by Sørensen and Auken (2004) and Halkjær et al. (2006). The nominal survey altitude of the transmitter in the Flinders and Gilbert survey was ~30 m, but this varied depending on the presence of trees, power lines, bores and related anthropogenic features. The transmitter, mounted on a lightweight frame (Figure 2.4), is an eight-sided loop with an area of 347.52 m^2 (Joseph and Williamson 2013). It is divided into segments for transmitting a low moment in one turn and a high moment in all four turns. SkyTEM is capable of operating in a dual transmitter mode (Sørensen and Auken, 2004), and for the Assessment all data were acquired using interleaved low and high-moment transmitter modes. Data are pre-processed by filtering and then stacked resulting in data output every 0.5 s (equating to approximately 15 m on the ground). In the low-moment mode, a low current, high base frequency and fast switch-off of the transmitter pulse provides early time data for shallow imaging. This is in contrast to high-moment mode, where a more powerful current is employed at a lower base frequency, in order to provide late time data for deeper imaging.

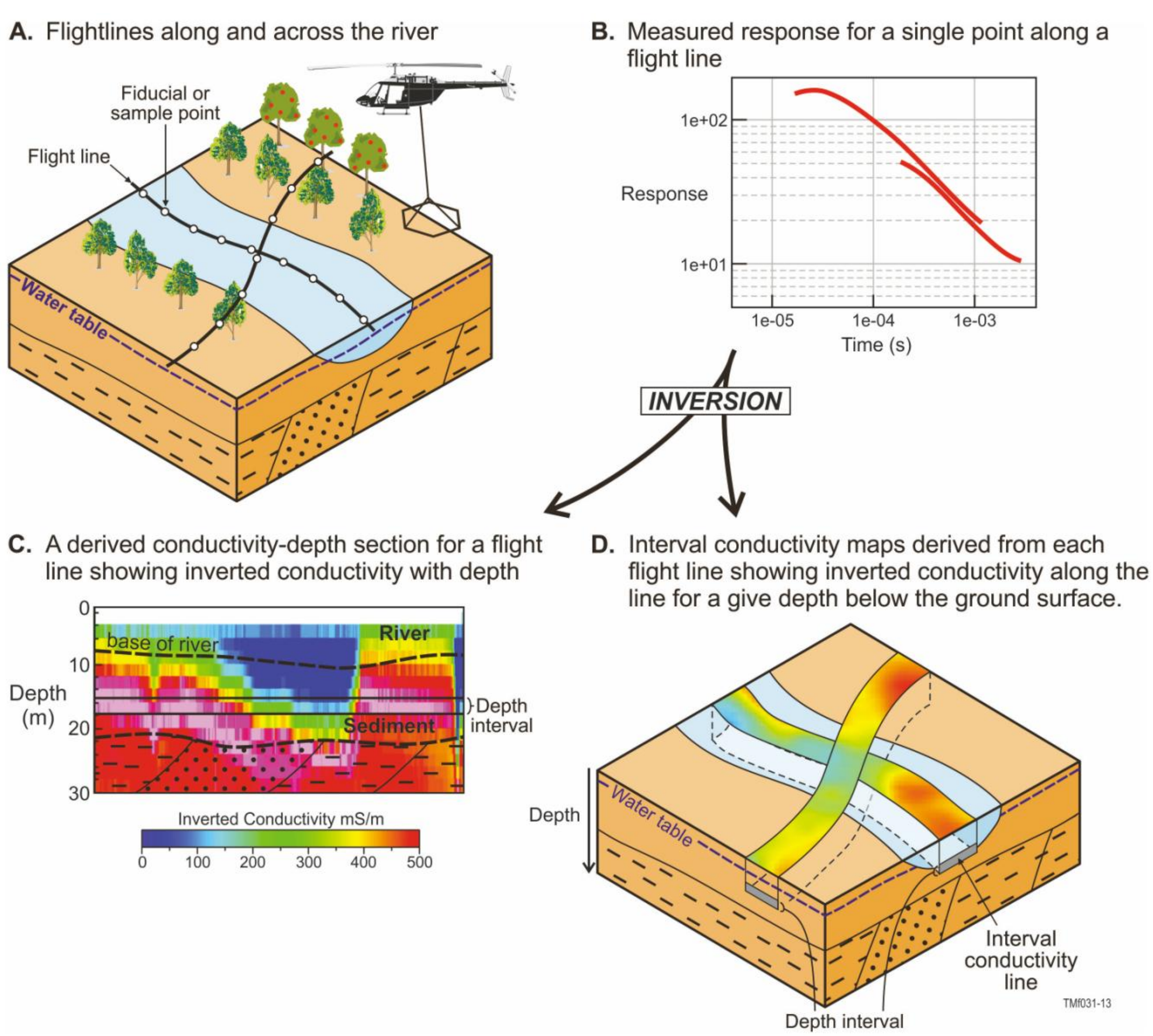


Figure 2.3 Schematic representation of helicopter EM (in this example a time domain EM system) data acquisition and interpretation in longitudinal river surveys. Data are acquired along parallel flight lines, with data recorded at regular intervals along each flight line and resampled into individual points known variously as soundings, stations and fiducials (Panel A). The EM transmitter and receiver are towed beneath the helicopter with the receiver measuring the secondary responses as a function of time (Panel B). The measured response can be used to determine the conductivity-depth function by transformation or inversion, and derived conductivity-depth values can be calculated for each observation, taking account of the elevation of the system above the ground, and then stitched together into sections (Panel C), to provide a representation of the 2D variation of conductivity, sometimes referred to as a “para-section”. Conductivity depth profiles can be combined into a 3D gridded volume from which arbitrary sections, horizontal depth slices (or interval conductivity images) and iso-surfaces can be derived showing the spatial distribution of conductivity as it varies with depth (Panel D). These maps can be shown as elevations (mAHD) or as depth intervals below the ground surface ground surface.

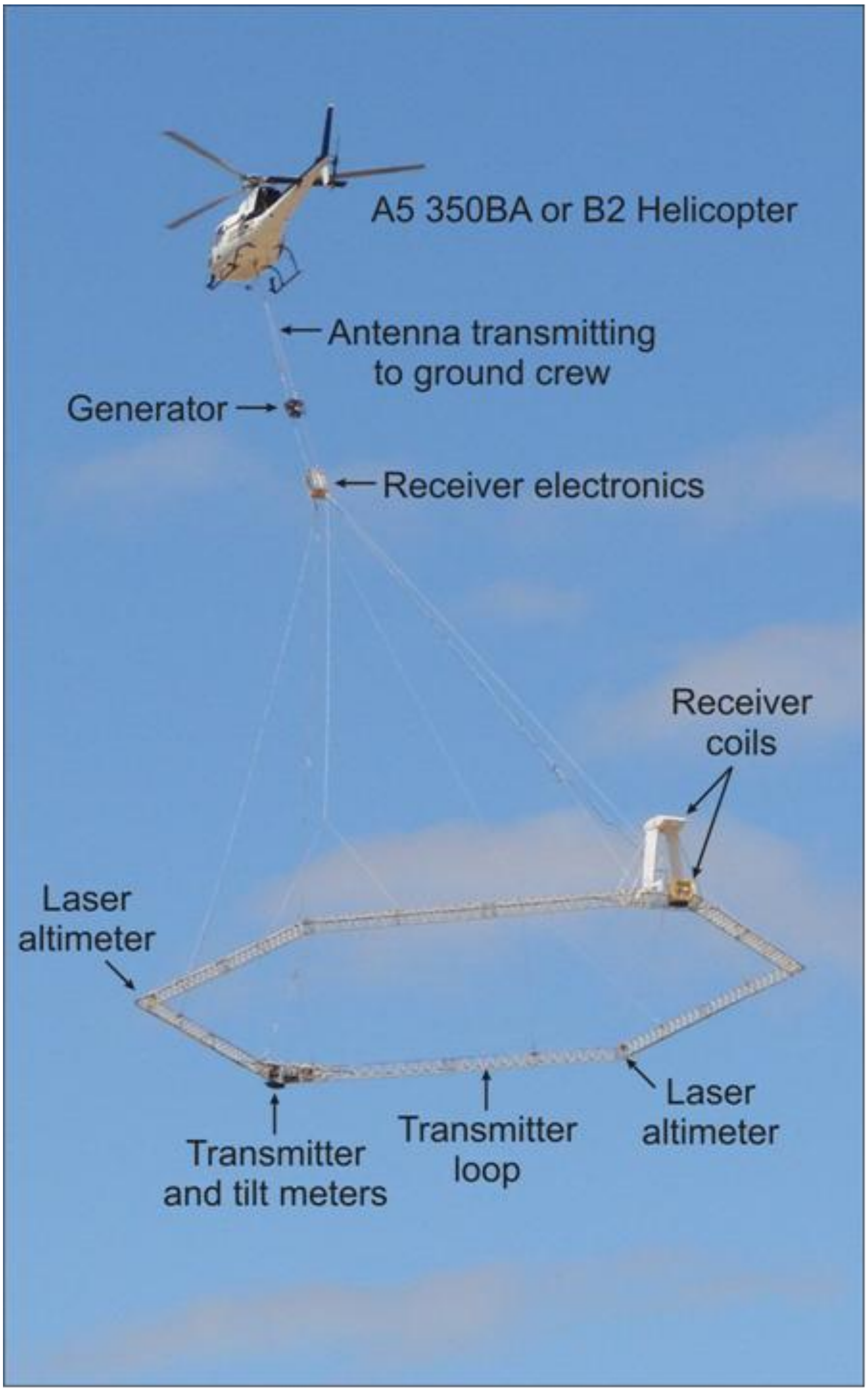


Figure 2.4 SkyTEM TDEM system in flight mode

2.1.6 AEM DATA ACQUISITION

The SkyTEM survey was flown between the 26th November 2012 and 12th December 2013 (Joseph and Williamson 2013), with sections along both the Gilbert and Flinders Rivers covered. Over 1830 kilometres of data were acquired (Figure 2.5). In the Flinders catchment data acquisition was restricted to its upper reaches. In the Gilbert catchment, data acquisition took place adjacent to and south of Einasleigh, along the Einasleigh River, along a stretch of the river that runs past Georgetown, and in the middle reaches of the Gilbert River. Additional details relating to the survey are provided in Joseph and Williamson (2013).

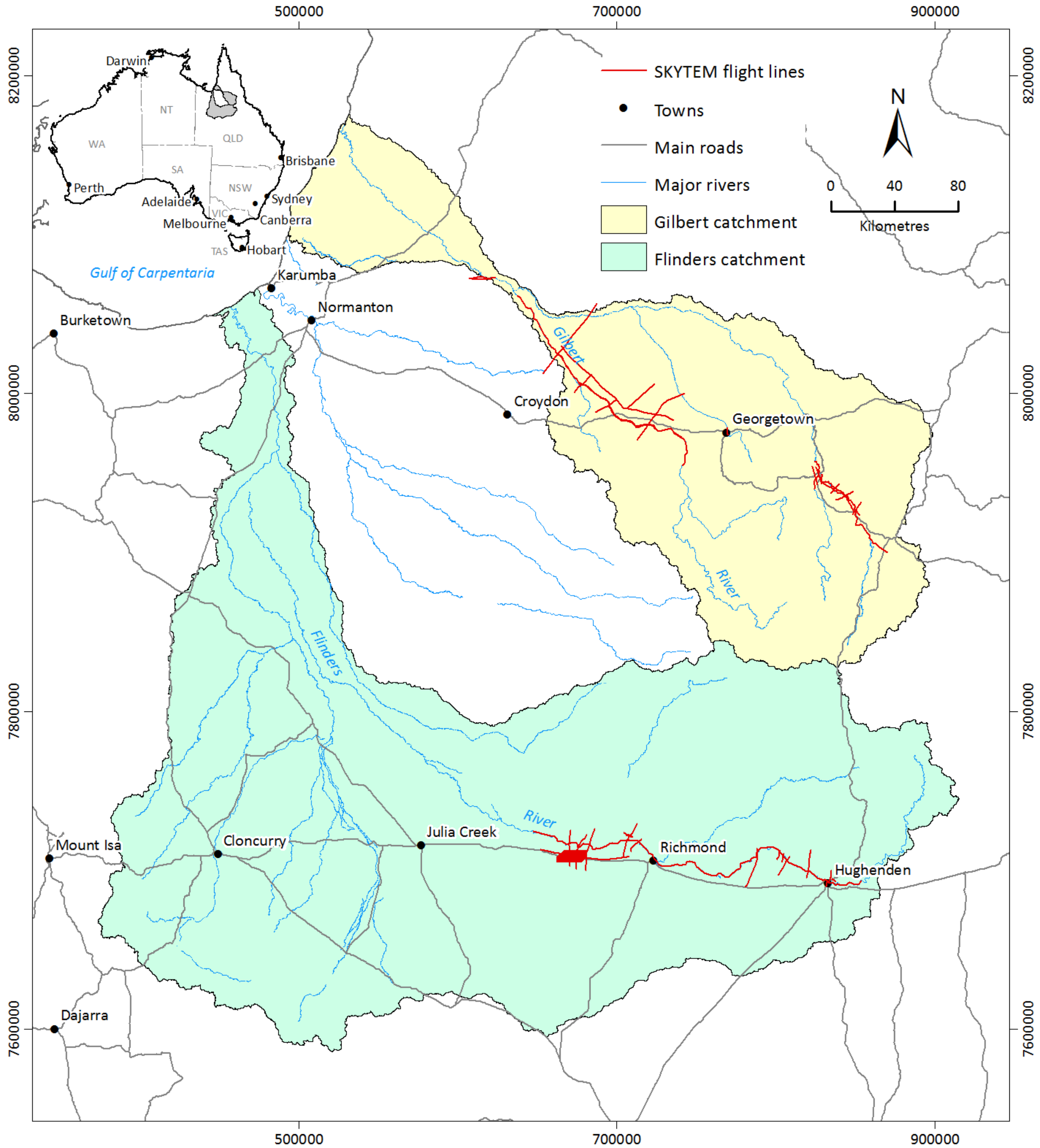


Figure 2.5 Location of SkyTEM survey lines in the Flinders and Gilbert catchments

2.2 AEM processing and inversion

Although AEM systems operate with a specified sampling rate, airborne geophysical data are still collected and resampled into individual points known variously as soundings, stations and fiducials (Figure 2.3). In the case of the SkyTEM system, this discretisation of data is natural since it operates with dual-moments and both low and high moment data are acquired along a flight line before being merged into a single station for inversion. Inversion is a process that involves the transformation of a geophysical data into a model of the earth's physical properties, in this case subsurface conductivity.

2.2.1 AEM DATA PROCESSING

Once AEM data acquisition was complete, the data were assessed for quality. They were then subject to further processing, including noise removal. In this activity, we used the Arhus Workbench (Auken et al.2009) for processing the survey data. The Workbench has been designed specifically for examination, processing and inversion of AEM geophysical surveys, and is capable of displaying survey data in a manner consistent with GIS applications. The data acquired in the Flinders and Gilbert catchments were examined for a consistency in the quality of decays, noise characteristics, and electromagnetic coupling to man-made structures such as powerlines, fences, sheds, and pipelines. An along-line averaging filter was applied to the data, and the low- and high-moment stations were splined and reconciled to coincident station points so that each point (station) in the survey has both moments of data associated with it. In areas of high cultural noise, the AEM data is culled, thereby reducing the amount of spurious data points and reducing the possibility of erroneous interpretation (Viezzoli et al. 2012).

2.2.2 AEM DATA INVERSION

Every station of an AEM survey contains information about the conductivity about the ground beneath it. However, as indicated earlier, the signal measured by an AEM system at a particular location is a record of the time rate of change of the secondary magnetic field induced in the ground due to the excitation of the primary field generated by the transmitter loop on the air. Taking into consideration the current pulse, the waveform duration and strength, altitude, pitch, roll, receiver position and receiving characteristics for the secondary signal, it is possible to calculate a model of the conductivity-depth structure of the earth that could be responsible for the measured response. This is known as the *inversion approach* to measured data. It relies on an accurate description of the system and a calculation of the forward response of the physical phenomenon of induction in the ground due to an airborne transmitting loop. In this report, we use the program *em1dinv* (Auken et al. 2005) which is a forward and inverse modeller of 1D layered conductivity-depth models.

The SkyTEM data sets for the two catchments studied were inverted using a spatially-constrained inversion (SCI) methodology and is described by Viezzoli et al. (2008). The SCI is a quasi-3D inversion methodology, based on the 1D forward response of em1dinv, with 3D spatial constraints from neighbouring stations. The spatial constraints allow prior information (e.g., the expected geological variability of the area) to migrate along and through the dataset by limiting the rate of change of conductivity for individual layers; both vertically at the single station and laterally along and across the flight lines. Given that data are present in single lines, the inversion methodology operates in a manner similar to the laterally-constrained inversion (LCI) method of (Auken et al. 2005). Output inversion models balance the information present locally within an individual TEM sounding against information carried by the constraints. SCI has a demonstrated applicability in semi-layered environments such as those expected for the FGARA survey areas (see Viezzoli et al. 2009 and Viezzoli et al. 2010). Figure2.6 shows a schematic describing how spatial constraints are applied on the inversion parameters for an AEM sounding. The constraint applied to the calculation of the conductivity at an individual layer is determined by the vertical constraints at the sounding site, and by the conductivity of nearby locations. The strength of the constraints is set at the beginning of the inversion run, and need to be adjusted according to the expected variability (both laterally and vertically).

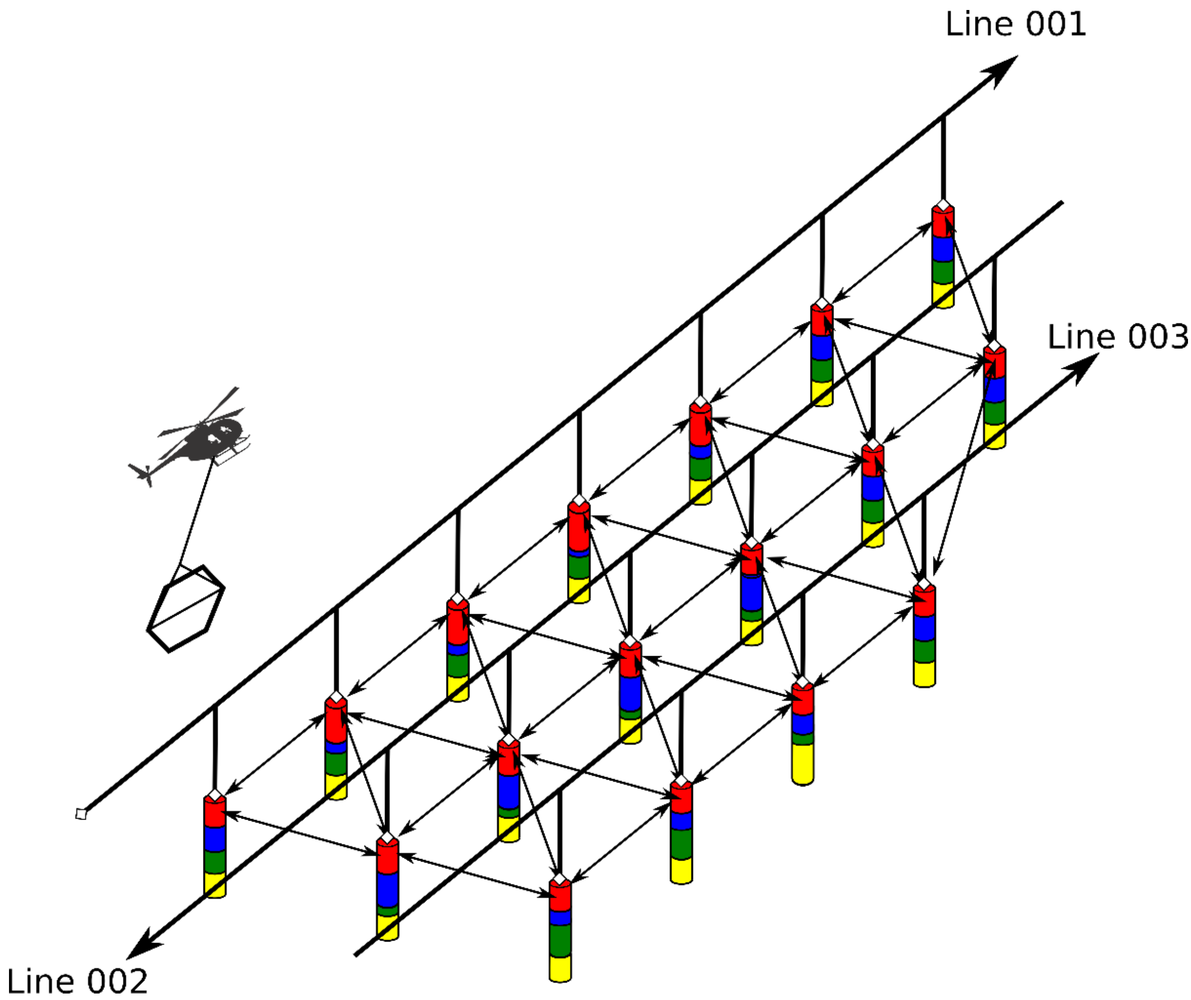


Figure 2.6 Schematic showing the spatial constraints applied to inversion parameters on individual soundings for the first layer (in red), for a few-layer inversion algorithm. Similar constraints exist between other layers (layer 2 (blue), 3 (green) and 4 (yellow)) as well as vertically between adjacent model parameters at a single sounding.

The SkyTEM data have been inverted using 30-layer conductivity models. The last layer is a half-space that extends to infinite depth, and the thickness of each layer was not allowed to change during the inversion. This type of inversion is known as a smooth-model inversion, since the constraints on thickness are hard (constrained to not change), while the constraints on conductivity of each layer, and across layers, is soft (allowing for smooth changes of conductivity values across vertical layers). The inversion is started with a ground conductivity chosen specifically for each layer of the inversion. Lateral constraints of the conductivity values are scaled with a power law function from a base level of 25m, meaning that the constraint that controls conductivity from one station to another drops with the inverse of distance. Vertical and horizontal constraints to the model parameters are set quite low, given that the SkyTEM data for this survey is was characteristically low-noise. An understanding that the variability in conductivity both laterally and vertically was expected to be quickly-varying (although low for Australian conditions) also influenced the choice of the constraints employed.

Conductivity-depth sections and interval conductivity data were then generated for all lines across both catchments.

3 AEM Interpretation and results

3.1 Catchment results

Results from an interpretation of inverted SkyTEM data are considered for each catchment in turn. These analyses are limited in scope and their full value will only be realised when examined in the context of existing ground data, and where they are used to guide further on-ground investigations.

