Department of Natural Resources and Mines
Office of Groundwater Impact Assessment

Groundwater connectivity between the Condamine Alluvium and the Walloon Coal Measures

A hydrogeological investigation report

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Queensland Government

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Abbreviations

3-D	Three-dimensional
bp	Barometric pressure
CB	Carn Brea (e.g. CB-17 is a bore located in the Carn Brea area)
CMA	cumulative management area
CSG	coal seam gas
DA	Daleglade (e.g. DA-16 is a bore located in the Daleglade area)
DNRM	Department of Natural Resource and Mines
DOC	dissolved organic carbon
EIS	environmental impact statement
GAB	Great Artesian Basin
GWDB	Groundwater Database
GWML	Global meteoric water line
KCB	Klohn Crippen Berger Ltd
Kh	horizontal hydraulic conductivity
Kv	vertical hydraulic conductivity
LP	Lone Pine (e.g. LP-14 is a bore located in the Lone Pine area)
m/day	metres per day
mBGL	metres below ground level
MLU	Multi-Layer Unsteady state (modelling package)
OGIA	Office of Groundwater Impact Assessment
PCA	principal component analysis
QUT	Queensland University of Technology
QWC	Queensland Water Commission
SAR	sodium adsorption ratio
TDS	total dissolved solids
UNSW	University of New South Wales
UWIR	Underground Water Impact Report
XRD	X-ray diffraction
XRF	X-ray fluorescence

Summary

Purpose and scope

The Condamine Alluvium is incised into the Walloon Coal Measures in most of the central part of the alluvium. The Walloon Coal Measures is the target for coal seam gas (CSG) production along the western margins of the Condamine Alluvium footprint which can therefore potentially impact the groundwater resources of the Condamine Alluvium. The degree of impact will depend partly upon the hydraulic connectivity between the Condamine Alluvium and the Walloon Coal Measures.

The Office of Groundwater Impact Assessment (OGIA) has been progressively improving knowledge about the connectivity in the Condamine Alluvium since the publication of the first Surat Underground Water Impact Report (UWIR) in 2012 under the Condamine Connectivity Project ('the project'). Outcomes of the project and other studies have resulted in the predictions of the impact of CSG development in the Condamine Alluvium footprint being revised, as described in the Surat UWIR 2016.

The project has used multiple lines of investigation, including: reinterpreting geology with particular focus on the contact between the Condamine Alluvium and the Walloon Coal Measures; mapping regional groundwater level differences between the two systems; analysing the hydrochemistry of the two systems; and drilling, coring and running pumping tests at representative sites and numerically analysing the test data.

The project has been led by OGIA with collaborative arrangements with other parties, including Arrow Energy for drilling and pump testing investigations and Queensland University of Technology for assessing the hydrochemistry.

This report summarises the approach used for these investigations, the results and the conclusions from the project. New knowledge from the project has been incorporated into the regional groundwater flow model developed by OGIA to support preparation of the Surat UWIR 2016.

Context and background

The groundwater resources of the Condamine Alluvium have been extensively developed and are used for a range of water supply purposes including irrigation, urban use, commercial use, industrial use, stock-intensive, aquaculture, and stock and domestic uses. About 85 per cent of the Condamine Alluvium groundwater use is associated with the irrigation sector.

The Quaternary age Condamine Alluvium is incised into the Jurassic Surat Sediments which subcrop in most of the area forming the bedrock to the alluvium. The most significant of the Surat Sediments associated with the Condamine Alluvium is the Walloon Coal Measures, underlying most of the central part of the Condamine Alluvium, and the Springbok Sandstone, wedged between the Condamine Alluvium and the Walloon Coal Measures along the western margin. The Main Range Volcanics underlies the Condamine Alluvium tributaries further east and sits above the Walloon Coal Measures. A representative 3-D schematic of the regional geological and hydrogeological setting around the Condamine Alluvium is shown in Figure ES 1.

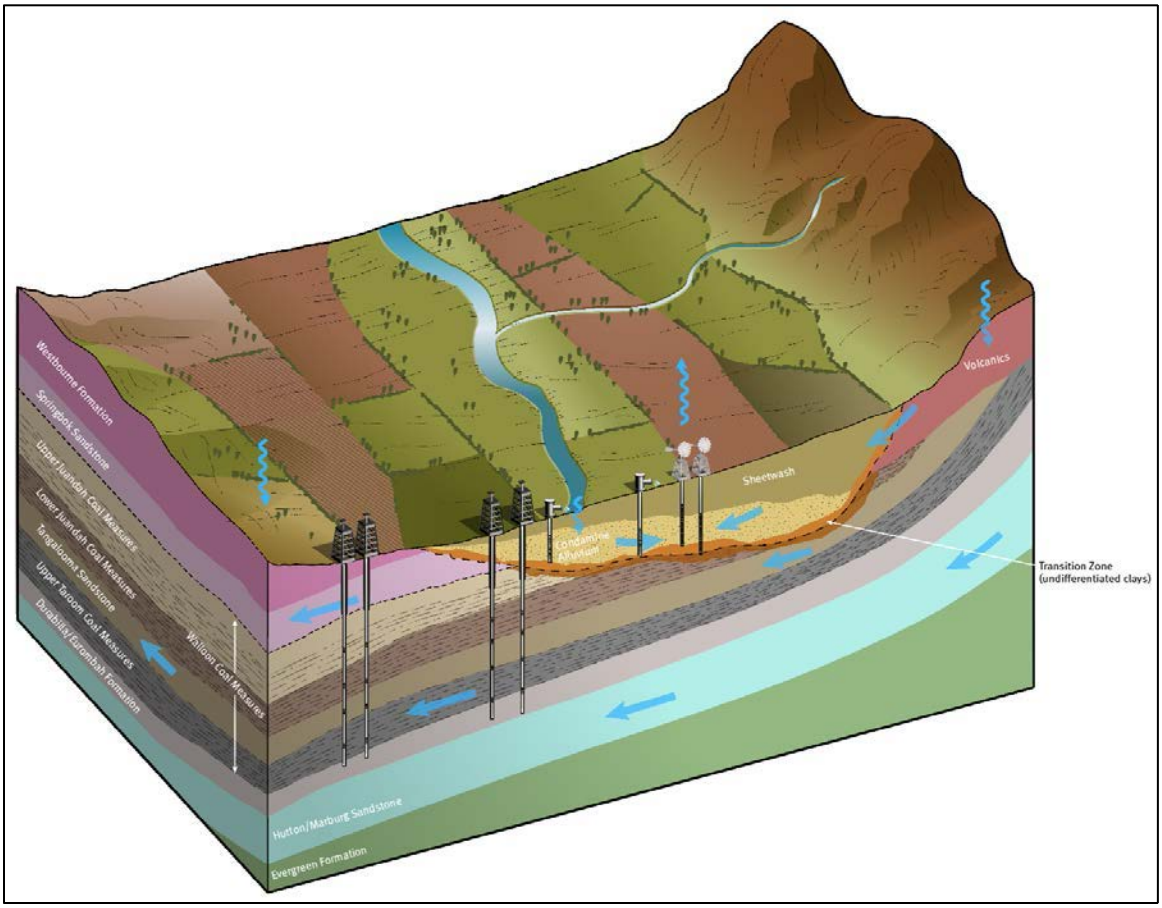

Figure ES 1 Schematic representation of regional geological and hydrogeological setting around the Condamine Alluvium

The Condamine Alluvium functions as a single regional aquifer system of connected sand bodies within a skeleton of clay layers. The granular alluvium of mainly sand and gravel layers in the lower part of the alluvium is overlain by a thick sheetwash deposit of finer material with higher clay content. The granular alluvium is the most transmissive part of the alluvium and is, therefore, the main source of groundwater. The alluvium tends to be finer in the downstream direction and along the margins; as a result, groundwater yields are higher towards the southern central part of the alluvium. Tertiary Sediments exist irregularly along relict drainage features below the Condamine Alluvium and are hydraulically connected to the alluvium.

The contact between the Condamine Alluvium and the underlying Walloon Coal Measures is characterised by a combination of basal alluvial clays of the Condamine Alluvium and the weathered upper part of the Walloon Coal Measures, which is often indistinguishable and dominated by multi-coloured clay. In places, the same relationship exists between the Condamine Alluvium and the Springbok Sandstone. The term **transition zone** is used in this report to represent this clay-dominated horizon at the base of the Condamine Alluvium.

The Condamine Alluvium is a major aquifer system. It is recharged primarily by leakage from the Condamine River and its tributaries in the east and southeast. Currently, most of the discharge is from groundwater extraction through private water bores. Prior to development, groundwater flow in the Condamine Alluvium had been predominantly southeast to northeast. Over the past few decades, the flow pattern has changed and groundwater now flows toward the depressions that have developed as a result of groundwater extraction in those areas. On a regional basis, the underlying Walloon Coal Measures is generally considered to be an aquitard, although its groundwater is used extensively for stock and domestic supplies where it outcrops or where groundwater is found at shallow depth. In the area, the Walloon Coal Measures is recharged through the Main Range Volcanics and outcropping sandstone units along the eastern and southeastern margins. Groundwater flow in the Walloon Coal Measures in the Condamine area is generally to the northwest.

Important characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures are shown schematically in Figure ES 2. Four hydrostratigraphic units can be identified:

1. the Condamine Alluvium (an aquifer) which is taken to include the Tertiary Sediments where present
2. the low-permeability transition zone of undifferentiated clay between the base of the Condamine Alluvium and un-weathered Walloon Coal Measures (an aquitard)
3. the firm mudstone/siltstone above the uppermost coal seams within the Walloon Coal Measures (an aquitard)
4. the part of the Walloon Coal Measures that has largely connected coal seams in a matrix of mudstone, siltstone and fine sandstone and which may be the target for CSG extraction.

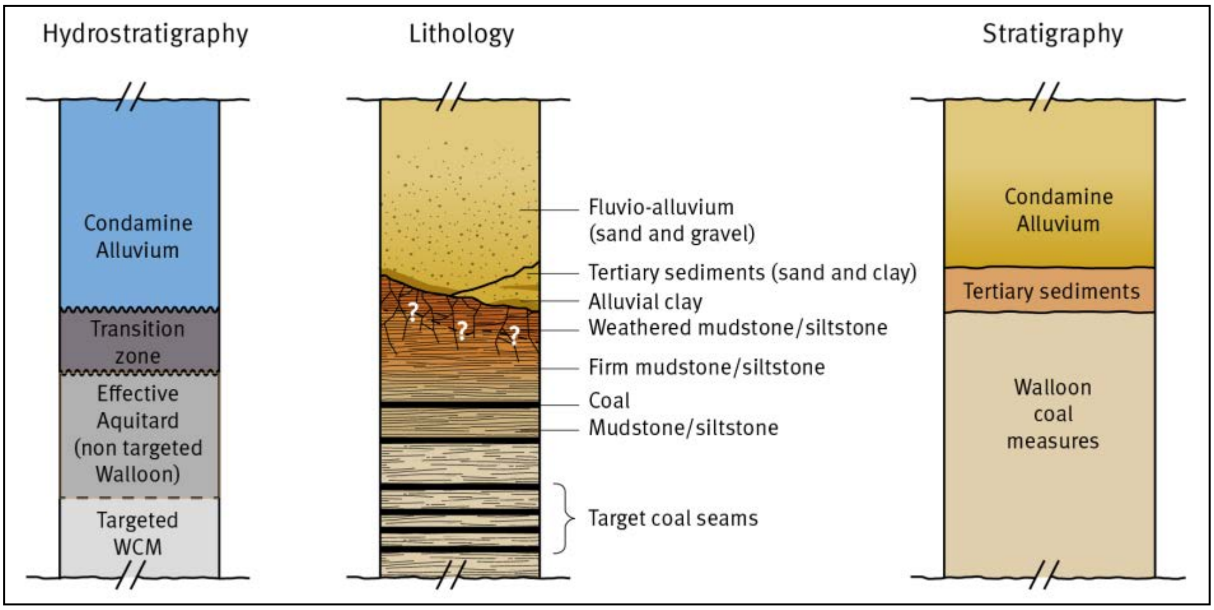

Figure ES 2 Conceptual schematic representation of interface between the Walloon Coal Measures and the Condamine Alluvium

Investigations and assessments of connectivity

Interpretation and modelling of the geology

Geological interpretation and geological modelling were undertaken to improve understanding of the main geologic units within the area, particularly for the transition zone and the underlying sediments, to identify the presence or absence of physical barriers to flow between the Walloon Coal Measures and the Condamine Alluvium.

Data from about 3,500 existing bores was supplemented with additional data from bores drilled by the project and, where available, geophysical data. The data provided a consistent basis for interpreting formation boundaries and developing the Condamine Geo Model which represents: the sheetwash (with topsoil); the granular alluvium; the transition zone; and the upper Surat Sediments which mainly comprise the Walloon Coal Measures. The Condamine Geo Model was also used in the construction of the regional geological model developed by OGIA to support the preparation of the Surat UWIR 2016.

The lower boundary of the transition zone is the base of the weathered horizon of the Walloon Coal Measures. This lower boundary may be marked either by the first recorded coal seam or by unweathered mudstone. Mapping shows that the transition zone underlies much of the central area of the Condamine Alluvium. It is not, however, a continuous layer; where present, it ranges in thickness from less than one metre to just over 15 metres. The upper part of the Walloon Coal Measures above the shallowest coal seams is dominated by mudstone and siltstone which provides a further barrier to water movement between the potential CSG target coal seams and the overlying alluvium.

Surveying and mapping of groundwater levels

Mapping of groundwater levels was undertaken to identify the spatial distribution of differences between groundwater level in the Condamine Alluvium and water pressures in the Walloon Coal Measures. The way the two groundwater systems have responded to extraction from the Condamine Alluvium over recent decades provides information about connectivity between them.

Although groundwater level maps for the Condamine Alluvium have been prepared under previous studies, no attempt had been made to map the groundwater pressure surfaces in the underlying Walloon Coal Measures. To fill this critical gap for the connectivity study, bores were identified across the Condamine Alluvium footprint that are thought to provide information on water pressure in the Walloon Coal Measures. Some of these bores which were accessible for water level measurements were surveyed to collect groundwater level data and water samples for chemical analysis. The new data together with existing data was used to prepare up-to-date groundwater level maps for the Condamine Alluvium and the Walloon Coal Measures and to analyse the relative differences.

The results indicate that groundwater levels in the more developed parts of the Condamine Alluvium have been lowered substantially by irrigation extraction over the past 60 years, significantly altering the flow pattern in the alluvium. Groundwater levels in the Walloon Coal Measures have not materially changed, resulting in a difference of 5–20 metres between the formations across much of the central part of the Condamine Alluvium. This demonstrates that there is a significant impediment to flow between the two formations.

Assessment of the hydrochemistry

An assessment of the available hydrochemical data was carried out to identify hydrochemical indicators of any past mixing of water between the Condamine Alluvium and the Walloon Coal Measures. One area of interest was the area of relatively high salinity in the Condamine Alluvium which could have resulted from movement of water from the Walloon Coal Measures into the alluvium. Another was the area with a large groundwater level difference from the Walloon Coal Measures into the Condamine Alluvium which could cause water to move between the formations if significant connectivity existed.

The assessment used major ion data analyses from some 3,000 groundwater samples from private water supply bores, monitoring bores and CSG wells. A number of advanced assessment techniques were used including multivariate analysis. These techniques were effective for analysing important underlying differences in hydrochemistry of the two systems and corresponding differences in the hydrochemical evolution of water in each system.

The assessment found that the underlying hydrochemical signatures of the two formations are different and are more likely to be the result of chemical evolution within the formations rather than the result of the movement of water between the formations.

Aquifer pumping tests

Pumping tests and associated drilling were also implemented to establish the geological and hydrogeological characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures. Water was pumped form the Condamine Alluvium and pressure responses were monitored at multiple levels in the two formations. The data was analysed to provide estimates of the vertical hydraulic conductivity of the transition zone material separating the Condamine Alluvium from the underlying Walloon Coal Measures.

Tests were carried out at two locations of different hydrogeological settings. One was located about 15 kilometres east of Cecil Plains in an area of significant groundwater level depression due to irrigation development; the other was 25 kilometres northwest of Dalby.

The project established nested observation bores near an existing high-capacity bore drawing water from the Condamine Alluvium. The observation bores were set in the alluvium and permeable horizons just above the transition zone, in the shallowest permeable coal seams of the Walloon Coal Measures, and at a lower level in the Walloon Coal Measures that could potentially contain CSG. During drilling, continuous core samples were collected to establish the physical characteristics of the geological material in and around the interface, supplemented with geophysical logging and lab testing of geological material.

Pumping tests were carried out for at least 30 days. All field operations were carried out by Arrow Energy with full OGIA involvement. Monitoring of the observation bores continued after pumping and through the recovery period. Monitoring at these high-value monitoring sites will continue indefinitely to assess responses to long-term pumping cycles and other influences.

The pumping test data was analysed using a range of techniques. The results suggest that around the sites there was no significant cross-formational flow in response to pumping during the tests. Quantitative analysis indicates vertical hydraulic conductivities of the material between the formations of around 10^{-6} m/day, which is typical of a highly effective aquitard.

Conceptualisation of connectivity

Conceptualisation, as well as the confidence in conclusions about the connectivity, has improved significantly as a result of project investigations.

Groundwater flow in the Condamine Alluvium and the Walloon Coal Measures is mainly horizontal. Vertical flow and interaction between the two formations is impeded by a combination of the transition zone and the firm mudstone/siltstone interburden above the coal seams. The degree to which the flow is impeded depends upon the combined thickness and vertical hydraulic conductivity of these two layers.

The first barrier to flow between the formations is the transition zone which is present across much of the area. There are some areas where the transition zone is absent, particularly near the margins of the Condamine Alluvium. Due to the angular contact of the Walloon Coal Measures with the Condamine Alluvium, some of the upper coal seams along the western flank of the alluvium may come into contact with the alluvium where the transition zone is absent. In most of this area, however, the Springbok Sandstone and the Westbourne Formation are also wedged between the Condamine Alluvium and the Walloon Coal Measures, providing a significant barrier to flow along the western flank of the alluvium.

The second barrier to flow between the formations is the firm mudstone/siltstone interburden of the upper Walloon Coal Measures above the depth at which commercial CSG could be found. The shallow coal seams are not targeted for CSG development and a minimum separation distance of 30 metres is intended between the base of the Condamine Alluvium and the target coal seams. A combination of the upper undeveloped part of the Walloon Coal Measures and the transition zone will therefore function as an aquitard.

Some water supply bores targeting the Condamine Alluvium have been drilled into the top of the Walloon Coal Measures due to the difficulty in identifying the base of alluvial clays during drilling. However, these bores are unlikely to significantly affect connectivity between the formations since they are typically only screened in the Condamine Alluvium and extend only a short distance into the underlying Walloon Coal Measures.

Conclusions

The clay-dominated transition zone and the mudstones of the upper Walloon Coal Measures act as a physical barrier that impedes groundwater flow between the formations.

Persistent differences in groundwater levels between the formations, and the flow patterns within the formations, demonstrate that there is impediment to flow between the formations.

Hydrochemical data suggests that there has been little past movement of water between the formations, even in areas where significant groundwater level differences have existed for some time.

Detailed aquifer pumping tests at two sites showed that, in and around those sites, there was no significant flow of water between the formations in response to pumping. Quantitative analysis of the pumping tests indicates that the vertical hydraulic conductivity of the material between the formations is that of a highly effective aquitard.

It is concluded that the level of hydraulic connectivity between the Condamine Alluvium and the Walloon Coal Measures is low.

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Main Report

1 Introduction

1.1 Background

Current and proposed coal seam gas (CSG) development in Queensland's Surat Basin entails large-scale depressurisation of the Walloon Coal Measures coal beds which could indirectly impact the groundwater resources of overlying and underlying aquifers, including the Condamine Alluvium. The potential impact was assessed and is documented in the Underground Water Impact Report (UWIR) for the Surat Cumulative Management Area (QWC, 2012) published by the Office of Groundwater Impact Assessment (OGIA) (then the Queensland Water Commission). Since then, OGIA has progressively improved the knowledge of the groundwater flow system as new data and information has become available, ensuring that predictions of the future impacts of Surat Basin CSG development are as sound as possible.

1.2 The Condamine connectivity project

As part of its work to improve knowledge of the groundwater flow systems in the Surat Basin, OGIA has carried out the Condamine Connectivity project ('the project') which aimed to improve understanding of the groundwater connectivity between the Condamine Alluvium and the Walloon Coal Measures. This report summarises the project's background, methodology and conclusions.

The focus of the project is the central Condamine Alluvium (Figure 1-1). The tributaries of the Condamine Alluvium are not considered in detail in this project because, for the most part, they are not near those locations where CSG development is proposed or they are not in direct contact with the Walloon Coal Measures in areas where CSG development is proposed.

The improved knowledge from the project has supported more accurate assessment of the potential impacts of CSG development on groundwater in the Condamine Alluvium through regional groundwater flow modelling done by OGIA and described in the Surat UWIR 2016.

1.3 Context

The groundwater resources of the Condamine Alluvium have been extensively developed and are used for a range of water supply purposes including irrigation, urban use, commercial use, industrial use, stock-intensive use, aquaculture, and stock and domestic use. About 85 per cent of the Condamine Alluvium groundwater is used by the irrigation sector. A map of the Condamine Alluvium footprint is presented in Figure 1-1.

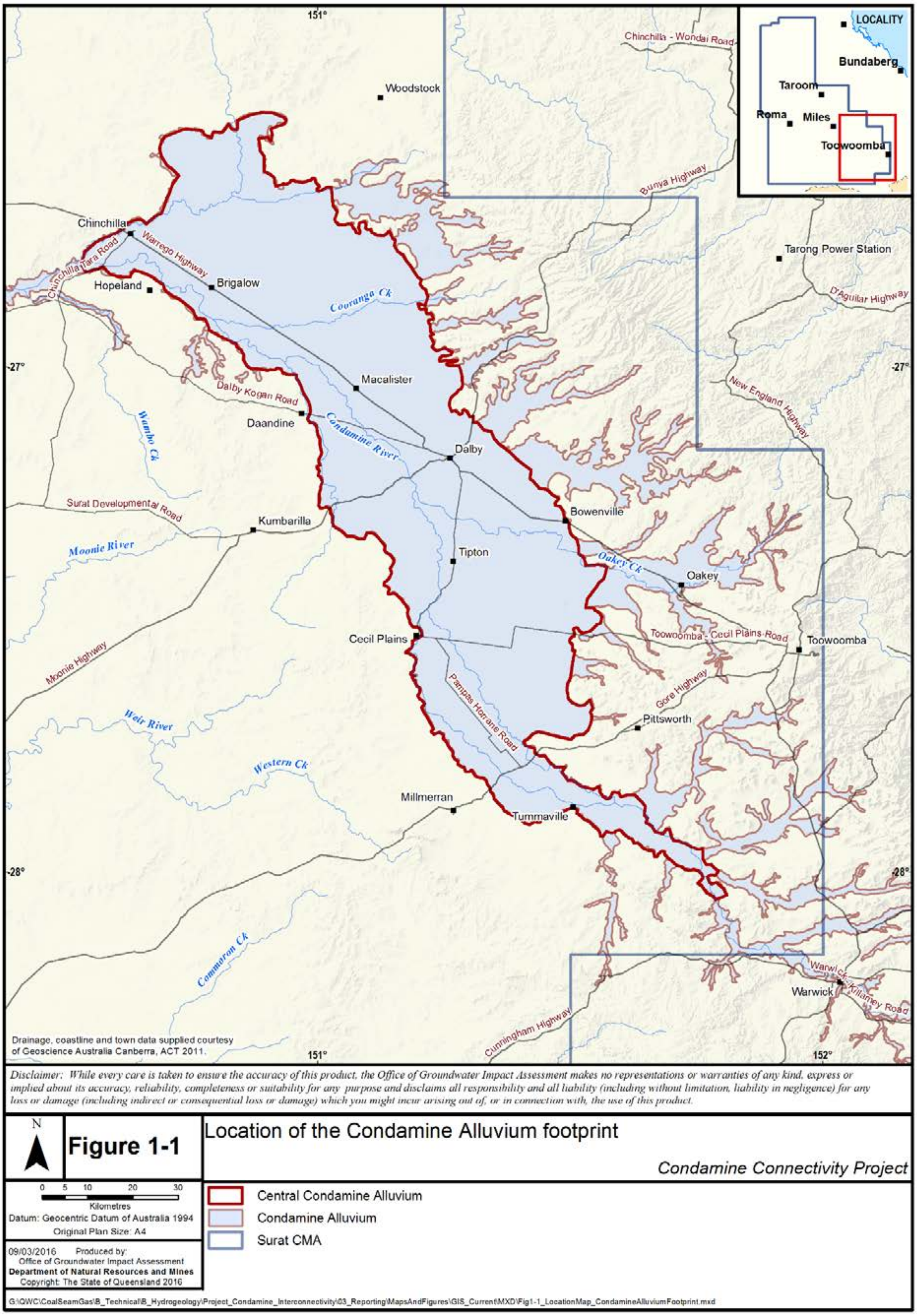

Figure 1-1 Location of the Condamine Alluvium footprint

Most of the area of the Condamine Alluvium lies on top of the Walloon Coal Measures. It is incised into the Walloon Coal Measures to a depth of up to 120 metres around Dalby. The contact between the Condamine Alluvium and the underlying bedrock is characterised by a combination of basal alluvial clays of the Condamine Alluvium and the weathered upper part of the Walloon Coal Measures (Lane, 1979). This layer, which has low hydraulic conductivity due to the predominance of clay, was referred to as the 'transition layer' in the 2012 UWIR (QWC, 2012). In this project, it is referred to as the '**transition zone'.** The term 'zone' is used rather than 'layer' because 'layer' implies a lithological formation that is formed from sediments deposited during a particular geological age.

The geological and hydraulic characteristics of the transition zone, in combination with the unweathered parts of the underlying Walloon Coal Measures, influence connectivity between the Condamine Alluvium and the coal seams. The focus of the project was to improve our understanding of the physical and hydraulic characteristics of these units and the potential for flow between them.

1.4 Overview of the project approach

The project was a collaboration led by OGIA with major input from Arrow Energy and contributions from other research institutes. The project followed multiple lines of investigation comprising the following four interrelated components:

- **interpretation and modelling of the geology** to map the transition zone, which is the interface between the Condamine Alluvium and the Walloon Coal Measures, using primary interpretation of bore data
- **surveying and mapping of groundwater levels** of the Condamine Alluvium and the Walloon Coal Measures to establish historic and current differences in groundwater levels between the two formations
- **assessment of the hydrochemistry** to test hypotheses about mixing groundwater between the Condamine Alluvium and the Walloon Coal Measures
- **aquifer pumping tests** and associated drilling at selected sites to establish the physical and hydraulic characteristics of the transition zone and establish high-value long-term monitoring sites.

The feasibility of using airborne electromagnetic methods for mapping the transition zone was also assessed. It was concluded that these methods were unlikely to be effective and they were not pursued further.

For each investigation component, all available historical data was used and the new data was collected through the project.

1.5 Project implementation

OGIA led the overall project design and implementation including data analysis, project management, reporting, the investigation components of the hydrochemical assessment, pumping test analysis, geological modelling, groundwater level mapping and numerical modelling.

Arrow Energy completed the drilling, installation of nested piezometers, aquifer pumping tests, related complementary investigations (such as the coring and lab analysis), and parts of the numerical analysis of the pumping test data.

Queensland University of Technology (QUT) carried out a hydrochemical assessment that complements the work carried out by OGIA.

1.6 Related assessments and studies

Many assessments of the hydrogeology of the Condamine Alluvium have been completed since development of the water resource began in the 1960s. These assessments focussed on the water balance components for the purpose of achieving sustainable management of the groundwater resource. A list of these studies is presented in Table 1-1.

Table 1-1 List of studies about the groundwater resources of the Condamine Alluvium

Reference	Title
Lumsden (1966)	Condamine Valley Groundwater Investigations. Hydrogeological Report on Eight 1:50,000 Map Sheets
Exon (1976)	Geology of the Surat Basin in Queensland
Lane (1979)	Progress Report on the Condamine Underground Investigation to December 1978
Huxley (1982)	The Hydrogeology, Hydrology and Hydrochemistry of the Condamine River Valley Alluvium
SKM (2002)	South-East Queensland Recycled Water Project – Darling Downs Hydrological Study. Groundwater Modelling
Kelly and Merrick (2007)	Groundwater Knowledge and Data Gaps in the Condamine Alliance Area
Barnett and Muller (2008)	Upper Condamine Groundwater Model Calibration Report
KCB (2010a)	Central Condamine Alluvium Data Availability Review
KCB (2010b)	Central Condamine Alluvium Stage II – Conceptual Hydrogeological Summary
KCB (2011a)	Central Condamine Alluvium Stage III – Detailed Water Balance
KCB (2011b)	Central Condamine Alluvium Stage IV – Numerical Modelling
Dafny and Silburn (2013)	The Hydrogeology of the Condamine River Alluvial Aquifer, Australia: A Critical Assessment
Dafny (2014)	Temporal Trends of Groundwater Levels in the Condamine Catchment 2007-2013

Since 2010, studies have been directed at improving understanding of the connectivity between the Condamine Alluvium and the Walloon Coal Measures in response to concerns of CSG impacts on the groundwater resource of the Condamine Alluvium (QWC, 2012), (Arrow Energy, 2012) and (Arrow Energy, 2013).

In 2012, the Queensland Water Commission (QWC) presented the conceptualisation and numerical modelling of groundwater flow in the Surat Cumulative Management Area (CMA), including the Condamine Alluvium. The impact of all planned CSG water extraction on water resources was assessed. It was concluded that, while groundwater pressures in the Walloon Coal Measures would fall significantly if CSG development proceeded as planned at the time, groundwater levels in the Condamine Alluvium would fall by 0.5 metre on average, with a maximum of 1.2 metres on the western edge, under the cumulative impact scenario based on 95th percentile. Declining pressures in the Walloon Coal Measures were predicted to start affecting groundwater levels in the Condamine Alluvium by about 2017, with maximum impacts in groundwater levels occurring between 2060 and 2075. Leakage from the Condamine Alluvium to the Walloon Coal Measures was predicted to be about 1,100 ML/year over the next 100 years.

As part of the environmental impact statement (EIS) for the Surat Gas Project (Arrow Energy, 2012), a numerical groundwater flow model was created by Arrow Energy to assess potential groundwater impacts from proposed CSG development. The assessment was later revised, using the OGIA regional groundwater flow model, for the supplementary EIS (Arrow Energy, 2013). That assessment provided the cumulative impact assessment from extraction of CSG for all projects in the Surat Basin.

The Australian Government commissioned a project for an international literature review about aquifer connectivity which also included a brief discussion of connectivity in the Surat Basin (CSIRO, 2014).

The Queensland Department of Natural Resource and Mines (DNRM) developed a transient groundwater flow model to support water allocation and management in the Condamine Alluvium (KCB, 2011b). This model was used by OGIA in 2012 in combination with the regional groundwater flow model for the Surat Basin to assess impacts on the Condamine Alluvium from CSG development (QWC, 2012).

Researchers at QUT are using geochemical data to investigate existing and potential interactions between bedrock and alluvial aquifers in the upper Condamine River catchment. This project is being implemented in stages and includes a baseline hydrochemical assessment of bedrock and alluvial aquifers, using existing data and new hydrochemical and isotope data, to improve the conceptual understanding of connectivity between bedrock and alluvial aquifers. Preliminary outcomes of the study have been incorporated in the project.

Researchers at the University of New South Wales (UNSW) are also assessing the extent of hydraulic connectivity between the Walloon Coal Measures and water supply aquifers within the Condamine River catchment. Project components include examining groundwater chemistry; measuring the concentration of methane in groundwater and air; analysing historical groundwater level data and chemical data; and examining pumping impact scenarios.

1.7 Report layout

Chapters 2 and 3 describe the contextual background to the project. Chapter 2 provides hydrogeological background information and Chapter 3 describes the approach and methodology used for the project.

Chapter 4 details the geological interpretation and geological modelling component of the project.

Chapter 5 details the groundwater level survey and mapping component of the project.

Chapter 6 details the hydrochemical assessment component of the project.

Chapter 7 details the aquifer pumping tests and associated drilling component of the project.

Chapter 8 summarises the conclusions from the project, based on the synthesis of all outcomes from the investigation components.

2 Regional setting and context

2.1 Geomorphology

The Condamine Alluvium was deposited in a depression in the Surat Basin and Clarence-Moreton Basin. The sediments originally formed as a result of geological uplift, sagging, deformation and erosion. Deposition is believed to have occurred in the following general stages (KCB, 2010b):

- During the Tertiary period, a terminal lake formed in the Surat/Clarence-Moreton depression, resulting in low-energy deposition of lacustrine sediments. The Condamine River evolved once the lake was filled with sediments.
- The Condamine River generally maintains a meandering form on the west side of the plain. Sheetwash deposits, driven by smaller-scale streams flowing from the east with steeper gradients, pushed the Condamine River to the west of the centre of the plain. These streams deposited broad sheetwash fans at the confluence.
- Overprinting this system is the constant reworking of sediments, by the Condamine River and by secondary streams and watercourses. These processes have largely obliterated any traditional concept of an alluvial channel that may have existed and have resulted in the largely heterogeneous nature of individual gravel and sandy layers within the strata.

Some of the relevant and key elements of contemporary geomorphology of the Condamine River and Condamine Alluvium (KCB, 2010a) (Lane, 1979) are as follows:

- The headwaters of the Condamine River commence near Killarney (near the Queensland–NSW border) at an elevation of approximately 800 metres.
- The central feature of the catchment is the Condamine River plain which is about 40 kilometres wide and 160 kilometres long.
- Downstream of Tummaville, the Condamine Alluvium widens into a broad plain, with elevation ranging from approximately 380 metres to 300 metres near Chinchilla.
- The river flows north-northwest to Chinchilla, then abruptly flows westward towards the junction with Dogwood Creek, after which the system is known as the Balonne River.
- The only two stream channels of significant size flowing over the Condamine Alluvium are the Condamine River and the North Branch (Anabranch).
- A number of smaller streams to the east of the plain do not flow into the Condamine River, but discharge onto the plain, forming fans of more sandy material than the surrounding black soil plains.

2.2 Climate

There are more than 30 rainfall stations with long-term data within and near the Condamine Alluvium. Median monthly rainfall (mm) categorised by station elevation is summarised in Figure 2-1. These stations show a seasonal consistency, with much more rainfall occurring between October and March than between April and September. Monthly rainfall during the summer is typically between 50 mm and 100 mm, and during the winter between 25 mm and 50 mm. There is some correlation between rainfall and elevation, with median annual rainfall of: 597 mm at stations below 300 metres; 651 mm at stations between 300 and 400 metres; 696 mm at stations between 400 and 500 metres; and 715 mm at stations above 500 metres (KCB, 2010a).

Cumulative rainfall excess and deficit at Dalby from 1950 to 2014, relative to the long-term average, is shown in Figure 2-2. There was generally an excess of rainfall during the period from at least 1950 to 1990, with approximately 50 mm/year more than the long-term average throughout this period. From 1990 through 2014, there has generally been a deficit of rainfall, with approximately 60 mm/year less than the long-term average (BOM, 2014).

Potential evaporation across the Condamine Alluvium typically ranges from 1,600 mm/year to 1,900 mm/year, exceeding rainfall by a factor of between 2.4 and 3.1 (KCB, 2010b).

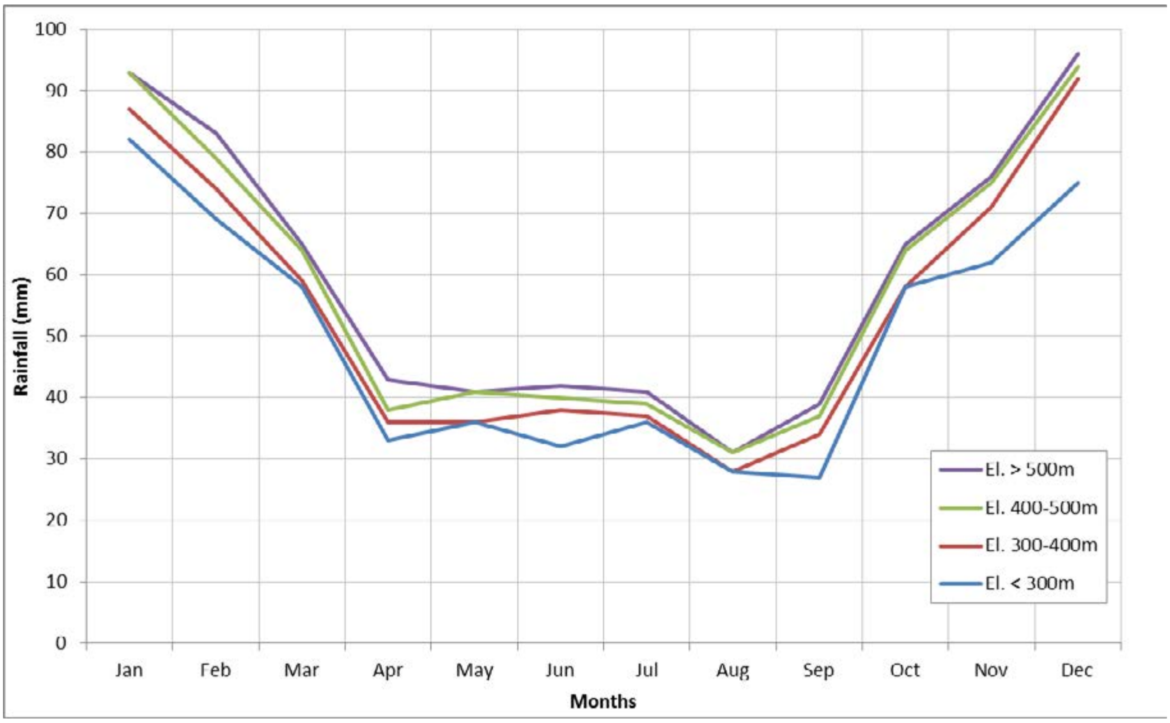

Figure 2-1 Long-term median monthly rainfall by station elevation in the Condamine Alluvium area

Figure 2-2 Cumulative rainfall excess/deficit (mm) relative to the long-term average at Dalby, 1950–2014

2.3 An overview of regional geology and groundwater systems

This section provides a contextual overview of regional geology and groundwater systems in the project area. A more detailed description of geology and hydrogeology is provided in later chapters.

A representative 3-D schematic of the regional geological and hydrogeological setting in and around the Condamine Alluvium is shown in Figure 2-3.

The Condamine Alluvium straddles the Surat Basin to the west and the Clarence-Moreton Basin to the east. The two underlying sedimentary basins form part of the **Great Artesian Basin (the GAB)** system, which is comprised of Jurassic sandstone, siltstone and mudstone formations, generally dipping to the west. The **Walloon Coal Measures**, a part of this GAB system, subcrops beneath most of the central area of the Condamine Alluvium and forms the bedrock for the Condamine Alluvium. The Walloon Coal Measures contains strings of mostly disconnected coal seams within a matrix of predominantly mudstone and siltstone. The Marburg Sandstone (equivalent to the Hutton Sandstone in the Surat Basin) occurs along the eastern margin but does not come in contact with the Condamine Alluvium except in a small area in the south. The Main Range Volcanics, which outcrops at higher elevations along the east and southeast of the Condamine Alluvium, overlies the Walloon Coal Measures and the Marburg Sandstone and underlies the Condamine Alluvium, particularly along the tributary systems. The Springbok Sandstone and the Westbourne Formation are wedged between the Condamine Alluvium and the Walloon Coal Measures towards the western margin. These formations lie unconformably over the Walloon Coal Measures erosional surface and are often indistinguishable from each other in this area; as a result, they are also referred to collectively as part of the Kumbarilla Beds.

The Quaternary **Condamine Alluvium** includes the lower granular alluvium and an upper wedge-shaped sheetwash deposit that thins towards the west. In terms of groundwater, the granular alluvium is the main transmissive part of the Condamine Alluvium, although it typically comprises less than 10 metres of fine, mixed and granular (sand and gravel) horizons. The heterogeneity in sediments within the alluvium reflects the complex depositional environments ranging from high-energy riverine to low-energy lacustrine. The groundwater resources of the Condamine Alluvium generally provide high yields and good water quality, and have been extensively developed for irrigation and other purposes since the 1960s. The alluvium tends to be finer in the downstream direction and along the margins; as a result, groundwater yields are higher towards the southern central part of the alluvium. There is also a general increase in salinity in the downstream direction and along the margins.

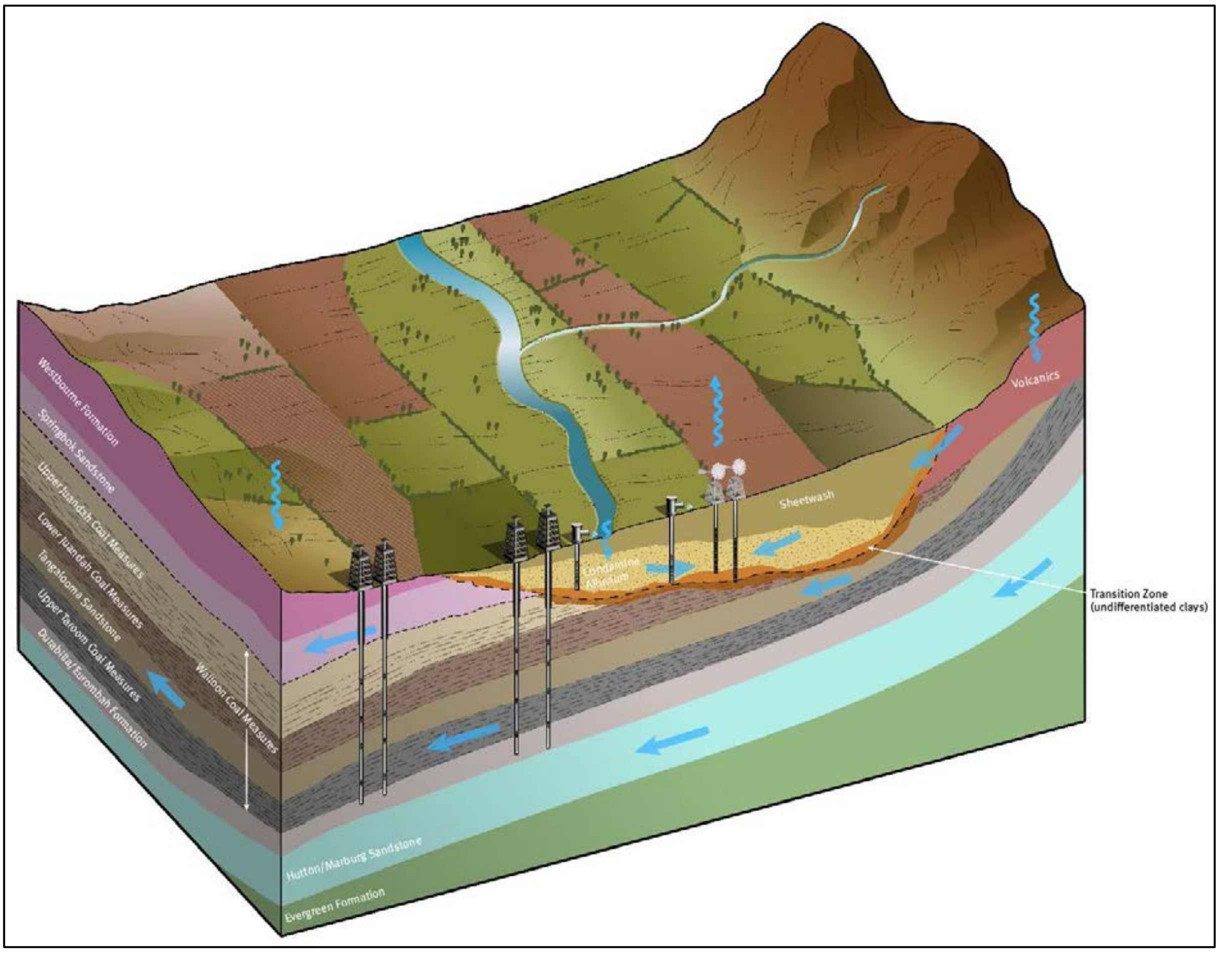

Figure 2-3 3-D schematic of the regional hydrogeological setting around the Condamine Alluvium

The contact between the Condamine Alluvium and the underlying Jurassic sedimentary basement (predominantly the Walloon Coal Measures) is characterised by a combination of basal alluvial clays of the Condamine Alluvium and the weathered upper part of the Walloon Coal Measures, which are often indistinguishable and dominated by clay. The term '**transition zone**' is used in this report to refer to this clay-dominated horizon of undifferentiated origin, and the clay is referred to as 'undifferentiated clay'. This clay is generally discontinuous across the Condamine Alluvium footprint and ranges in thickness from less than one metre to just over 10 metres.

The Condamine Alluvial system has been traditionally conceptualised as a single connected groundwater system with little or no interaction with underlying bedrocks (Huxley, 1982) (Lane, 1979) (KCB, 2010b). Before groundwater development started, groundwater flow in this system was predominantly southeast to northwest; however, flow is now towards depressions in groundwater levels which have developed over recent decades as a result of groundwater extraction. Recharge to the Condamine Alluvium is complex and there are differing views on the relative significance of different recharge pathways. The most common and prevalent view is that the alluvium is mainly recharged from river and stream flow leakage (39 to 115 mm/year). Diffuse rainfall recharge is expected to be limited by the high clay content of near-surface soils and sheetwash. Discharge is mostly through extraction and downstream lateral flow.

Groundwater flow in the underlying GAB system is also to the northwest and is believed to be locally recharged through the Main Range Volcanics and outcrop areas along the eastern and southeastern margins. A significant upward gradient in groundwater levels from the GAB to the Condamine Alluvium in the central area has developed because of water extraction from the alluvium (see Chapter 5).

2.4 Previous estimates of water balance components

Water balance components of the Condamine Alluvium, including the flux exchange with the underlying bedrocks, have been estimated by a number of earlier investigations and are compiled in a recent study (KCB, 2011a). A table extract (Dafny & Silburn, 2013) provided as Appendix 1 lists the various estimates. A summary of reported ranges is presented in Table 2-1. Care is needed in drawing conclusions from these reported values as they often refer to different geographical footprints.

These earlier studies have reported an imbalance between the inflowing and outflowing water balance components, with outflow exceeding inflow. The imbalance ranges from as high as 50,800 ML/year (Lane, 1979) to almost nil (Barnett & Muller, 2008), with most studies reporting an imbalance of around 20,000 ML/year. The most uncertain component associated with the water balance is the recharge.

Estimates of inflow from surrounding aquifers, mainly the Main Range Volcanics, the Springbok Sandstone and the Walloon Coal Measures, have been based on hydraulic head differences between formations and assumptions about the hydraulic conductivity of intervening layers. The estimates of the exchange of flux with the Walloon Coal Measures vary widely, mainly due to a lack of long-term spatially distributed groundwater level data in the Walloons (Dafny & Silburn, 2013) (Hillier, J.R, 2010) (KCB, 2011a).[1]

[1] Lane (1979) estimated 8,050 ML/year of loss through the base of the alluvium and along the western edge (including the Springbok Sandstone and the Walloon Coal Measures) using a transmissivity of 134 m^2/d, while SKM (2003) assumed a vertical hydraulic conductivity (Kv) of $1x10^{-5}$, 8 metres average head difference and 35 metre thick basal clay, to arrive at a leakage estimate of 1,649 ML/year.

Table 2-1 Summary of water balance components of the Condamine Alluvium from previous studies

Water balance component	Water balance range (ML/year)	
	Minimum	Maximum
Condamine Alluvium		
Upstream inflow	-	1,163
Eastern tributaries inflow	250	2,800
Downstream outflow	244	645
Bedrock inflow		
Main Range Volcanics	380	1,604
Other sandstone formation NE and SW	390	4,242
Walloon Coal Measures	–1,650	3,650
Streambed recharge	11,158	32,635
Diffuse recharge (rainfall & deep drainage)	5,110	30,956
Extraction	–31,000	–47,400

2.5 Water bores in the Condamine Alluvium

OGIA assessed records of water bores across the Surat CMA to identify the aquifers that the bores are accessing. About 6,500 water bores are recorded in the DNRM groundwater database (GWDB) as ‘active’ (existing usable water bores) within the Condamine Alluvium footprint, as shown in Figure 2-4. Of these, about 3,800 access water from the Condamine Alluvium (Table 2-2).

Some 2,700 of the active bores access aquifers other than the Condamine Alluvium. Most of these bores are located in the tributary areas or along the eastern or western margins of the Condamine Alluvium where it is relatively thin. Older records are often uncertain; however, it is likely that most of these bores access the Main Range Volcanics or alluvium associated with the tributary streams. The few bores that access water from the Walloon Coal Measures beneath the central part of the Condamine Alluvium do so primarily for stock and domestic use. Some of these bores were constructed in recent years because of a moratorium on drilling new bores in the Condamine Alluvium.

Stock and domestic bores are typically drilled to 8–10 inch diameters (203–254 mm) and installed with 5.5–8 inch (140–203 mm) casing and screens. Irrigation bores are drilled to larger diameters of about 15 inches (380 mm) and are typically installed with 8–10 inch (203 –254 mm) casing and screens. Steel casing was used until the 1970s, after which PVC became more common. Multiple screens are installed across sandy and gravelly units of the alluvium. The annular space between the bore wall and casing/screen is typically left open or filled with gravel, often to the top. Bentonite in combination with grout has been used to isolate formations in more recent times. Bores constructed within the last two decades are likely to be sealed with surface grout.

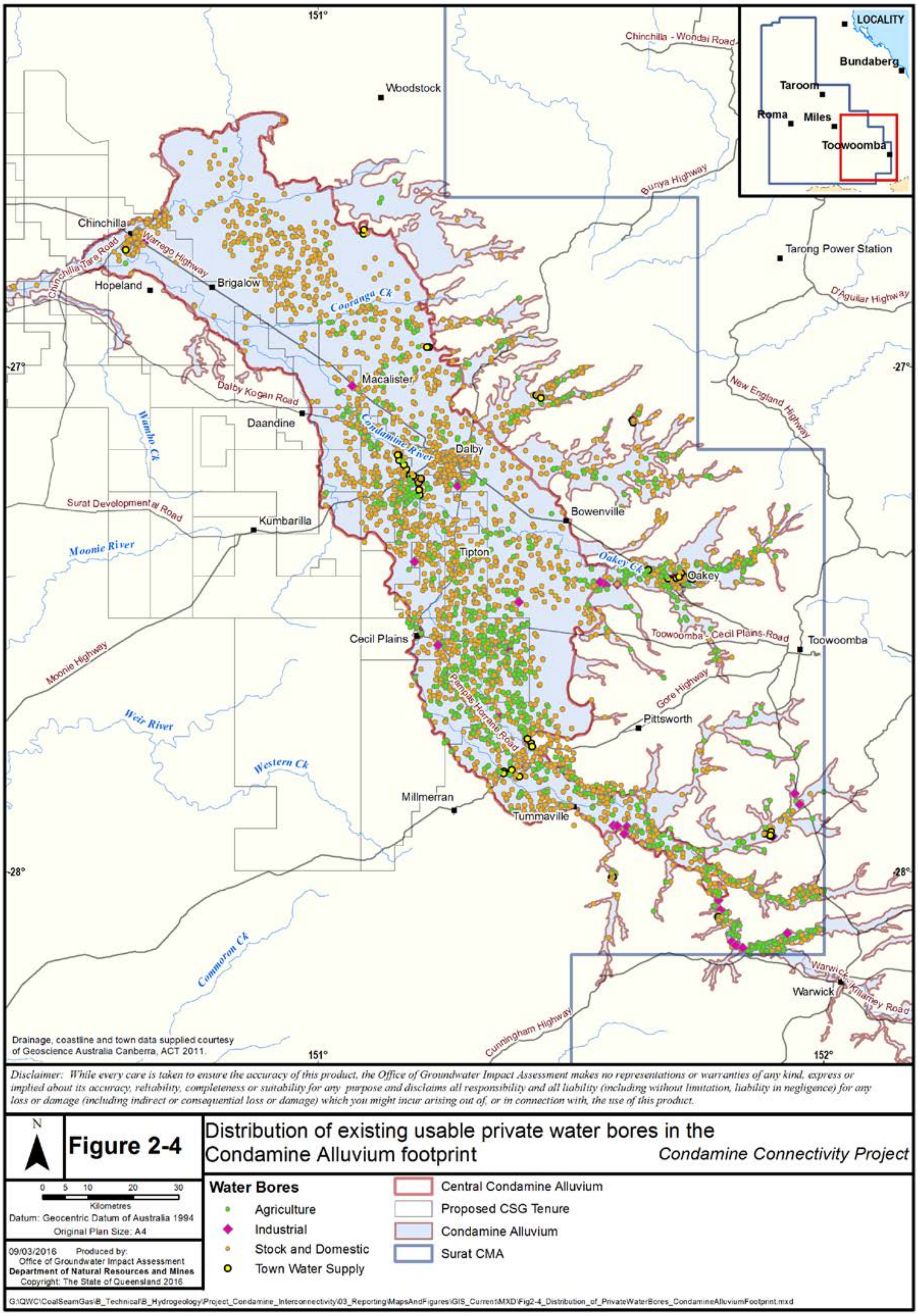

Figure 2-4 Distribution of existing usable private water bores in the Condamine Alluvium footprint

Table 2-2 Summary of water bores in the Condamine Alluvium

Purpose	No. of bores	Estimated use (ML/year)
Monitoring bores	600	-
Water supply		
Agriculture	1,052	64,251
Industrial	33	1,476
Stock & domestic	2,709	2,069
Town water supply	59	4,227
Sub-total (water supply)	3,853	69,953

Some water bores targeting the Condamine Alluvium were drilled into the top of the Walloon Coal Measures because it is often difficult to distinguish the weathered upper bedrock from a layer of alluvial clay. In these cases, drilling would have continued until traces of coal or mudstone were encountered. Most of these bores are located along the margins of the alluvium and the tributary areas where the alluvium is relatively thin and less productive for groundwater supplies. In the productive central Condamine area, records suggest that some three per cent of bores were drilled into the upper Walloon Coal Measures. Given the nature of the formation material, any annular open space is likely to have filled with formation material. Because of the limited penetration and closing of any annular space, it is unlikely that these bores significantly influence connectivity between the formations.