3.2 Flinders catchment

As mentioned previously, the SkyTEM data acquired over the Flinders catchment (Figure 3.1) was processed to produce sections (referred to as conductivity-depth sections) that show the conductivity of the ground as it varies with the depth below the ground surface. The geophysical data were collected in lines along the upper reaches of the Flinders River and across the main river systems in this part of the catchment.

The sections and maps generated provide a spatial picture of changes in ground conductivity along or adjacent to the main channel of the Flinders River and, where the lateral traverses are present, an indication of the lateral conductivity structure associated with the Flinders River alluvial and underlying aquifer systems. An example of the ground conductivity presented for four depth intervals below the ground is presented in Figure 3.2.

Panel D shows that at depth (~18.5 – 21.4m) the sub-surface sediments and bedrock of the Flinders catchment are characterised by a varying conductivity, and in places these ground conductivities are relatively high (>1000 mS/m). For example the conductivities to the north and west of the Maxwelton grid (at the western end of the survey area), are relatively higher than those encountered further to the east. In the data acquired along the Flinders River, higher conductivities are noted in the section beneath the river for a reach east of Richmond and also for a reach just west of Hughenden (Figure 3.2). These higher conductivities are attributed to a poorer groundwater quality contained in the sediments that underlie the river in these areas. This may be significant if there is an upward head from these areas which discharges the more saline groundwater into the bed of the river and into the alluvial aquifer adjacent to the river.

In Panels A and B, the data suggest that the conductivity of the river bed and some adjacent areas in the alluvial aquifer, the conductivities are relatively low (~400 mS/m and less). This may reflect the presence of fresher groundwater in the bed sands along the river and in adjacent areas.

In the areas east of Richmond, and west of Hughenden, the persistence of the higher conductivity zones up towards the surface from the deeper sediments supports the notion of an upward movement of more saline groundwater from depth in these areas. Ground conductivities appear to be higher away from the river as indicated in the transects that cross the river in a roughly N-S direction. Several subsets of the acquired data were examined, and the areas chosen for more detailed study are shown in Figure 3.3.

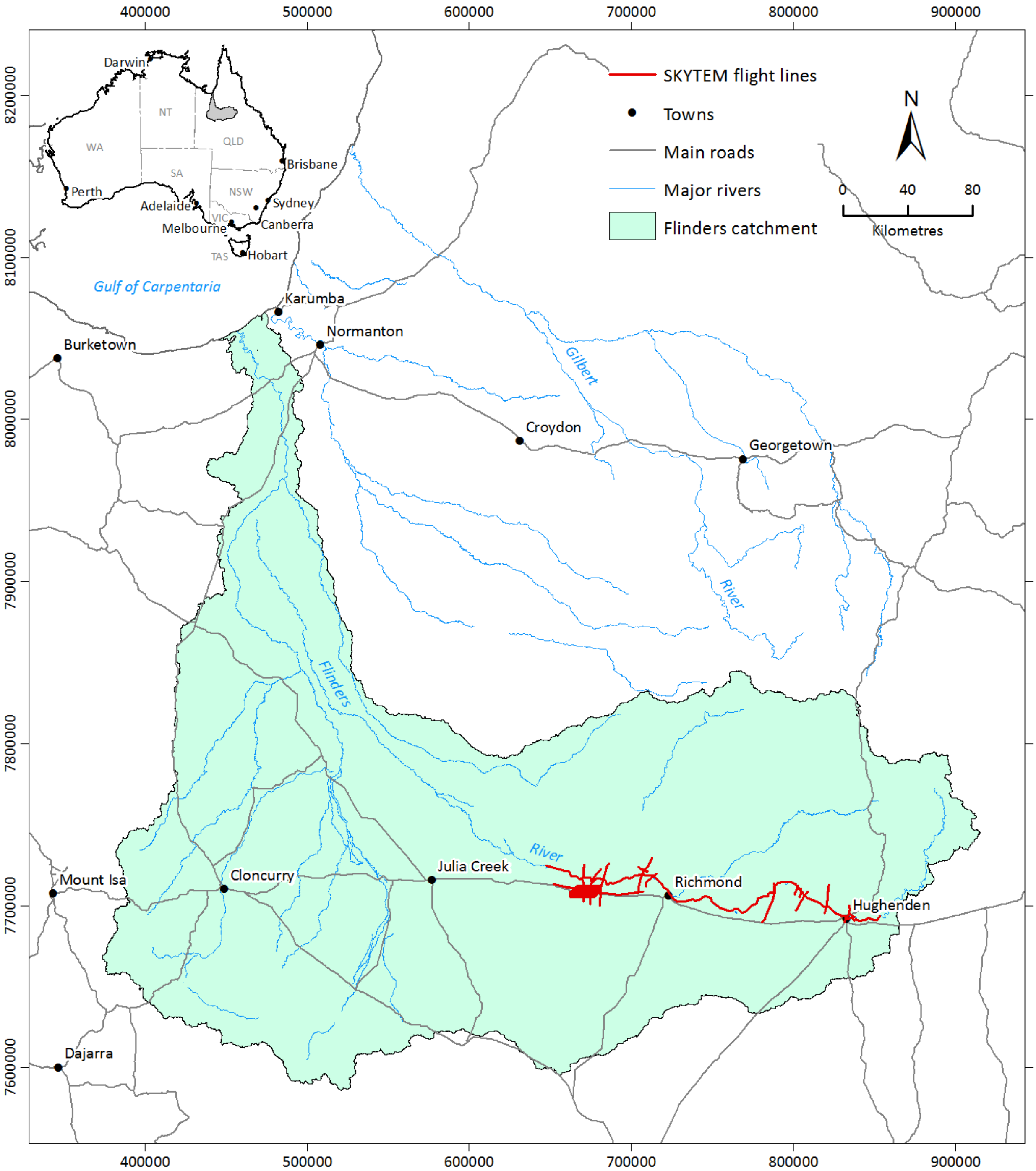


Figure 3.1 Location of SkyTEM flightlines in the upper reaches of Flinders catchment

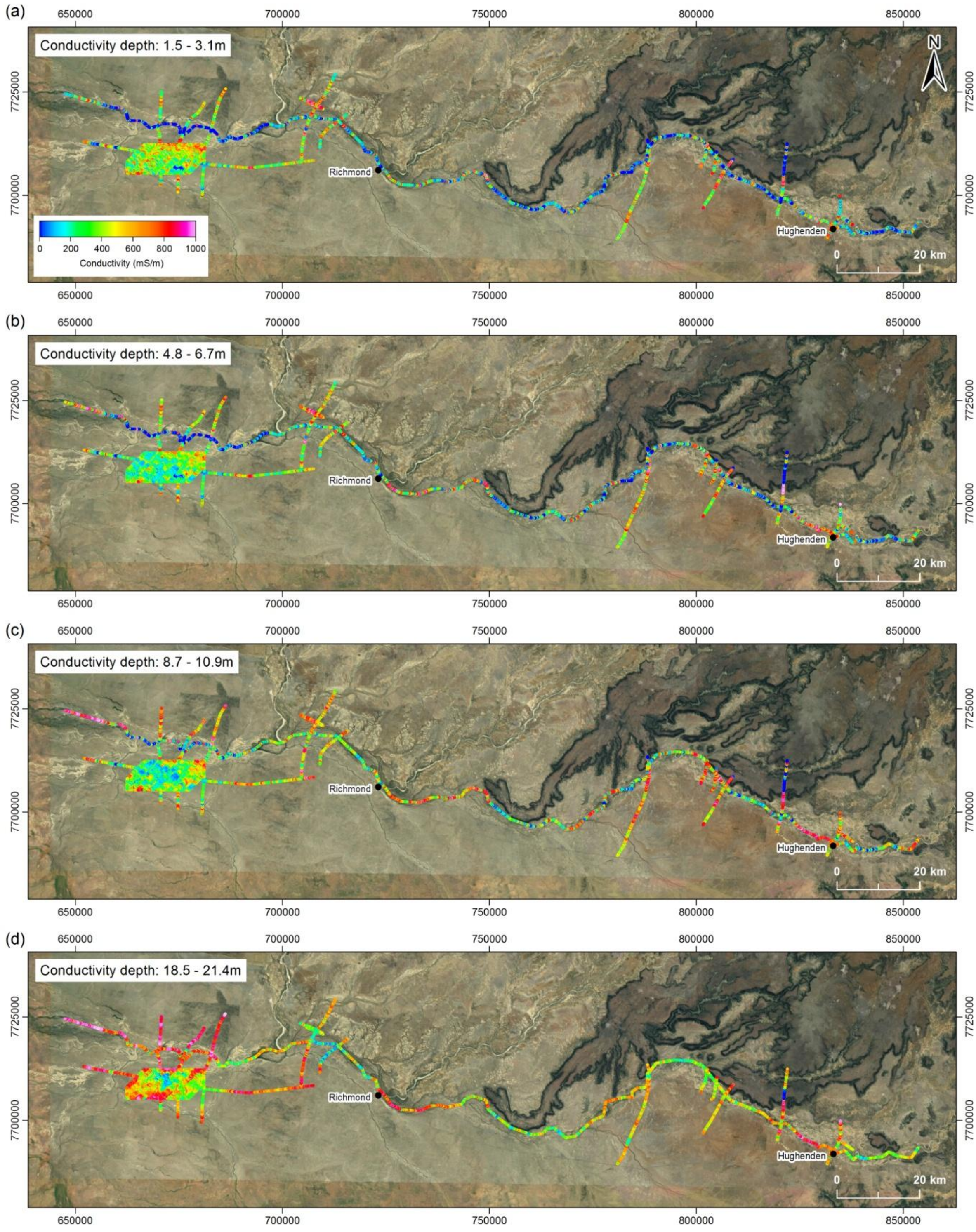


Figure 3.2 Maps of ground conductivity for four depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface. Panel (a) shows an average conductivity for the ground between 1.5 and 3.1m; Panel (b) an average conductivity for a depth 4.8 and 6.7m below the ground surface; Panel (c), an average conductivity for a depth 8.7 and 10.9m below the ground surface; and Panel (d), an average conductivity for a depth 18.5 and 21.4m below the ground surface.

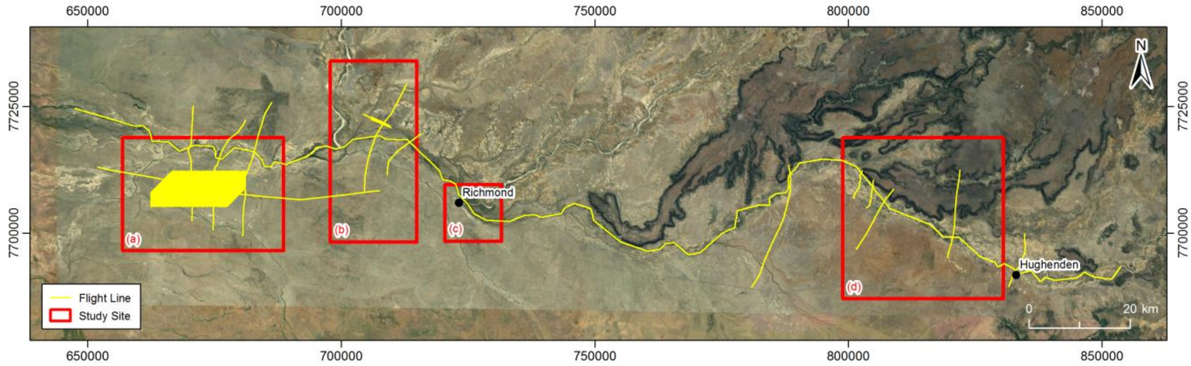


Figure 3.3 Flinders River AEM survey lines (yellow) with individual study areas defined by the rectangular boxes.

Maxwelton

In the Maxwelton area (Figure 3.3 rectangle area (a)), a grid of AEM survey lines was collected with a line spacing of 300m. The area covered is shown in Figure 3.4.

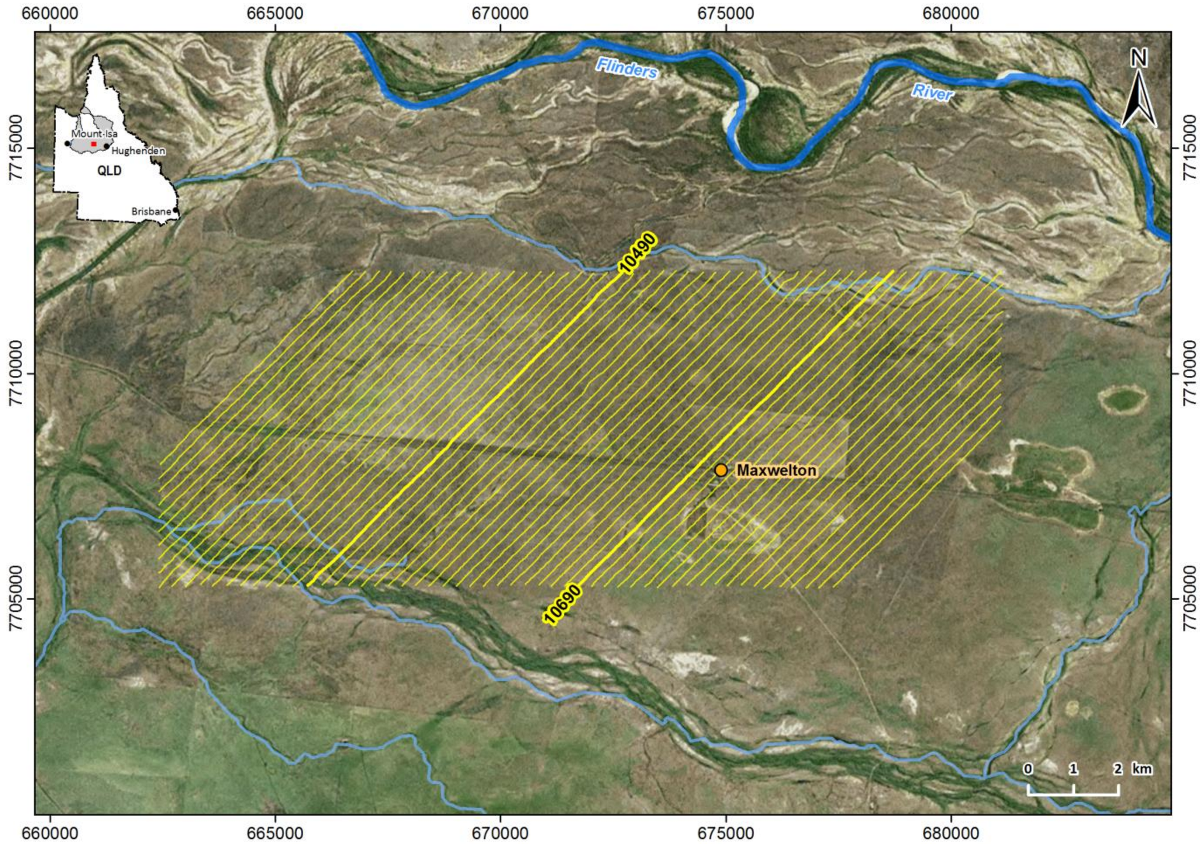


Figure 3.4 AEM flightline map for Maxwelton/O'Connell Creek area. Flightlines are shown in yellow. Sections from those line numbers are lines discussed in the text.

The AEM data have been imaged as a series of conductivity-depth slices, showing how conductivity below the ground surface changes with depth. Figure 3.5 shows the ground conductivity for the Maxwelton area at different depth intervals from the surface to over fifty five metres below the ground surface.

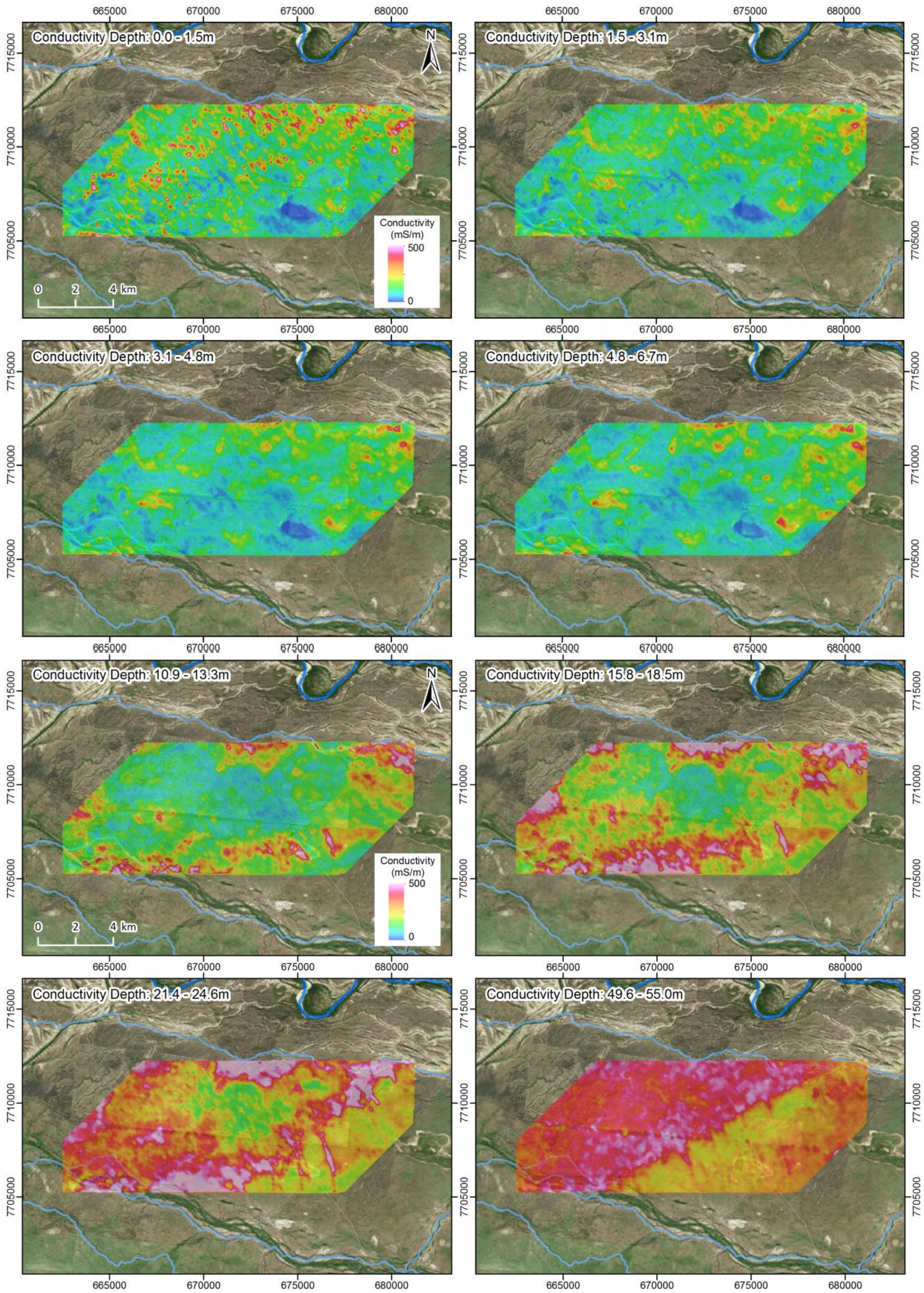


Figure 3.5: Maps of ground conductivity at different depth intervals from the surface to over fifty five metres below the ground surface for the Maxwelton/O'Connell Creek area. Maps have been scaled to show conductivity ranges between 0 and >500 mS/m.

Higher ground conductivities are noted in the northern part of the area with a suggestion that some of the elevated conductivities are associated with contemporary stream channels that are incised across the area. Whether these correspond to more clay-rich alluvial sediments or accumulation of salts in the soils as a result of discharge remains to be determined. Between ten and thirty metres below the ground (Figure

3.5), a zone of relative low conductivity is defined occupying the central part of the surveyed area. This is interpreted as an area of relatively fresh groundwater in younger alluvium, forming a mound above an older sequence of sediments containing more brackish groundwater. At approximately fifty metres below the ground surface, this feature has disappeared, replaced by a zone of higher conductivities which we interpret to be brackish to saline groundwater in a deeper aquifer. The sharp boundary, trending NNE-SSW in the deepest interval conductivity, defines a boundary between two sedimentary units, with the contrast in conductivity attributed to a contrast in the quality of the groundwater they contain (Figure 3.5).

The presence of an alluvial aquifer, with what is interpreted as relatively fresh groundwater, overlying a deeper aquifer containing brackish groundwater, is also illustrated in conductivity-depth sections across the Maxwelton area for individual flight lines. The sections for Lines 10490, and 10690 shown in Figures 3.6 and 3.7, correspond to the lines shown in Figure 3.4.

These conductivity-depth sections suggest a 10-20 m thick unit of relatively low conductivity, overlying sediments of the Rolling Downs Group that may contain fresh to brackish groundwater. The cause of the sharp change in ground conductivity at depth remains undetermined, but may be related to a change in sediment type, and perhaps a change in groundwater quality. To complement the geophysics on-ground work is required to fully ascertain the hydrogeology of the Maxwelton area.

If a relatively fresh groundwater resource does exist in the alluvium underlying the soils in the Maxwelton area, it could provide a limited resource for irrigation, if required. The fresh groundwater indicated in the subsurface sediments has the potential to be used as a target for pumping, which may be used to keep groundwater levels low in irrigated areas, thereby reducing the likelihood of secondary salinity. The AEM data suggests that groundwater quality in the subsurface is good, although the water will probably still contain salts that will be concentrated through evaporation.

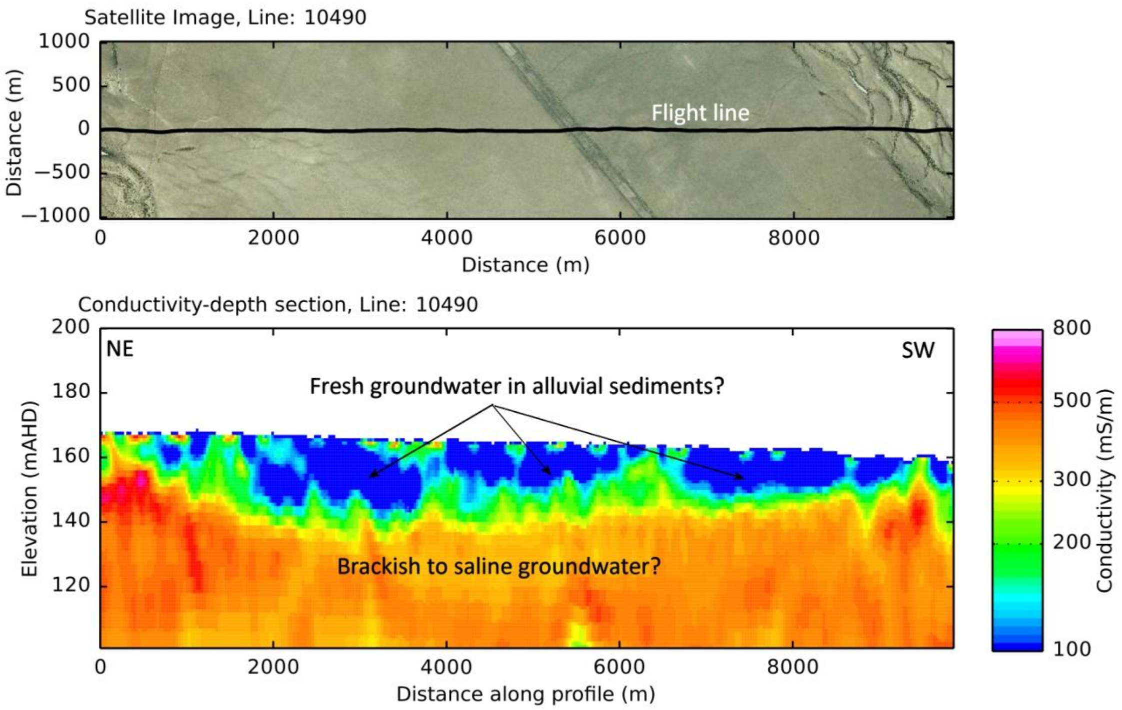


Figure 3.6 Conductivity-depth section (lower panel) for flightline 10490 (see Figure 3.4 for location). Location of flight line on a satellite image is shown in upper panel.

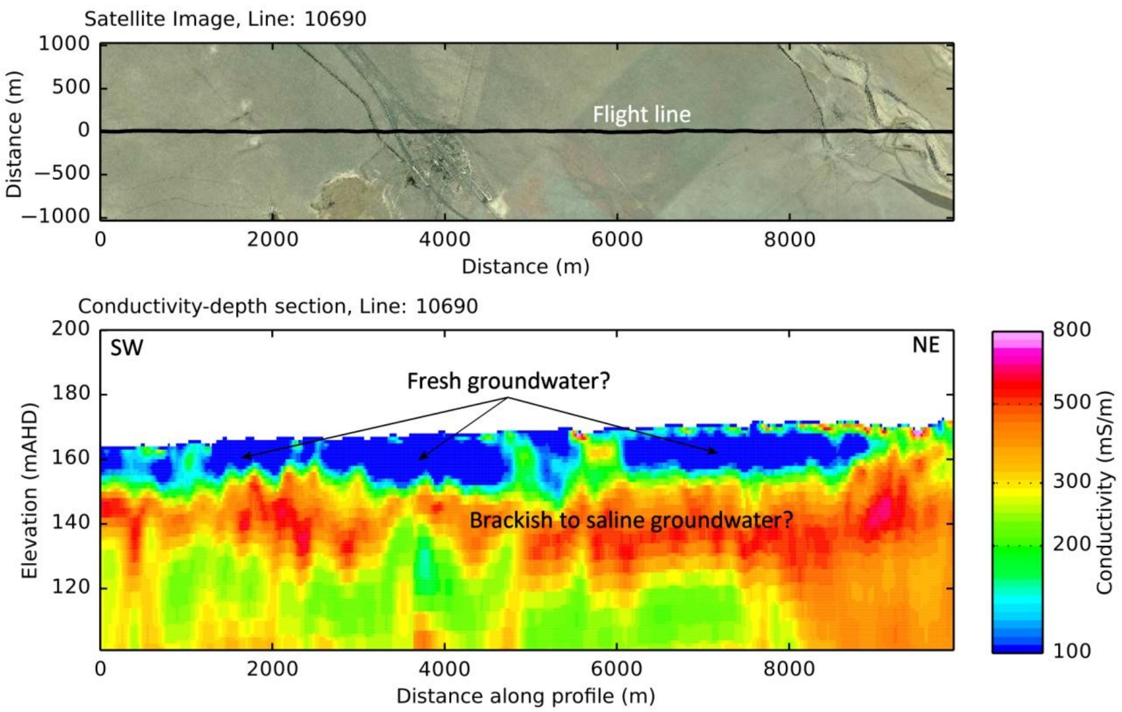


Figure 3.7 Conductivity-depth section (lower panel) for flightline 10690 (see Figure 3.4 for location). Location of flight line on a satellite image is shown in upper panel.

O'Connell Creek Storage

In order to better define the potential of the proposed O'Connell Creek storage, a N-S line of geophysics was acquired (Figure 3.3- rectangle area (b) and Figure 3.8), was acquired parallel to the potential dam axis. A conductivity-depth section for this line is shown in Figure 3.9. The inverted conductivity data suggests either a fold in the sediments of the Rolling Downs Group striking at right angles to the orientation of the Creek, or that the sediments are distorted (folded) along a fault, the orientation of which is unclear. The resistive unit is interpreted to correspond to the Toolebuc Limestone or Toolebuc Formation, underlain by the more conductive Wallumbilla Formation, and overlain with the Allaru Mudstone, also being relatively more conductive.

A separate analysis of the regional airborne magnetics for the O'Connell Creek area indicates the presence of NW-SE linear structures which could be faults. The creek could have developed along one such fault, preferentially eroding and exploiting a line of weakness.

Whether there is potential for leakage from a dam to deeper aquifers along such a fault, if present, may need to be considered, and this feature should be targeted in future investigations relating to the proposed storage.

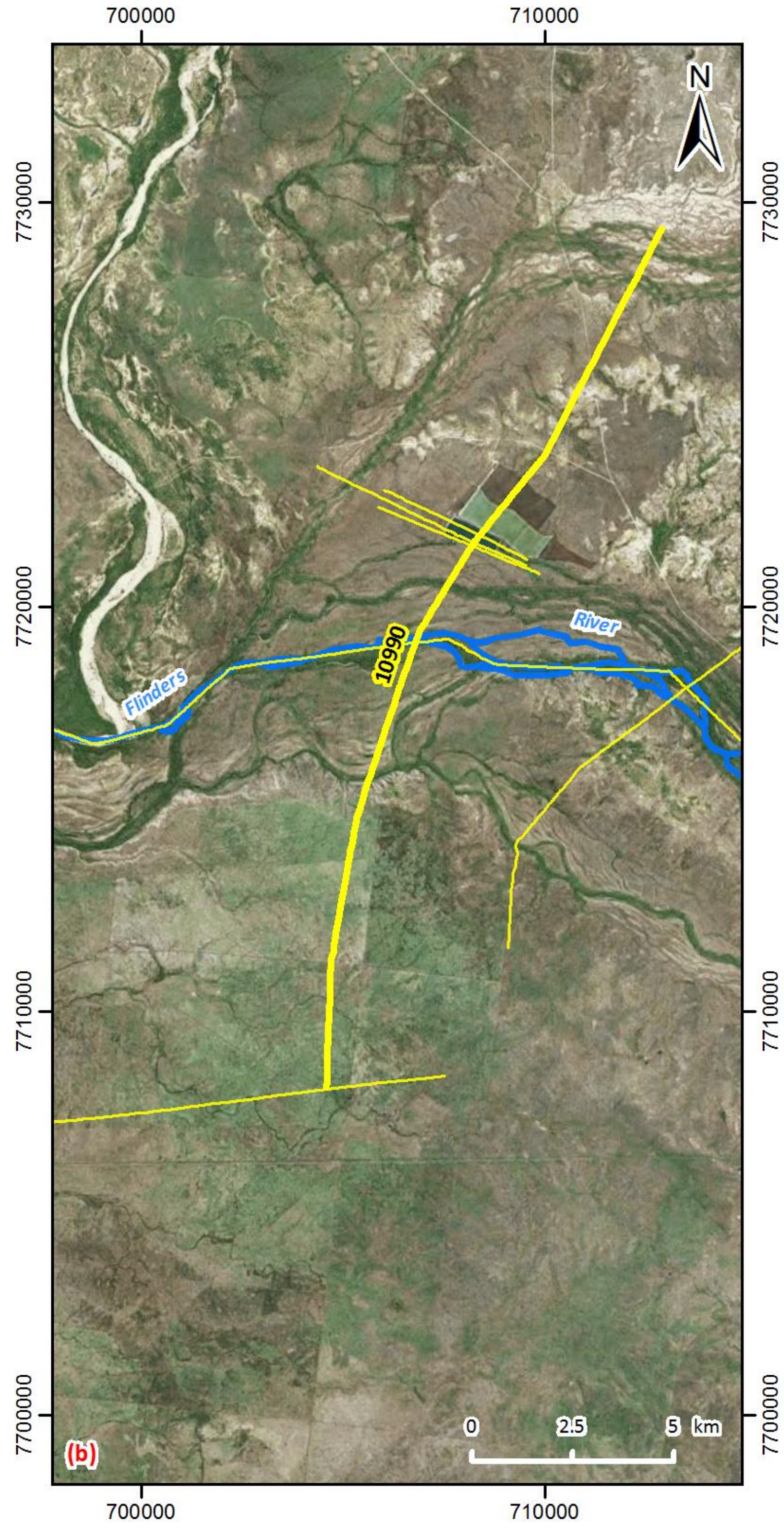


Figure 3.8 AEM flightline map for O'Connell Creek area (Area (b) in Figure 3.3). Flightlines are shown in yellow. An interpretation relating to a conductivity-depth section from line 10990 is discussed in the text.

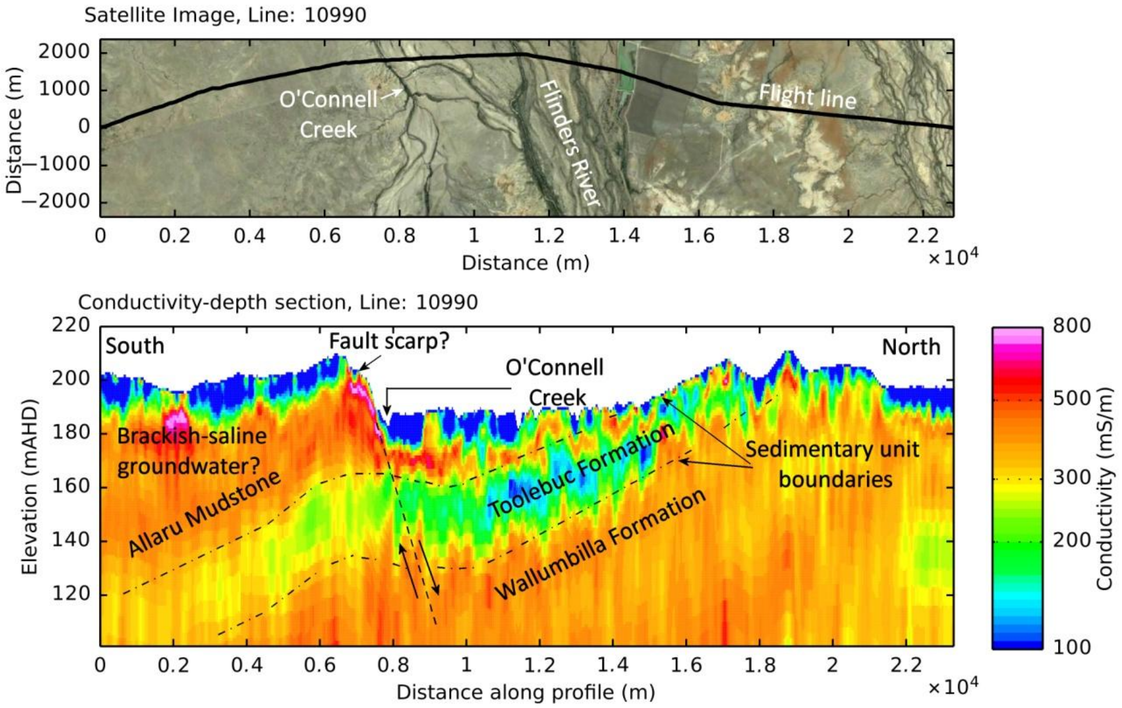


Figure 3.9: Conductivity-depth section (lower panel) for flightline 10990 (see Figure 3.8 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the proposed O'Connell Creek dam site.

Richmond River section

Along the river east of Richmond (Figure 3.3, rectangle (c) and Figure 3.10), the airborne EM indicates that the recent alluvium and bed sands of the current Flinders River to be in the range 5-15m thick. The modelled conductivity response suggests they could contain fresh groundwater, although the saturated thickness may not large (Figure 3.11). The section also suggests that elevated terraces adjacent to the contemporary channels of the Flinders River are more conductive. This may reflect a concentration of salts in these landscape elements through evapotranspiration. The AEM data also suggests that the contact between the recent alluvium and underlying sediments of the Rolling Downs Group is irregular. Potentially localised recharge from the overlying alluvial aquifer may occur, although in places the underlying sediments may discharge more saline groundwater into the river and sediments. Additional, targeted investigations would confirm this.

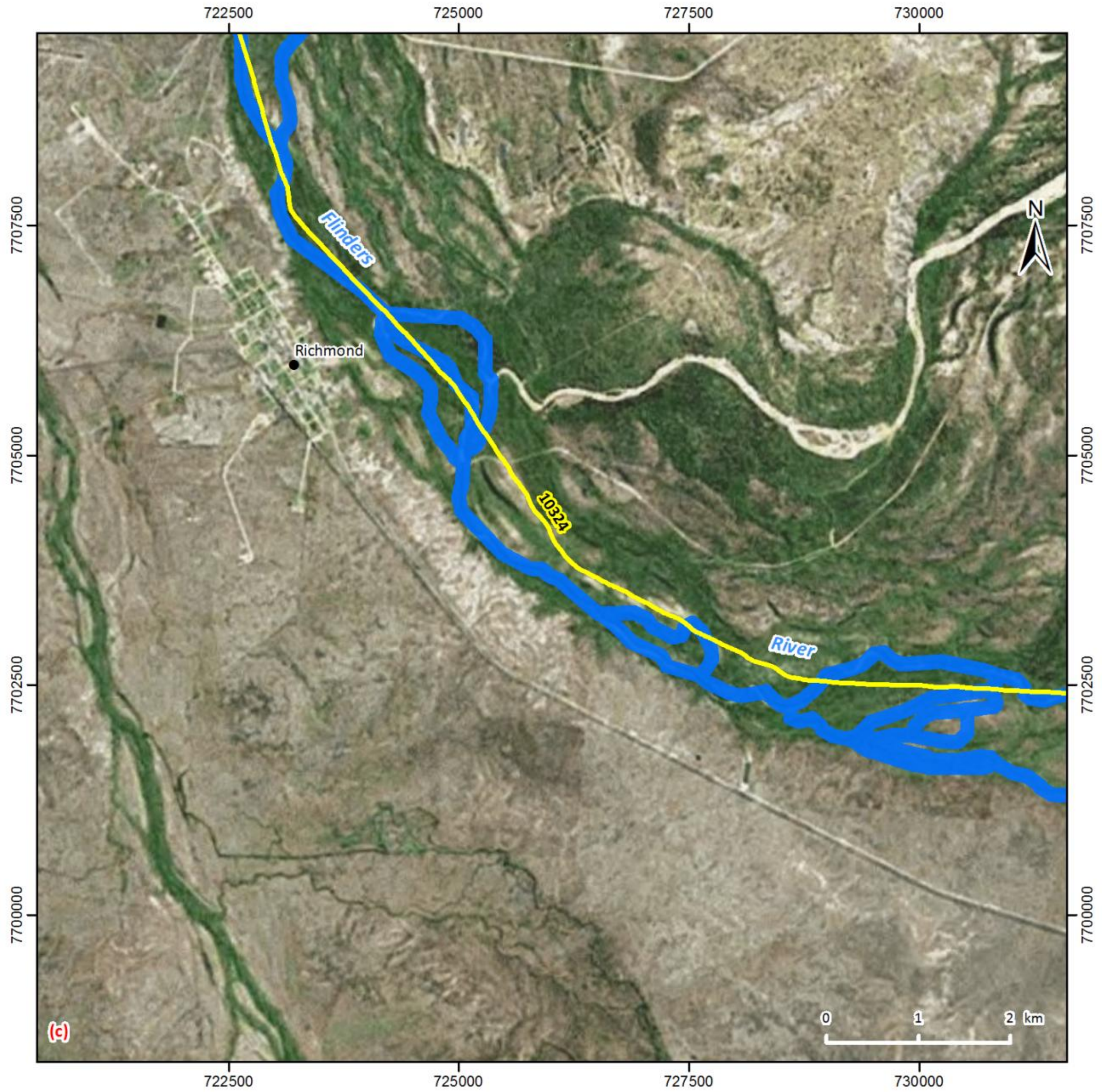


Figure 3.10 AEM flightline map for Richmond area (Area (c) in Figure 3.3). The helicopter EM system flightline are shown in yellow. A section from this line is discussed in the text.

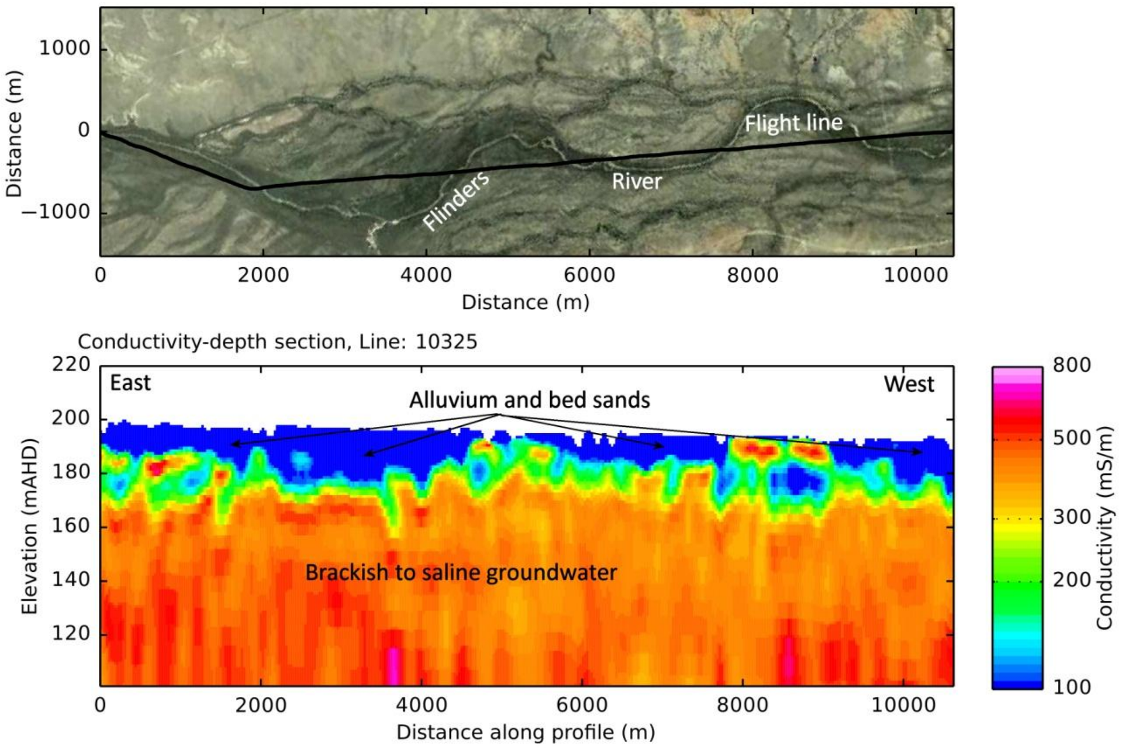


Figure 3.11 Conductivity-depth section (lower panel) for flightline 10324/5 (see Figure 3.10 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the line of the Flinders River and adjacent alluvial terraces.

Sturgeon Basalt Province

Several AEM survey lines were acquired across the Rolling Downs Group onto the Sturgeon Basalts (Figure 3.3, rectangle (d), and Figure 3.12). Two lines that transect the Finders River alluvium onto the Basalts are considered here, specifically lines 10230 (combined with line 10210) and 10211. One line that follows the course of the Flinders River is also examined (Line 10322).

The conductivity-depth sections suggest that the water levels beneath the Sturgeon Basalt are significantly higher than in adjacent alluvial aquifers of the Flinders River. This implies relatively high recharge rates over the basalts. Elevated water levels beneath the basalts result in a significant hydraulic gradient towards the river. The conductivity section suggests the groundwater may discharge into the soils that flank the basalt scarps. High evapotranspiration concentrates salts in these soils and in the alluvial aquifer adjacent to the Flinders River, causing the elevated ground conductivities observed in the AEM sections (see Figures 3.13 and 3.14).

In Figure 3.13. the high level alluvium overlying the Rolling Downs Group (e.g. at 6200 m and 9000 m to 14,000 m distance along the profile) has a low conductivity and if these areas were developed for irrigation secondary salinisation would most likely occur at the break of slope (e.g. at 5900m and 8500 m distance along profile). The recent alluvial material adjacent to the Flinders River (e.g. at about 2750 m distance along profile) also contain low levels of salt.

Along the northern flanks of the Flinders River the suggested hydraulic gradient towards the river indicates there is potential for the Sturgeon Basalt to provide base flow to the River and to its tributaries such as Porcupine Creek (Figure 3.14).