2.6 Groundwater use

Extraction of groundwater from the Condamine Alluvium is primarily for irrigation water supply. Figure 2-5 shows the growth of water entitlements over time, which is mostly for irrigation but also for town supply and industrial purposes. It should be noted that water entitlements for irrigation represent maximum allowable annual extraction, while the actual use varies from year to year depending on availability. Actual irrigation usage is routinely below the entitlement. Most irrigation, town supply and industrial bores are metered.

Although the number of rural stock and domestic bores and urban/peri-urban bores is large relative to the number of irrigation bores, the volume of water taken is much smaller. These bores are not metered, but the volume that can be taken is limited by the purpose for which the water can be used. To prepare the Surat UWIR 2016, OGIA updated the estimates of water used from these bores. Current estimates of water used from the Condamine Alluvium are summarised in Table 2-2.

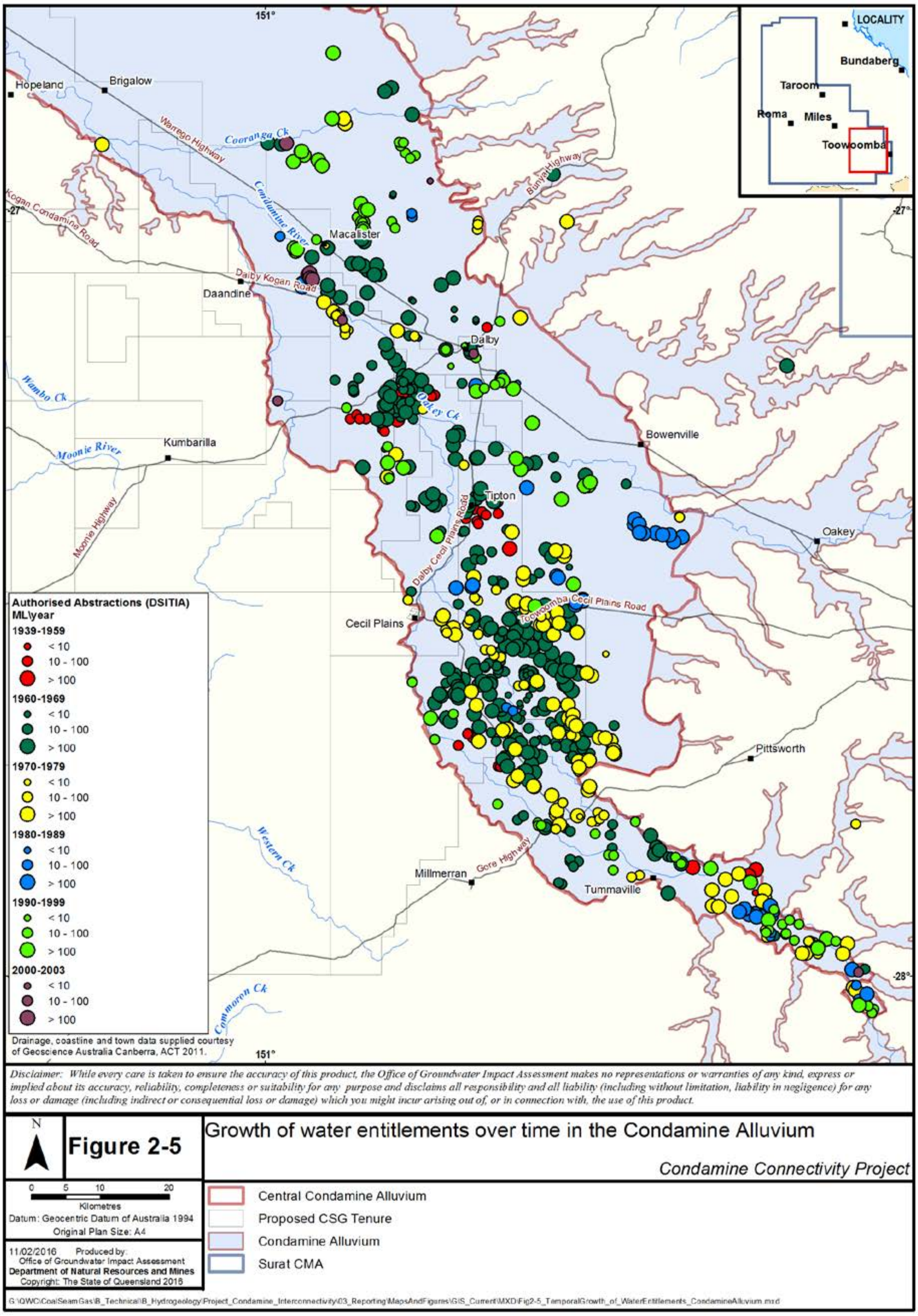

Figure 2-5 Growth of water entitlements over time in the Condamine Alluvium

Previous studies have concluded that groundwater extraction rates from entitlement bores have been relatively stable since the 1980s at about 45,000 ML/year (KCB, 2010b) (SKM, 2002) (DNRW, 2008) (SKM, 2003) excluding the stock and domestic use. Variations in water use estimates are likely to result from different methods used for estimating unmetered water use, seasonal variations and different reference footprints.

2.7 Groundwater level trends

It is widely accepted that, on average, inflows of groundwater to the Condamine Alluvium are exceeded by outflows, with the largest outflow being extraction from groundwater bores. As a result, groundwater levels in the Condamine Alluvium have fallen across most of its footprint over much of the past 50 years (KCB, 2010b).

The GWDB contains groundwater level data from a large number of bores within the Condamine Alluvium footprint, including regular long-term groundwater level records from hundreds of DNRM monitoring bores distributed across the area. The majority of these monitoring bores are screened in the Condamine Alluvium. Only a few monitoring bores with long-term records of groundwater levels reflect groundwater conditions in the Walloon Coal Measures.

Long-term groundwater level trends from selected bores in the Condamine Alluvium and the underlying Walloon Coal Measures (where available) are shown in Figure 2-6 to illustrate spatial variability. The data for both formations is plotted at the same scale to illustrate relative variations over time and space.

In the southern area, groundwater levels in the Condamine Alluvium have been relatively stable over the past 40 years, fluctuating by less than five metres, with little or no seasonal variation.

In the southern central area, to the south of Dalby and east of Cecil Plains, a significant groundwater depression began to form in the Condamine Alluvium in the 1960s as a result of groundwater extraction. Groundwater levels in this area fell by about 25 metres between 1965 and 2010 and appear to have stabilised in recent years. In most bores, large seasonal fluctuations observed are related to seasonality in groundwater extraction. There are no corresponding Walloon Coal Measures monitoring bores in this central part of the alluvium with long-term records of groundwater levels.

In the central area, around Dalby, a significant groundwater depression began to form in the Condamine Alluvium in the 1990s as a result of groundwater extraction. Levels in this area fell by up to 15 metres between 1960 and 2010 and have generally stabilised or recovered since 2007. This recovery is believed to be the result of decreasing extraction combined with increased recharge over this period (Dafny & Silburn, 2013). In most bores, large seasonal fluctuations observed are a result of seasonality of groundwater extraction. Bore 42231390 is screened in the Walloon Coal Measures, near bore 42230159, and recorded a groundwater level fall of five metres between 1990 and 2010.

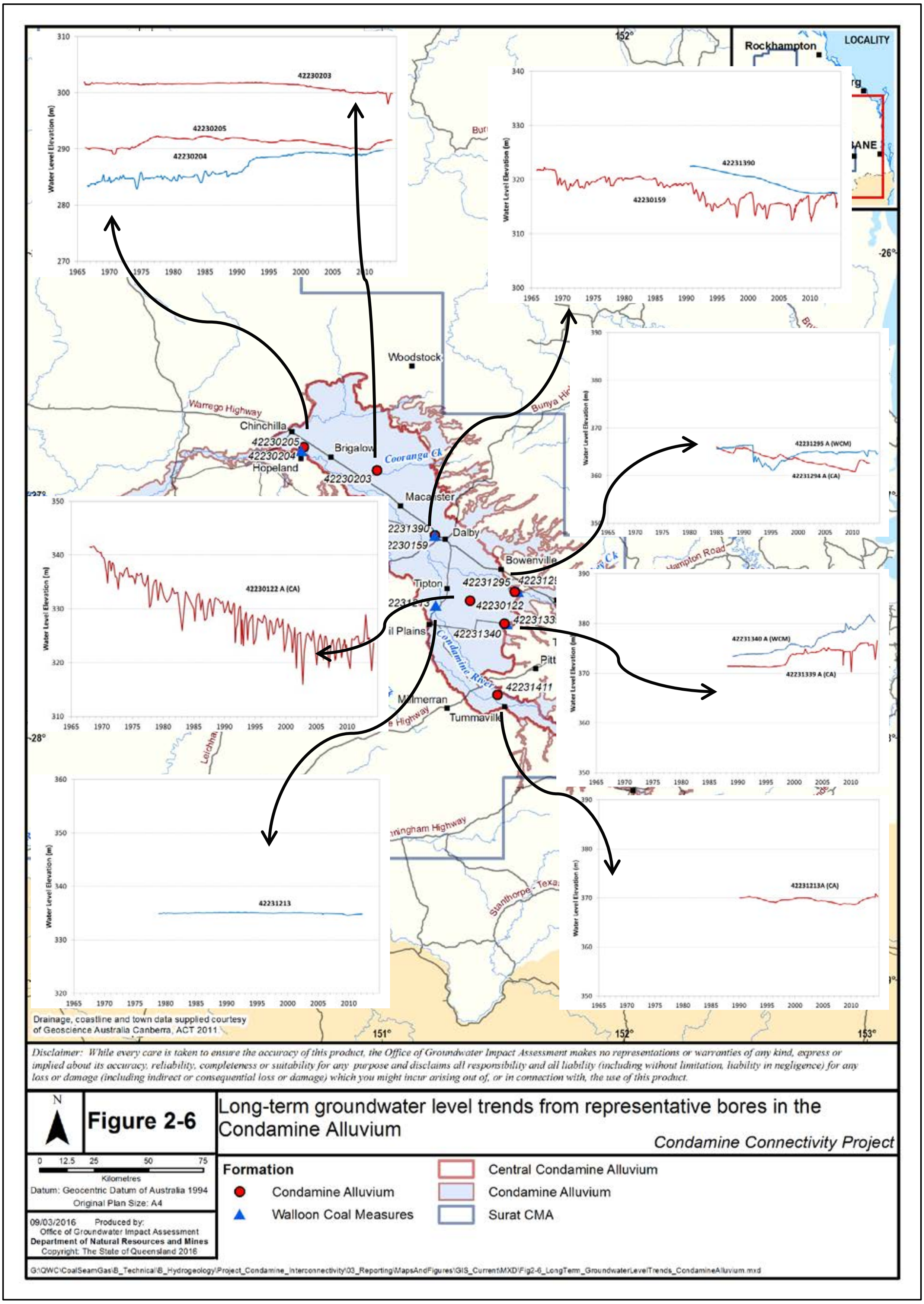

Figure 2-6 Long-term groundwater level trends from representative bores in the Condamine Alluvium

Along the western flank, groundwater levels in the Condamine Alluvium have generally been stable over at least the past 50 years, fluctuating by less than five metres, with little or no seasonal variation. Large and rapid groundwater level rises occurred in some bores following floods in 2010 and 2011. Bore 42231213 is screened in the Walloon Coal Measures and has recorded little groundwater level change since 1979, despite being located just west of the southern central area.

Along the eastern flank, groundwater levels in the Condamine Alluvium have generally been stable or have risen to some extent over at least the past 50 years. Levels in most bores have fluctuated by less than five metres, with little or no seasonal variation. Bores 42231295 and 42231340 are screened in the Walloon Coal Measures, just east of the southern central area. The level in bore 4223195 has fluctuated by less than five metres since 1985, while the level in bore 42231340 has risen by seven metres since 1989.

In the northern area, groundwater levels in the Condamine Alluvium have also generally been relatively stable over at least the past 50 years. Bore 42231204 is screened in the Walloon Coal Measures and has recorded a groundwater level rise of seven metres since 1966.

2.8 Current and proposed CSG development near the Condamine Alluvium

Existing and proposed CSG development around the Condamine Alluvium is along the western margin of the Condamine Alluvium, extending in an arc from Chinchilla in the north to Millmerran in the south. Distribution of existing CSG wells, wellfields and relevant petroleum and gas tenures is shown in Figure 2-7. Not all of the relevant petroleum tenure area will necessarily be developed. The area from which CSG will eventually be produced is expected to be much smaller than the area of tenure shown in Figure 2-7. OGIA obtained data on planned CSG development from petroleum tenure holders for the purpose of preparing the Surat UWIR 2016. The distribution of tenures around the Condamine Alluvium by planned production start date is shown in Figure 2-8. The life of a gas field is expected to be about 25 years.

Very shallow coal seams typically do not contain economically viable CSG reserves. Most of the planned development area near or under the Condamine Alluvium is held by Arrow Energy, which plans to target only those coal seams that are at least 150 metres below the surface and 30 metres below the Condamine Alluvium. This implies a vertical separation of at least 30 metres between the base of the Condamine Alluvium and the uppermost target coal seams that would experience a reduction in water pressure. In the more westerly areas, where the Condamine Alluvium is relatively thin, the separation distance would be greater.

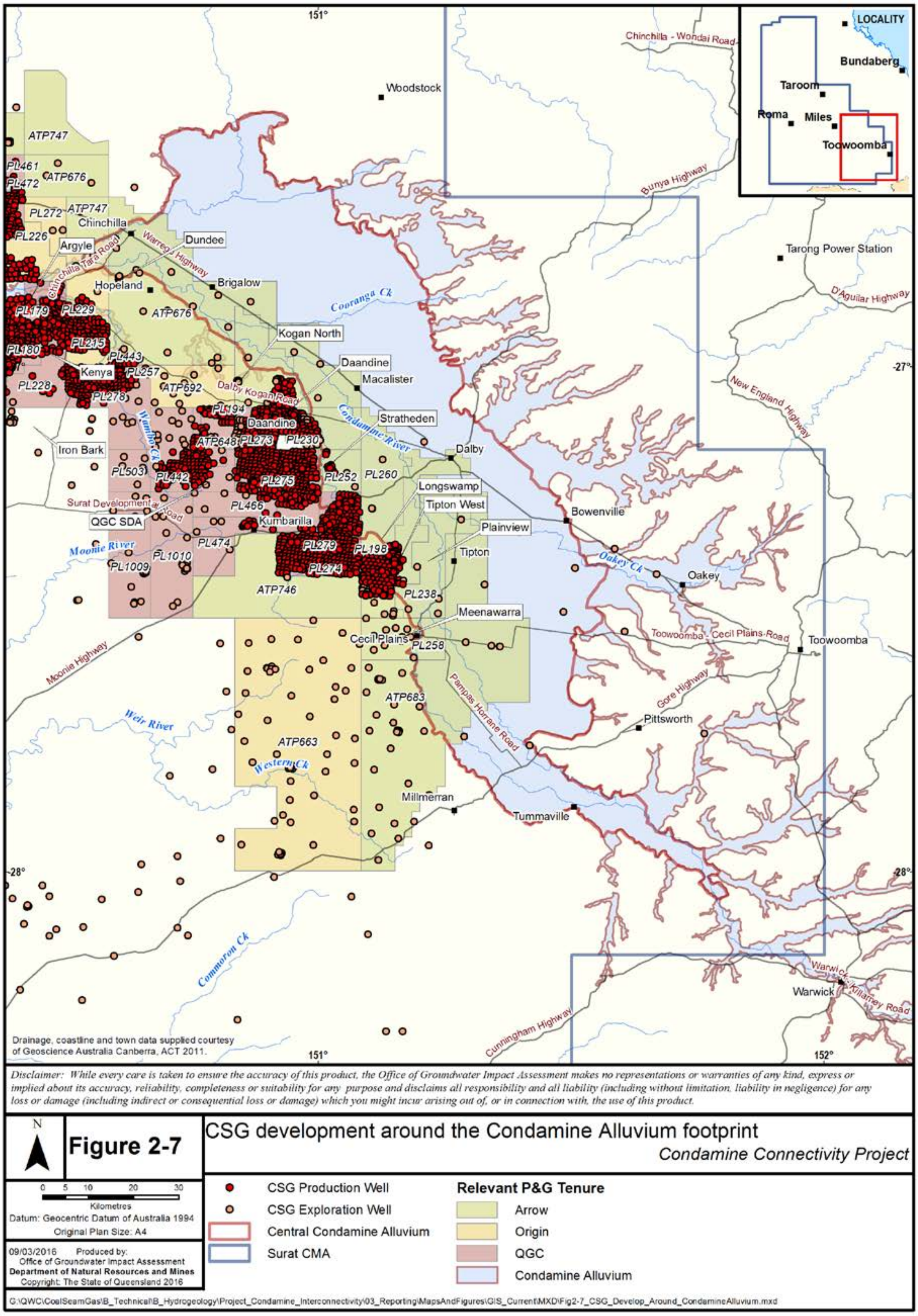

Figure 2-7 CSG development around the Condamine Alluvium footprint

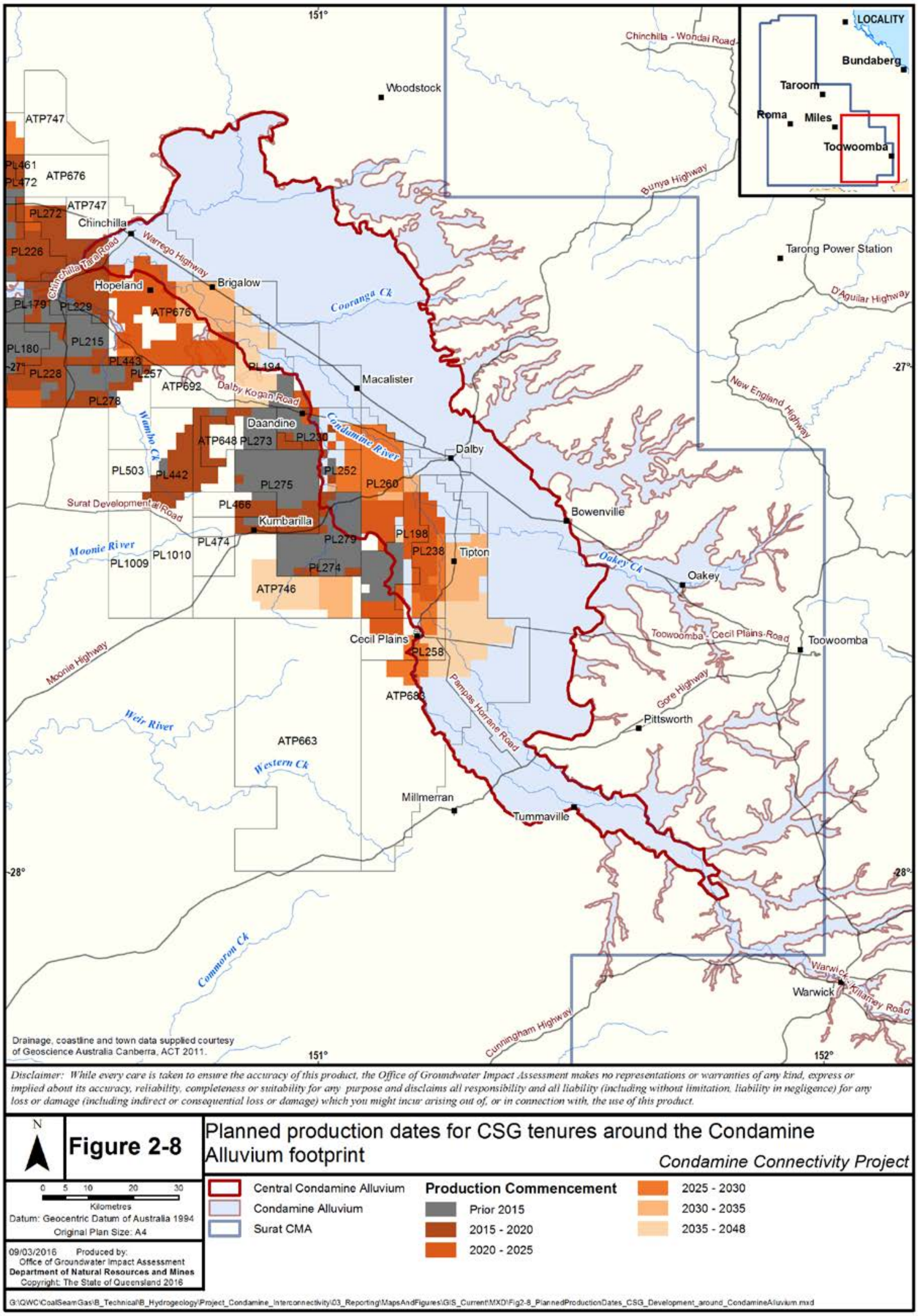

Figure 2-8 Planned production dates for CSG tenures around the Condamine Alluvium footprint

3 Project approach and methodology

3.1 The concept of groundwater connectivity

A range of terms and definitions are used to describe the flow between geological formations. The terms ‘aquifer connectivity’ and ‘aquifer interconnectivity’ are widely used but are often interpreted differently. The Australian Government reviewed the literature on aquifer connectivity (CSIRO, 2014) and noted differences in terminology[2]. There is no generally accepted scheme for classifying or categorising aquifer connectivity.

For the purpose of this project, the term ‘**connectivity**’ means the ease of or resistance to the flow of groundwater between formations depending upon the inherent properties of the formations. If no material separates the formations, connectivity depends on weighted average of the vertical hydraulic conductivity (K_v) of the two formations. If material is separating the formations, connectivity depends on the vertical hydraulic conductivity and the thickness of the separating material. This definition is similar to the one described by others (Rennard & Allen, 2011).

As the thickness and vertical hydraulic conductivity of geological formations typically vary spatially, the connectivity between the two formations also varies spatially and can be highly dependent on the scale of the formation. A significant body of literature indicates that hydraulic conductivity increases with increased scale of measurement. This is due to the presence of preferential flow paths at larger scales, including areas of higher primary permeability, as well as secondary permeability features such as fractures and faults (CSIRO, 2014).

Connectivity alone is not enough to induce the flow of groundwater between two geological formations. A hydraulic gradient between the formations is needed for flow to occur. The rate of flow between two formations is dependent on the magnitude of the hydraulic gradient between them and the thickness and vertical hydraulic conductivity of the separating material. There can also be a significant time lag between pumping from one formation and a hydraulic response in another formation (QWC, 2012).

3.2 Conceptual basis for the Condamine Alluvium connectivity investigations

CSG development in the vicinity of the Condamine Alluvium involves pumping water from the coal seams of the Walloon Coal Measures. This will decrease the water pressure in the coal seams and induce a hydraulic gradient between the coal seams and the overlying and underlying materials, including the Condamine Alluvium and the ‘interburden’ (mudstone,

[2] *‘….aquifer connectivity is a term that describes the groundwater interaction between aquifers that are separated by an aquitard (often termed inter-aquifer leakage), or between different parts of the same aquifer (intra-aquifer connectivity). It is dependent upon the lithology of aquitards and aquifers, and their integrity and spatial continuity. Fractures, faults and open or inadequately-sealed boreholes can form preferential flow paths that also affect connectivity. The degree of connectivity and the rate of water and solute transfer between aquifers are strongly influenced by local and regional hydraulic pressure and dissolved mineral concentration gradients. As aquifer systems are dynamic, these gradients are constantly changing with time, as groundwater is recharged or removed from the system…’*

siltstone and sandstone) of the Walloon Coal Measures itself. Depending upon the degree of connectivity between the Condamine Alluvium and the coal seams of the Walloon Coal Measures, this hydraulic gradient could cause groundwater to flow downwards from the Condamine Alluvium into the depressurised coal seams of the Walloon Coal Measures.

An overview of the regional groundwater system in the area is provided in Section 2.3, where the concept of the transition zone is introduced to represent undifferentiated clays comprising alluvial clay and/or weathered mudstone along the contact between the Condamine Alluvium and the Walloon Coal Measures. The geological and hydraulic characteristics of the transition zone and the upper unweathered part of the Walloon Coal Measures will influence the connectivity between the Condamine Alluvium and the coal seams of the Walloon Coal Measures. This project therefore focused investigations on understanding the physical and hydraulic characteristics of these units and on evidence of current or past flow between the Condamine Alluvium and the Walloon Coal Measures.

3.3 Methodology

The project used multiple lines of investigation comprising the following interrelated components. Outcomes from the components were then synthesised to arrive at overall conclusions.

3.3.1 Interpretation and modelling of the geology

Interpretation and modelling of the geology was undertaken to map the two main units in the context of the project—the transition zone and the underlying sedimentary units of the Surat Basin to the west and the Clarence-Moreton Basin to the east (Figure 2-3), collectively referred to as the **Surat Sediments** in this report. Historical data and additional data from bores drilled as part of the project was reinterpreted to provide a consistent basis for the interpretation of geological material and formation boundaries. Geophysical logs were also reinterpreted, particularly for the Surat Sediments. The feasibility of using airborne electromagnetic methods for mapping the transition zone was also assessed. The method was found to be ineffective for mapping the transition zone and was not pursued further.

A 3-D geological model, the Condamine Geo Model, was developed for the Condamine Alluvium including the sheetwash (with topsoil), granular alluvium, transition zone and upper contact of the Surat Sediments. As a separate OGIA research project to support the development of the regional groundwater flow model for the Surat UWIR 2016, a regional geological model for the consolidated sediments of Surat Sediments was also developed. The interpreted surface of the bottom of the transition zone from the Condamine Geo Model was used in developing the regional geological model in the Condamine Alluvium area.

Details of geological interpretations, results and analysis are provided in Chapter 4.

3.3.2 Surveying and mapping of the groundwater levels

Mapping of groundwater levels in the Condamine Alluvium and the Walloon Coal Measures was undertaken to identify spatial distribution of differences between the groundwater levels in the two formations. Such differences can provide evidence of potential for groundwater to flow across the two formations and, hence, can also provide information about the vertical connectivity between them.

Although groundwater level maps for the Condamine Alluvium had been developed previously in various studies, no attempts had been made to map corresponding pressure surfaces in the Walloon Coal Measures. To fill this gap, across the Condamine Alluvium, footprint bores were identified that are screened in the Walloon Coal Measures and are near bores that are screened in the Condamine Alluvium. A survey was carried out to collect water level data and water samples from the identified bores. The groundwater level data collected from this survey, in combination with other monitoring data from the Condamine Alluvium, was used to prepare groundwater level maps for the Condamine Alluvium and the Walloon Coal Measures. Relative differences in groundwater levels were derived from these maps for analysing aquifer connectivity, as detailed in Chapter 5.

3.3.3 Assessment of the hydrochemistry

An assessment of hydrochemical data was carried out to characterise the hydrochemistry of the Condamine Alluvium and the underlying formations. This characterisation was then used to assess the hydrochemical evolution and the possibility of past intermixing of water between the two formations. The hydrochemical data was derived from about 3,000 groundwater samples from private water supply bores, monitoring bores and CSG wells.

The assessment primarily used available major ion chemistry data. A number of assessment techniques were used including the principal component analysis (PCA) and K-means cluster analysis (KCA). These techniques were effective in analysing large datasets and supporting analysis of hydrochemical evolution. Details of the analysis are presented in Chapter 6.

3.3.4 Aquifer pumping tests

Pumping tests and associated drilling were implemented to establish the geological and hydrogeological characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures at locations likely to be representative of different hydrogeological settings. Water was pumped from the Condamine Alluvium and pressure responses were measured at multiple levels in the two formations.

The pumping test program was aimed at obtaining representative vertical hydraulic conductivities of the transition zone and the upper Walloon Coal Measures. This was a major undertaking of the project and involved:

- drilling nested piezometers at two sites
- taking core samples for mineralogical assessment and laboratory measurements of permeability
- water quality sampling and analysis
- running pumping tests for 30 days or more.

All field operations were carried out by Arrow Energy with full OGIA involvement. Data will continue to be collected from the sites in the long term. Results from the aquifer pumping tests were used in the development of the regional groundwater flow model. Details of the drilling, pumping tests and analysis are presented in Chapter 7.

4 Interpretation and modelling of the geology

4.1 Overview and purpose

The Quaternary fluvio-alluvial deposits straddle the Surat Basin to the west and the Clarence-Moreton Basin to the east (Figure 2-3). The Jurassic sedimentary units of the two basins are collectively referred to as the **Surat Sediments** in this report. The Surat Sediments interfinger across the Kumbarilla Ridge – a subsurface bedrock high, running roughly north-south as shown in Figure 4-1. Towards the eastern margin, the Tertiary age Main Range Volcanics wedges between the underlying sedimentary sequence of the Surat and Clarence-Moreton basins and the overlying Condamine Alluvium. The Condamine Alluvium includes the lower granular alluvium and an upper wedge-shaped sheetwash deposit that thins out towards the west.

The geology of the Condamine Alluvium has been studied and mapped extensively using data from a large number of water supply bores (Huxley, 1982) (KCB, 2010a), however, the focus of those studies was water supply needs and management of the groundwater resource, particularly in the central part of the Condamine Alluvium. A number of investigations (Huxley, 1982) (SKM, 2002) (KCB, 2010a) have also mapped the hydraulic basement of the Condamine Alluvium as the deepest productive sands above underlying clay, which is often referred to as the ‘bottom clay’, ‘basal clay’ or ‘multi-coloured clay’ in drilling logs.

This clay at the bottom of the Condamine Alluvium is likely to be a combination of basal alluvial clays of the Condamine Alluvium and the weathered upper part of the Walloon Coal Measures (Lane, 1979). Bore log data is usually inadequate to distinguish between these sources of clays. For the purpose of this project, we refer to this undifferentiated clay-dominated horizon as the transition zone. Past studies have paid little attention to the underlying bedrock of the transition zone, or to its distribution and hydraulic properties, because it has been considered to form an impermeable hydraulic basement.

Understanding the distribution, thickness and hydraulic nature of the transition zone and its interface with the underlying Walloon Coal Measures is critical to the assessment of the connectivity. As part of this project, drill log data was therefore geologically reinterpreted to map the transition zone and the geology of the underlying bedrock.

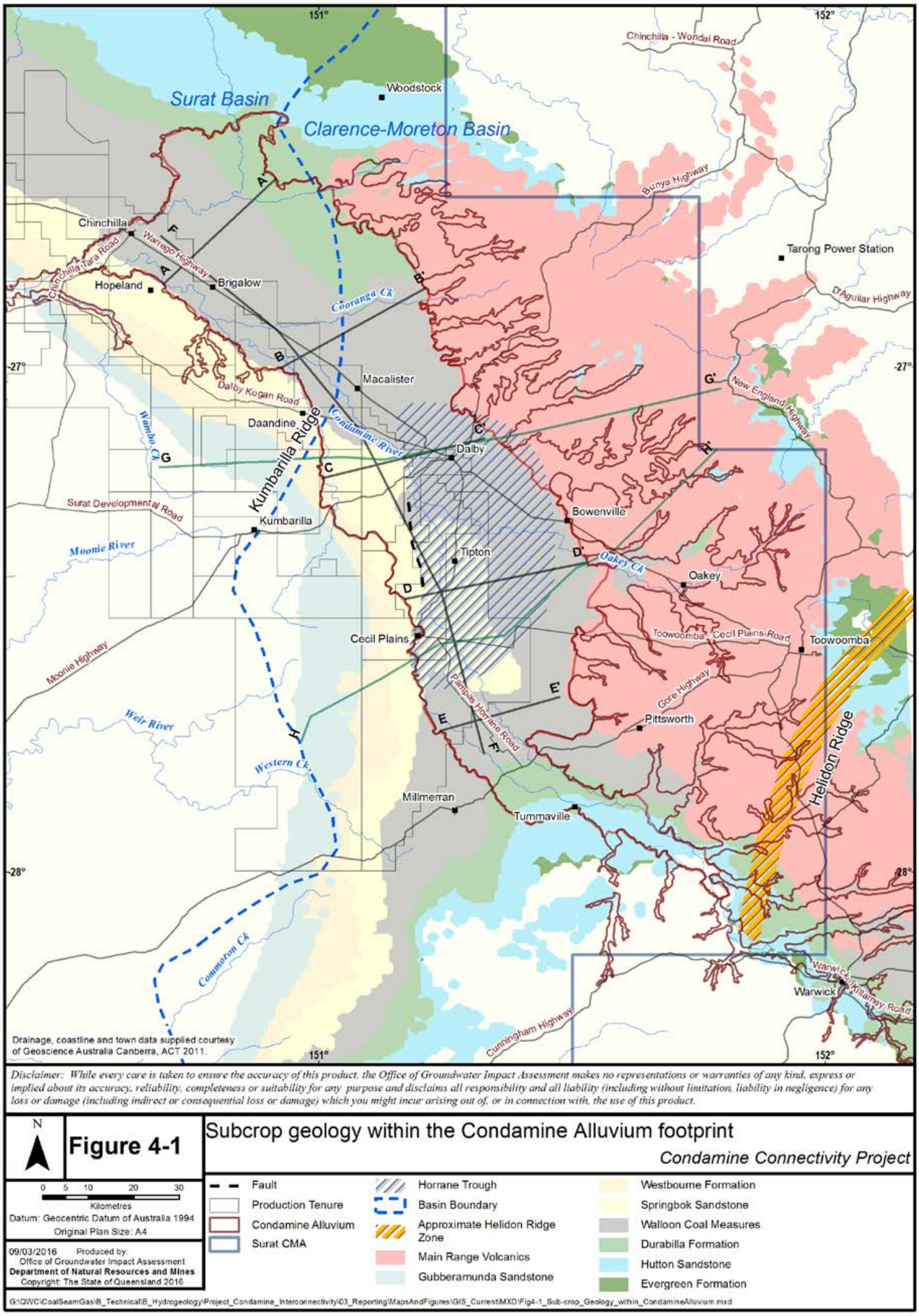

Figure 4-1 Subcrop geology within the Condamine Alluvium footprint

4.2 Construction of the Condamine Geo Model

A 3-D geological model, the Condamine Geo Model, was constructed for the central Condamine Alluvium by reinterpreting historical drill logs. The model delineates:

- the Condamine Alluvium including the sheetwash (with topsoil) but excluding the eastern alluvial tributaries
- the granular alluvium
- the transition zone
- the upper contact of the Surat Sediments.

The model is based primarily on information from private water bores and monitoring bores recorded in the GWDB.

In a separate research project, OGIA constructed a regional geological model of the Surat and Clarence-Moreton basins, including the formations underlying the Condamine Alluvium and the Main Range Volcanics, to support the development of the regional groundwater flow model for the Surat UWIR 2016. This regional geological model was constructed using petro-physical data mainly from petroleum and gas wells supplemented by seismic interpretations, structural mapping and some water bores (OGIA, 2016). The interpreted surface of the bottom of the transition zone in the Condamine Geo Model was used in the construction of the regional geological model.

4.2.1 Data sources

The primary source of geological data used in constructing the Condamine Geo Model was the GWDB which includes data for more than 150,000 bores in Queensland, including their location, depth, installation details and lithology (rock type)—as reported by a driller or geologist while drilling—and interpreted stratigraphy. The level of detail and consistency of lithology descriptions varies greatly between bores. Data from more than 3,500 bores in the central Condamine Alluvium was used for geological interpretation and modelling.

Lithology from CSG well Daandine 164 (DA-164), drilled by Arrow Energy to the west of Dalby in 2013, was included because it was available at the time the Condamine Geo Model was constructed. Data from other CSG wells was not included because logging of these wells generally had not included the Condamine Alluvium; however, the CSG wells were included as part of the regional geological model because the well logs contained useful information about the underlying Surat Sediments.

The potential of airborne electromagnetic methods to assist in mapping the transition zone across the Condamine Alluvium footprint was evaluated. Mira Geoscience Ltd carried out a desktop feasibility assessment and concluded that airborne electromagnetic methods would be ineffective for mapping the transition zone due to the low resistivity of the sheetwash and low resistivity contrast between the transition zone and overlying and underlying units (Mira Geoscience, 2014).

4.2.2 Methodology

Rockworks Version 15 software was used for reviewing and interpreting geological data and for geological modelling. An iterative approach of interpreting, modelling and verifying the model was used to yield a final model that generally reflects logged lithology while adhering to accepted depositional models of the Condamine Alluvium.

4.2.2.1 Geological interpretation and modelling

The process of constructing the model comprised the following steps:

- Compile geological data from the GWDB for more than 3,500 bores within an area encompassing the Condamine Alluvium footprint and extending far enough beyond the footprint to incorporate geological basement data.

- Cleanse and simplify the lithologic descriptions to permit bulk sorting and interpretation.

- Import the data into Rockworks and process to define lithologies corresponding to granular material (sand and gravel), fine material (silt and clay), basalt (Main Range Volcanics) and Surat Sediments.

- Manually interpret stratigraphic unit boundaries along a series of sections crossing the Condamine Alluvium; then, using Rockworks, construct the model to create surfaces representing the top of the Surat Sediments, the transition zone and the granular Condamine Alluvium. These steps were repeated a number of times to improve the model in areas of high bore density and/or poor log quality.

- Produce a final model including a number of control points within the central part of the model, to shape the system geometry in areas of data scarcity, and around the perimeter of the model, to represent the limit of the Condamine Alluvium. Modelled surfaces were smoothed slightly to better represent the expected nature of stratigraphic units.

4.2.2.2 Verifying the model

A number of independent checks were performed on the final modelled surface elevations to validate the fit between modelled surfaces and manual interpretation of stratigraphic unit elevations. A simple linear regression analysis of manually interpreted unit elevations at bores, compared to modelled surface elevations, yielded R^2 values of 0.92 for the top of the granular alluvium, 0.82 for the top of the transition zone and 0.77 for the top of the Surat Sediments. This implies that, at some locations, modelled surfaces would deviate slightly from interpreted logs at the same location. This is common and is considered appropriate for the purpose of this project.

4.3 Inferred geology of the Surat Sediments under the Condamine Alluvium

4.3.1 Surat Sediments

The Jurassic sedimentary rocks of the Surat Basin underlying the Condamine Alluvium generally dip downwards to the west, as shown in Figure 4-2. Key units in terms of potential groundwater interactions with the Condamine Alluvium are described below.

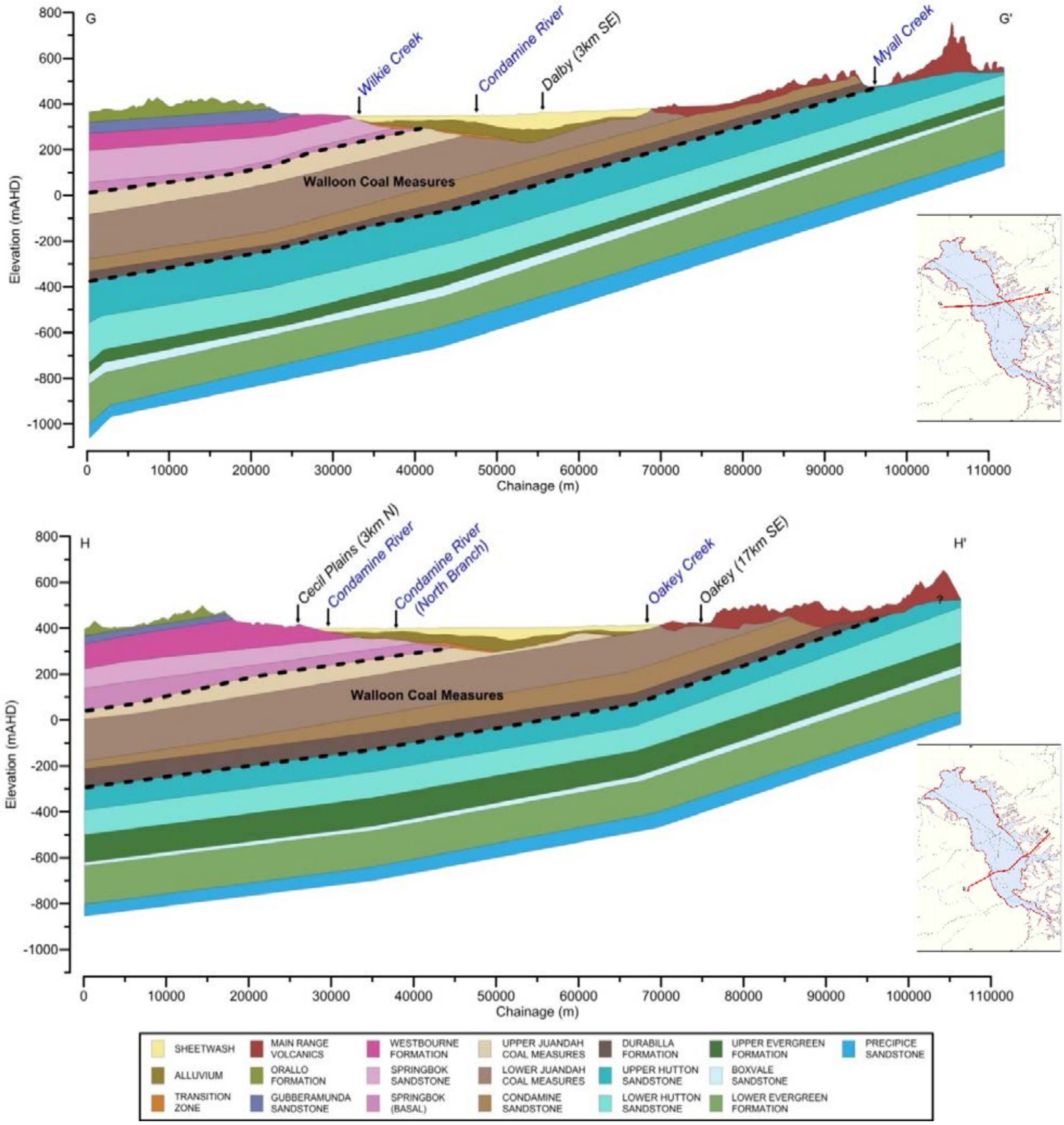

Figure 4-2: Regional geological cross sections across the Condamine Alluvium

The Jurassic sediments comprising the Orallo Formation, the Gubberamunda Sandstone, the Westbourne Formation and the Springbok Sandstone form a gentle ridge—the **Kumbarilla Ridge**—along the western margin. In the past, these sediments have collectively been referred to as part of the Kumbarilla Beds. With more data becoming available in recent years, it is now possible to differentiate the component formations and, therefore, the term Kumbarilla Beds is not used further in this report. The Kumbarilla Ridge forms the boundary between the Surat Basin to the west and the Clarence-Moreton Basin to the east. The sedimentary formations of the two basins interfinger (change from one type to another) across the ridge which runs roughly north-south, passing between Daandine and Macalister, as shown in Figure 4-1. The upper units of the Surat Sediments outcrop extensively to the west of the Condamine Alluvium and subcrop beneath the alluvium along much of its western flank. They generally consist of sandstone with some conglomerate, siltstone, mudstone, claystone and shale (Jell P.A, 2013).

The **Walloon Coal Measures** underlies the Springbok Sandstone with an erosional contact to the west of the Condamine Alluvium and forms the bedrock for much of the Condamine Alluvium. It outcrops only in isolated areas to the east of the Condamine Alluvium. The Walloon Coal Measures generally consists of mudstone, siltstone, fine sandstone and coal seams. Coals in the Walloon Coal Measures are thin, discontinuous seams interbedded in (lying between beds of) generally low-permeability sediments. The net coal is less than 10 per cent of the total formation thickness and includes up to 45 laterally discontinuous individual coal seams of varying thicknesses (Ryan, et al., 2012). Individual coal plies (coal-dominated bands) are typically less than 0.4 metres thick and only occasionally reach a thickness of one metre. Laterally, the coal plies extend from 500 metres to about 3,000 metres (Ryan, et al., 2012), (Hamilton, et al., 2014). The coal seams are the main target for CSG development in the area. Previous studies suggest that the collective thickness of the Walloon Coal Measures is typically less than 500 metres in the vicinity of the Condamine Alluvium (Hillier, J.R, 2010); this is broadly consistent with OGIA's regional geological model which suggests an average thickness of about 400 metres in the area.

Regionally, the Walloon Coal Measures is subdivided into **Juandah Coal Measures**, Tangalooma Sandstone, Taroom Coal Measures, and the Eurombah or Durabilla Formation. Using petro-physical and lithological information, it is possible to divide the Juandah Coal Measures regionally into upper and lower units. The Upper Juandah Coal Measures typically consists of thicker coal seams and a sandier interburden than the underlying Lower Juandah Coal Measures, where the interburden is mainly mudstone and siltstone. The Upper and Lower Juandah Coal Measures are divided into (from top to bottom) the Kogan, Macalister, Wambo and Argyle seams (Scott, et al., 2004). The boundary between the Upper and Lower Juandah Coal Measures is the base of a blocky sandstone above the last mudstone of the Lower Juandah Coal Measures. The CSG industry refers to this sandstone as the Juandah Sandstone or Wambo Sandstone (Ryan, et al., 2012).

In some areas of the Surat Basin, the **Tangalooma Sandstone** can be seen separating the Lower Juandah Coal Measures from the Taroom Coal Measures; however, the Tangalooma Sandstone is poorly developed as a sandstone unit (Ryan, et al., 2012). While sandstone dominates the unit, it includes significant amounts of finer-grained sediments and coal. It shales out in the southern part of the Taroom Trough and is hard to identify in the Condamine Alluvium area. Close to the Condamine Alluvium, the Lower Juandah and Taroom Coal Measures are therefore hard to distinguish from one another because the Taroom Coal Measures is also dominated by thin coal seams with fine-grained interburden (OGIA, 2016).

The **Taroom Coal Measures** can also be divided regionally into upper and lower units. The lowermost coal seams of the Lower Taroom Coal Measures (or Condamine Coal Measures, as it is referred to in some literature) comprise thicker coal seams than the Walloon Coal Measures above it. The interburden is generally fine-grained but is sandier than the Upper Taroom Coal Measures above it.

Scott et al. (2004) defined the sandstone unit at the base of the Walloon Coal Measures as the **Durabilla Formation**. Others (Green, et al., 1997), (Ryan, et al., 2012) could not consistently differentiate between the **Eurombah Formation** and the Durabilla Formation across the basin and, therefore, treated them as a single unit. The Durabilla Formation is defined in the regional geological model as the coal-free interval between the top of the Hutton Sandstone and the first coal seam of the Walloon Coal Measures. It comprises interbedded labile sandstone and mudstone.

The primary targets of CSG development in the Condamine Alluvium area are the Lower Juandah Coal Measures, the Lower Taroom Coal Measures and the Upper Juandah Coal Measures.

The **Hutton Sandstone**, which is equivalent to the Marburg Sandstone in the Clarence-Moreton Basin, conformably underlies the Durabilla Formation and conformably overlies the Evergreen Formation beneath the Condamine Alluvium. To the east of the Condamine Alluvium, it underlies the Main Range Volcanics in some areas and outcrops extensively. It is mainly sandstone, with interbedded siltstone and shale, and minor amounts of coal and mudstone (Jell P.A, 2013). The Main Range Volcanics is wedged between the Condamine Alluvium and the Surat Sediments. Due to scarcity of representative, good-quality, deep well/bore data along the eastern margin, the Main Range Volcanics contact with the Condamine Alluvium and the Surat Sediments is poorly mapped.

Structurally, part of the Clarence-Moreton Basin that forms the bedrock to the Condamine Alluvium is the Cecil Plains Sub-basin. The deepest part of the Cecil Plains Sub-basin is a subtle depression called the **Horrane Trough**, reported to be a half graben[3] and believed to be formed by strike-slip faulting (O'Brien, et al., 1993). The fault is known as the Horrane Fault. The inferred movement along the fault is minor (within 20–35 metres). Both the trough and the fault are represented in the regional geological model.

A subtle north-northeast to south-southwest trending basement structure that separates the Laidley Sub-basin to the east and the Cecil Plains Sub-basin to the west was recently identified by Geoscience Australia and informally named the **Helidon Ridge** (Ransley & Smerdon, 2012). Sediments drape over this ridge with a regional change in dip, which may control groundwater flow. It is suggested by the same researchers that the ridge acts as a groundwater divide within the Clarence-Moreton Basin.

The modelled elevation of the surface of the Surat Sediments—the bedrock of the Condamine Alluvium—is shown in Figure 4-3.

[3] A depression with a fault along one side

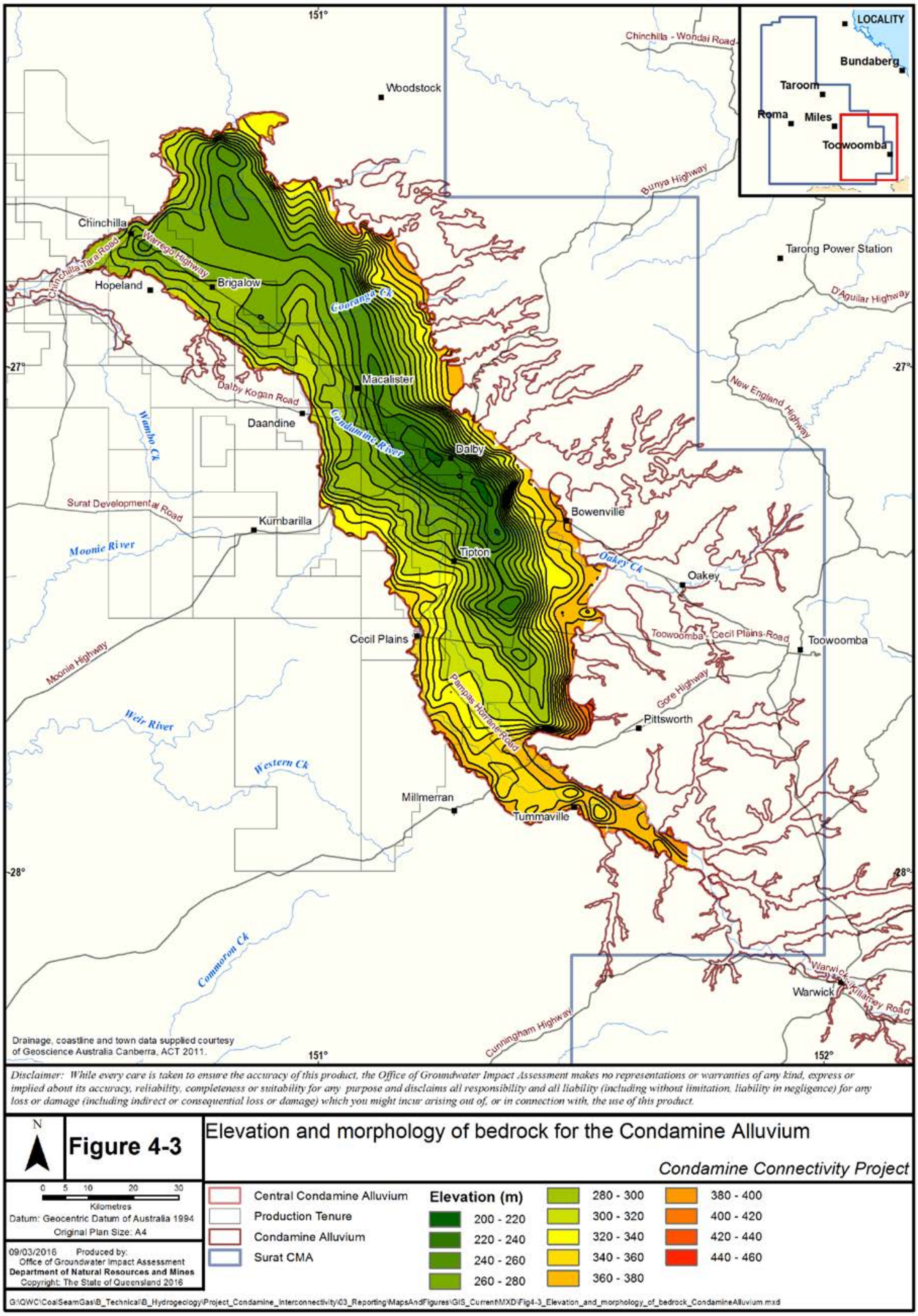

Figure 4-3 Elevation and morphology of bedrock for the Condamine Alluvium

The Surat Sediments surface reflects that the Condamine Alluvium is incised into the Surat Sediments, with highs along both edges of the Condamine Alluvium footprint and lows running along the thalweg (the lowest points along the length of the valley) to the east of the central axis of the Condamine Alluvium footprint. The deepest point of the thalweg is at an elevation of approximately 220 metres in the area around Dalby. The surface of the Surat Sediments is also the bottom of the transition zone.

4.3.2 Main Range Volcanics

The Main Range Volcanics is located east and southeast of the Condamine Alluvium, with the main (southern) body of basalt extending almost parallel with the Condamine Alluvium to the southeast, near Killarney. This main sequence is aligned northwest to southeast, with an approximate outcrop 25 kilometres wide and 60 kilometres long.

The Main Range Volcanics was formed during a single long period of epeirogenic uplift, with sub-aerial extrusion of basalts in the Oligocene-Miocene period. The formation consists of alkaline olivine basalt, most of which appears to have been erupted from fissures along the line of the present day Main Range. Most of the Main Range Volcanics has been extensively eroded and is covered in some areas by alluvium, in particular by the Condamine Alluvium tributaries. The Main Range Volcanics is commonly more than 150 metres thick but is thinner underneath the Condamine Alluvium area. For example, it is only about 30 metres thick near Dalby (Exon, 1976) (KCB, 2010b).

The eastern margin of the Main Range Volcanics corresponds to the surface water divide formed by the Great Dividing Range, with westerly surface water flows merging with the Condamine River via the Glengallan, Dalrymple, Kings, Hodgson and Oakey creeks (KCB, 2010b).

4.3.3 Condamine Alluvium depositional surface

The depositional history and chronology described below is based on previous studies (KCB, 2010b), personal communications with other workers, and geological interpretations arising from the project.

Within the Condamine Alluvium footprint, Surat Basin sediments were eroded down to the Walloon Coal Measures. The erosion continued until the Tertiary period. As a result, a weathering profile developed within the Walloon Coal Measures, from fresh at depth to extremely weathered at the top. The Walloon Coal Measures is so weathered towards the top of the profile that the typical fabric of the Walloon Coal Measures (such as fine laminae) is no longer observed in core data and the typical geophysical signatures tend to be attenuated.