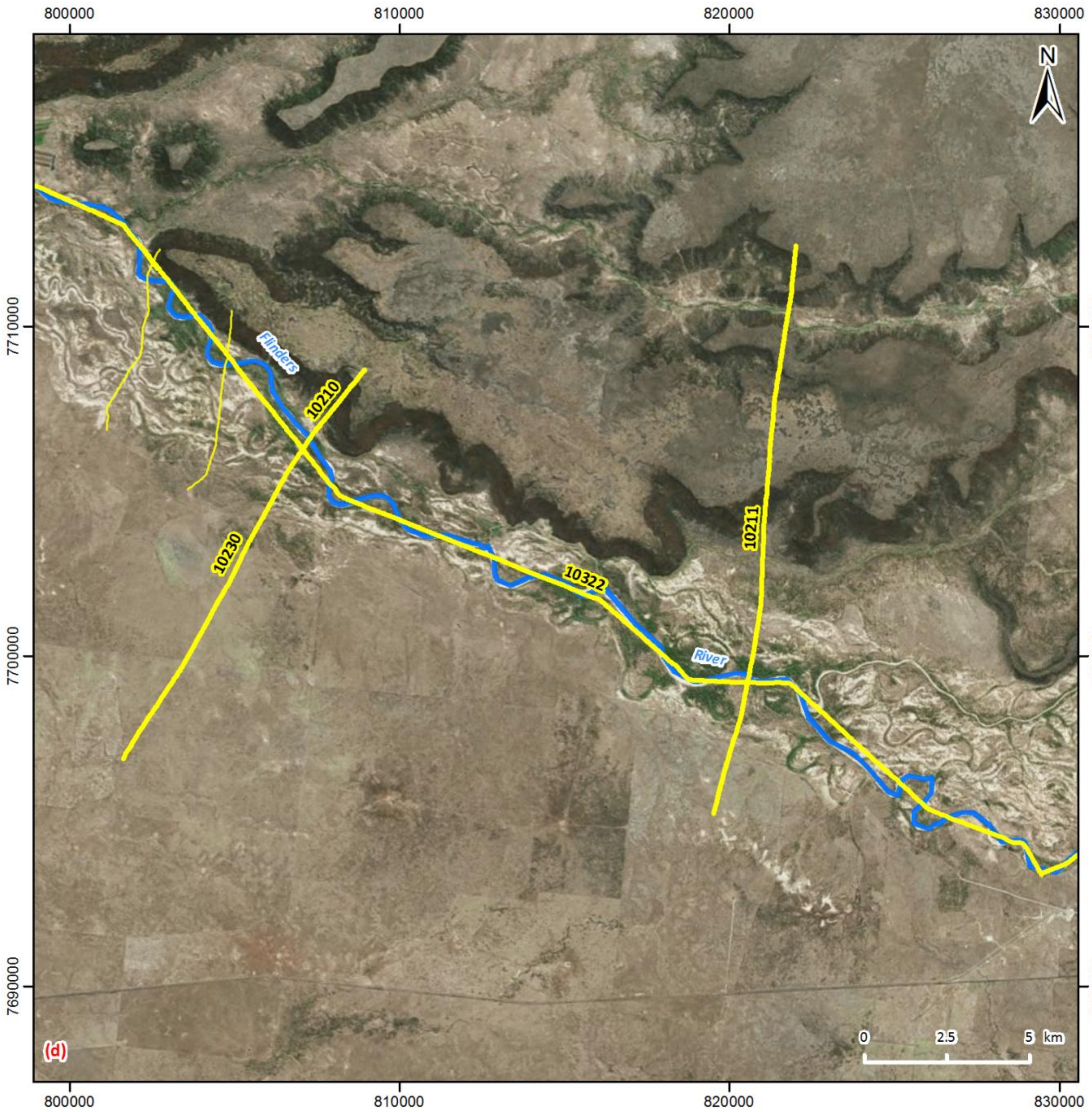


Figure 3.12 Location diagram for flightlines adjacent to the Sturgeon Basalts (Area (d) in Figure 3.3) which flank the northern edges of the Flinders River floodplain to the west of Hughenden. Flightlines discussed in the text are numbered.

The conductivity-depth section for the longitudinal line (Figure 3.15) that follows the Flinder River, indicates that the bed sands adjacent to the basalts may contain fresher groundwater, as they appear resistive in the conductivity image. However, further upstream the conductivities in the near surface increase and imply the presence of brackish to saline groundwater in the alluvium and underlying sediments.

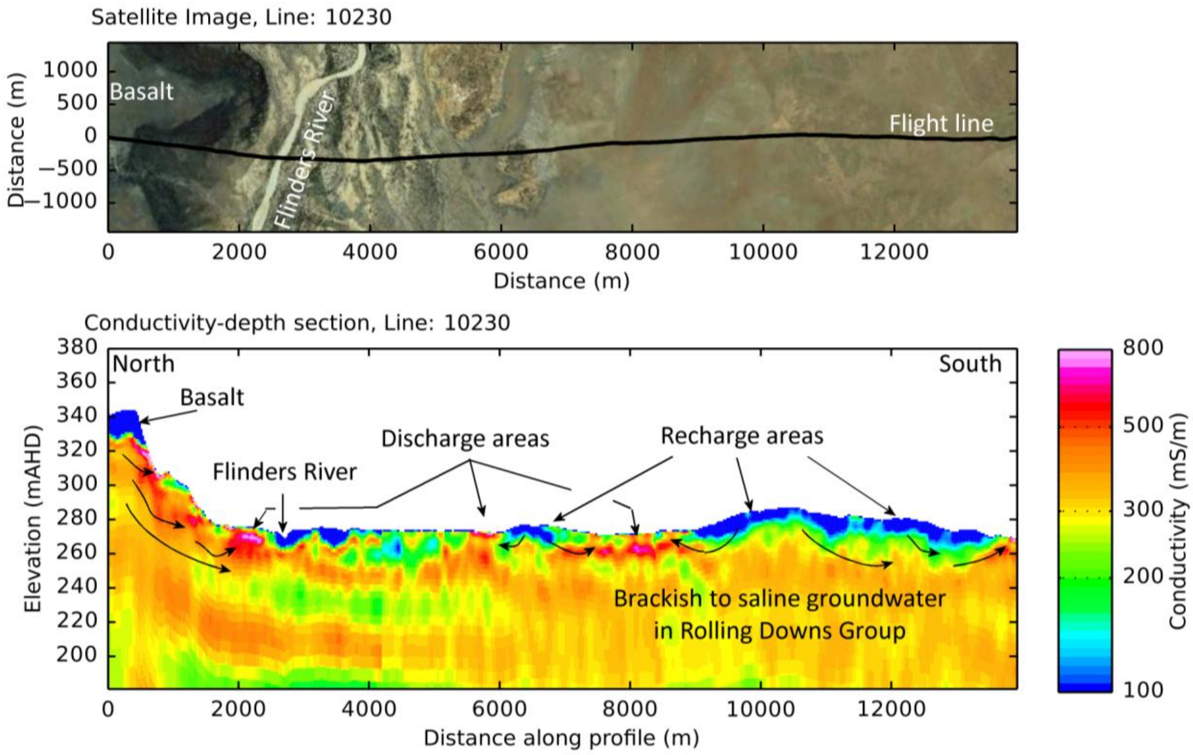


Figure 3.13: Conductivity-depth section (lower panel) for flightline 10230 (combined with 10210) (see Figure 3.12 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the line of the Flinders River onto the Sturgeon Basalt to the north (right side of section).

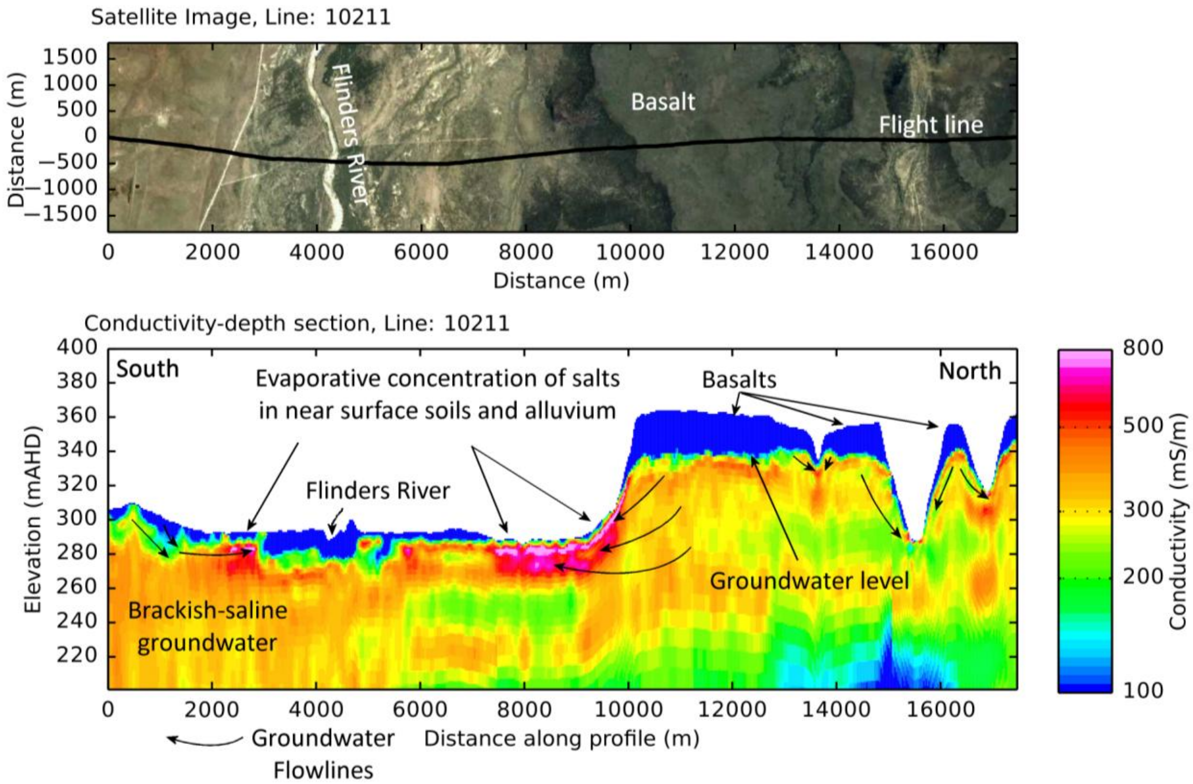


Figure 3.14: Conductivity-depth section (lower panel) for flightline 10211 (see Figure 3.12 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the line of the Flinders River onto a more extensive outcrop of the Sturgeon Basalt to the north (right side of section).

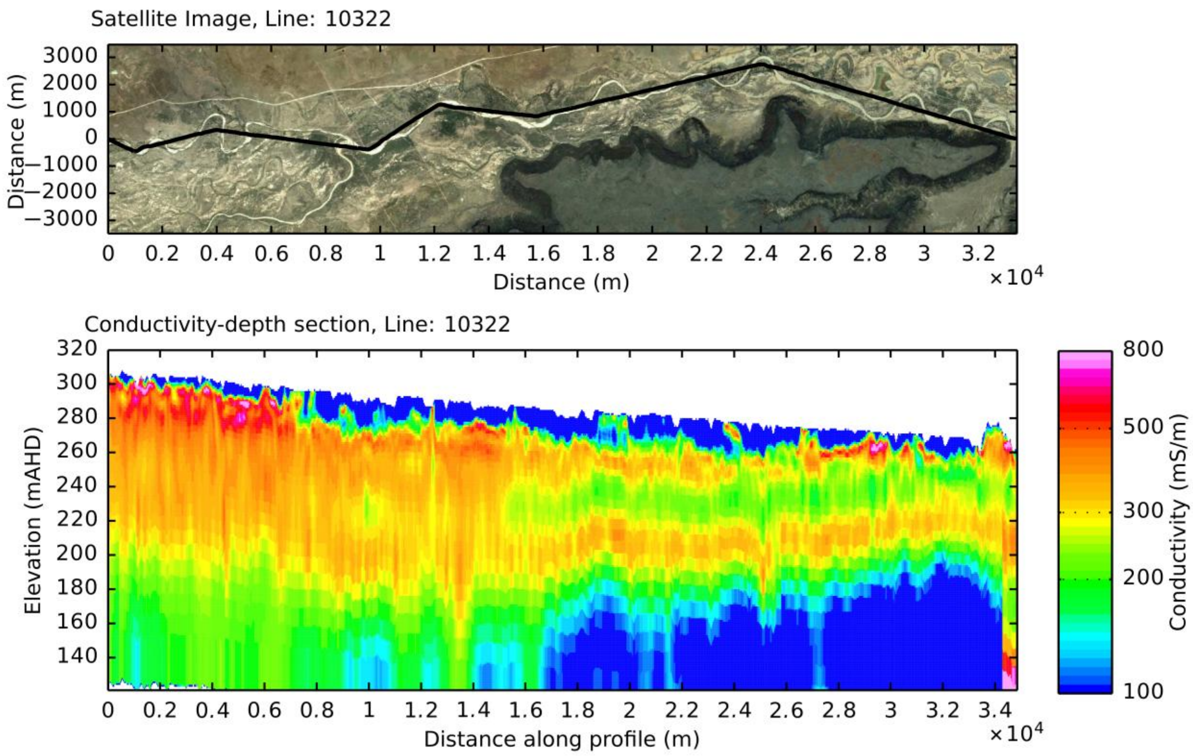


Figure 3.15: Conductivity-depth section (lower panel) for flightline 10322 (see Figure 3.12 for location). Location of flight line on a satellite image is shown in upper panel. This flight line follows the line of the Flinders River and indicates the alluvial bed sands may contain relatively fresh groundwater (blue region in near surface) but that upstream (left side of image), towards Hughenden, the data suggest groundwater quality may become poorer.

3.3 Gilbert catchment

In the Gilbert catchment, data acquisition was concentrated along the Einsleigh River, adjacent to and south of the town of Einasleigh, and along the Gilbert River to the west of Georgetown (Figure 3.16).

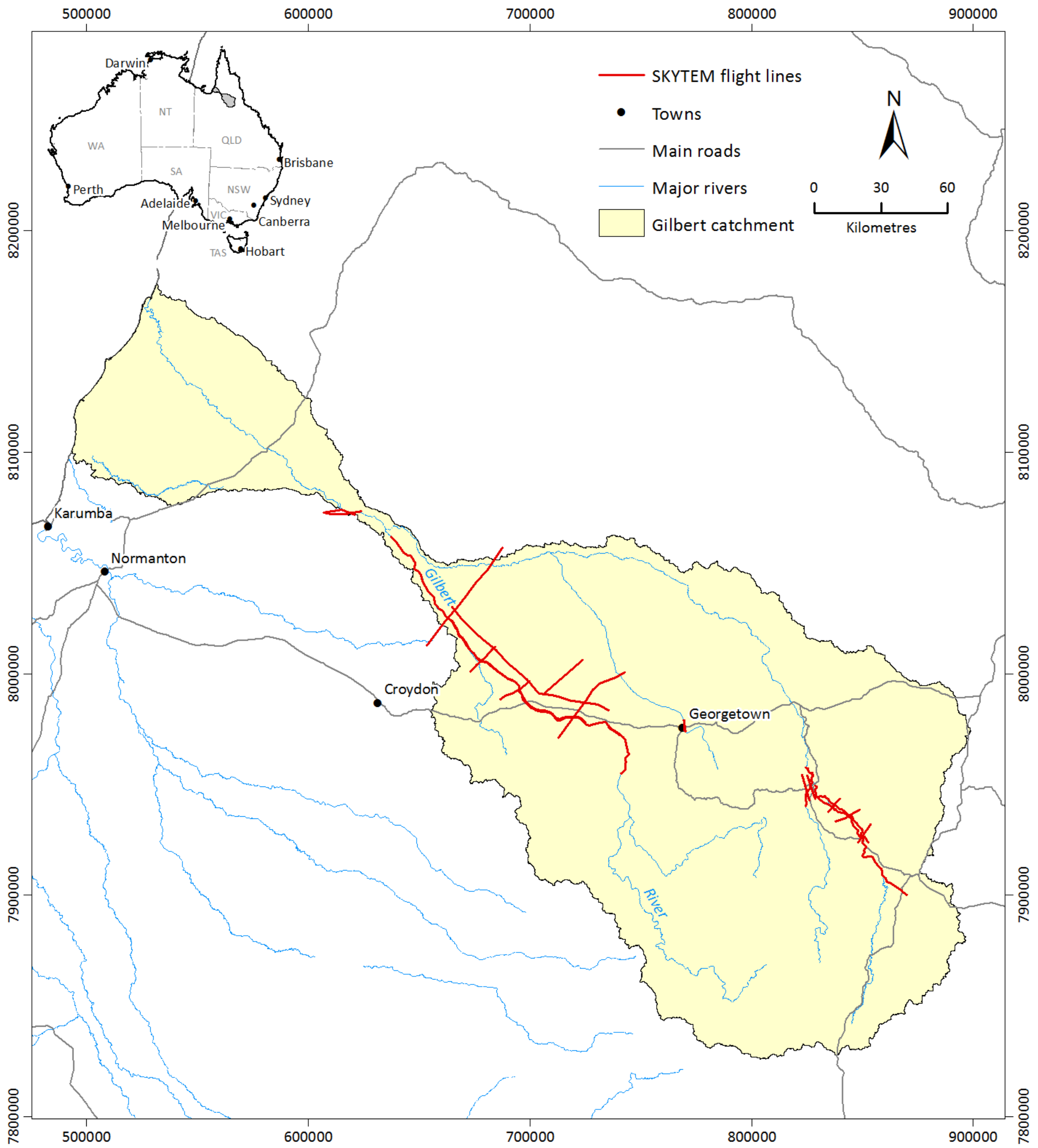


Figure 3.16 Location of SkyTEM survey lines in the Gilbert River catchment

Einasleigh River

Observed ground conductivities for the Einasleigh area were generally lower than those modelled for the Flinders catchment, except in areas adjacent to the town of Einasleigh, referred to as Einasleigh Common. A map of the lines surveyed is shown in Figure 3.17. Figure 3.18 details the interval conductivities modelled for the top 20 m, from the ground surface down. Elevated conductivities were noted in parts of the area, particularly in the near surface, where there was regolith cover mapped, away from, or adjacent to the Einasleigh River (Figure 3.19).

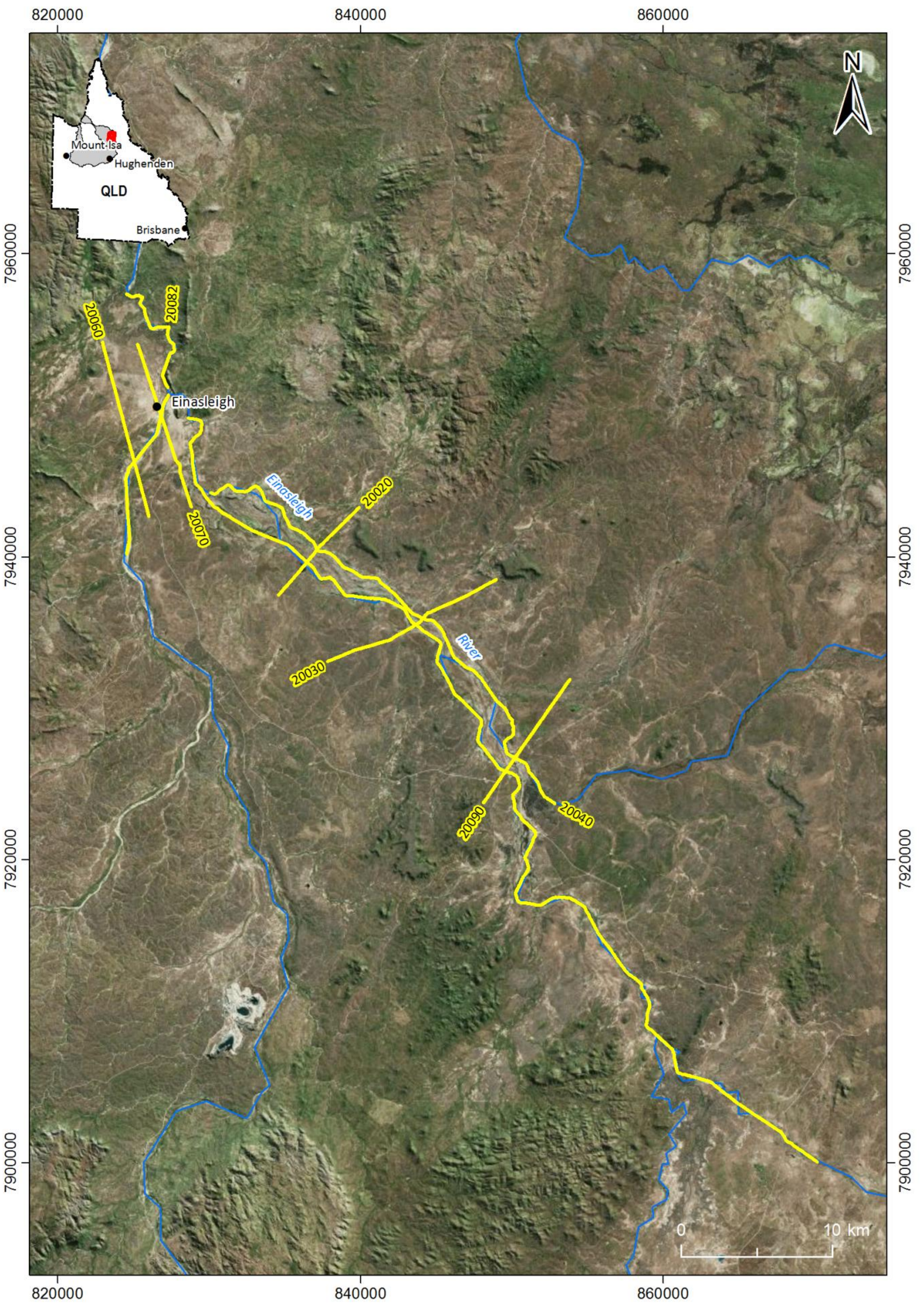


Figure 3.17 Map of AEM survey lines in the Einasleigh River area.

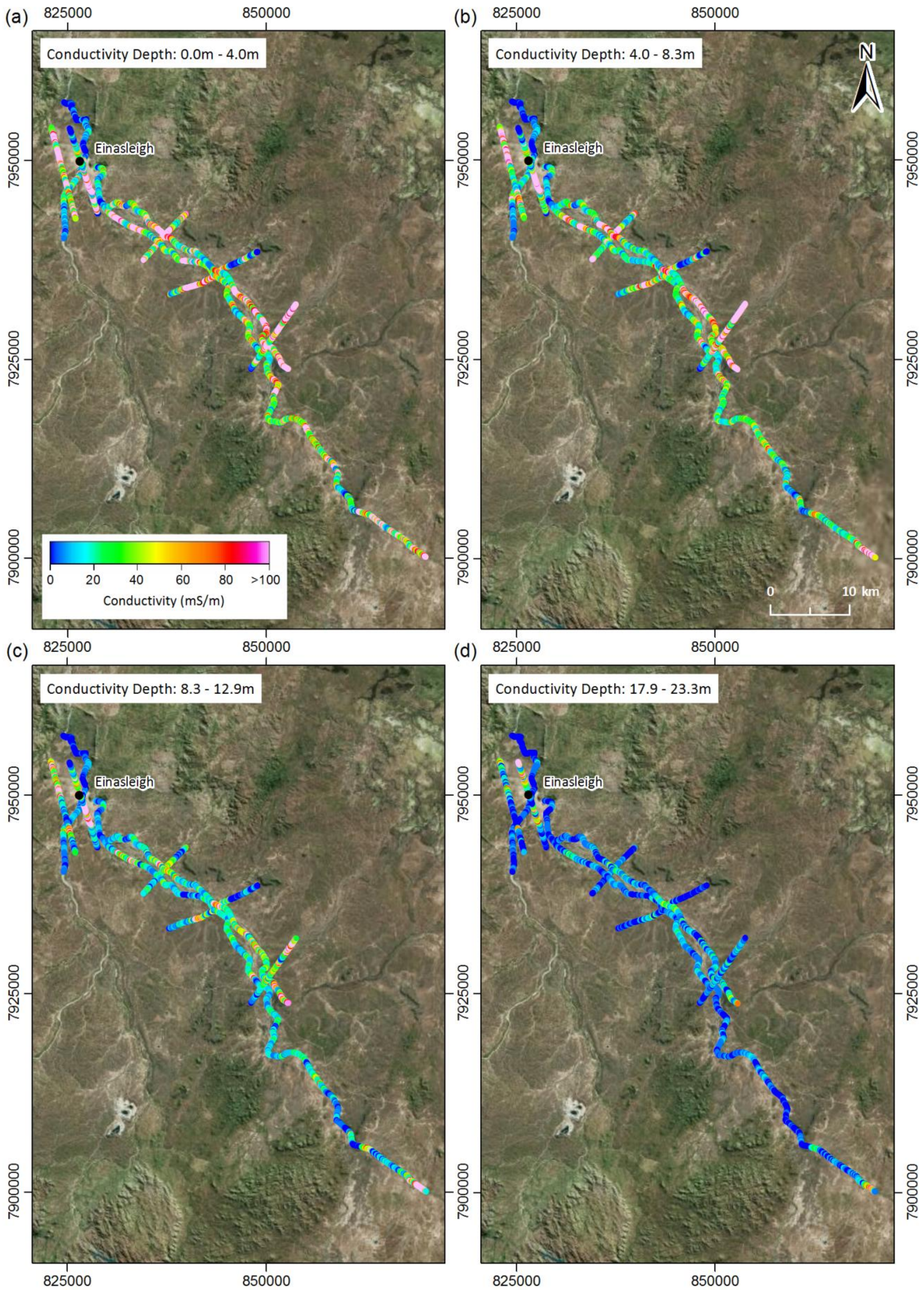


Figure 3.18 Maps of ground conductivity for four depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface in the Einasleigh River area. Panel (a) shows an average conductivity for the ground between 0 and 4m; Panel (b) an average conductivity for a depth 4 to 8.3m below the ground surface; Panel (c), an average conductivity for a depth 8.3 and 12.9m below the ground surface; and Panel (d), an average conductivity for a depth 17.9 and 23.3m below the ground surface.