Later in the Tertiary period, the environment changed from one of erosion to one of deposition. The exposed Walloon Coal Measures and then other Surat Sediments, together with the Main Range Volcanics, formed the bedrock for the deposition of Condamine Alluvium under a fluvio-lacustrine environment. As a result, **Tertiary Sediments** (mainly sandy) were deposited in local depressions in the relict drainage surface over the weathered Walloon Coal Measures; in places, they are mixed with reworked Walloon Coal Measures material which, in core samples, appears to be brecciated. The sands within the Tertiary Sediments generally contain marginally more clay than the overlying floodplain alluvium, as observed from coring at two pumping test sites (described in detail in Chapter 7). Although this Tertiary Sediments unit has never been mapped, its existence has been anecdotally reported (pers comm John Hillier).

In the Quaternary period, sediments of the Condamine Alluvium were deposited on top of the weathered Walloon Coal Measures and the Tertiary Sediments, with coarser material being deposited along the channel and fluvial silt and clay elsewhere. At some places, alluvial sand (granular alluvium) was deposited on top of eroded Tertiary Sediments.

4.3.4 The transition zone

A combination of weathered Walloon Coal Measures and low-energy, lake-deposited early Tertiary Sediments derived mainly from the Walloon Coal Measures were compressed beneath the overlying later Tertiary and Quaternary alluvial deposits of coarse sand, silt and clay (the Condamine Alluvium). As a result, it is hard to determine the difference between the upper weathered profile and the low-energy deposited silt and clay which directly overlies the firm mudstone and, occasionally, the coal seams of the Walloon Coal Measures.

This clay-dominated horizon at the bottom of the Condamine Alluvium is a combination of basal alluvial clays of the Condamine Alluvium, the lower clayey part of the Tertiary Sediments (where present) and the weathered upper part of the Walloon Coal Measures. These materials are often indistinguishable in observations recorded in bore logs, which often refer to ‘clay’, ‘basement clay’, ‘basal clay’, or ‘red, yellow and grey coloured clay’. However, the basal material is sometimes also described as ‘silty clay’, ‘sandy clay’, ‘gravelly clay’, ‘shale’, ‘tuff’, or ‘highly weathered rock’. These terms would likely describe basal alluvial clays and weathered Walloon Coal Measures. As stated previously, this undifferentiated clay-dominated horizon is referred to as the ‘transition zone’ in this report.

The transition zone sits above the firm Walloon Coal Measures but below the Condamine Alluvium and higher-energy Tertiary Sediments, where present. It also sits between the Springbok Sandstone and the Condamine Alluvium in places where the two are in direct contact, such as the western margins of the Condamine Alluvium; although, given the more sandy nature of the Springbok Sandstone and relatively steeper slope along the western margins, the transition zone tends to be very thin or absent in those areas.

The lower bound of the transition zone is more difficult to interpret from water bore records because there is a gradual change from the firm Walloon Coal Measures to the overlying weathered horizon. From records of bores that do not report firm mudstone, it is likely that a clay layer further up the profile has been interpreted as the top of the transition zone. In some cases, the recorded coal has been interpreted as the lower bound of the transition zone.

The cross-sections in Figure 4-4 illustrate the variability in the estimated thickness and extent of the transition zone underlying the granular alluvium along the length of the Condamine valley. Figure 4-5 shows the modelled transition zone thickness contours (isopach) which have been derived from the difference between the modelled base of the granular alluvium and the top of the underlying consolidated strata (predominantly Walloon Coal Measures). Because the thickness is derived in this way, it may differ from the actual interpreted transition zone at the location of individual bores. Interpreted thicknesses from individual bore logs with their locations (logged thickness) are also show in Figure 4-5.

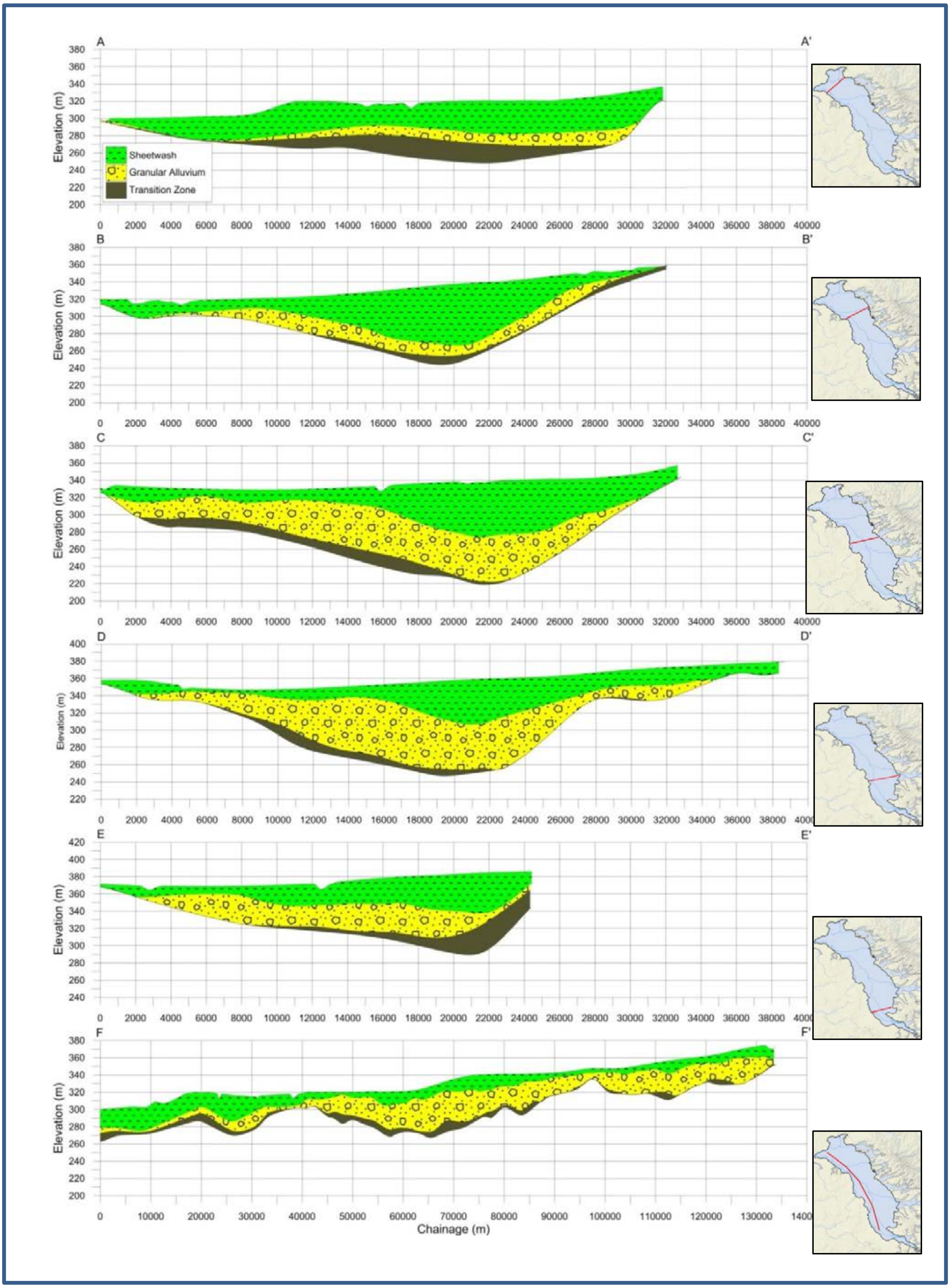

Figure 4-4 Representative cross sections across the Condamine Alluvium footprint

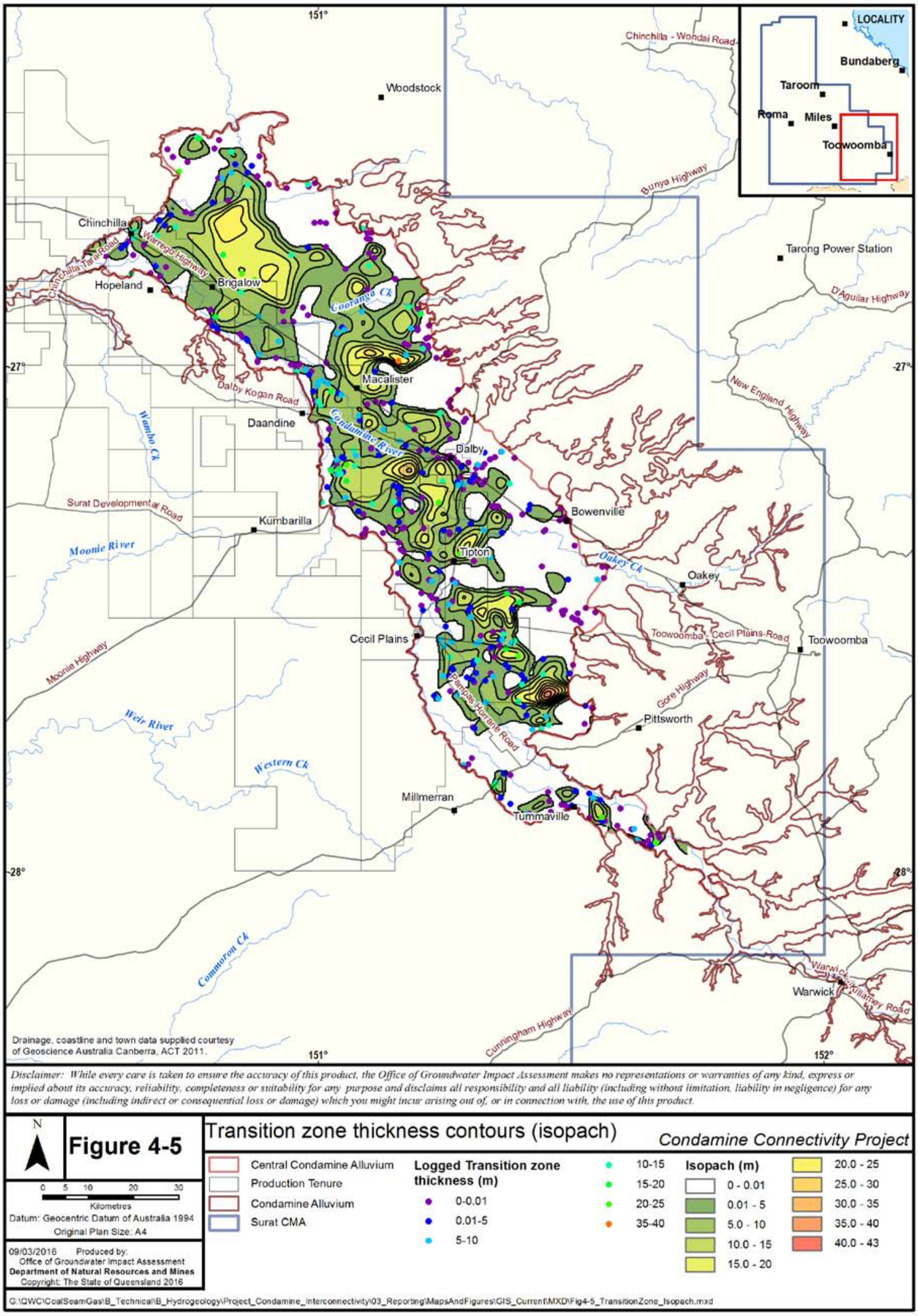

Figure 4-5 Transition zone thickness contours (isopach)

The transition zone is generally discontinuous across the Condamine Alluvium footprint and, where present, ranges from less than one metre to just over 15 metres in thickness. The Condamine Geo Model suggests that the transition zone is expected to be less than five metres thick over about 40 per cent of the area. Various ranges of thickness with corresponding percentage coverage are presented in Table 4-1. The methods and assumptions adopted in interpreting the transition zone thickness in individual bore logs, and then interpolating this thickness data, were conservative. The resulting transition zone thickness shown in Figure 4-5 is, therefore, likely to be an underestimate of the actual extent and thickness.

Table 4-1 Modelled transition zone thickness

Thickness of transition zone (metres)	Modelled coverage of area (%)
<5	40
5–10	31
10–15	15
15–20	9
>20	4

Based on the thickness of the transition zone shown in Figure 4-5, three broad areas can be identified that run parallel to the Condamine Alluvium depositional valley:

- a relatively small area towards the western flank of the alluvial valley where the transition zone is mainly thin or absent and sits, for most part, between the Condamine Alluvium and the Springbok Sandstone
- a central zone where the largely continuous and relatively thick transition zone is mainly over the Walloon Coal Measures
- an area towards the eastern flank of the valley where the transition zone appears to be largely absent.

This distribution of transition zone thickness is consistent with the depositional environment described earlier in Section 4.3.3.

The Walloon Coal Measures underlying the Condamine Alluvium dips towards the south-west at around 0.5 degrees, on average, and subcrops underneath the alluvium at an angle along the erosional surface. Due to this angular contact between the Walloon Coal Measures and the Condamine Alluvium, some of the interbedded coal seams of the Walloon Coal Measures along the western flank of the alluvium may come into contact with the lower surface of the transition zone or directly with the granular alluvium in places where the transition zone is absent, such as along the Horrane Trough. In most of this western flank area, however, the Springbok Sandstone and the Westbourne Formation are also wedged between the Condamine Alluvium and the Walloon Coal Measures. In any remnant areas where permeable coal seams do sit directly against granular alluvium, there is the potential for greater connectivity between the Walloon Coal Measures and the Condamine Alluvium, particularly in areas which are also affected by CSG extraction.

As outlined in Section 2.8, economic quantities of gas are not usually found within 150 metres of the surface and a separation distance of 30 metres below the Condamine

Alluvium is planned by the tenure holder. As such, the coal seams targeted for production to the west of the Condamine Alluvium are likely to come in contact with the Condamine Alluvium about 7–12 kilometres further east. As the typical lateral extent of coal seams is about 0.5–3 kilometres (refer to Section 4.3.1), connectivity via this pathway is unlikely.

Towards the east of the Condamine Alluvium, direct contact between the target coal seams and granular alluvium is unlikely, even in areas where the transition zone is absent, since the coal measures dip to the south-west while the alluvium thins out to the north-east.

4.3.5 Condamine Alluvium

The Quaternary Condamine Alluvium includes the alluvium and the sheetwash deposits of the Condamine River and its tributaries which form the broad plain between Chinchilla and the area east of Millmerran (KCB, 2010a), as shown in Figure 4-1. It is composed of varying lithologies, is up to 120 metres deep, and comprises two important hydrostratigraphic units—sheetwash and granular alluvium—which are described below.

4.3.5.1 Sheetwash

Sheetwash (including topsoil) occurs as a wedge of generally fine materials (silt and clay) or mixed sandy materials abutting the eastern wall of the Condamine River plain and overlying the more varied granular alluvium. In many places, individual clay and silt horizons are more than 20 metres thick and there is generally a complete absence of clean sand horizons, except in some areas where sediments have been reworked by higher-energy stream fans from the east. These coarse-grained sand horizons are generally less than one metre thick and are likely to be laterally discontinuous. Sheetwash acts as a confining layer in areas where clays are thick and laterally continuous and it is not highly conducive to recharge.

The modelled sheetwash thickness (isopach) is shown in Figure 4-6. Its spatial distribution across the Condamine Alluvium footprint is also shown in cross-sections in Figure 4-4. The sheetwash wedge overlies almost all of the modelled area, with an average thickness of about 25 metres. It is thinnest near the edges of the Condamine Alluvium and generally thickest overlying the thalweg of the Condamine Basin, reaching a maximum thickness of close to 100 metres to the southeast of Dalby.

4.3.5.2 Granular alluvium

The granular alluvium underlies the sheetwash over most of the Condamine Alluvium footprint, pinching out along the edges of the Condamine Alluvium where the sheetwash is in direct contact with the Surat Sediments. The average modelled thickness of the granular alluvium is about 16 metres and reaches a maximum thickness of 77 metres to the east of Cecil Plains.

Granular alluvium typically presents as a wide range of relatively thin (less than 10 metres), fine, mixed and granular (sand and gravel) horizons separated by clay lenses representative of the complex depositional environment (riverine high-energy to lacustrine low-energy). Generally, the fines content increases in the downstream direction, with much higher groundwater yields generally encountered towards the south of the Condamine Alluvium footprint than to the north.

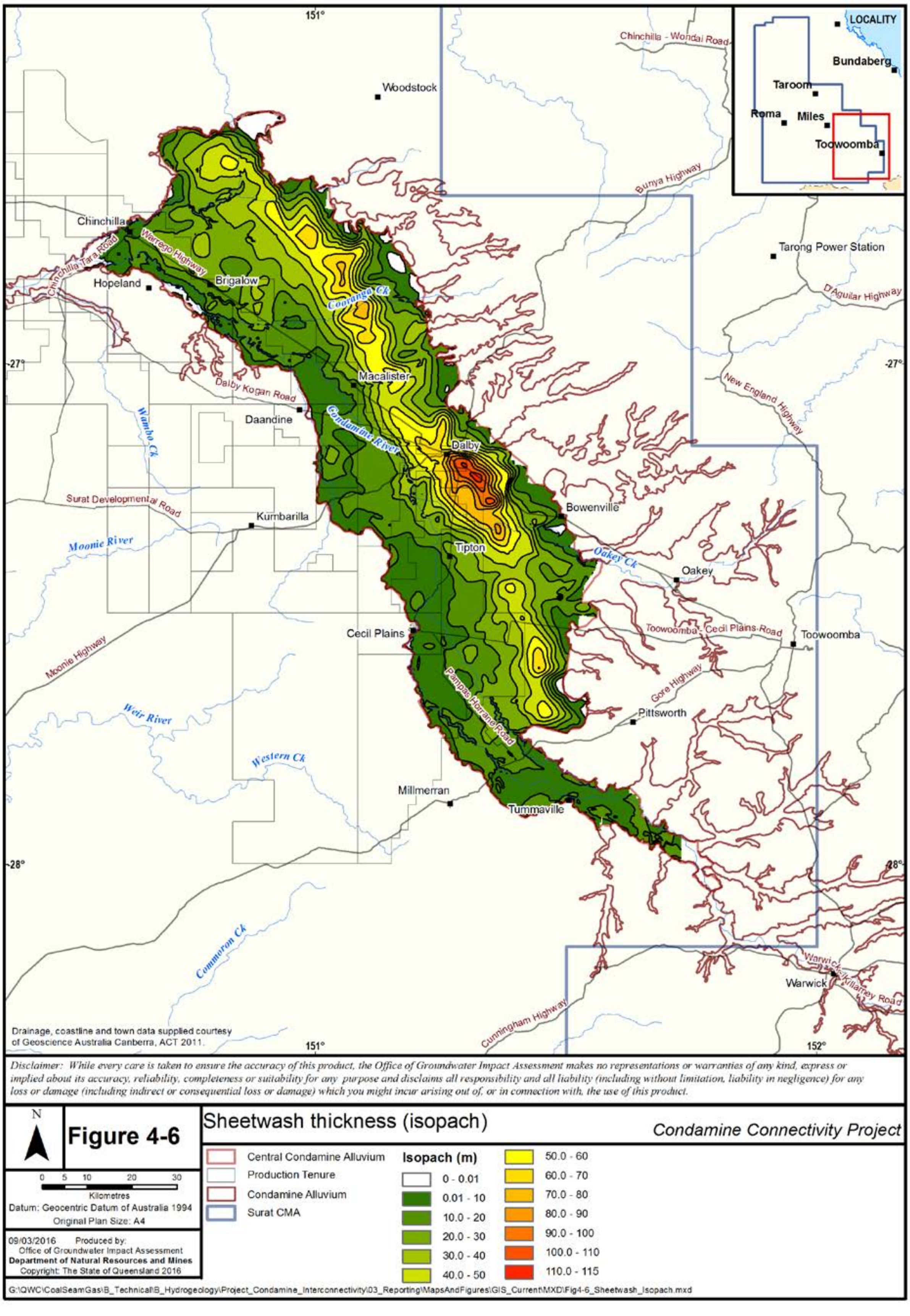

Figure 4-6 Sheetwash thickness (isopach)

The granular alluvium extends from the bottom of the sheetwash to the contact with the transition zone, or to the Surat Sediments where the transition zone is absent. The transition from sheetwash to granular alluvium is defined by a marked increase in the presence of clean sand and gravel units. Lithology logs in the GWDB describe the granular alluvium as being composed of numerous interbedded horizons ranging from clean sand or gravel to clay, each of which is generally less than 10 metres thick.

Figure 4-4 shows the cross-sections of the granular alluvium across the Condamine Alluvium footprint. Figure 4-7 shows the modelled granular alluvium thickness.

4.4 Conclusions

The geology of the Condamine Alluvium has been studied and mapped in the past, with a focus on the granular alluvium which is the main source of groundwater supplies. This project has mapped in detail the interface between the Condamine Alluvium and the Walloon Coal Measures. The transition zone, a zone of undifferentiated clay that sits between the two formations, has been interpreted from bore logs and from geophysical data to prepare an isopach map showing the thickness of the transition zone across the Condamine Alluvium footprint.

The transition zone, as interpreted, is a discontinuous horizon and is dominated by clay. Where present, it will physically impede flow between the two formations. In places, the transition zone is absent because alluvial sand and gravel sits directly above the underlying mudstone, siltstone and, in some cases, coal seams of the Walloon Coal Measures. Along part of the western flank, where the transition zone is absent, the alluvium is also separated from the Walloon Coal Measures by a wedge of the Springbok Sandstone and the Westbourne Formation. Along the eastern flank and close to the margin of the Condamine Alluvium with the Main Range Volcanics, there are significant areas where the transition zone is thin or absent; however, the target coal seams are unlikely to come in contact with the Condamine Alluvium in these areas since the coal measures dip to the southwest while the alluvium thins out to the northeast.

Tertiary Sediments, mainly sandy but including reworked bedrock, are present in some areas at the base of the Condamine Alluvium, infilling relict drainage features in the weathered Walloon Coal Measures.

The transition zone is a significant barrier to flow over a large part of the contact between the Condamine Alluvium and the target coal seams of the Walloon Coal Measures. The mudstones of the upper Walloon Coal Measures above the target coal seams are a further barrier.

Relevant geologic information from the project has been incorporated into the regional geological model that is used in the development of the regional groundwater flow model for the Surat UWIR 2016.

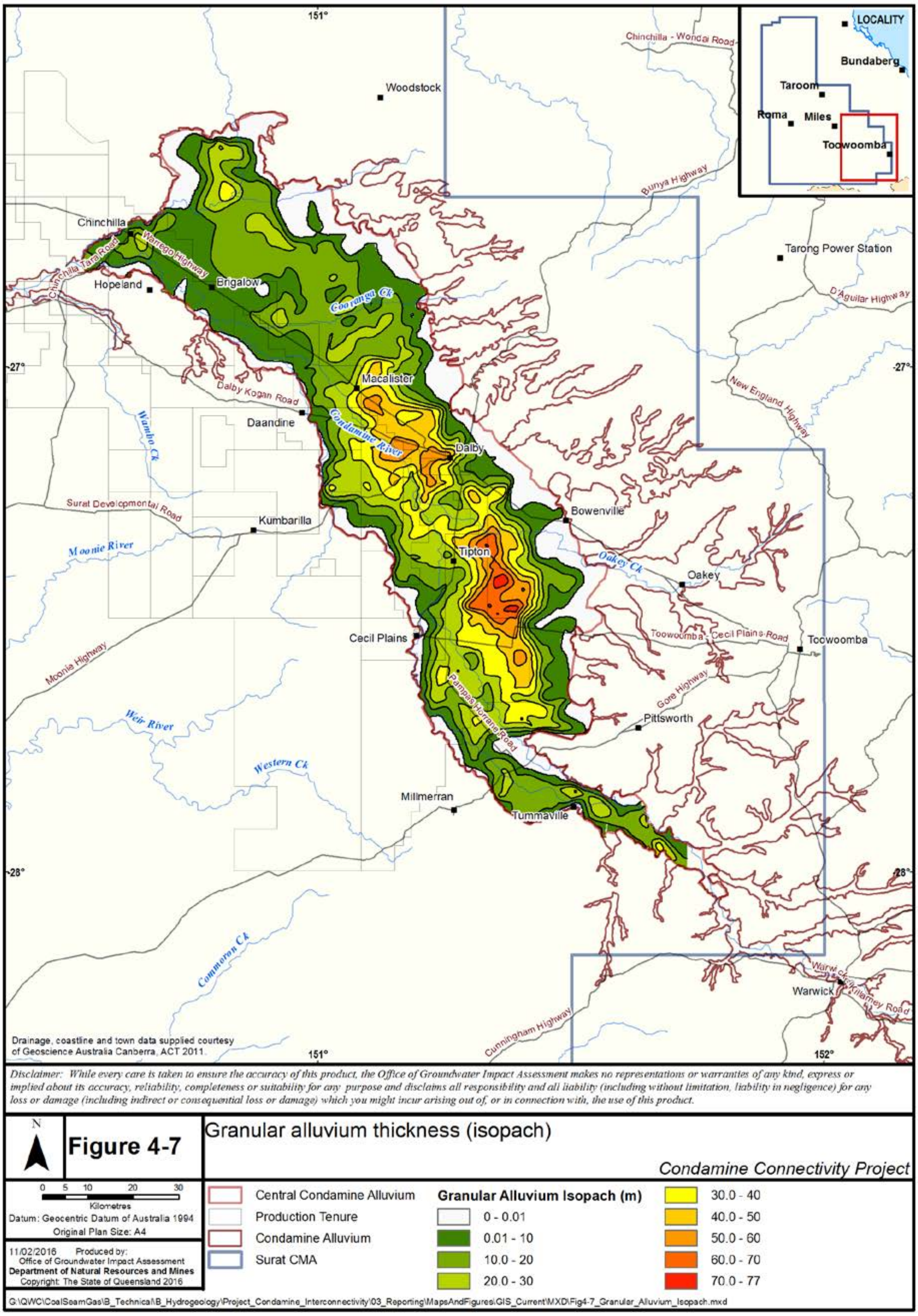

Figure 4-7 Granular alluvium thickness (isopach)

5 Surveying and mapping of groundwater levels

5.1 Overview and purpose

Spatial and temporal distribution of differences in hydraulic head[4] (or groundwater level) between the Condamine Alluvium and the Walloon Coal Measures (vertical hydraulic gradient) can provide evidence of potential for groundwater to vertically flow across the two formations.

The Condamine Alluvium has been exploited for water supply since 1940. Groundwater management has increased over time, with regulation of the drilling of additional bores and the extraction of water (Section 2.5). An extensive network of about 600 monitoring bores has been developed in the Condamine Alluvium footprint during this period and is maintained by DNRM. Most of these monitoring bores access the Condamine Alluvium because it is the main source of water supply. The few monitoring bores that are exclusively screened in the Walloon Coal Measures tend to be along the margins of the alluvium where it is relatively less productive. In these marginal areas, the source of supply is from the Walloon Coal Measures, the Main Range Volcanics or the Springbok Sandstone.

Although groundwater level maps for the Condamine Alluvium have been prepared under various studies (KCB, 2010b), no attempts have been made to map corresponding groundwater level/pressure surfaces in the Walloon Coal Measures. To fill this gap, OGIA identified bores across the Condamine Alluvium footprint that are screened in the Walloon Coal Measures and that are near bores screened in the Condamine Alluvium. A survey was carried out to collect water level data and water samples from these bores. OGIA used the groundwater level data generated from this survey, in combination with other monitoring data from the Condamine Alluvium, to prepare groundwater level maps for the Condamine Alluvium and the Walloon Coal Measures and maps of relative hydraulic head differences between the two formations.

5.2 Terminology

The Condamine Alluvium is largely a semi-confined aquifer and the Walloon Coal Measures beneath the Condamine Alluvium footprint is a confined aquifer. The terms ‘hydraulic head’ for individual points and ‘piezometric surface’ for corresponding surfaces are therefore the correct technical terms for such aquifers. However, for simplicity and ease of referencing, the more generic terms ‘groundwater level’ and ‘groundwater level map’ are used in the report to refer to hydraulic head and piezometric surface respectively.

5.3 Surveying of groundwater levels

The groundwater level survey program was commissioned by OGIA and carried out by Klohn Crippen Berger between July 2013 and September 2013 for the bores selected. The condition of the bores was checked to make sure they were suitable for groundwater level

[4] Hydraulic head, or piezometric head, includes pressure head and elevation head for a confined aquifer. It is the driving force for fluid movement. For simplicity the term ‘groundwater level’ is used in this report as synonym to hydraulic head.

measurements. If suitable, groundwater levels were measured and water samples were collected for chemical analysis.

A total of 229 bores in 85 clusters were identified for survey. A cluster consisted of groups of bores in close proximity with at least one bore accessing the Condamine Alluvium and one bore accessing the Walloon Coal Measures. Most of the bores surveyed were private water supply bores and, therefore, the process included liaising with landholders for access and scheduling purposes. There was good participation from landholders. Of the 229 bores identified, 127 bores were successfully accessed and found to be suitable for survey. These bore locations are shown in Appendix 2.

5.4 Basis for groundwater level mapping

Groundwater level maps for the Condamine Alluvium and the Walloon Coal Measures were prepared using the following data:

- groundwater levels from individual bores, collected during the July 2013 to September 2013 survey
- groundwater levels reported in the GWDB for the preceding three months for the Condamine Alluvium bores, and the preceding 12 months for the Walloon Coal Measures bores
- groundwater levels reported by Arrow Energy in 2014 and 2015 from a number of newly constructed monitoring bores specifically screened in the upper part of the Walloon Coal Measures.

The resulting dataset had groundwater levels from 268 Condamine Alluvium bores which were well distributed across the Condamine Alluvium footprint, except in the area north of Macalister and east of Chinchilla. Pumping from individual bores can cause steep variations in local groundwater levels, so the contours for the groundwater level maps were developed manually to reflect broad patterns.

Mapping the Walloon Coal Measures groundwater levels was more complex than for the Condamine Alluvium due to a relative scarcity of data from the Walloon Coal Measures, uneven distribution of the data points and some uncertainty in the interpretation of the contact between the Walloon Coal Measures and the Condamine Alluvium. For these reasons, interpolating the groundwater levels of the Walloon Coal Measures was more subjective as compared to the Condamine Alluvium.

The GWDB data pertaining to the Walloon Coal Measures bores was manually verified to identify bores screened in the Walloon Coal Measures and hydraulically isolated from the Condamine Alluvium. This involved reviewing bore construction and lithology records.

Under the monitoring strategy specified in the Surat UWIR (2012), OGIA runs an ongoing groundwater level monitoring program to improve the quality and distribution of the Walloon Coal Measures data across the Condamine Alluvium footprint. This monitoring data will continue to be collected and, over time, will enable further improvement in groundwater level mapping.

5.5 Mapped groundwater levels

5.5.1 Condamine Alluvium

The mapped Condamine Alluvium groundwater levels are shown in Figure 5-1. The map is a snapshot for the period 2013 to 2014. Levels are at an elevation of more than 380 metres at the southern end of the Condamine Alluvium footprint and less than 300 metres in the north, near Chinchilla. The major feature is the large depression in the groundwater levels to the east of Cecil Plains, where levels are as low as 315 metres. In a second smaller depression immediately east of Dalby, levels are as low as 320 metres. These depressions correspond with areas of relatively high groundwater extraction.

5.5.2 Walloon Coal Measures

The mapped Walloon Coal Measures groundwater levels are shown in Figure 5-2. The map is a snapshot for the period 2013 to 2014, based on 23 bores across the footprint. The bores included are listed in Appendix 3.

Although the mapped surface is based on data from a limited number of bores and CSG wells screened at different depths within the Walloon Coal Measures, the general spatial trend in levels adequately reflects groundwater levels across the Walloon Coal Measures.

The depressions observed in the Condamine Alluvium groundwater level map do not appear to be present in the Walloon Coal Measures. This observation is also supported by data from two locations in the area of the Cecil Plains depression (one at Carn Brea and one of the pumping test sites east of Cecil Plains) where high-confidence monitoring installations at multiple stratigraphic levels were recently established.

5.5.3 Relative differences in groundwater levels

The difference in the groundwater levels of the Condamine Alluvium and the Walloon Coal Measures is shown in Figure 5-3. Except for some areas along the eastern and western margins, groundwater levels in the Walloon Coal Measures are up to 35 m above the groundwater levels in the Condamine Alluvium (i.e. an upward hydraulic gradient). The gradient tends to be higher in the upstream part of the alluvium and in areas southeast of Cecil Plains and Dalby where depressions exist in the Condamine Alluvium groundwater levels. It should be noted that, while in some locations the gradient is actual measurement at those locations (for example, southeast of Cecil Plains), in other areas the gradient was estimated based on groundwater levels interpolated using nearby data points. Although this limitation may affect the magnitude of the gradient in these latter areas, it is unlikely to affect the overall pattern. In most central areas, a difference of about 5–20 metres is likely to exist; in the area southeast of the Cecil Plains, an actual difference of 17–20 metres is observed from high-quality data points.

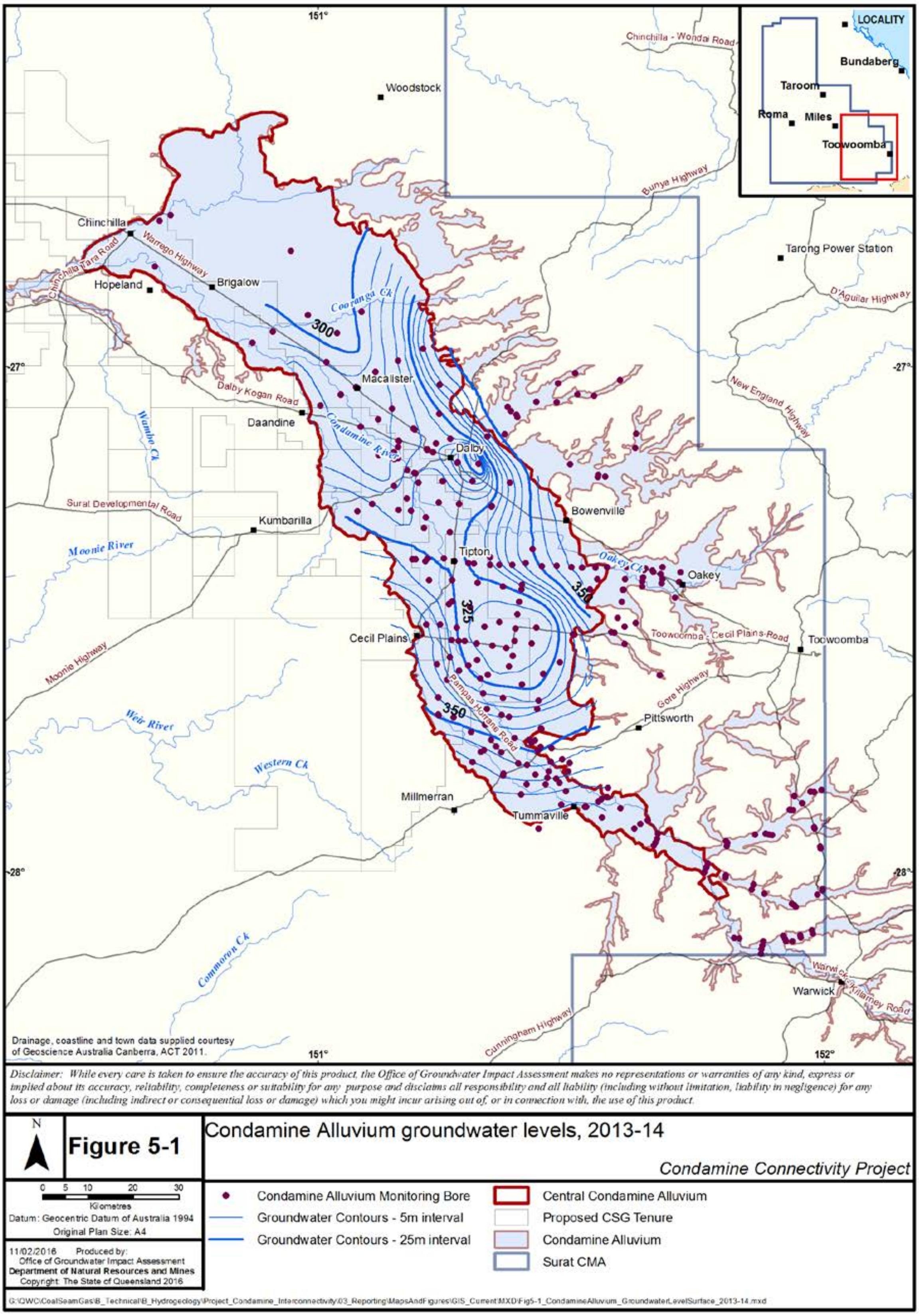

Figure 5-1 Condamine Alluvium groundwater levels, 2013–14

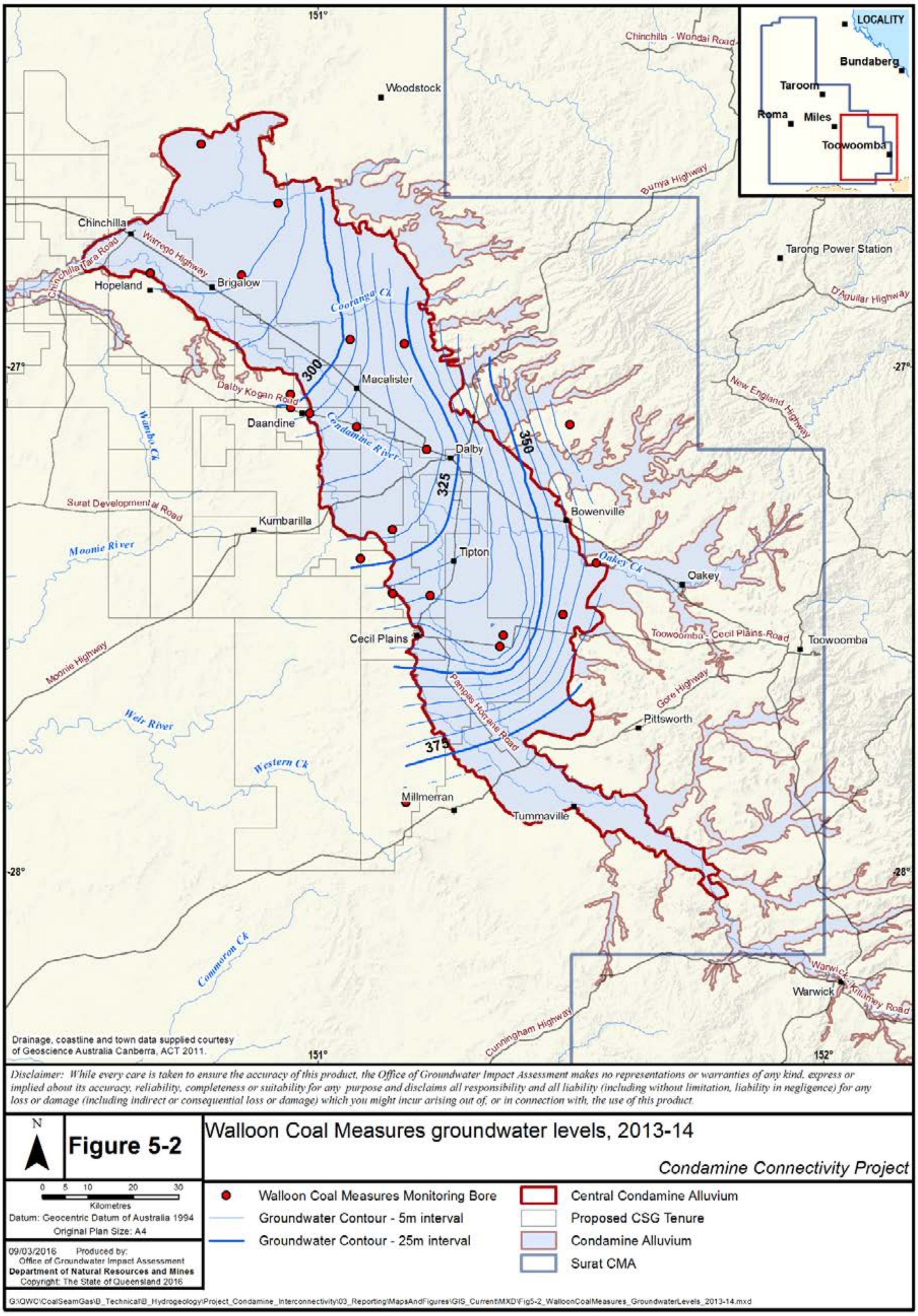

Figure 5-2 Walloon Coal Measures groundwater levels, 2013–14

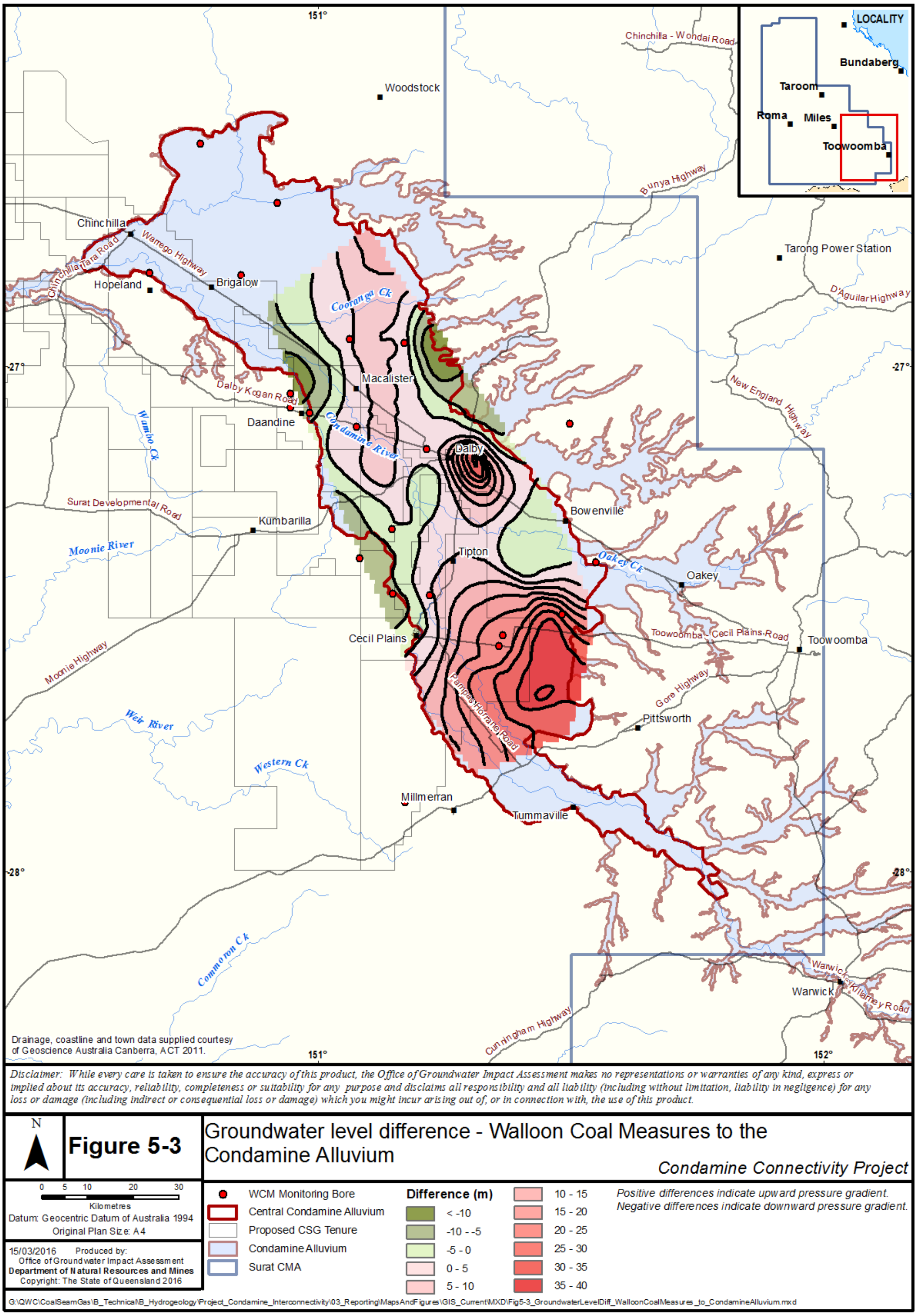

Figure 5-3 Groundwater level difference – Walloon Coal Measures to the Condamine Alluvium

5.6 Analysis

Relative differences in regional groundwater levels and flow patterns between two stacked groundwater systems are a good indicator of the degree of connectivity between the systems. If groundwater levels in one system respond quickly to changes in the other system, the two systems are considered to have high connectivity. A weak and delayed response would indicate an impediment to flow between the systems and, hence, low connectivity. Similarly, persistent differences in regional groundwater flow patterns between two systems would suggest little interaction and, therefore, low connectivity.

There are large differences in hydraulic conductivity and storativity between the Condamine Alluvium and the Walloon Coal Measures. The Walloon Coal Measures is a heterogeneous confined groundwater system with much lower hydraulic conductivity and storativity than the Condamine Alluvium. As a result, even a small amount of outflow from the Walloon Coal Measures will create a much larger fall in groundwater levels in the Walloon Coal Measures compared to the Condamine Alluvium.

Within this context, the following observations are made about differences in groundwater level patterns in the Condamine Alluvium and the Walloon Coal Measures.

Historical groundwater levels in the Condamine Alluvium are well understood (KCB, 2010b) and are shown in Figure 5-4 for each decade between 1940 and 2010. It is evident that large depressions in groundwater levels gradually developed as a result of extensive groundwater extraction which began around the 1960s. In contrast, little is known about the historical groundwater levels in the Walloon Coal Measures; however, considering the hydrogeological setting, it is reasonable to assume that before water began to be extracted, groundwater levels in the Walloon Coal Measures would have been similar to or slightly lower than the groundwater levels in the Condamine Alluvium.

Groundwater levels in the Condamine Alluvium have fallen over recent decades as a result of water extraction. Currently, there is a difference of 5–20 metres between the Condamine Alluvium and the Walloon Coal Measures across most of the extensively developed central part of the Condamine Alluvium. This persistent difference indicates that there is a significant impediment to flow between the formations. It is relevant that, because of the low storativity of the Walloon Coal Measures, even a small amount of flow from the Walloon Coal Measures would have resulted in a large fall in groundwater levels in that formation but this has not been observed.

There are also differences in the groundwater flow patterns in the two formations, indicating low connectivity. The current groundwater level surface for the Walloon Coal Measures (Figure 5-2) does not correlate with the depressions in groundwater levels in the Condamine Alluvium (Figure 5-1). If there had been significant flow from the Walloon Coal Measures into the Condamine Alluvium in response to the head difference, then the flow pattern in the Walloon Coal Measures would be towards the areas of depression in the Condamine Alluvium. Although the data is limited, groundwater level pattern in the Walloon Coal Measures does not suggest this.

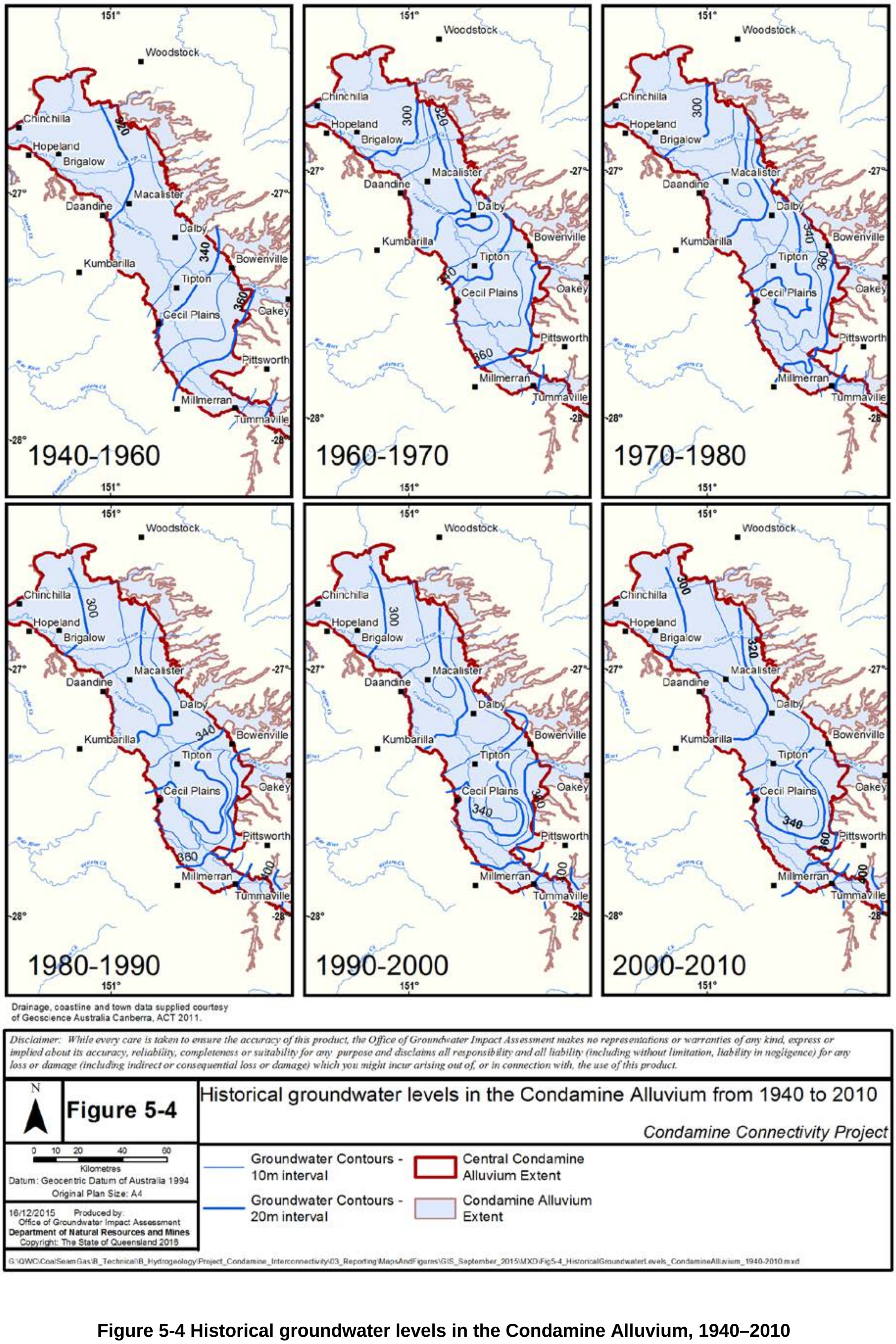

Figure 5-4 Historical groundwater levels in the Condamine Alluvium, 1940–2010

5.7 Conclusion

The differences in groundwater levels and flow patterns in the Condamine Alluvium and the Walloon Coal Measures demonstrate that, at a regional scale, an impediment to flow exists between the two formations, suggesting low connectivity.

6 Assessment of the hydrochemistry

6.1 Overview and purpose

The purpose of this assessment was to characterise the hydrochemistry of the Condamine Alluvium and the underlying formations from historical data, and then use this characterisation to assess the hydrochemical evolution and the possibility of past intermixing of water between the Condamine Alluvium and the Walloon Coal Measures. The assessment was also driven by the suggestion that the higher levels of salinity recorded in parts of the Condamine Alluvium could be due to the movement of water from the Walloon Coal Measures into the Condamine Alluvium (Hillier, J.R, 2010).

This hydrochemical assessment has primarily used available major ion chemistry data. Some isotopic analysis was also used to supplement the assessment. A number of assessment techniques were used, including the relatively simple statistical and spatial analysis of individual hydrochemical parameters, and piper diagrams. However, more advanced multivariate statistical analysis tools, such as the principal component analysis (PCA) and the K-means cluster analysis (KCA) were found to be most useful. These techniques were effective in analysing correlation among the multiple parameters for large datasets. Analysing the correlation, in turn, supported analysis of hydrochemical evolution and its implications for cross-formational flow.

6.2 Data sources and validation

The original dataset was acquired from 3,524 samples representing 2,305 bores or sample points. Of these, 3,409 analyses were obtained from the GWDB and the remaining 115 analyses were obtained from petroleum tenure holders. The analyses were selected based on the availability of measurable concentrations of major cations and anions. A process of data validation reduced the number of analyses to 3,275 samples from 2,160 sample points. As part of the validation process:

- analyses done before 1980 were rejected because of limited details of sampling and analysis methods
- analyses representing duplicate data points were removed
- analyses that reported values below lower detection limits or above upper detection limits were removed
- analyses that reported pH below 5 or above 10 were removed, as these values are assumed to be outliers due to sample contamination or analytical error
- analyses with ion imbalances of more than five per cent were removed, as these values suggest analytical error.

All analyses included data for at least 12 hydrochemical parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), chloride (Cl^-), fluoride (F^-) and sulphate (SO_4^{2-}).

6.3 Data analysis and results

6.3.1 Methods and techniques

A range of statistical methods of varying complexity were tested and used:

- descriptive statistics (mean, median, standard deviation, standard error of mean) (XLSTAT, 2014)
- piper diagrams (Winston, 2000)
- principal component analysis (PCA), using XLSTAT software (XLSTAT, 2014)
- K-means cluster analysis (KCA), using XLSAT software (XLSTAT, 2014) and
- statistical and spatial analysis of hydrochemical clusters.

The absolute and relative concentration of hydrochemical parameters (variables) are interdependent to varying degrees depending on rock-water interaction resulting in hydrochemical evolution. Therefore, analysis and interpretation of data for inferring hydrochemical evolution requires not only an understanding of spatial variations and patterns in an individual variable, but also an understanding of complex relationships with interdependent variables. Application of descriptive statistics based on single variables, although providing a useful insight, was not sufficient in itself. Similarly, piper diagrams were useful for visualising dominant water types but their application in interpreting potential mixing between different water types was limited.

To discover patterns or classes in the large dataset and to identify underlying relationships for further interpretation, two complex multivariate (involving two or more parameters) analysis techniques were used: principal component analysis (PCA) and the K-means cluster analysis (KCA). These analyses were followed by spatial analysis of patterns identified.