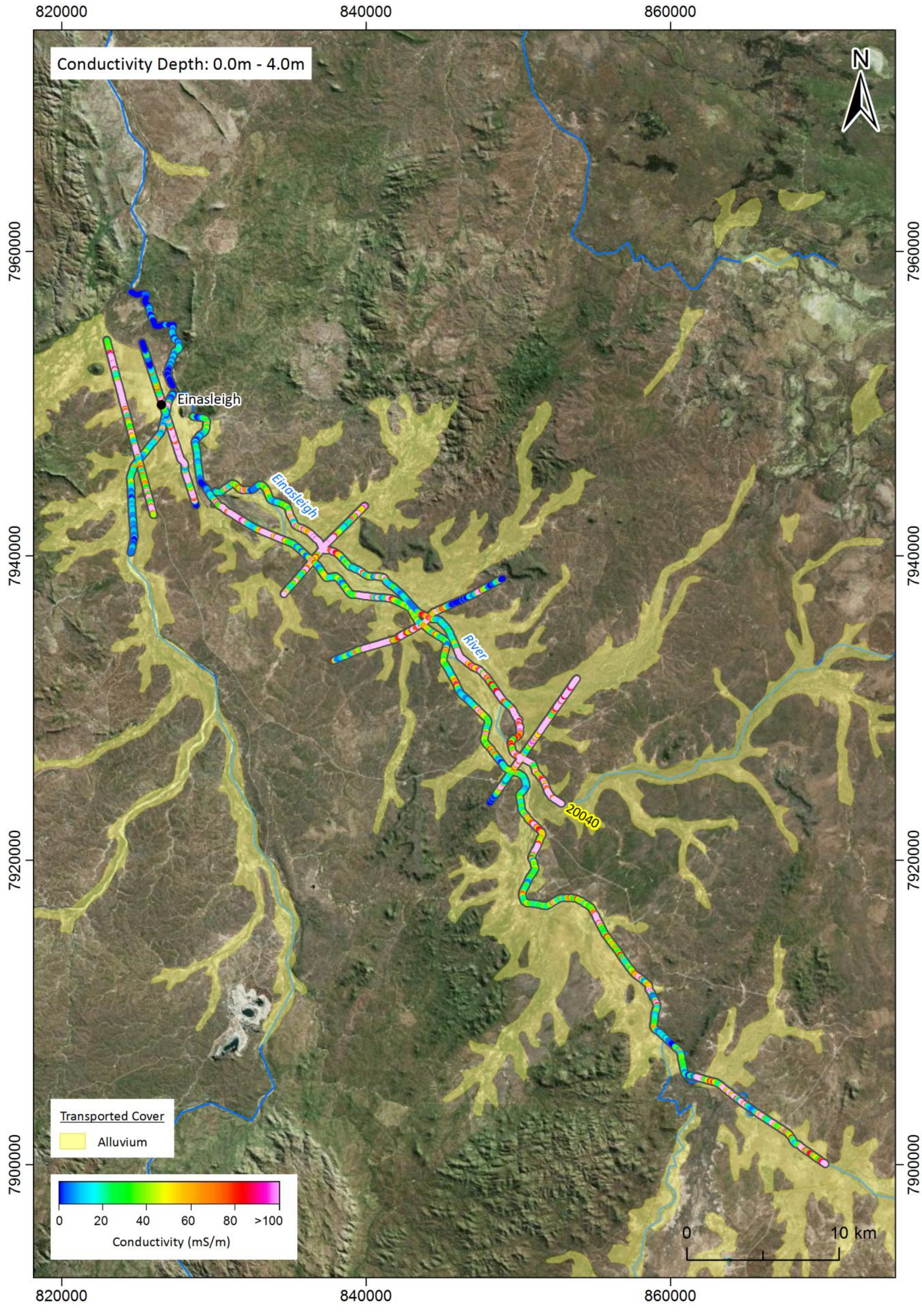


Figure 3.19 Map of ground conductivity for one depth interval showing spatial patterns of ground conductivity for the ground between 0 and 4 m below the ground surface, overlain on a satellite image showing the mapped distribution of alluvium. High near surface conductivities are primarily confined to areas of transported cover.

Conductivity-depth sections (Figure 3.20 and 3.21) which transect the Copperfield River and show the ground conductivity of the soils and regolith of the Einasleigh Common area north and South-east of the

town are relatively high. These observations accord with information collected over these areas in separate studies, which suggests that a combination high subsoil salinity and saline groundwater, coupled with poor drainage would make these areas challenging to develop for irrigation.

A conductivity-depth section for a sub-set of the AEM data acquired along the Einasleigh River, to the north of Einasleigh itself, is displayed in Figure 3.22. Conductivities are low in the subsurface with the basement being primarily metamorphic rocks of varying composition. Abrupt breaks in the observed conductivity structure are interpreted to represent litho-structural boundaries (see Figure 3.22), that may coincide with faults, or changes in lithology type. Further on-ground work would be required to verify this. There are no clearly defined bedsand sequences observed in the AEM section for this reach of the river. South-east of Einasleigh, flightline 20040 (Figure 3.23) which tracks along the NE anabranch of the Einasleigh River, indicates that the alluvium and associated terraces, in the near surface, are relatively conductive, and that beneath this conductive layer the basement rocks comprising granites and granodiorites are resistive.

This pattern is reflected in other flightlines that transect the Einasleigh River, including lines 20020 (Figure 3.24) and 20030 (Figure 3.25). Flightline 20020 crosses a variable regolith developed over fractured crystalline basement rocks, and the regolith comprising alluvium, colluvium, and saprolite are represented by the conductive near surface layer. The AEM data also maps sub-vertical conductors that may represent the weathering along fractures and faults developed in the basement. A similar conductive regolith structure is observed in flightlines 20030 (Figure 3.25) and 20090 (Figure 3.26) both of which cross the Einasleigh River.

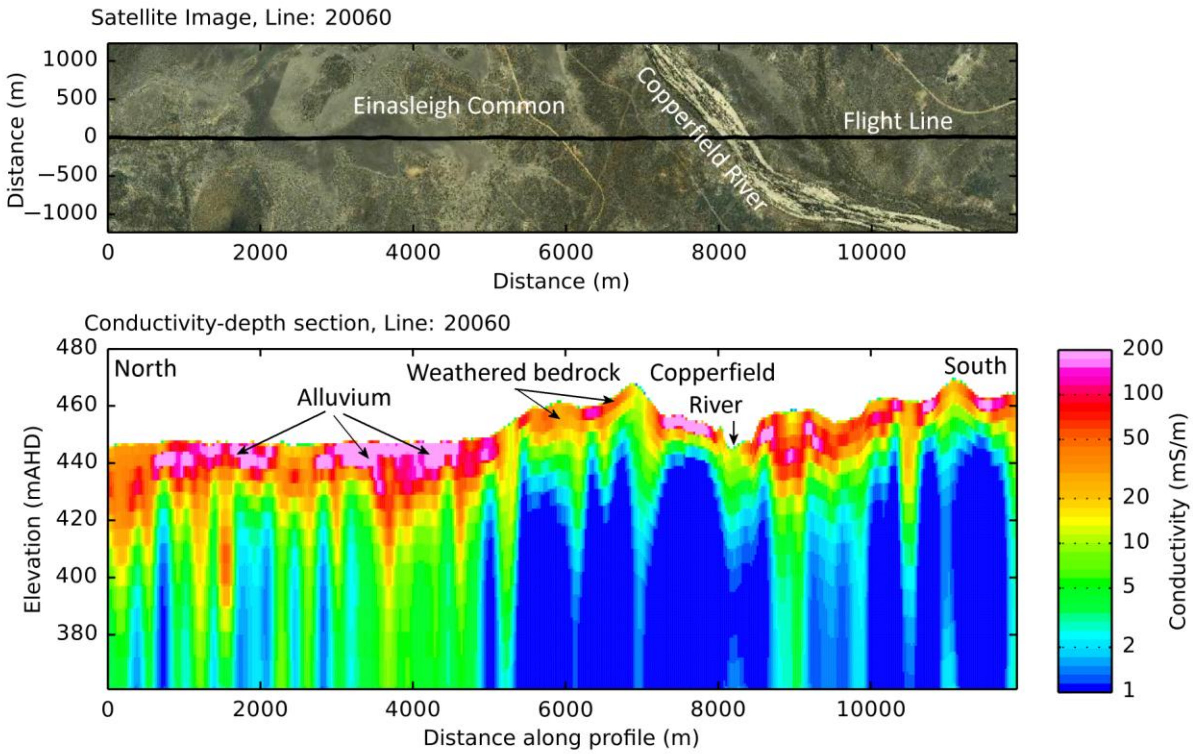


Figure 3.20 Conductivity-depth section (lower panel) for flightline 20060 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Copperfield River in the south and covers part of Einasleigh Common to the north (left side of section). High conductivities greater than ten metres thick are noted over the Common.

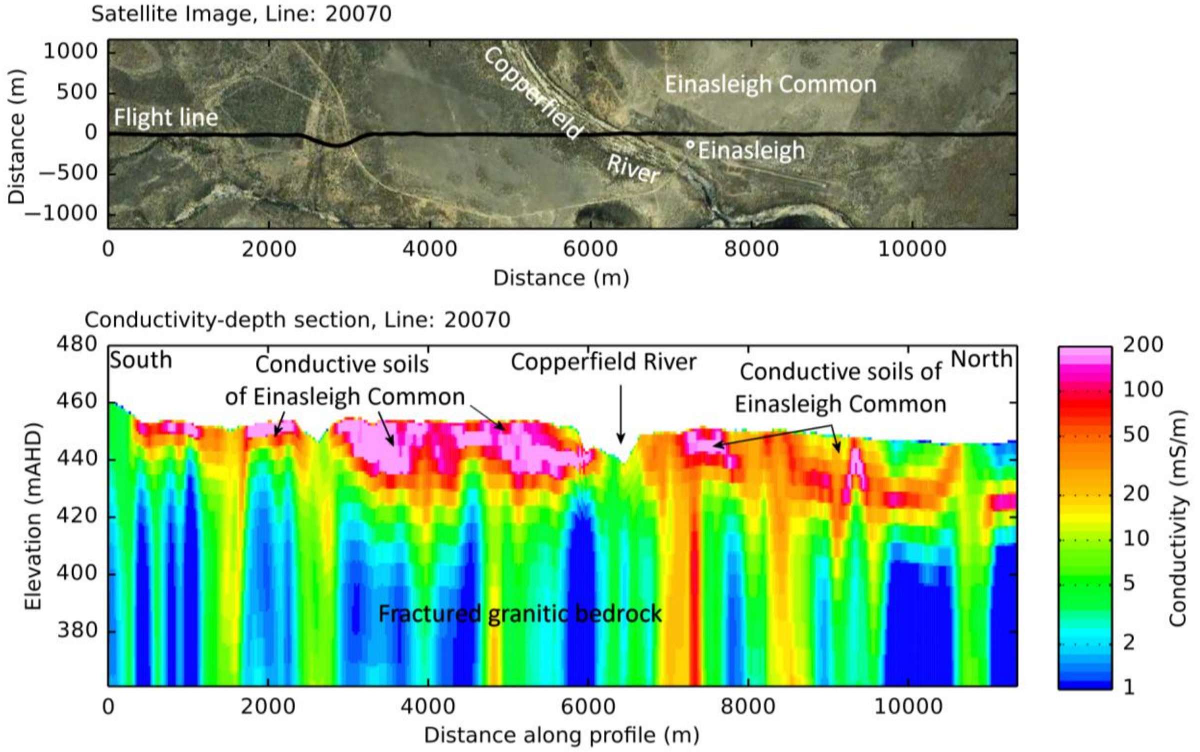


Figure 3.21 Conductivity-depth section (lower panel) for flightline 20070 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Copperfield River and the township of Einasleigh and extends across Einasleigh Common to the north (right side of section) and south (left side of section). High conductivities greater than ten metres thick are noted over the Common.

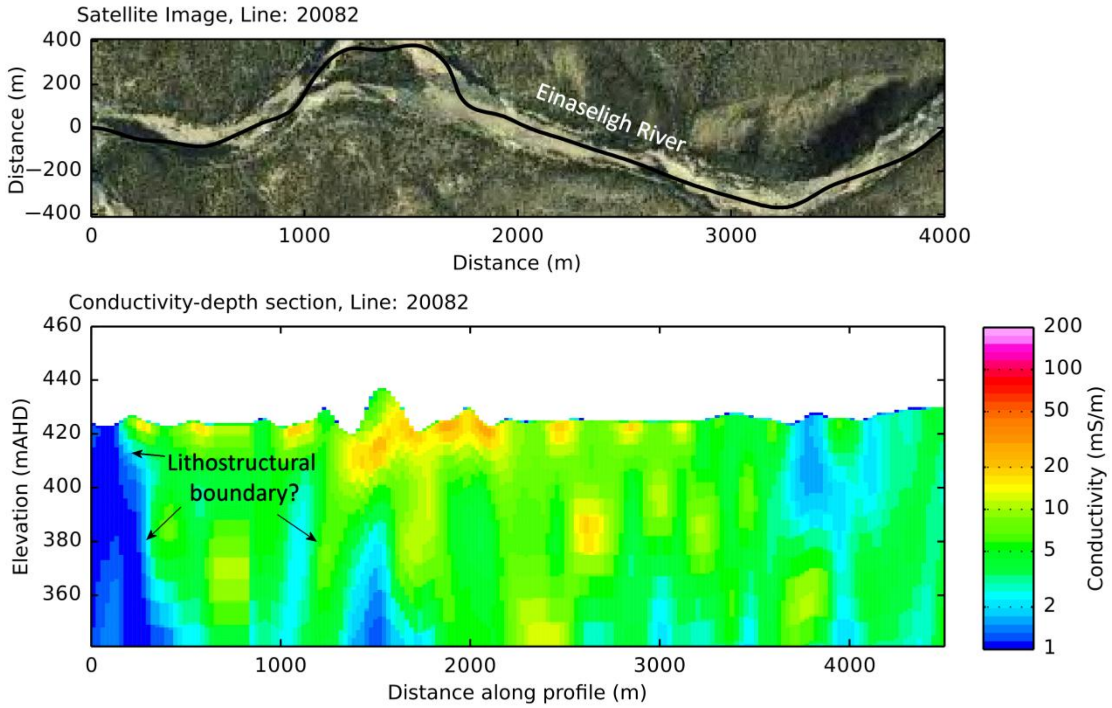


Figure 3.22 Conductivity-depth section (lower panel) for flightline 20082 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line follows the Einasleigh River north of the Einsaleigh township.

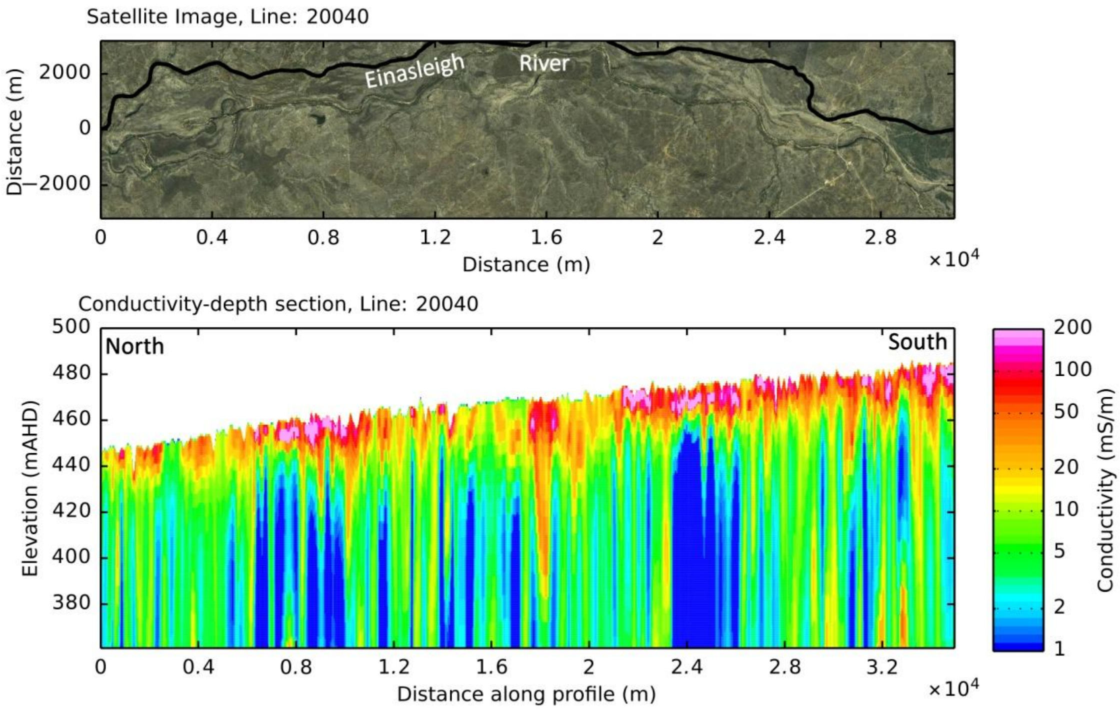


Figure 3.23 Conductivity-depth section (lower panel) for flightline 20040 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line covers the north-eastern section of the Einasleigh River to the south-east of the Einasleigh township

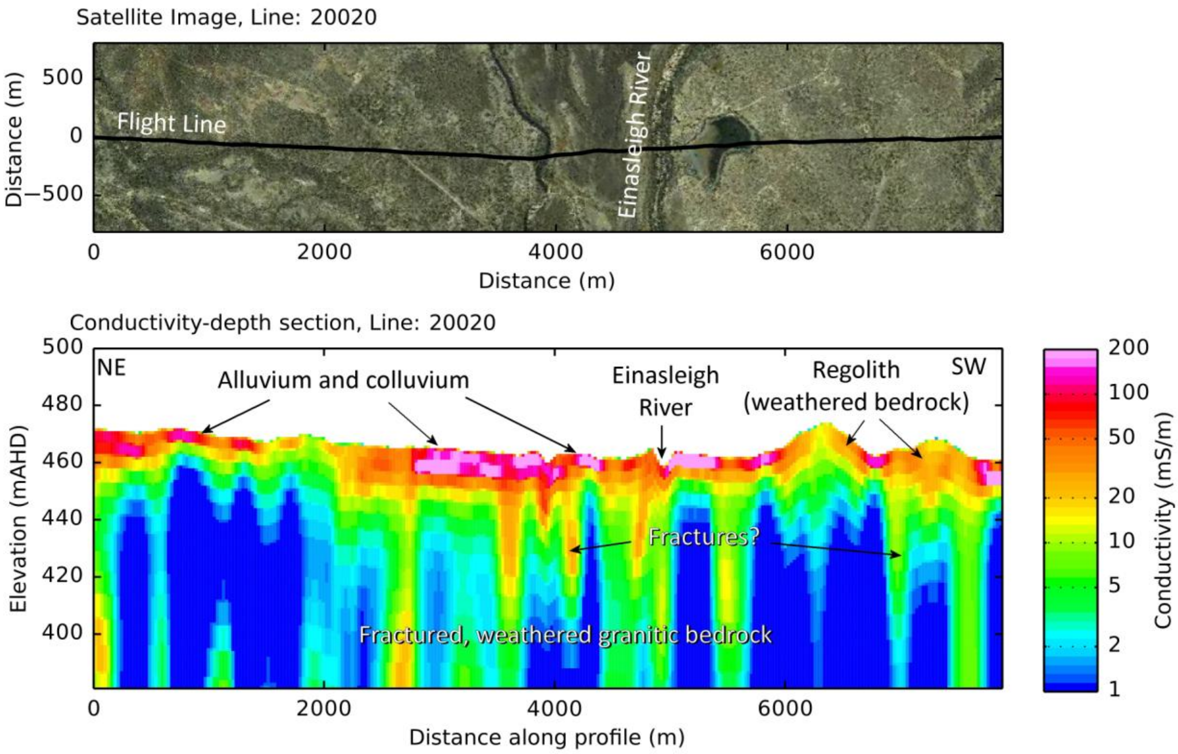


Figure 3.24 Conductivity-depth section (lower panel) for flightline 20020 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Einasleigh River running SW-NE.