PCA is a statistical technique that is used to identify interrelationship or co-relationships across hydrochemical parameters and then to reduce multiple hydrochemical parameters into three or four components that represent the dominant relationships. The technique is particularly useful for hydrochemical analysis because it comprises a number of parameters with complex interdependences. PCA helps to statistically identify, from a large number of possibilities, those interdependences that are significant (principal components) and that create most of the variance in the data. Once these interdependences are identified, the hydrochemical evolution can then be inferred based on these relationships and their relative contributions (loading).

The KCA is also a statistical analytical tool that is used for categorising the hydrochemical data of samples of similar kinds based on multiple variables rather than a single variable. It is a way of classifying the data into groups or clusters in such a way that the degree of association between two or more variables in a cluster is maximised. It should be mentioned that the best number of clusters (k) leading to the greatest separation (distance) is not known in advance. Generally, the data is clustered based on an initial estimate of the number of clusters and then adjusted, having regard to the intended use of the analysis, to arrive at the most useful number and characteristics of clusters. The cluster analysis is used to discover the underlying groups without explaining why the groups are formed, which is a matter of interpreting the hydrochemical evolution.

Ratios of individual concentration of a hydrochemical variable, or combination of variables, against each other or with reference to a standard (such as seawater), are also a useful technique for identifying relationships among the variables and as an indicator of a specific hydrochemical process or processes. For example, the relationship between Na^+ and Cl^- is used to identify the mechanism for acquiring salinity in semi-arid or arid regions, and to quantify the atmospheric contribution. A higher ratio of Na^+/Cl^- to Cl^- (above the ratio for seawater) suggests limited contribution from atmospheric precipitation (i.e. recharge) and that high levels of major ions are most likely derived from weathering of rock, forming minerals, and from anthropogenic sources. Similarly, the ratio of $Ca^{2+}+Mg^{2+}$ to Cl^- is constant for seawater, irrespective of concentration or dilution, resulting in a straight line on a plot of $Ca^{2+}+Mg^{2+}$ against Cl^-. If a groundwater sample analysis plots above the seawater line, this indicates that the dissolution of weathered rock is contributing to groundwater, while a sample below the line indicates ion exchange or precipitation.

6.3.2 Results of the hydrochemical assessment

Hydrochemical assessment was carried out for seven geological formations including the Condamine Alluvium, Walloon Coal Measures, Main Range Volcanics, Gubberamunda Sandstone, Springbok Sandstone, Hutton/Marburg Sandstone and Precipice/Helidon Sandstone. The results presented here focus on the Condamine Alluvium, the Main Range Volcanics and the Walloon Coal Measures as they are the formations important for connectivity in the Condamine Alluvium footprint.

6.3.2.1 Hydrochemical type

All major aquifers in the area have the $Na\text{-}HCO_3\text{-}Cl$ hydrochemical type, except for the Walloon Coal Measures, the Springbok Sandstone and the Hutton/Marburg Sandstone which have $Na\text{-}Cl\text{-}HCO_3$. A summary of major ion concentrations for the Condamine Alluvium, the Main Range Volcanics and the Walloon Coal Measures is shown in Table 6-1. The Walloon Coal Measures has much higher concentrations of Na^+, HCO_3^-, Cl^-, SAR (sodium adsorption ratio) and TDS than the Condamine Alluvium and the Main Range Volcanics. In particular, SAR and the percentage of Ca^{2+} and Mg^{2+} contributed from weathering of rock minerals differ greatly between the Condamine Alluvium and the Walloon Coal Measures for each cluster class.

Cluster analysis resulted in the identification of four classes that were also assessed for hydrochemical types using piper diagrams (Figure 6-1). The piper diagrams clearly separate higher-salinity classes 3 and 4 (red) from the lower-salinity classes 1 and 2 (green) for both the Condamine Alluvium and the Walloon Coal Measures.

Table 6-1 Hydrochemical composition of water in the Condamine Alluvium, Main Range Volcanics and the Walloon Coal Measures

Aquifer	Hydrochemical type	Major ions	Mean (mg/L)	Median (mg/L)	Range (mg/L)	No. of observations
Condamine Alluvium	(Na-HCO3-Cl)	Na^+	347	195	27—900	1,133
		HCO_3^-	408	390	6–973	
		Cl^-	585	235	8—900	
		SAR	7 (no unit)	5	1–56	
		TDS	1,371	827	200–16,700	
Main Range Volcanics	(Na-HCO3-Cl)	Na^+	128	100	15–1,340	980
		HCO_3^-	357	345	6–1,150	
		Cl^-	272	180	10–3,300	
		SAR	4 (no unit)	2	1–35	
		TDS	778	651	75–5,470	
Walloon Coal Measures	(Na-Cl-HCO3)	Na^+	1,062	730	63–6,331	367
		HCO_3^-	614	508	12–16,50	
		Cl^-	1,537	940	35–11,058	
		SAR	51 (no unit)	22	1–219	
		TDS	3,209	2,283	326–18,999	

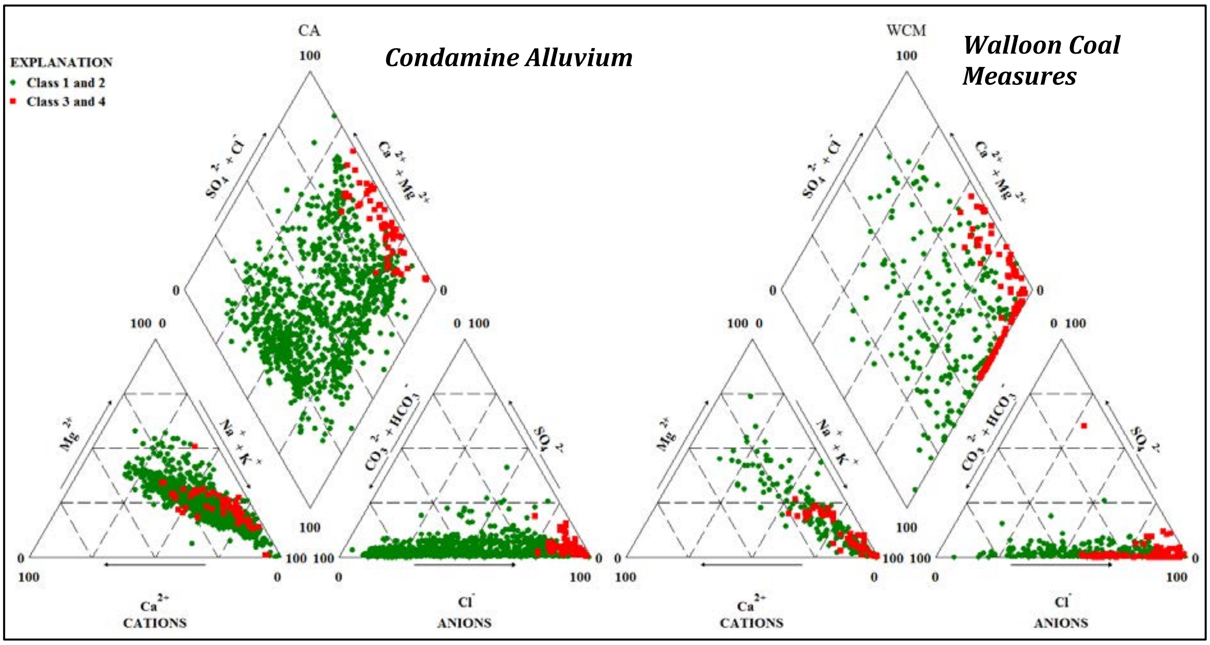

Figure 6-1 Piper diagram for the water type in the Condamine Alluvium and the Walloon Coal Measures

6.3.2.2 The principal component analysis

A principal component analysis (PCA) was carried out on the total dataset across all aquifers, resulting in four principal component factors. Together, these four factors account for 80.5 per cent of the variance in the total dataset.

The first factor (F1) represents EC, TDS, Na^+, Ca^{2+}, Mg^{2+}, and Cl^- while the second factor (F2) represents pH, HCO_3^- and F^-. These two factors (F1 and F2) together account for 63.8

per cent of the variance in the dataset; F1 alone accounts for 46.4 per cent of the variance. The correlations between the 12 hydrochemical parameters, and between the individual variables and their principal component factors, are depicted in the correlation circle in Figure 6-2. The correlation circle is a graphical tool for determining which variables contribute the most to the formation of the principal component factors. In Figure 6-2, each primary variable is represented by a vector (red line). The angle of a vector relative to the two axes reflects the degree of association between the variables, and the length of the vector reflects its relative contribution. Similarly, the angle of each vector relative to other vectors reflects the degree of correlation between the variables. Variables separated by small angles are correlated, whereas those separated by 90° angles are independent. For example, the plot for the Condamine Alluvium suggests that Na^+, TDS, Ca^{2+}, Mg^{2+}, and Cl^- are all positively correlated with each other; however, changes in these variables have little effect on the variables of the other components (pH, HCO_3^-, F^- and SiO_2).

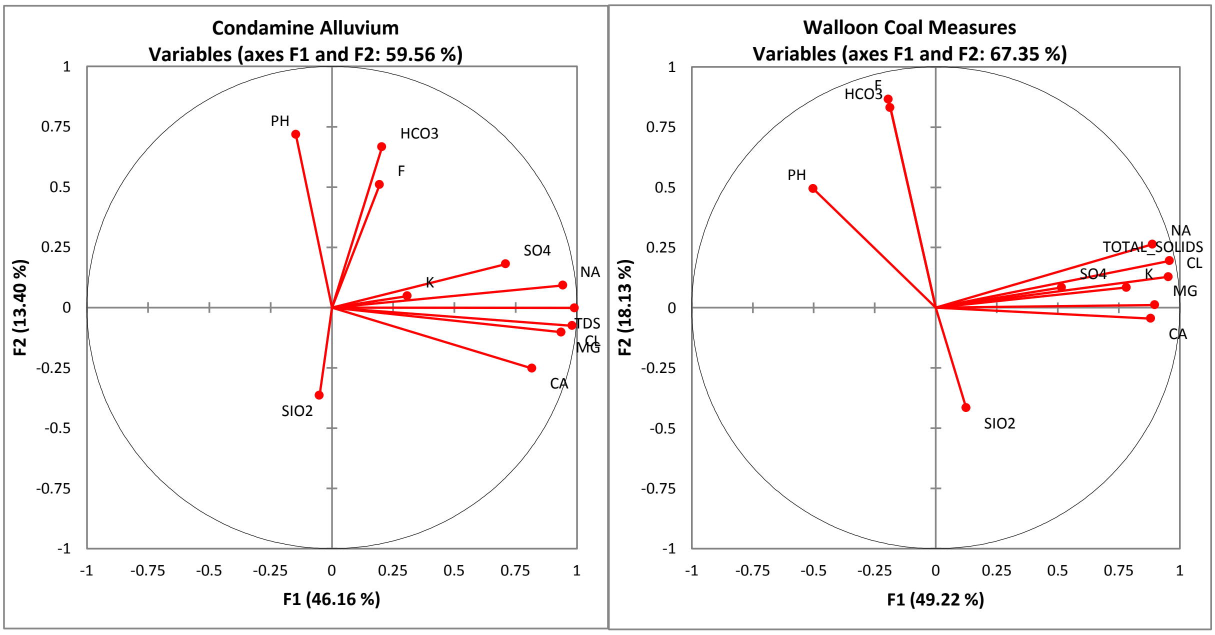

Figure 6-2 Graph showing relationship and contribution of hydrochemical parameters for principal component factors F1 and F2 for the Condamine Alluvium (left) and the Walloon Coal Measures (right)

The analysis revealed the following major differences between the Walloon Coal Measures and the Condamine Alluvium:

- There is a relatively greater contribution (loading) of K^+ in the F1 relationship and higher correlation with other major ions for the Walloon Coal Measures compared to the Condamine Alluvium.
- There is a greater contribution of F^- and HCO_3^- in the F2 relationship, with high correlations between them for the Walloon Coal Measures, whereas for the Condamine Alluvium, pH and HCO_3- are the major contributors to F2.
- There is a greater contribution of SO_4^{2-} in the F1 relationship for the Condamine Alluvium, compared to the Walloon Coal Measures.

6.3.2.3 K-means cluster analysis

The K-means cluster analysis (KCA) resulted in all data from all aquifers being partitioned into four distinct homogeneous (similar) cluster classes, based on similarities between parameters within the clusters. Partitioning of data was performed on the full data set, irrespective of the aquifer. The four classes were found to be satisfactory for the purpose of follow-up analysis, as their spatial distribution also showed a pattern. An underlying assumption is that each cluster class reflects a unique hydrochemical environment and hydrochemical evolution pattern.

Each class is characterised by a distinct combination of hydrochemical parameters, in terms of mean values for their respective classes and variables. The cluster class values for the Walloon Coal Measures and the Condamine Alluvium are summarised in Table 6-2.

Table 6-2 Hydrochemical data by cluster class for the Condamine Alluvium and the Walloon Coal Measures (mean concentrations)

Cluster class	Percentage of bores	No. of samples	TDS	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	pH	SAR
			(mg/L)						
Condamine Alluvium									
Class 1	70	777	654	153	41	33	174	8	5
Class 2	25	294	2,078	558	86	96	959	8.1	11
Class 3	4	48	5,513	1,434	252	273	3,045	7.9	17
Class 4	1	14	12,146	3,010	638	651	7,130	7.5	20
Walloon Coal Measures									
Class 1	35	131	828	234	38	30	264	8.2	12
Class 2	30	104	2,636	759	59	54	980	8.2	51
Class 3	30	111	5,059	1,810	54	38	2,456	8.2	99
Class 4	5	21	12,461	3,777	423	369	7,130	7.8	40

It is evident from Table 6-2 that, while salinity as the measure of TDS increases from Class 1 to Class 4, the mean concentrations of other variables vary significantly across the classes and the aquifers. For example, the SAR differs markedly between the Condamine Alluvium and the Walloon Coal Measures for each cluster class.

Spatial distribution of cluster classes with mean TDS values for the Condamine Alluvium and the Walloon Coal Measures is shown in Figure 6-3. The Condamine Alluvium bores belonging to classes 1 and 2 are mostly distributed in the floodplains of the Condamine River and its main tributaries. The Walloon Coal Measures bores belonging to Class 1 are distributed in the east of the footprint of the Condamine Alluvium, around the basalt regions with higher rainfall; bores belonging to classes 3 and 4 are around the western margins of the Condamine Alluvium; and bores belonging to Class 2 are on both margins.

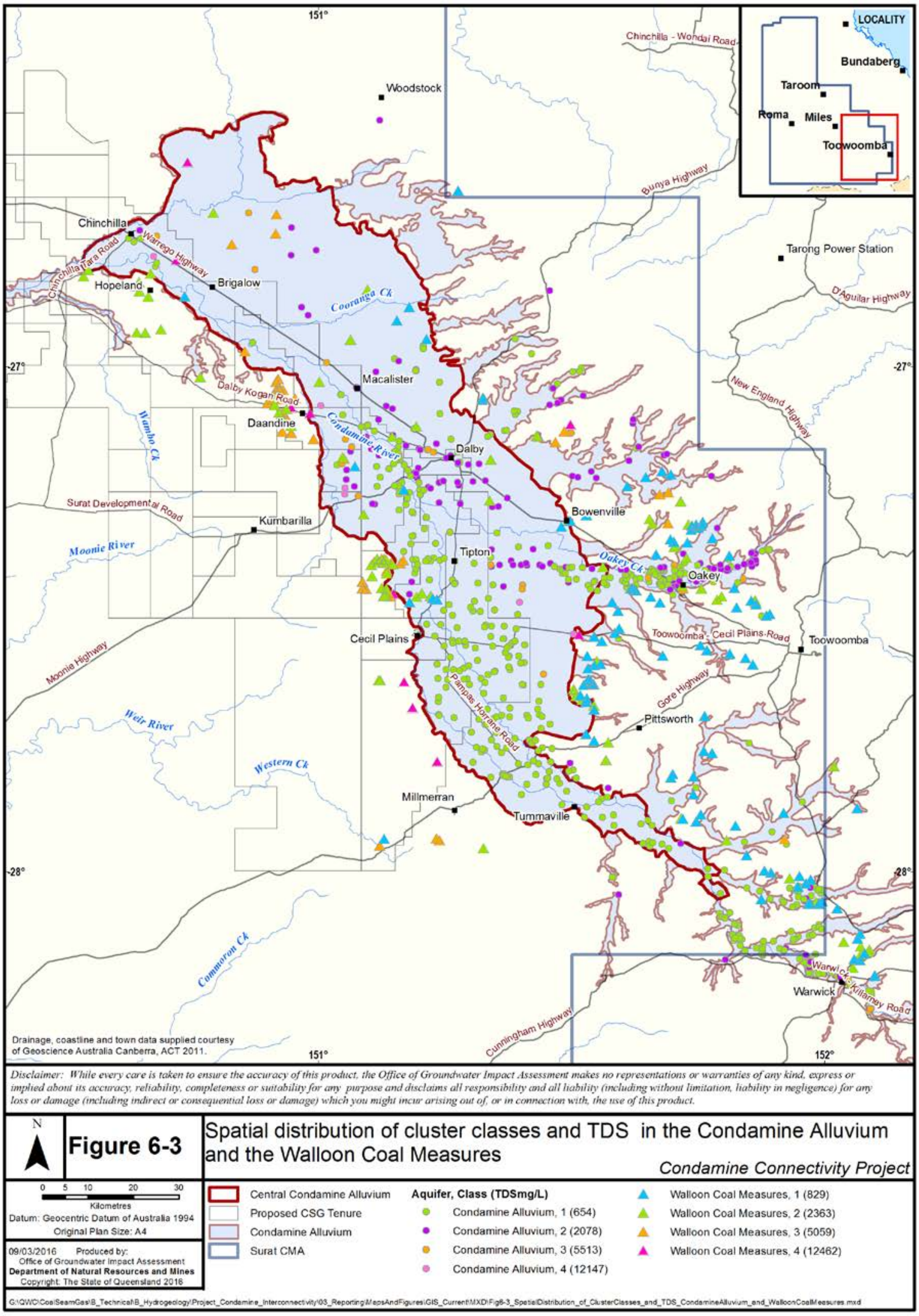

Figure 6-3 Spatial distribution of cluster classes and TDS in the Condamine Alluvium and the Walloon Coal Measures

6.3.2.4 Ratios of hydrochemical variables

For the cluster classes of the Condamine Alluvium, Walloon Coal Measures and Main Range Volcanics, the ratio of Ca^{2+}+ Mg^{2+} to Cl^- is plotted in relation to the seawater line (Figure 6-4) and summarised in Table 6-3 and Table 6-4. The plots also differentiate samples representing their respective classes obtained from cluster analysis. In general, most of the data points are above the line for the Main Range Volcanics and the Condamine Alluvium, while a large proportion of data points for the Walloon Coal Measures are below the line, particularly for Class 3.

As explained earlier, a groundwater sample plotting above the seawater line indicates that the dissolution of weathered rock is contributing to groundwater, while a sample below the line indicates ion exchange or precipitation.

Table 6-3 Selected ionic ratios by cluster class for the Condamine Alluvium

Cluster class	No. of samples	Mean concentration or standard deviation	TDS (mg/L)	Na^+/Cl^-	$(HCO^{3-})/Cl^-$	$SO4^{2-}/Cl^-$
1	**777**	**Mean**	**654**	**1.15**	**3.85**	**0.12**
		Stdev		0.61	3.00	0.13
2	**294**	**Mean**	**2,078**	**0.61**	**0.58**	**0.11**
		Stdev		0.21	0.36	0.14
3	**48**	**Mean**	**5,513**	**0.47**	**0.17**	**0.08**
		Stdev		0.12	0.11	0.07
4	**14**	**Mean**	**12,146**	**0.43**	**0.07**	**0.07**
		Stdev		0.08	0.04	0.06

Table 6-4 Selected ionic ratios by cluster class for the Walloon Coal Measures

Cluster class	No. of samples	Mean concentration or standard deviation	TDS mg/L)	Na^+/Cl^-	$(HCO^{3-})/Cl^-$	$SO4^{2-}/Cl^-$
1	**131**	**Mean**	**828**	**1.12**	**2.36**	**0.10**
		Stdev		0.87	2.36	0.13
2	**104**	**Mean**	**2636**	**0.83**	**0.92**	**0.04**
		Stdev		0.48	0.96	0.08
3	**111**	**Mean**	**5059**	**0.80**	**0.47**	**0.04**
		Stdev		0.21	0.36	0.27
4	**21**	**Mean**	**12461**	**0.53**	**0.05**	**0.04**
		Stdev		0.08	0.04	0.05

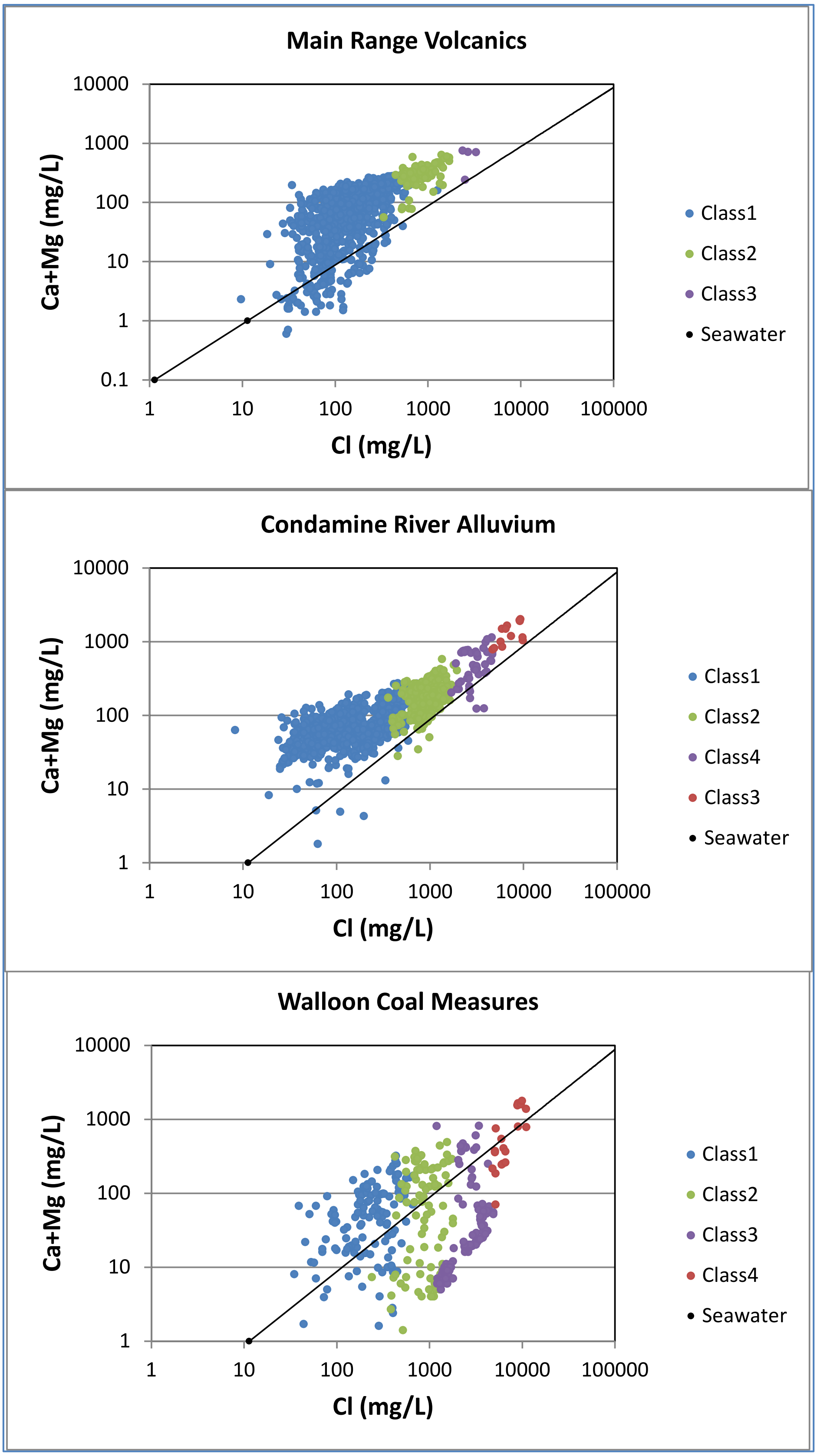

Figure 6-4 The ratio of Ca^{2+}+Mg^{2+} to Cl^{-} by cluster class for the Main Range Volcanics, Condamine Alluvium and Walloon Coal Measures

6.3.3 Ongoing isotopes sampling and analysis

Analysing stable isotopes (^{18}O and deuterium) and radiocarbon isotopes (^{14}C) can provide valuable insights about aquifer characteristics and potential mixing between two different groundwater types. Isotopic data is scarce, however, particularly for the Condamine Alluvium and the Walloon Coal Measures groundwater types.

Limited isotopic sampling and analysis of closely located Walloon Coal Measures and Condamine Alluvium bores, in the central and northwestern parts of the alluvium, indicates that Walloon Coal Measures water is more than 25,000 years old, whereas Condamine Alluvium water is between 5,000 and 10,000 years old.

These results are preliminary. Isotopic analysis requires a rigorous sampling and analysis protocol involving multiple isotopic sources before conclusions about age can be reached with confidence.

6.4 Assessment and discussion of results

6.4.1 General

A simple comparison of salinity involving only EC or TDS is an indicator of general quality of groundwater; however, similarities in EC or TDS between two datasets do not necessarily indicate similar hydrochemistry, because concentrations of ions and ion ratios can differ significantly between datasets. Therefore, any conclusions of potential mixing of groundwater between two closely associated aquifers based only on the assessment of a single variable can be misleading.

A multivariate analysis and more focused analysis of major ions and their ratios, as described in previous sections, provides a more comprehensive perspective about the hydrochemical evolution and cross-formational flow.

6.4.2 Hydrochemical evolution

As rainwater infiltrates the soil zone and becomes part of the saturated zone's groundwater, flowing from recharge to discharge areas, its chemistry is altered by the effects of a variety of geochemical processes (Freeze & Cherry, 1979). In general, the least-mineralised water is found closest to the main recharge zones and the salinity of the water increases along the flow paths.

The average Cl^- content of continental rocks is negligible and does not contribute to groundwater chemistry, so most of the Cl^- in groundwater is from rainwater and recycled salts. For this reason, relative concentrations of other ions to Cl^- are a good indicator of hydrochemical evolution.

The mean concentrations of variables for the four classes (Table 6-2) indicate a gradual decrease in relative proportion of Na^+ to Cl^- and a corresponding increase in salinity (TDS) from Class 1 to Class 4. This suggests that water belonging to Class 1 is freshly recharged and evolves to Class 4 following recharge. The presence of Class 1 groundwater is well correlated with the primary recharge areas, including high rainfall areas along the eastern margin of the Condamine Alluvium footprint and the Condamine River flood plain areas, particularly along the Condamine River itself.

Very high concentrations of salts in classes 3 and 4 are likely to be due to a combination of factors, including increased concentration of salt through evapotranspiration followed by salt mobilisation and leaching, and rock-water interactions occurring over a long time.

The principal component analysis, based on grouping of closely associated variables, indicated the types of minerals that might be involved in the evolution of the chemistry of groundwater in the Condamine Alluvium and the Walloon Coal Measures.