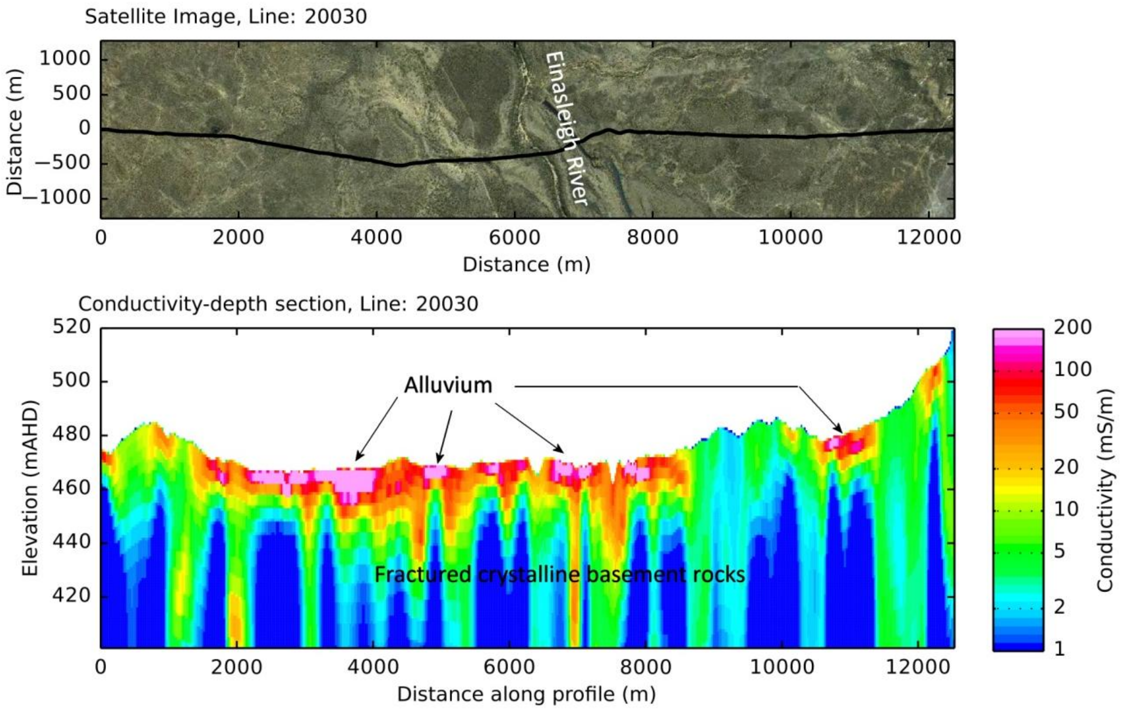


Figure 3.25 Conductivity-depth section (lower panel) for flightline 20030 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Einasleigh River running SW-NE.

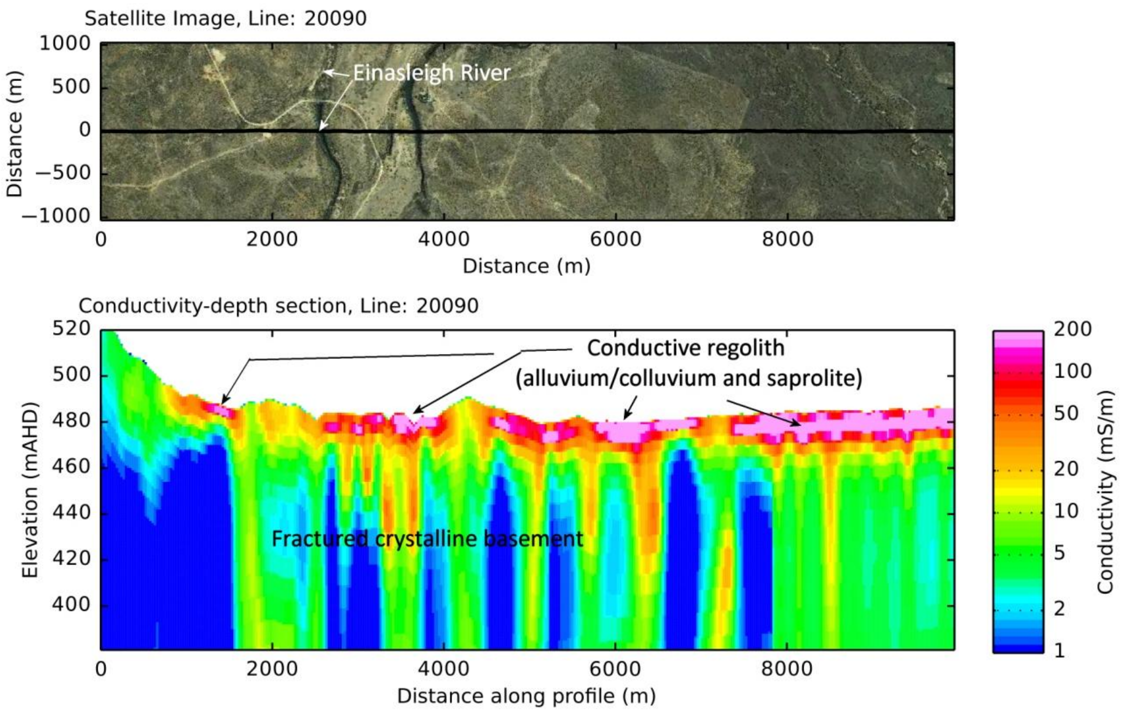


Figure 3.26 Conductivity-depth section (lower panel) for flightline 20090 (see Figure 3.17 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Einasleigh River running SW-NE.

The observed ground conductivity structure in Einasleigh area is interpreted to reflect the distribution of variable regolith materials across the landscape with the most conductive materials located in the near surface associated with alluvium, colluvium and in places saprolite. Their high conductivities are attributed to the accumulation of salt in porous but often relatively impermeable materials. At depth, the conductivity structure suggests a fractured crystalline basement. This is illustrated in Figure 3.27 which maps

conductivity at varying depths over regolith and basement type. Aquifer systems will be primarily associated with alluvial aquifers and fractured rocks, with the conductivity structure suggesting they contain relatively low quality groundwater.

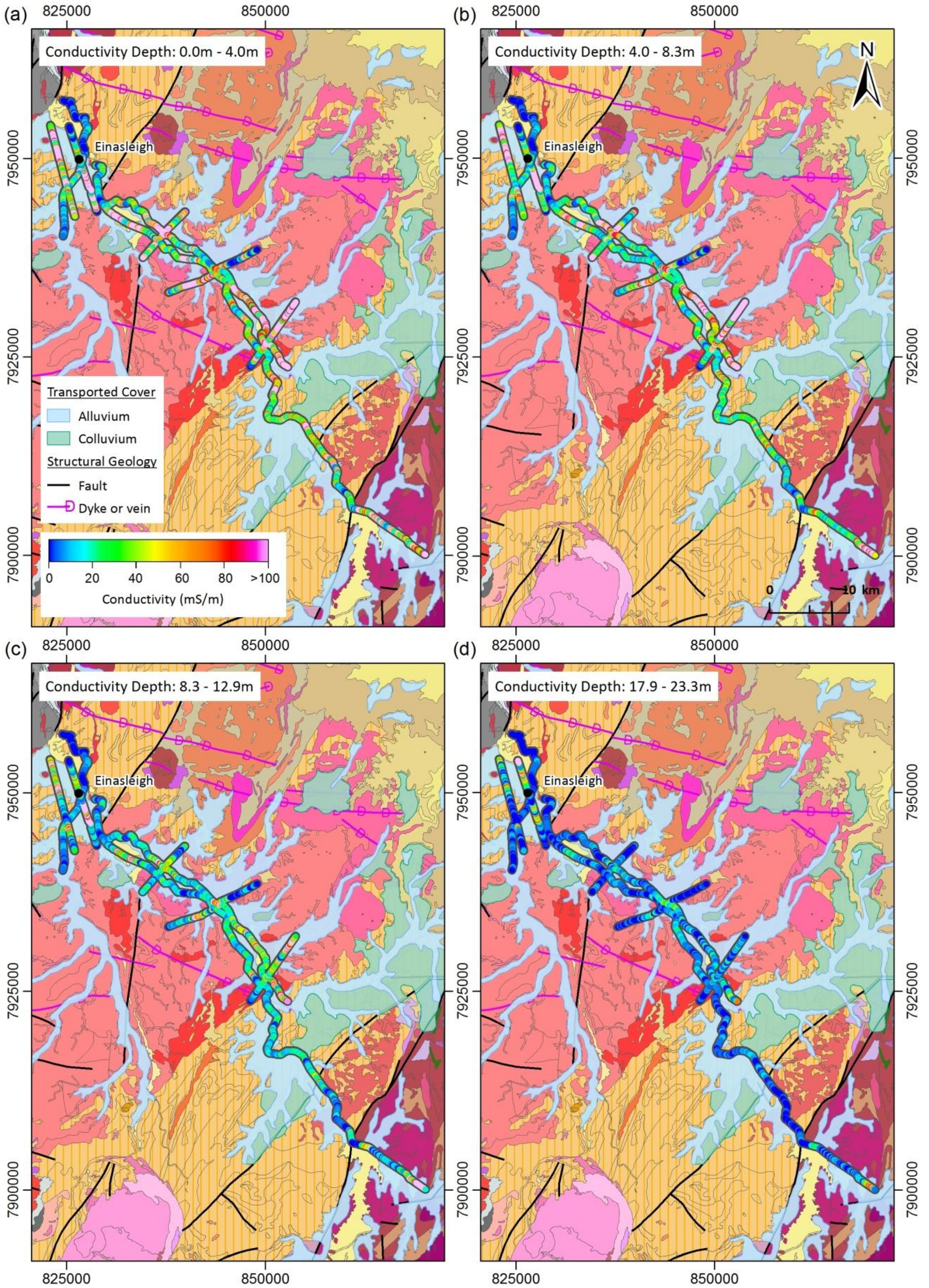


Figure 3.27 Maps of ground conductivity for four depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface in the Einasleigh River area. The depth intervals are overlain on geology. Panel (a) shows an average conductivity for the ground between 0 and 4m; Panel (b) for a depth 4 to 8.3m below the ground surface; Panel (c), for a depth 8.3 and 12.9m below the ground surface; and Panel (d), for a depth 17.9 and 23.3m below the ground surface. Lithology key is in Figure 3.28.

Bedrock Geology (100K)

QUATERNARY

- Barkers Basalt
- Chudleigh Basalt
- Mount Joy Basalt
- Murronga Basalt

LATE TERTIARY - QUATERNARY

- McBride Basalt Group

TERTIARY

- Tb

TERTIARY (Intrusive)

- Tb
- Tib

CARBONIFEROUS - PERMIAN? (Intrusive)

- bx-Gt

CARBONIFEROUS - PERMIAN (Intrusive)

- Kennedy Province

MIDDLE - LATE CARBONIFEROUS

- Beril Peak Rhyolite
- Mosaic Gully Rhyolite
- Yellow Jacket Rhyolite

MIDDLE - LATE CARBONIFEROUS (Intrusive)

- Caterpillar Microgranite
- Eva Creek Microgranite?

CARBONIFEROUS (Intrusive)

- Kennedy Province

EARLY CARBONIFEROUS

- Edmonds Creek Rhyolite
- McLennons Creek Rhyolite

EARLY CARBONIFEROUS (Intrusive)

- Lochaber Complex cone sheets
- Lochaber Granite
- Eastdale Granite
- Noel Micromonzonite
- Sues Creek Microgranite

LATE DEVONIAN - EARLY CARBONIFEROUS

- DCs
- Bulgeri Formation
- Gilberton Formation

SILURIAN (Intrusive)

- Eastdale Granite
- Dumbano Granite
- Eleven-B Granite
- McKinnons Creek Granite
- Mount Juliet Granite
- Oak River Granodiorite
- Puppy Camp Granodiorite
- Quinine Spring Granite
- Sg
- Skeleton Creek Granite
- Watch Hill Granodiorite

SILURIAN? (Intrusive)

- Christmas Hill Creek Trondhjemite
- Dry Bore Granite
- Mount Misery Granite
- Mount Webster Granodiorite
- Sg

ORDOVICIAN? (Intrusive)

- Lynwater Complex

LATE CAMBRIAN? - EARLY ORDOVICIAN

- Clayhole Schist

NEOPROTEROZOIC? - CAMBRIAN?

- Oasis Metamorphics

NEOPROTEROZOIC? - CAMBRIAN? (Intrusive)

- Oasis Metamorphics

NEOPROTEROZOIC - EARLY PALAEOZOIC (Intrusive)

- Lynwater Complex

NEOPROTEROZOIC? (Intrusive)

- PLdl

MESOPROTEROZOIC (Intrusive)

- Mywyn Granite
- PLg

PALAEOPROTEROZOIC

- Cassidy Creek Metamorphics
- Einasleigh Metamorphics

Figure 3.28 Basement lithology key for Figure 3.27.

Gilbert River

A map of the flightlines of AEM data acquired along and adjacent to the Gilbert River and adjacent to Georgetown is shown in Figure 3.29.

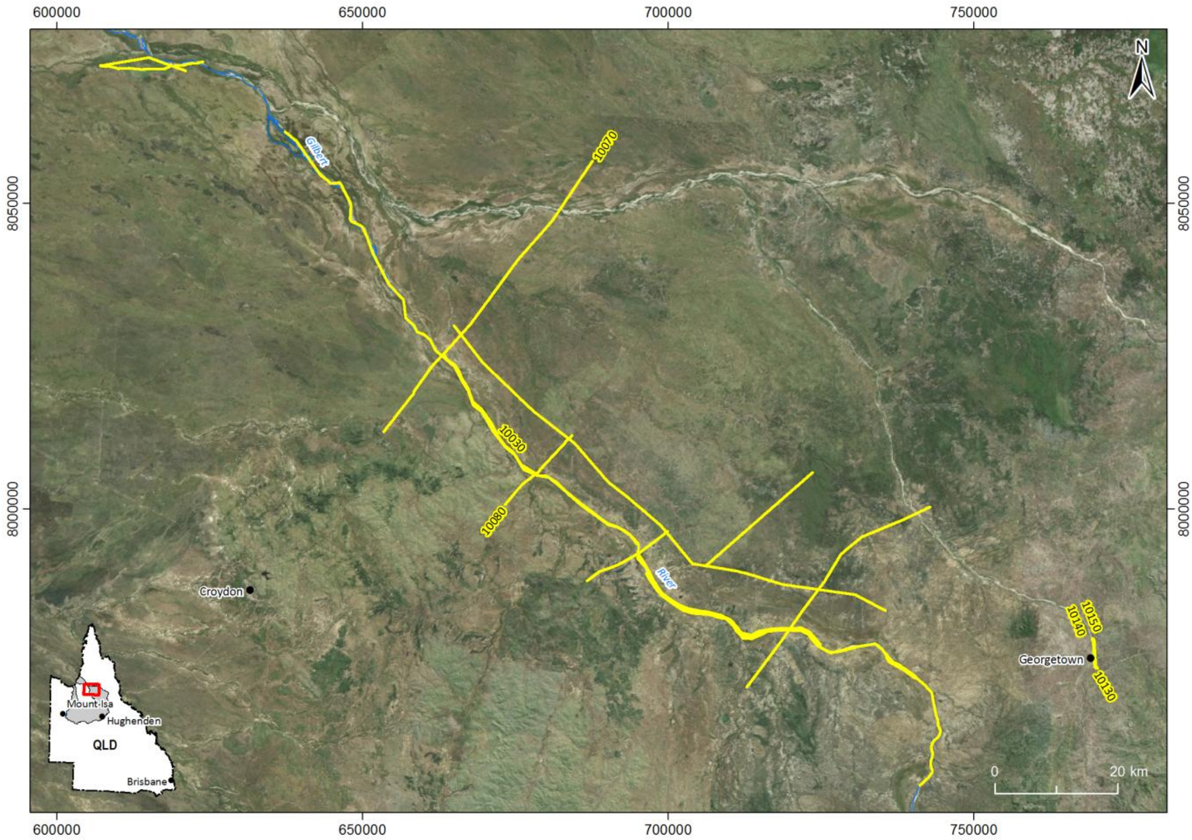


Figure 3.29 Map of AEM survey lines in the Gilbert River region.

The observed conductivity structure, represented by the conductivity-depth intervals plotted in Figures 3.30 and 3.31, indicates that the most conductive parts of the landscape are located in the lower reaches of the catchment, towards Strathmore Station. However, the conductivities are relatively low. For the flight line that follows the Gilbert River, conductivities increase westwards although they remain very low in the upper reaches of the river. The near surface conductivities, that might represent those for the alluvial aquifer or bedsands, suggest that any contained groundwater will have low salinities.

A conductivity-depth section for flight line 10070 (Figure 3.32) traverses Cainozoic age sediments of the Karumba Province, which overlie Cretaceous and Jurassic sediments of the Rolling Downs Group and Gilbert River Formation. The former exhibit high conductivities at depth. Along the western part of the survey line the near surface Cainozoic sediments are variably conductive, and in part very conductive (>200mS/m).

South east of line 10070, flightline 10080 (Figure 3.33) transects the Gilbert River. It covers a sequence of GAB sediments and indicates that they have low conductivities (fresh groundwater?). The section suggests that the alluvium is ~ 20 m thick, and more conductive than the substrate but this requires confirmation.

A longitudinal section (flightline 10030 – Figure 3.34), along the Gilbert River, indicates that at a regional scale the ground conductivities are moderate to high and that there are no clearly defined sources of fresher groundwater. A more focussed examination at finer scales may yield more information, but all the evidence from the AEM data suggests the recent alluvium and bed sands of the current Gilbert River to range from a few metres to ~15m thick and overly an irregular fresh and weathered basement sequence.

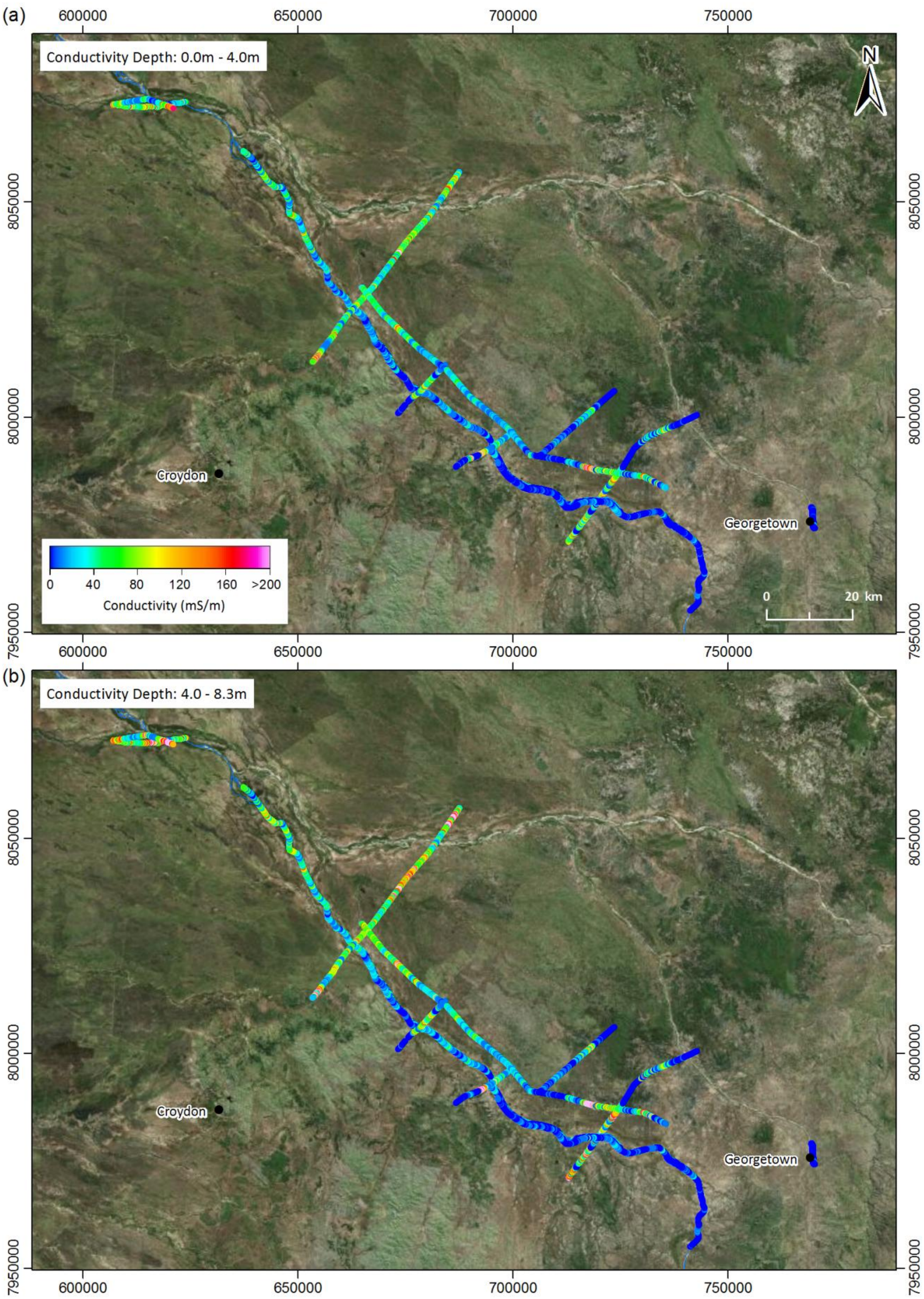


Figure 3.30 Maps of ground conductivity for two depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface in the Gibert River area. Panel (a) shows an average conductivity for the ground between 0 and 4m; Panel (b) an average conductivity for a depth 4 to 8.3m below the ground surface.

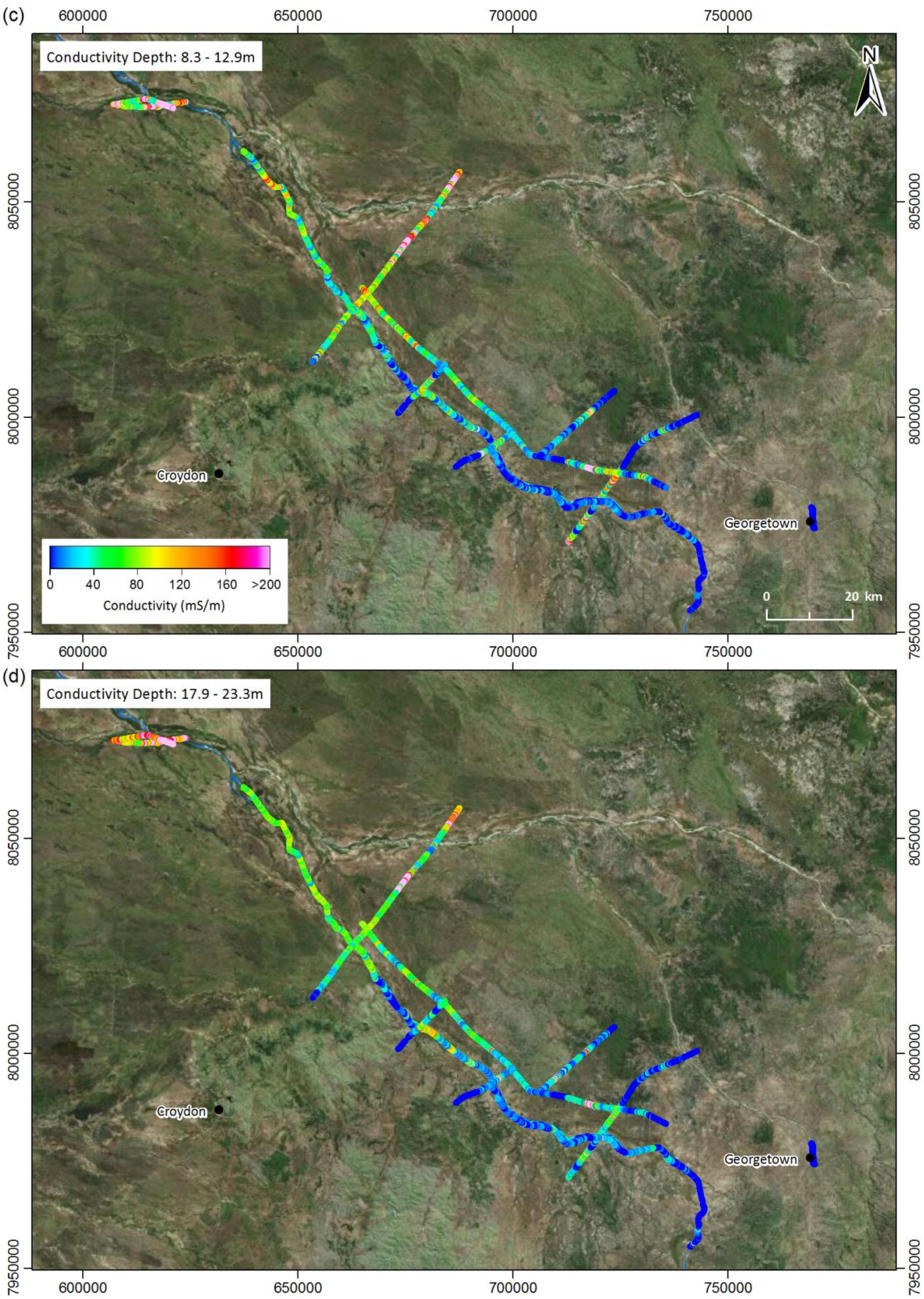


Figure 3.31 Maps of ground conductivity for four depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface in the Gilbert River area. Panel (c), shows an average conductivity for a depth 8.3 and 12.9m below the ground surface; and Panel (d), an average conductivity for a depth 17.9 and 23.3m below the ground surface.

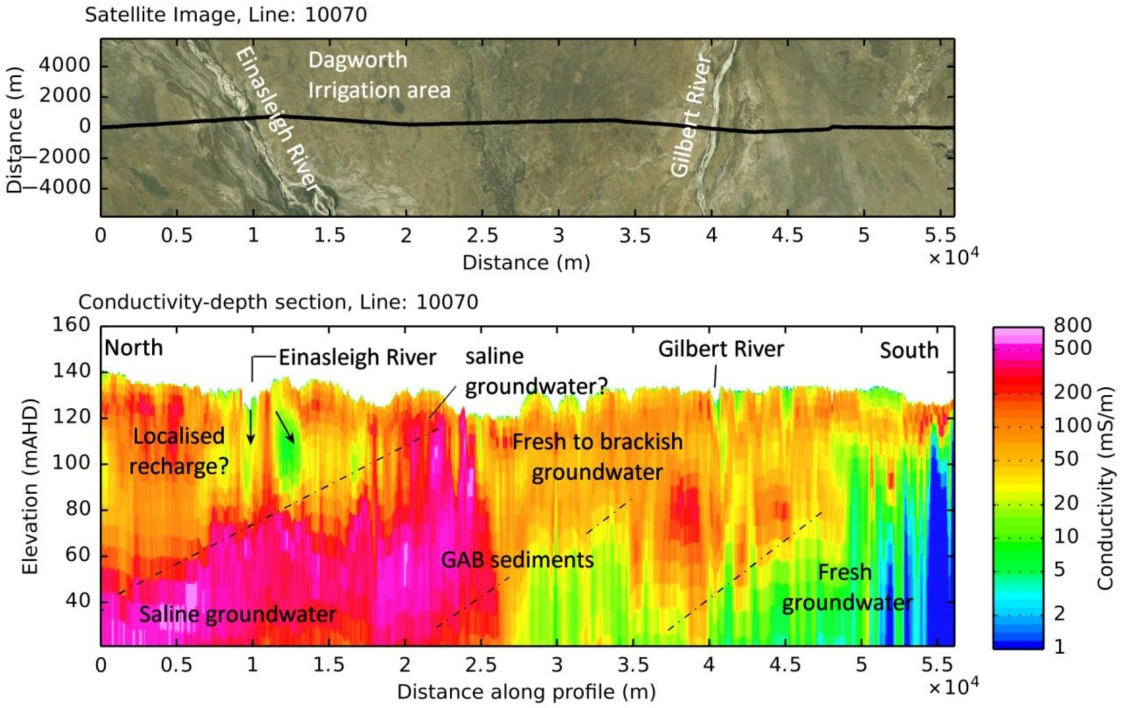


Figure 3.32 Conductivity-depth section (lower panel) for flightline 10070 (see Figure 3.29 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects both the Einasleigh and Gilbert Rivers running NE-SW.

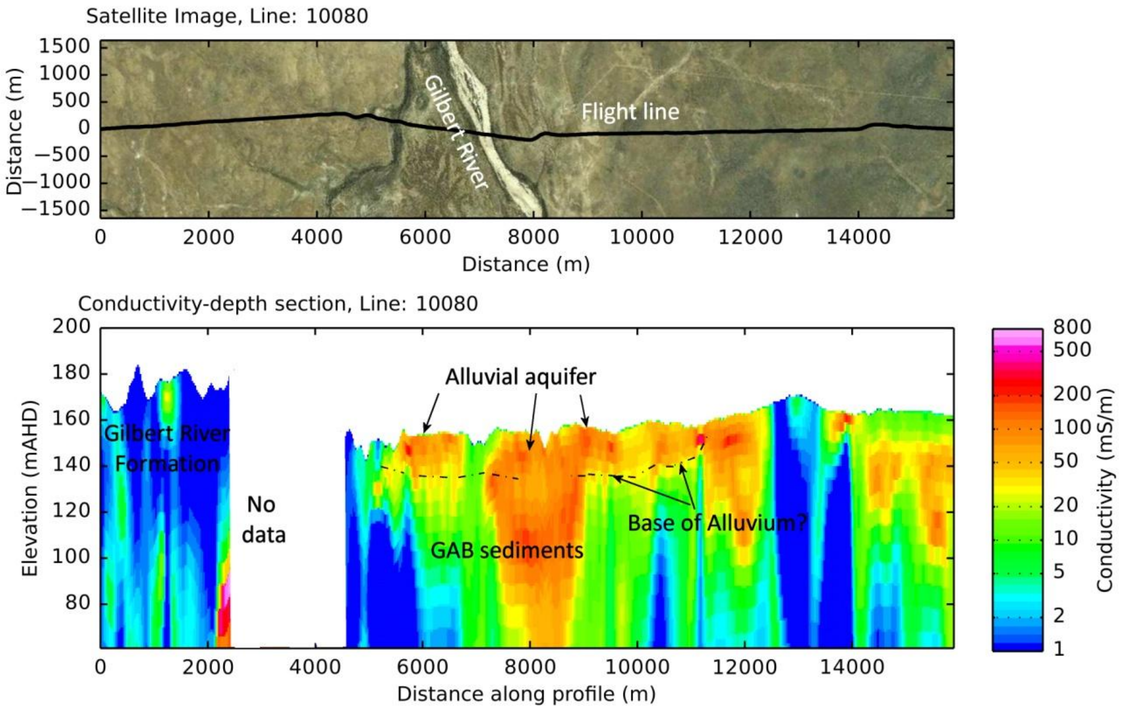


Figure 3.33 : Conductivity-depth section (lower panel) for flightline 10080 (see Figure 3.29 for location). Location of flight line on a satellite image is shown in upper panel. This flight line transects the Gilbert River running NE-SW.

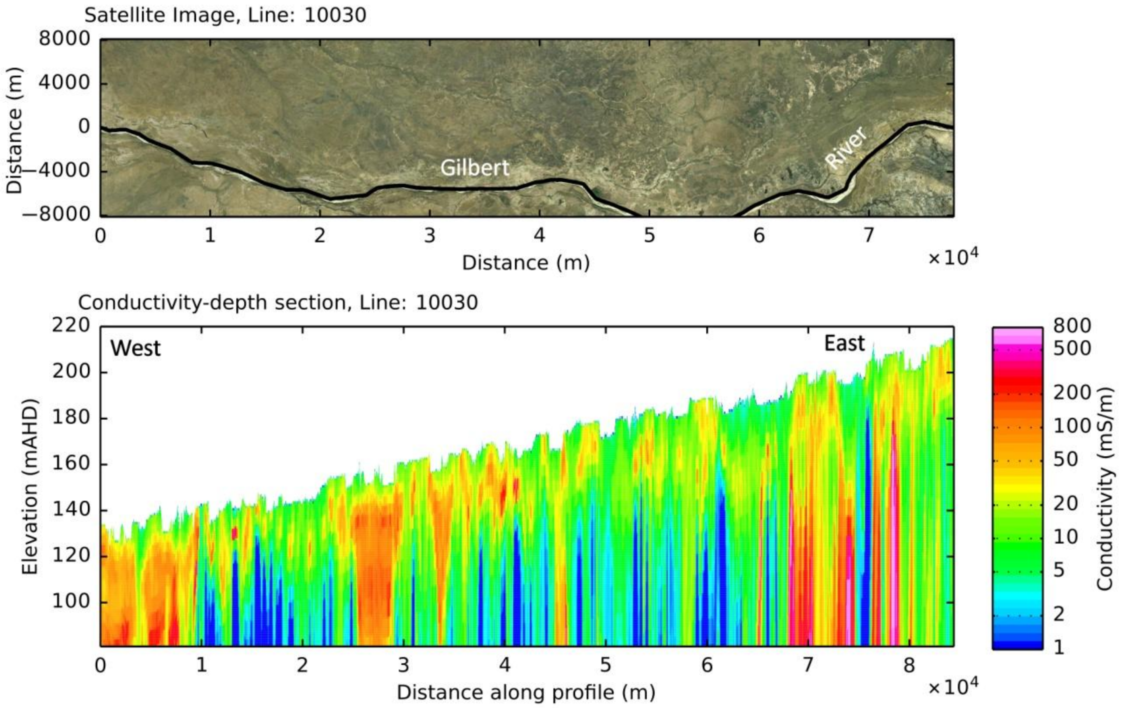
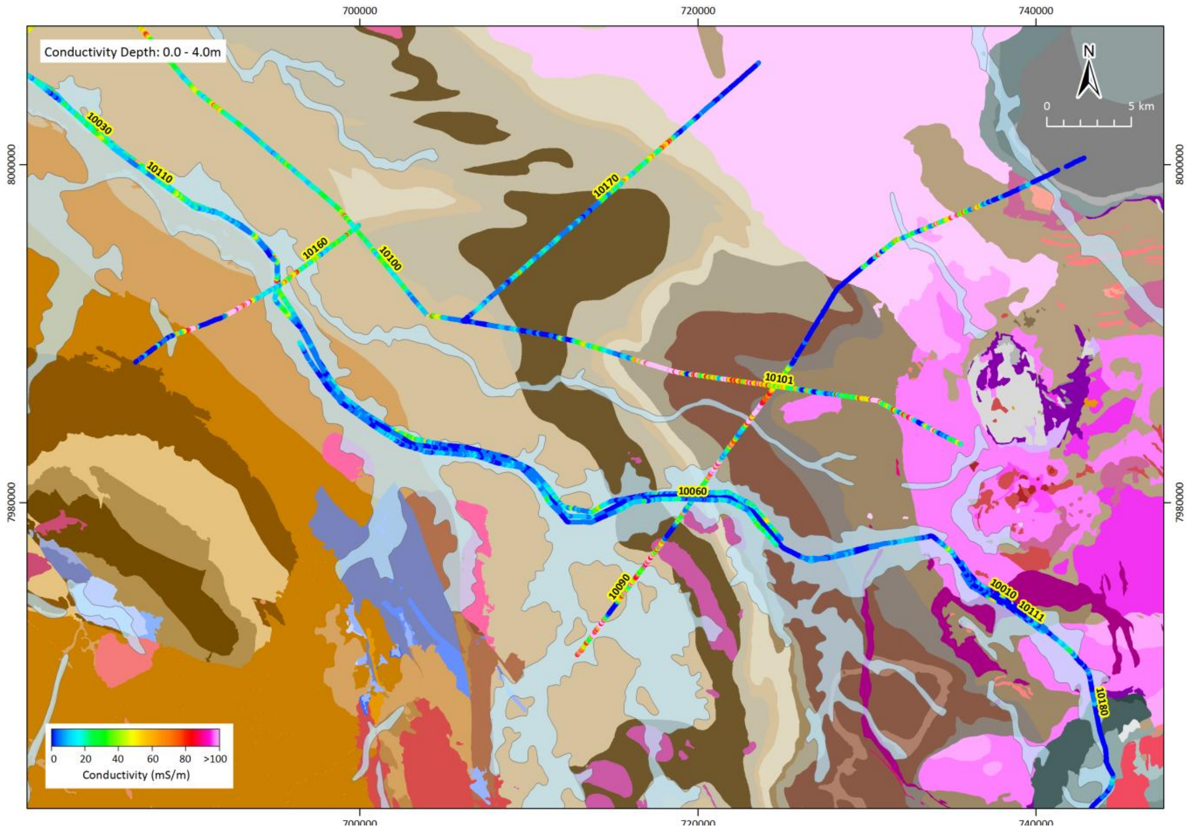


Figure 3.34 Conductivity-depth section (lower panel) for flightline 10030 (see Figure 3.29 for location) which follows the line of the Gilbert River running from east to west. Location of flight line on a satellite image is shown in upper panel.

Gilbert River Area:

The Gilbert river area approximately 50 kms west of Georgetown (Figure 3.29) was subject to more detailed analysis. Here the Gilbert River trends north-west across rolling hills and plains formed in deeply weathered metasediments and intrusives (Figure 3.35). In this reach of the river, the associated alluvium can extend a few kilometres either side of its current course. Along the river, the main aquifer is the bed sands, which vary in thickness from less than a metre up to approximately fifteen metres. In the AEM derived interval conductivities overlain on the geology (Figure 3.35 and 3.36), the alluvium/bed sands are generally characterised as having low , to very low conductivities, suggesting fresh water being present in the saturated part of the aquifer. Conductivities gradually increase along the Gilbert River to the north-west, but not significantly.

Away from the river higher conductivities are observed in a few places in the near surface. These may be associated with poorly drained areas which are removed from tributaries and larger creeks, areas that may be characterised by colluvium and/or weathered bedrock. A conductivity depth section for flightline 10090 (Figure 3.38) which traverses across both the Gilbert and Etheridge Rivers (most SE line in Figure 3.35 for location). It shows areas with colluvium NE of the Gilbert River commonly associated with elevated conductivities (higher groundwater salinity?). The AEM data also suggest there might be a significant hydraulic gradient between the Proterozoic metasediments (in the middle of the flight line), and the Gilbert River.



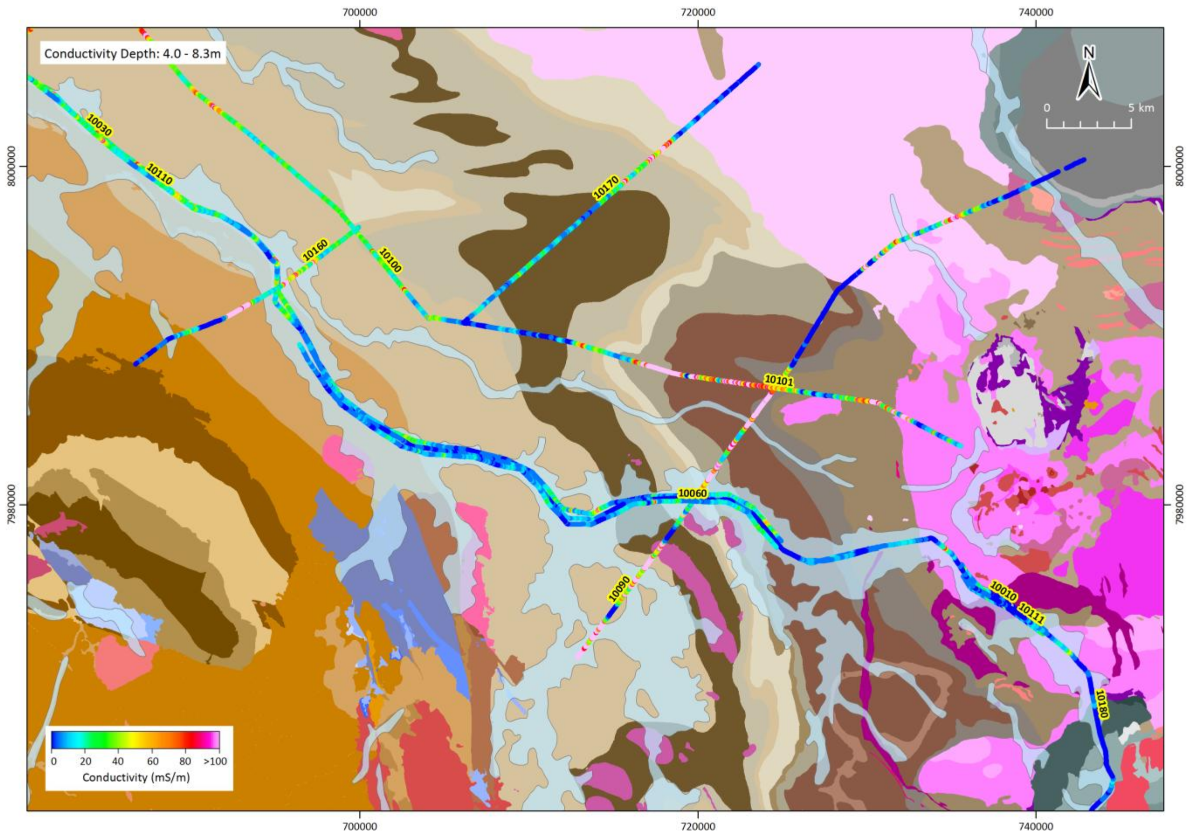


Figure 3.35 Maps of ground conductivity for two depth intervals showing spatial patterns of ground conductivity as it varies for different depths below the ground surface in the Gilbert River area. The depth intervals 0 and 4 m and 4 to 8.3 m are overlain on geology. Lithology key is shown in Figure 3.37.

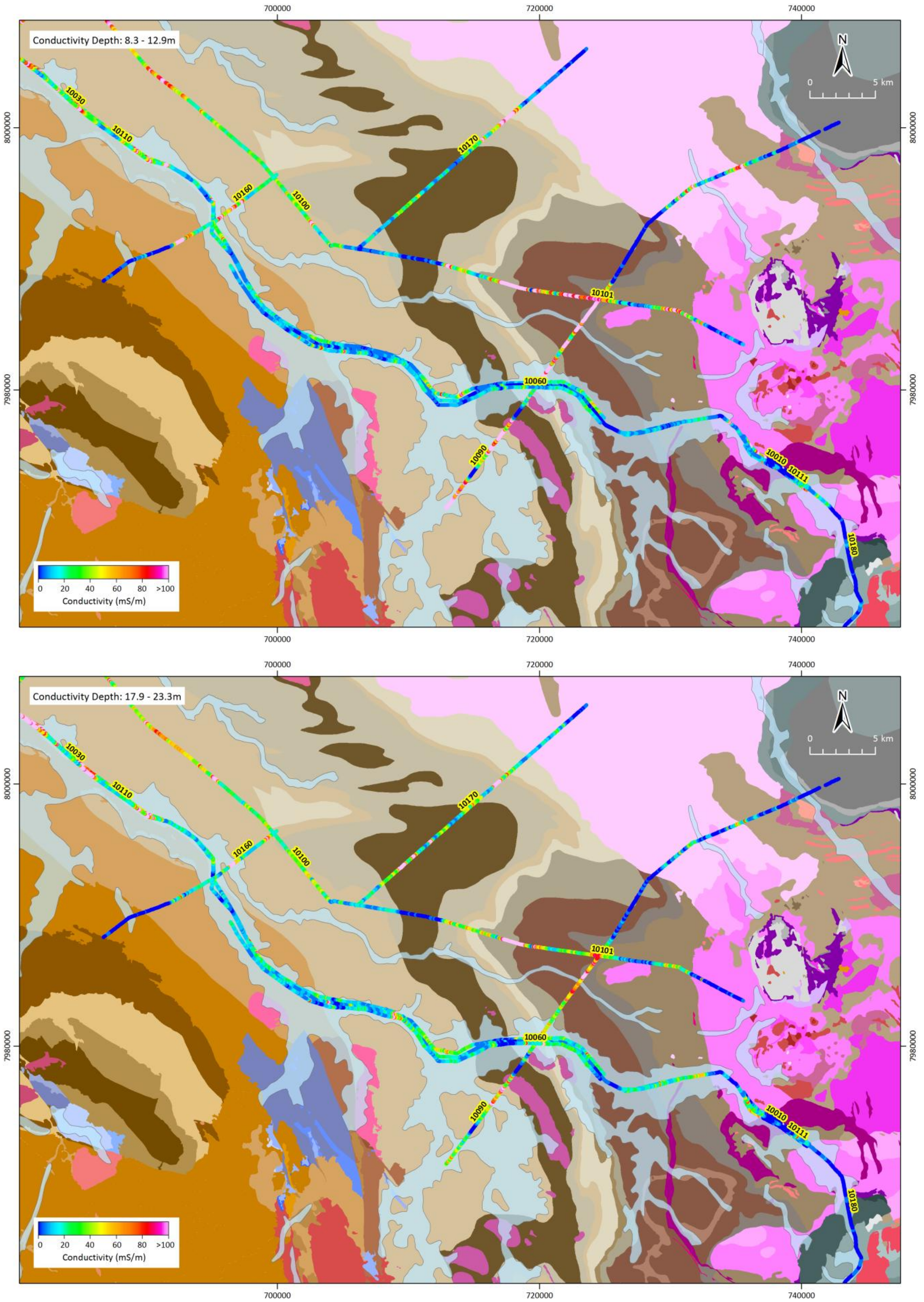


Figure 3.36 Maps of ground conductivity for two depth intervals showing spatial patterns of ground conductivity as it varies with depth below the ground surface in the Gilbert River area. The depth intervals 8.3 and 12.9m and 17.9 and 23.3m are overlain on geology. Lithology key is in Figure 3.37.

Transported Cover

Alluvium

Bedrock Geology

PERMIAN (Intrusive)

Awring Granodiorite

EARLY PERMIAN

Bullseye Rhyolite/c

Bullseye Rhyolite/r

Bullseye Rhyolite/r?

Bullseye Rhyolite/s

Bullseye Rhyolite/t

Bullseye Rhyolite/t?

Goat Creek Andesite

Goat Creek Andesite?

Linley Rhyolite

Little Pocket Dacite

McFarlanes Andesite

McFarlanes Andesite?

Ps-Croydon

EARLY PERMIAN (Intrusive)

Wallys Dolerite

LATE CARBONIFEROUS - EARLY PERMIAN?

Ant Hill Andesite Member

Ironhurst Formation/1

Ironhurst Formation/2a

Ironhurst Formation/2b

Puranga Rhyolite/3

Womblealla Rhyolite Member

CARBONIFEROUS - PERMIAN? (Intrusive)

bx-Gt

CARBONIFEROUS - PERMIAN (Intrusive)

CPir-Kennedy Province

MIDDLE - LATE CARBONIFEROUS

Dismal Creek Dacite

Huonfels Rhyolite Member

Huonfels Rhyolite Member/x

Namul Dacite

Scrubby Creek Rhyolite/a1

Scrubby Creek Rhyolite/r1

Scrubby Creek Rhyolite/r2

Scrubby Creek Rhyolite/r3

Scrubby Creek Rhyolite/r4

Scrubby Creek Rhyolite/r5

MIDDLE - LATE CARBONIFEROUS (Intrusive)

Mount Darcy Microgranodiorite

Mount Darcy Microgranodiorite/x

Mount Sircom Microgranodiorite

Prestwood Microgranite

LATE DEVONIAN - EARLY CARBONIFEROUS

Gilberton Formation

Gilberton Formation?

Spyglass Andesite Member

SILURIAN? (Intrusive)

Brandy Hot Granodiorite

Brandy Hot Granodiorite?

PRECAMBRIAN - PALAEOZOIC (Intrusive)

rh-Gt

MESOPROTEROZOIC? - NEOPROTEROZOIC?

Arrongulla Formation

Chulcee Formation

Chulcee Formation?

Dirie Sandstone

Guela Sandstone

MESOPROTEROZOIC? (Intrusive)

Forest Home Trondhjemite

Forest Home Trondhjemite?

MESOPROTEROZOIC

B-Creek Rhyolite

B-Creek Rhyolite/a

B-Creek Rhyolite?

Carron Rhyolite

Carron Rhyolite/a

Carron Rhyolite?

Idalia Rhyolite

Idalia Rhyolite/a

Idalia Rhyolite?

Littleton Dacite Member

Malacura Sandstone

Malacura Sandstone?

MESOPROTEROZOIC (Intrusive)

Delaney Granite

Forsayth Granite

Forsayth Granite/a

Forsayth Granite/bx

Forsayth Granite/1

Forsayth Granite/1?

Forsayth Granite/2

Forsayth Granite/2?

Forsayth Granite?

Georgetown Granite Complex

Macartneys Granite

Macartneys Granite?

Mount Turner Granite

Olsens Granite

Olsens Granite/f

Olsens Granite?

PALAEOPROTEROZOIC - MESOPROTEROZOIC?

Candlow Formation/1

Candlow Formation/1?

Candlow Formation/2

Candlow Formation/2?

Candlow Formation/3

Candlow Formation/3?

Heliman Formation

Heliman Formation/1

Heliman Formation?

Langdon River Mudstone

Langdon River Mudstone?

Stockyard Creek Mudstone Member

Townley Formation

Townley Formation?

White Bull Member

White Bull Member?

PALAEOPROTEROZOIC

Lane Creek Formation

Lane Creek Formation/s

Lane Creek Formation/s?

Lane Creek Formation/x

PALAEOPROTEROZOIC (Intrusive)

Cobbold Metadolerite

Figure 3.37 Basement lithology key for Figures 3.35 and 3.36.

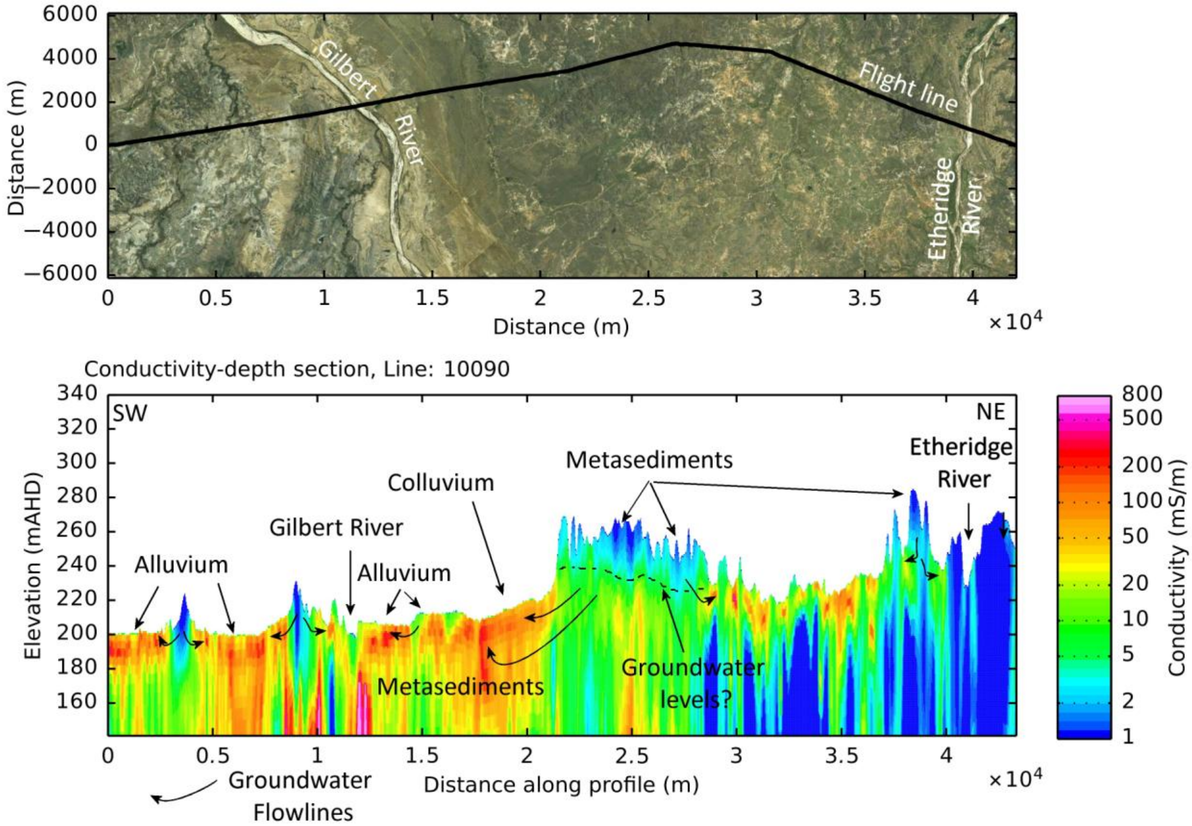


Figure 3.38 Conductivity-depth section (lower panel) for flightline 10090 which transects both the Gilbert and Etheridge Rivers, running NE-SW. The AEM data suggest that there could be a significant hydraulic gradient from the metasediments in the centre of the line towards the Gilbert River.

Georgetown

Three parallel flight lines were acquired along the Etheridge River adjacent the Georgetown township (Figure 3.39). The intent was to see whether the AEM data could resolve the younger alluvial and bedsands aquifers and provide some insight into their geometry and variability. The aim was to also determine whether there were additional areas associated with this aquifer that could be exploited to supplement the existing town water supply. The alluvium and bedsands of the Etheridge River overlie weathered intrusive rocks and metasediments in the area studied. The conductivity depth sections for flight line 10130 (centre line), 10140 (west bank of Etheridge River) and 10150 (east bank of Etheridge River) are shown in Figures 3.40, 3.41 and 3.42 respectively. Observed conductivities are low, and would indicate relatively fresh groundwater.

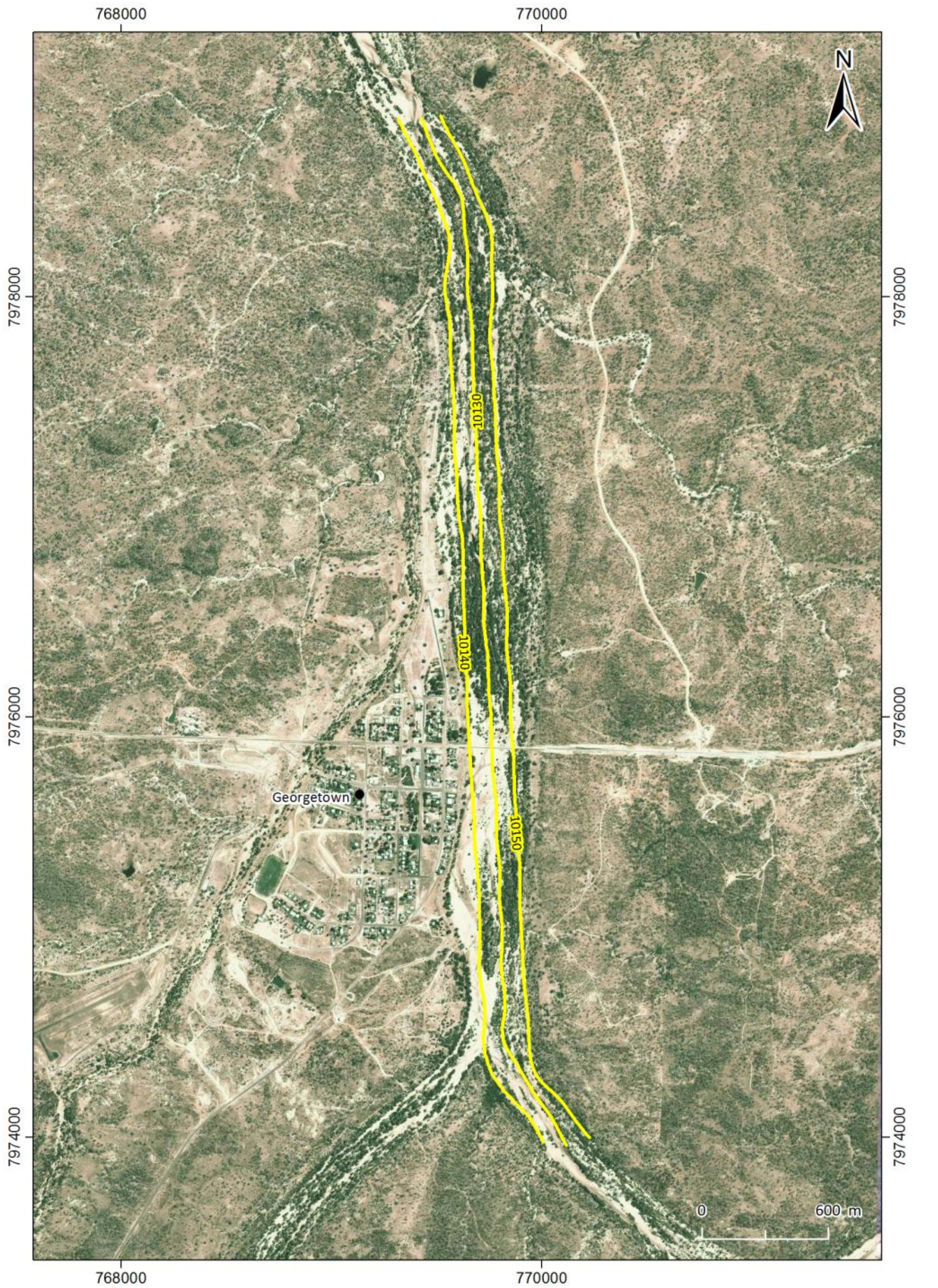


Figure 3.39 Flightline map for river adjacent to Georgetown in the Gilbert catchment.

The interpretation of the near surface conductivity structure along each of the three transects (Figures 3.40, 3.41 and 3.42) suggests that the alluvium/bed sands have a slightly more elevated conductivity relative to parts of the underlying fractured rock aquifer system. However, this needs to be tested. Whether the alluvial aquifer is laterally confined by rock bars in the subsurface also needs to be checked. The presence of a vertical to sub-vertical conductivity structure may be related to differential recharge/discharge, from the alluvial aquifer into the underlying fractured rock aquifer system beneath the river, or vice versa. Although the observed conductivity structure suggests a connection between the surface, and deeper parts of the profile, there is also no information to indicate whether the fractured rock system discharges into the overlying alluvial aquifer system.

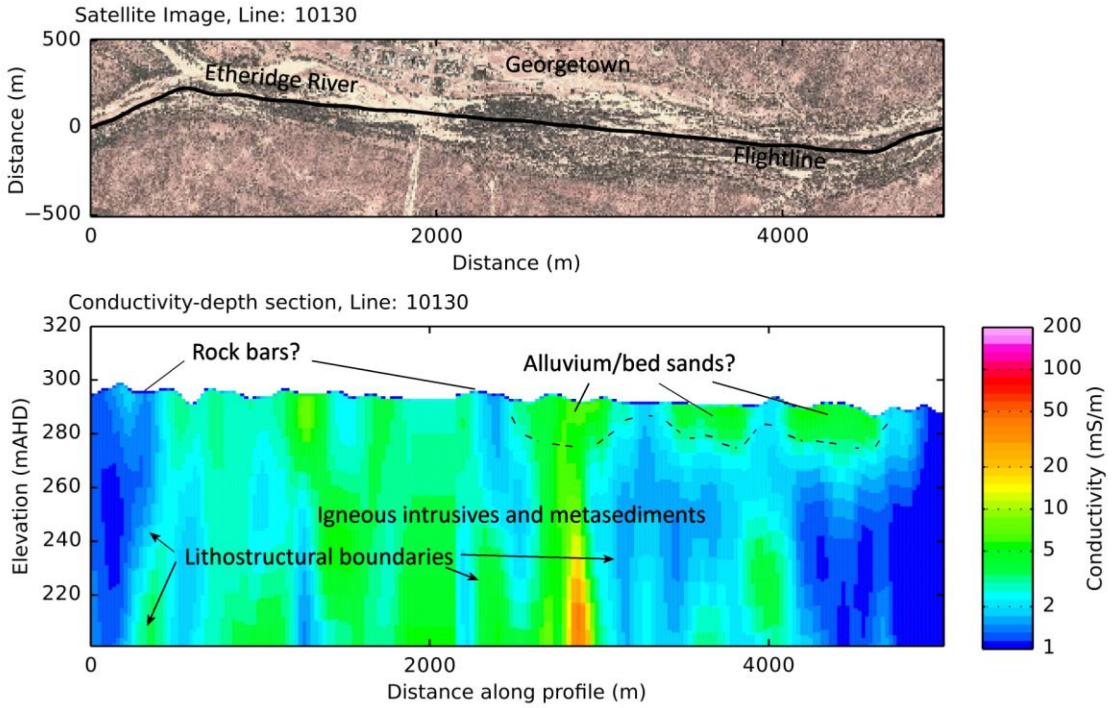


Figure 3.40 Conductivity-depth section (lower panel) for flightline 10130 (see Figure 3.39 for location). Location of flight line on a satellite image is shown in upper panel. This flight line follows the Etheridge River running south (left) to north (right).

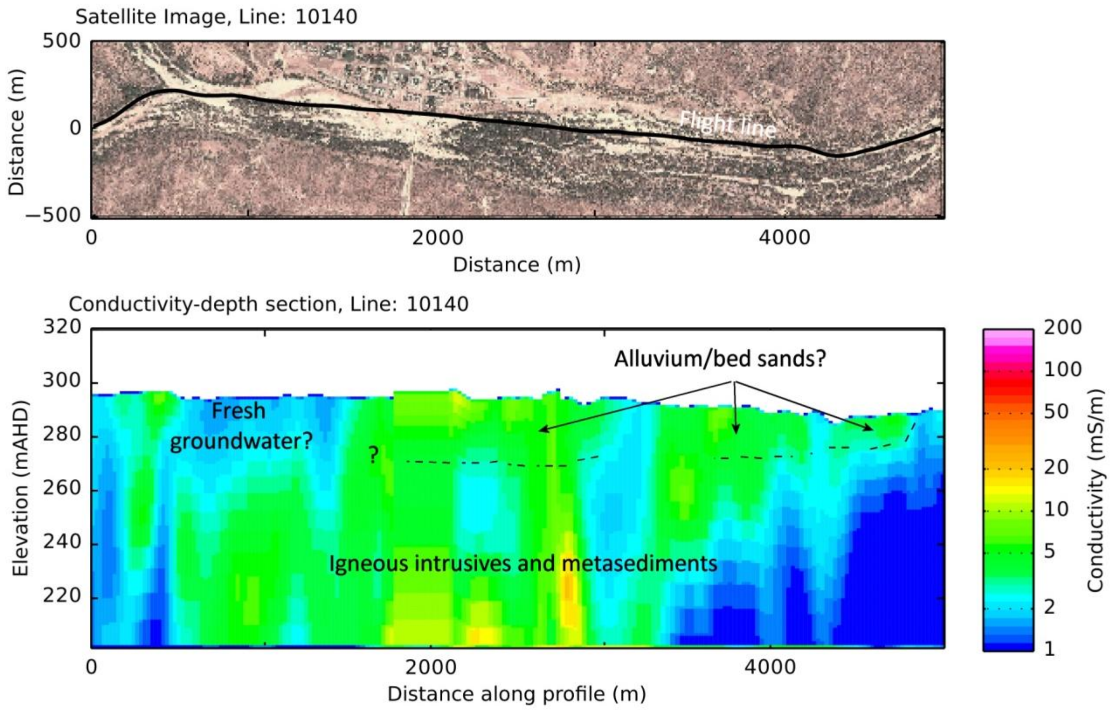


Figure 3.41 Conductivity-depth section (lower panel) for flightline 10140 (see Figure 3.39 for location). Location of flight line on a satellite image is shown in upper panel. This flight line follows the Etheridge River on its western bank.

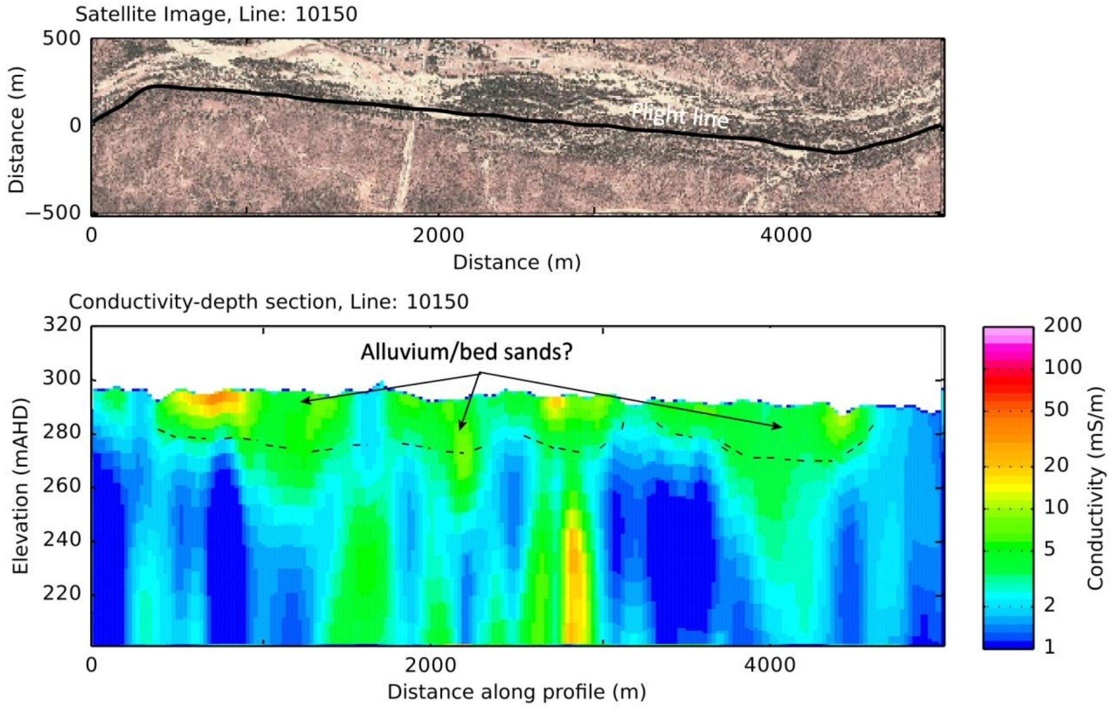


Figure 3.42 Conductivity-depth section (lower panel) for flightline 10150 (see Figure 3.39 for location). Location of flight line on a satellite image is shown in upper panel. This flight line follows the Etheridge River on its eastern bank.

4 Conclusions

4.1 Results against Tasks

Interpretation of geophysical data acquired from an AEM system, when combined with available geological data, provides independent evidence of aquifer architecture and litho-structural features that influence groundwater discharge. In the Flinders and Gilbert catchments the AEM data provided corroborative evidence for connectivity between the alluvial and bedsands aquifers and deeper aquifer systems. In places, the airborne EM data suggested base flow from deeper aquifers, and, in the case of basalts adjacent to the river systems could support local dry season flows and the persistence of pools. This information addressed a requirement of Task 1 by providing additional constraint on the determination of hydrogeological controls on groundwater variability and discharge.

Results from the geophysics provided information pertinent to water storage sites, including insight into geological structure and stratigraphy. This addressed Task 2.

By mapping near surface conductivity variations near surface soil salinity distribution was defined in several places in both catchments (Task 3). The airborne EM data corroborated information obtained by on-ground soil salinity studies in the Maxwelton and Einasleigh areas and provided additional information on the connection between surface salinity and deeper groundwater. The geophysics also supported observations on mid-slope discharge and salinisation in areas adjacent to basalts outcropping along the Flinders River.

The opportunity remains to employ the AEM data set acquired as part of the Assessment in further on-ground investigations, and would add value to when linked to salinity and groundwater resource investigations. An integrated interpretation of AEM data, when linked to a hydrogeological and soils data will provide additional confidence in the information they contain and should be encouraged.

4.2 Concluding remarks

Results from the targeted approach to airborne geophysical data acquisition that was employed in the Assessment have further demonstrated the effectiveness and value of this approach in data poor areas on northern Australia. In large catchments such as encountered here, the acquisition of high resolution helicopter EM data along select longitudinal river traverses and along lines that crossed the main river systems, have provided information that has corroborated existing knowledge and extended our conceptual understanding of landscape processes. However, realising the full benefit of these data requires that they be linked to other on-ground activities as was undertaken in the larger investigation of the two catchments.

4.3 References

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CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

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Water for a Healthy Country Flagship
Tim Munday
t +61 8 6436 8634
e tim.munday@csiro.au
w csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship.aspx