The higher concentrations of Ca^{2+} and Mg^{2+} in the Condamine Alluvium groundwater compared to the Walloon Coal Measures (Table 6-2) is likely to be due to contribution from carbonates (calcite and dolomite) and/or conglomerates that contain $CaCO_3^-$ and $CaMg(CO_3)$, which are abundant throughout the alluvium. There is also likely to be some contribution from weathering of olivine and pyroxene from the basalts of the Main Range Volcanics; however, the Main Range Volcanics is likely to be an influence on both the Condamine Alluvium and the Walloon Coal Measures in the eastern areas. High concentrations of $HCO3^-$ and low concentrations of Ca^{2+} and Mg^{2+} have also been reported for water in the Walloon Coal Measures and are due to carbonate precipitation and influence of sulphate reduction on bicarbonate concentrations (Van Voast, 2003).

The principal component analysis for the Condamine Alluvium and the Walloon Coal Measures indicates that, while the principal factors are not markedly different for the two formations, there are some differences in individual loading (or contribution) of the variables to the factors. There appears to be a higher contribution of SO_4^{2-} in the Condamine Alluvium, compared to the Walloon Coal Measures, along the F1 (Figure 6-2). Significantly higher concentration of SO_4^{2-} for the Condamine Alluvium is noted for the cluster Class 2 bores, distributed in the main cropping area around Dalby (Figure 6-3). This may be due to intensive agriculture and application of SO_4^{2-} in fertiliser which may have made its way to the groundwater in the Condamine Alluvium through irrigation return flows and leaching.

The second principal component factor (F2) for the Condamine Alluvium is alkalinity vector as characterised by high loadings of HCO_3^- and high pH, as both of these variables are related to alkalinity of the groundwater and can influence the weathering and chemical reaction processes. The concentrations of both K^+ and F^- were elevated in the Walloon Coal Measures compared to the Condamine Alluvium. This indicates that the source is likely to be from dissolution of alkali feldspars. Others have reported that the presence of K-feldspars in the Walloon Coal Measures could reach up to 10 per cent of the composition (Jell P.A, 2013). An increase in F^- in deeper bores is possibly due to the water becoming warmer and residing for longer at depth, which can increase dissolution of fluoride-bearing minerals and rocks (Nordstrom, et al., 1989), (Chae, et al., 2006).

The ratio of Ca^{2+}+Mg^{2+} to Cl^- in relation to the seawater line for the cluster classes (Figure 6-4) shows most of the data points are above the line for the Main Range Volcanics and the Condamine Alluvium. This is due to a greater contribution of Ca^{2+}+Mg^{2+} from the weathering in the Main Range Volcanics and the Condamine Alluvium. In comparison, a number of data points are below the line for the Walloon Coal Measures, indicating a different process which is likely to be the precipitation of Ca^{2+}+Mg^{2+} due to ion exchange and saturation processes.

The net contribution of major ions (Na^+, HCO_3^-, Ca^{2+} and Mg^{2+}) from rock-mineral weathering was also calculated in two steps for each cluster class. The first step was to average the percentage contribution of ions resulting from weathering after subtracting the seawater ion contribution. This estimated average value of major ions from rock-mineral weathering was then multiplied by the percentage of bores in the cluster class showing a positive contribution from weathered rock minerals.

SAR values (which relates to the ratio of Na^+ to Ca^{2+}+Mg^{2+}) are also reflective of the hydrochemical evolution of groundwater. In most groundwater systems, the concentration of Ca^{2+}+Mg^{2+} decreases in relation to Na^+ with increasing depth and the length of flow pathways. SAR values of the Walloon Coal Measures are much higher than the Condamine Alluvium for various cluster classes (Table 6-2), suggesting much longer flow pathways for groundwater in the Walloon Coal Measures. Also, the increase in mean SAR values from Class 1 to Class 4 suggests that the groundwater evolved from Class 1 to Class 4.

6.4.3 Cross-formational flow

Differences found between some of the important hydrochemical characteristics of the Condamine Alluvium and the Walloon Coal Measures suggest that there has been no significant movement of water. The differences are as below:

- Groundwater in the Walloon Coal Measures has much higher pH, Na^+, F^- and SAR compared to the Condamine Alluvium and the Main Range Volcanics. Also, the Walloon Coal Measures has lower concentrations of Ca^{2+} and Mg^{2+} compared to the Condamine Alluvium (Table 6-2).

- The proportions of Ca^{2+} and Mg^{2+} relative to Cl^- in the highly-evolved groundwater (Class 3) are different in each formation. For the Walloon Coal Measures, the Class 3 analyses fall above and below the seawater line (Figure 6-4), indicating that there is little or no contribution from weathering. For the Condamine Alluvium, the Class 3 analyses fall above the seawater line, indicating that weathering is the main source of Ca^{2+} and Mg^{2+}.

- For the Walloon Coal Measures groundwater, principal component analysis grouped HCO_3^- and F^- on the same principal component. For the Condamine Alluvium, these parameters were grouped on separate principal components. This suggests different sources and processes for F^- levels of the formations.

- Differences in the observed SAR values for cluster classes indicate a difference in water types between the Walloon Coal Measures and the Condamine Alluvium, and a longer flow path in the Walloon Coal Measures.

- Spatial analyses of sample points representing calcium percentage, derived from weathering of rock minerals and various concentrations of SAR, do not show similarities between closely located Walloon Coal Measures and Condamine Alluvium bores. Most of the Walloon Coal Measures bores with nil calcium from weathered rock minerals and very high SAR values are located in the western margins of the Condamine Alluvium.

- Although there are some cases of overlap in chemical characteristics of the Walloon Coal Measures and the Condamine Alluvium water, these overlaps are typically in recharge areas along the basalts and not in central or western parts of the Condamine Alluvium.

Other studies also offer insights into cross-formational flow between the two formations. A study by QUT researchers (Owen & Cox, 2015) found that potential flow between the Condamine Alluvium and the Walloon Coal Measures is localised around outcrops of sedimentary bedrock in upstream areas only. The study noted a distinct shift towards a low-salinity Na-HCO_3 water type and a brackish Na-HCO_3-Cl water type within the alluvium. Inverse modelling showed that water types can evolve via a combination of in-situ alluvial processes, including: diffuse recharge of rainfall or river water; the evolution of basalt-derived groundwater via gypsum dissolution plagioclase weathering; cation exchange and some carbonate precipitation and/or dissolution. The evolution of these water types is potentially influenced by overlying sodic alkaline soils and is often associated with a source of sulphate. Evapotranspiration is the dominant salinisation process in the alluvium; increases in calcium cations during salinisation indicate that brackish Na-Cl-HCO_3 groundwater in the underlying Walloon Coal Measures is unlikely to have a major influence on salinisation in the alluvium.

Another recent study by UNSW researchers (Iverach, et al., 2015) focussed on pathways for methane movement as indicators of connectivity. The study suggested local connectivity between the two systems, but that the extent of connectivity is low. The study tested the suitability of jointly using $\delta^{13}C$-CH_4, dissolved organic carbon [DOC] and ^3H activity in the groundwater to assess hydraulic connectivity. The study concluded that the measurements of the isotopic composition of CH_4, DOC and ^3H activity in the groundwater, and CH_4 in the air, can be used as an initial assessment of pathways of geological hydraulic connectivity with overlying coal measures targeted for CSG production. It notes the absence of ^3H activity in a subset of irrigation bores with detectable DOC, in association with $\delta^{13}C$-CH_4 signatures.

6.5 Conclusion

The multivariate principal component and K-means cluster analyses suggest significant differences in hydrochemistry within and between the Condamine Alluvium and the Walloon Coal Measures. These differences suggest that hydrochemically the two formations generally evolved separately, rather than there being a regional-scale cross-formational flow of water. In areas where the transition zone is largely absent, the limited data supports the same general conclusion.

7 Aquifer pumping tests and associated drilling

7.1 Overview and purpose

Pumping tests and the associated construction of observation bores were carried out to establish the geological and hydrogeological characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures at locations that are likely to be representative of the broader groundwater system. More specifically, the pumping test program was aimed at estimating representative vertical hydraulic conductivities of the transition zone and the upper Walloon Coal Measures.

The drilling and pumping test program was implemented collaboratively by OGIA and Arrow Energy. The program was designed by OGIA and all drilling and testing was carried out by Arrow Energy with full OGIA involvement. Analysis of results was carried out collaboratively by OGIA and Arrow Energy.

7.2 Selecting the pumping test sites

A set of criteria was developed to select representative sites for testing connectivity and establishing long-term monitoring installations. Sites were selected across the Condamine Alluvium footprint, taking into consideration the transition zone thickness, proximity to the CSG production areas, the impacts predicted in the UWIR (2012), proximity of the alluvium to the recorded coal at the site, the level of historical groundwater extraction, availability of high-yielding irrigation bores, site access, and suitability of the site for construction of observation bores.

Two sites were selected, as shown in Figure 7-1:

- The **Daleglade** site is about seven kilometres east of the western margin of the Condamine Alluvium footprint.
- The **Cecil Plains** site (also referred to as the Lone Pine site) is about 15 kilometres east of Cecil Plains.

The Daleglade site was selected because it represents the northern end of the productive part of the Condamine Alluvium with reasonable thickness (about 55 metres) and high transmissivity which supports high-capacity irrigation bores. In addition, the site is close to existing and proposed CSG development in the west, in areas where the UWIR (2012) predicted relatively higher impacts on the Condamine Alluvium and where the transition zone was expected to be less than 10 metres thick. A suitable pumping bore (RN 48017) was available for the test.

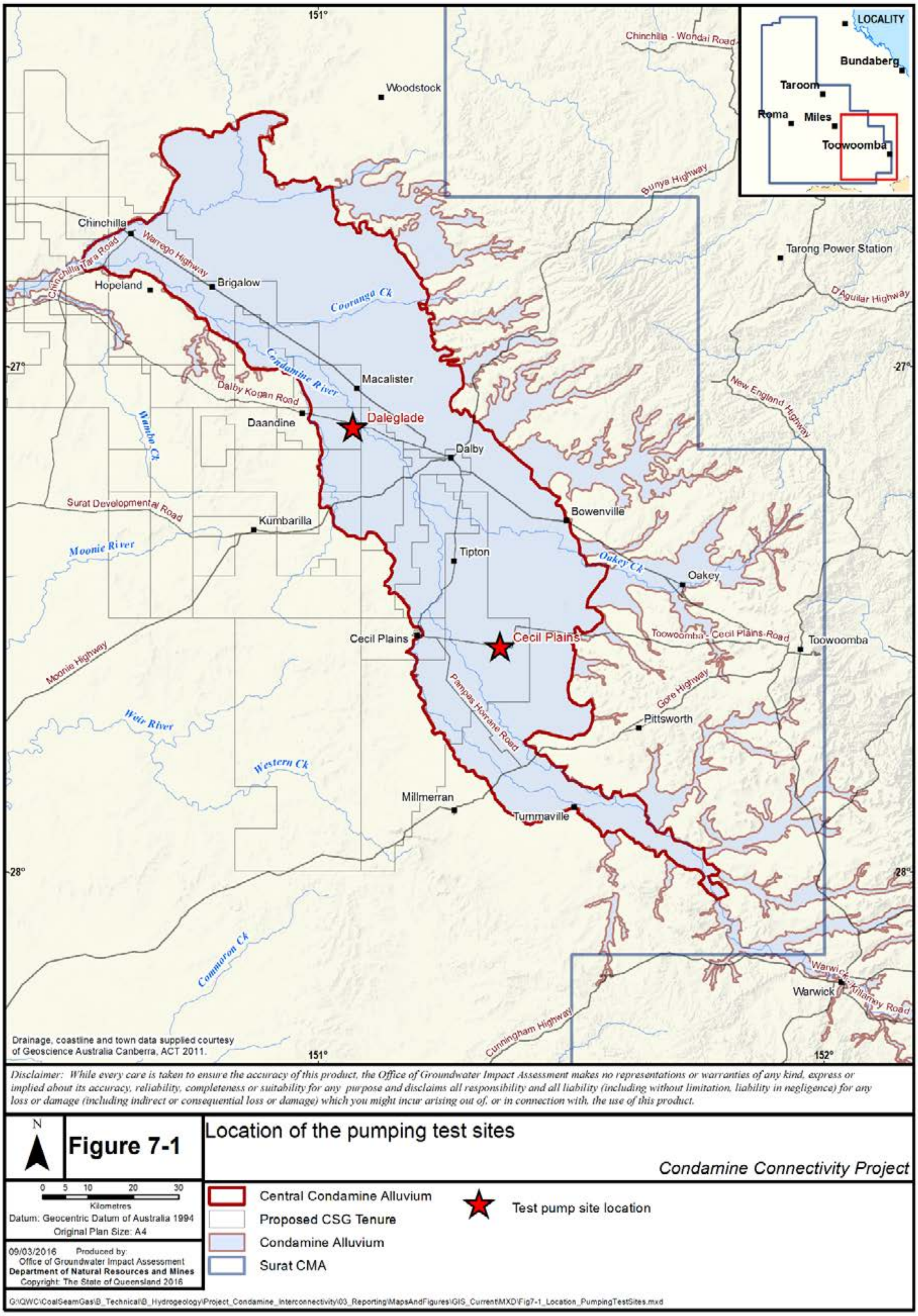

Figure 7-1 Location of the pumping test sites

The Cecil Plains site was selected because of the significant groundwater level depression in the Condamine Alluvium at the location. The area coincides with some of the heaviest groundwater extraction across the Condamine Alluvium footprint. It is also one of the most productive parts of the alluvium for groundwater extraction with close to 80 metres of alluvial thickness. The site is at the eastern margin of planned CSG development and the transition zone was expected to be relatively thin. A high-capacity pumping bore that taps the entire alluvial thickness was available for testing.

An additional site (Stratheden) was also considered because of the existence of a set of nested piezometers and the proposed production testing in nearby CSG wells. At this site, the Condamine Alluvium does not directly overlie the Walloon Coal Measures but is instead separated by a thick sequence of the Springbok Sandstone and Westbourne Formation; for this reason, the site was considered a relatively low-value site for the connectivity assessment. Should the production testing proceed, data will be collected for analysis which may provide information about the connectivity between the Walloon Coal Measures and the overlying Springbok Sandstone.

A further site, close to Dalby, was also identified as a potential site at an early stage of planning, but was later discarded for logistical reasons.

7.3 Designing the pumping tests

The pumping tests were designed to establish the geological and hydrogeological characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures.

To support the design of the pumping tests, OGIA developed a numerical tool to simulate groundwater level responses to pumping in various units under different scenarios. Simulations were performed using a range of parameters and different transition zone thicknesses. The simulations indicated that pumping from the Walloon Coal Measures for test purposes would be unlikely to induce a measurable drawdown in the Condamine Alluvium, even where granular alluvium is in direct contact with the Walloon Coal Measures, due to relatively high transmissivity and storativity of the alluvium.

As a result, an alternative approach was adopted that involved pumping from the Condamine Alluvium. It used existing irrigation bores that could induce drawdown in the Condamine Alluvium of 10 metres or more and, in turn, induce a measurable drawdown in the Walloon Coal Measures directly below the transition zone if enough connectivity existed between formations. The magnitude of this drawdown would depend upon the hydraulic characteristics of the transition zone and the rate and duration of pumping.

A conceptual diagram representing various hydrogeological units at test sites, together with a typical layout of the design, is shown in Figure 7-2. Existing irrigation bores that are screened to the base of the Condamine Alluvium were used as the pumping bores for the tests. Dedicated observation bores were installed within 10–100 metres of the pumping bores and individually screened in the hydrogeological units corresponding to:

- the Condamine Alluvium at about the same depths as the pumping bores
- the lowermost sandy unit immediately above the transition zone

- the uppermost coal seam encountered immediately below the transition zone
- the deeper coal seams.

Pressure transducers and data loggers were installed in the pumping and observation bores to automatically record groundwater levels during pumping tests and, following completion of the tests, for ongoing monitoring over the long term.

At each pumping test site, the suite of tests included a four- or five-step drawdown test to establish the appropriate pumping rate for a subsequent constant rate test. A constant rate pumping test was then carried out over 30 days or more. Recovery after the cessation of pumping was also monitored. Ongoing monitoring has continued since the completion of the test.

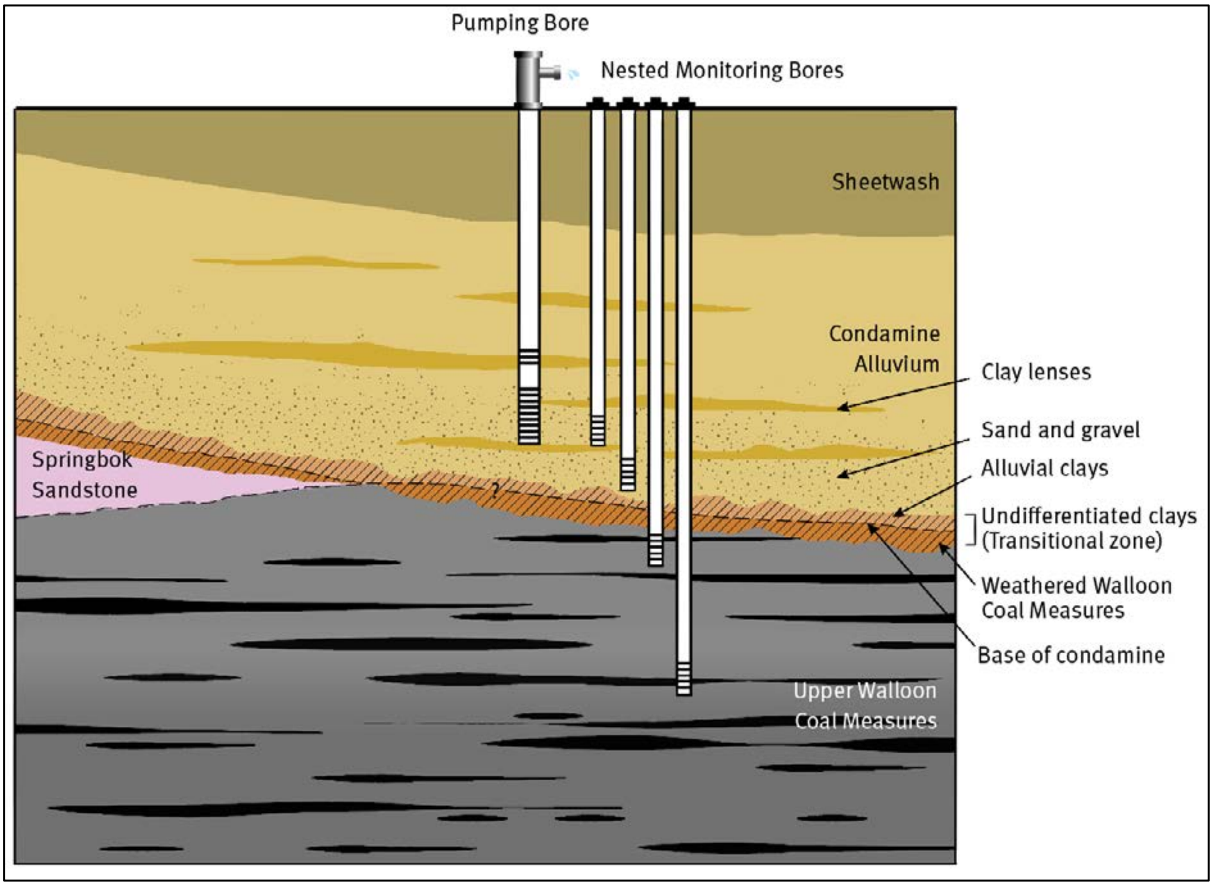

Figure 7-2 : Pumping test design schematic

The following investigations were also carried out as part of the pumping test program, to find out more about the local geology and hydrogeology:

- drilling and installation of nested observation bores targeted to various geological and hydrogeological units across the Condamine Alluvium and Walloon Coal Measures interface
- a suite of geophysical wireline logging to assist in interpreting borehole lithology

- coring of geological formations above and below the interface to establish site-specific geology, physical characteristics and sampling for laboratory analysis of mineralogy and hydraulic parameters
- hydraulic conductivity testing of core samples, using a centrifuge
- X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis of core samples to identify mineralogy
- groundwater sampling and hydrochemical analysis.

7.4 The Daleglade site

7.4.1 Site overview

The Daleglade site is located about seven kilometres east of the western margin of the Condamine Alluvium footprint, as shown in Figure 7-1. The site uses existing irrigation bore RN 48017 as the pumping bore, which is screened in the Condamine Alluvium.

This test site was selected because:

- the Condamine Alluvium is reasonably productive here and closer to the northern end of the most productive alluvium
- the site is relatively close to existing and proposed CSG development
- the transition zone was expected to be less than 10 metres thick
- the hydraulic gradient between the Condamine Alluvium and the Walloon Coal Measures was low to negligible.

A network of observation bores was installed in 2013 and the pumping test was completed between August and October 2013. The location of the observation bores with reference to the pumping bore is shown in Figure 7-3.

7.4.2 Drilling and installing the observation bores

Four observation bores—DA-161, DA-162, DA-163 and DA-164—were drilled and installed by Arrow Energy at the Daleglade site in 2013. The bore locations are shown in Figure 7-3 and bore installation details are summarised in Table 7-1.

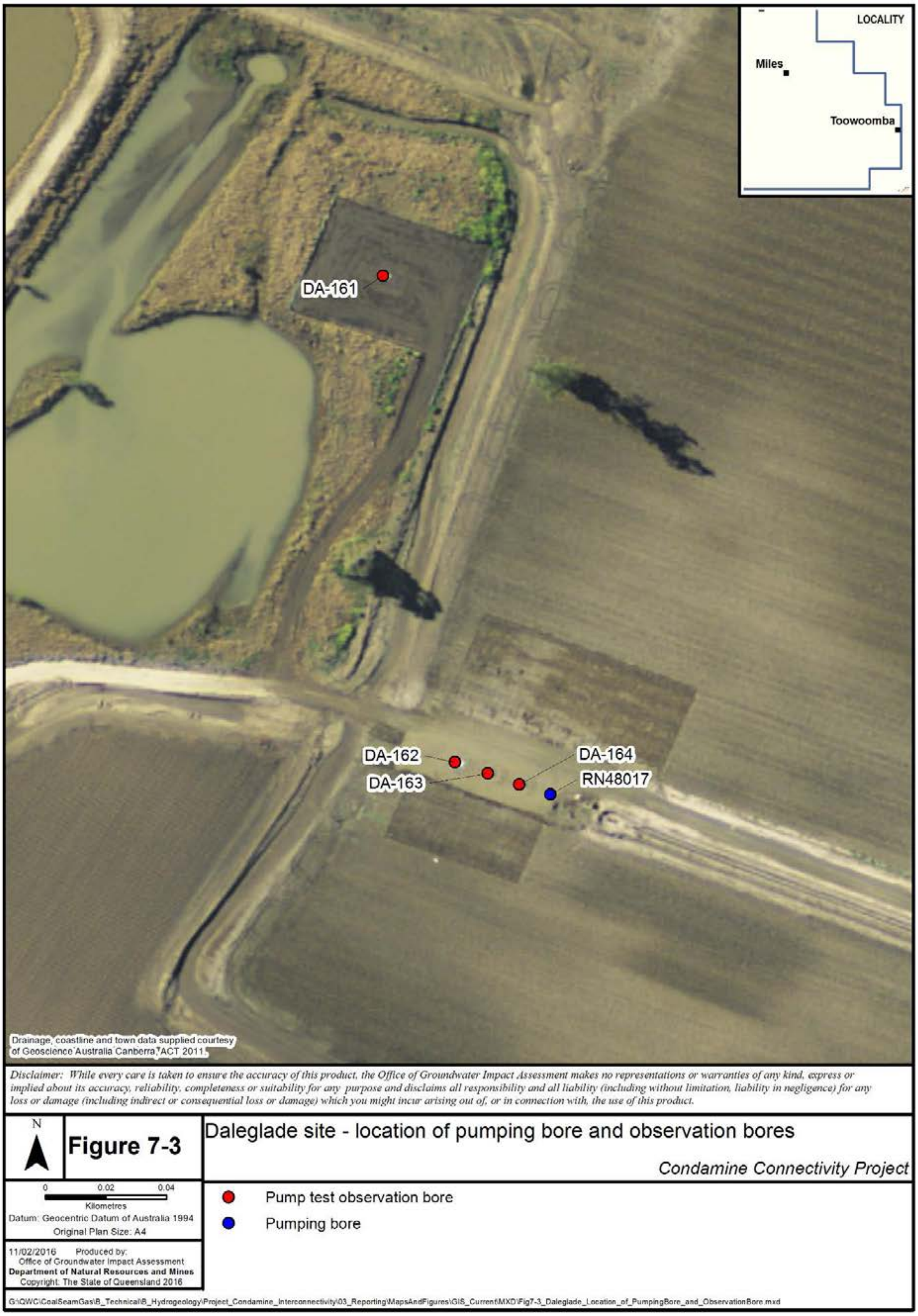

Figure 7-3 Daleglade site – location of pumping bore and observation bores

Table 7-1 Daleglade observation bores details

Bore ID	Total depth (mBGL)	Screen* top (mBGL)	Screen bottom (mBGL)	Screened unit	Distance from pumping bore (metres)
RN 48017 (pumping bore)	52.1	25.3	44.2	Condamine Alluvium	-
DA-161	59.0	45	51	Condamine Alluvium	179.0
DA-162	59.0	56	58.5	Condamine Alluvium	30.8
DA-163	69.5	62.5	64	Tertiary sediments	20.6
DA-164	104.3	81.5	83.5	Walloon Coal Measures	10.8

* Instead of screens, DA-163 and DA-164 were perforated to the desired depth after cement grouting.
mBGL = metres below ground level

DA-164 was initially drilled for investigation purposes and cored to 104 metres using an 85 mm core diameter. The bore was then converted to an observation bore with a 115 mm steel casing perforated from 81.5 metres to 83.5 metres in coal and cemented to ground level. A downhole gauge was installed to measure hydrostatic pressure. A suite of geophysical wireline logs were conducted including gamma, calliper, neutron porosity, resistivity and self-potential logs. A composite log is shown in Figure 7-4 and core images from selected depths are shown in Appendix 4. Observed lithology and stratigraphy is also shown in the composite log.

Observation bores DA-161, DA-162 and DA-163 were drilled and completed to various depths across the vertical profile from the Condamine Alluvium to the Walloon Coal Measures, as shown in Figure 7-4. The bores were drilled to 215 mm in diameter and installed with 115 mm steel casing and screens. The screens were surrounded by gravel pack, with bentonite plugs above and below, and cement grouted to the surface.

7.4.3 Geological and hydrogeological conditions

Geological modelling suggests that, at the Daleglade site, the Condamine Alluvium lies directly above the Walloon Coal Measures, with a small thickness of transition zone between them. Before these drilling investigations, data from deep drilling in the area was limited. A review of the deeper sectional geology at a more regional scale was undertaken to assess the broader relationship of the Walloon Coal Measures with the Condamine Alluvium. A regional section (Figure 4-2) runs east-west about five kilometres south of the pumping bore RN 48017, suggesting that the Upper Juandah Coal Measures subcrops at the site and that the unconformable contact of the Walloon Coal Measures with the overlying Springbok Sandstone is nearby, towards the west.

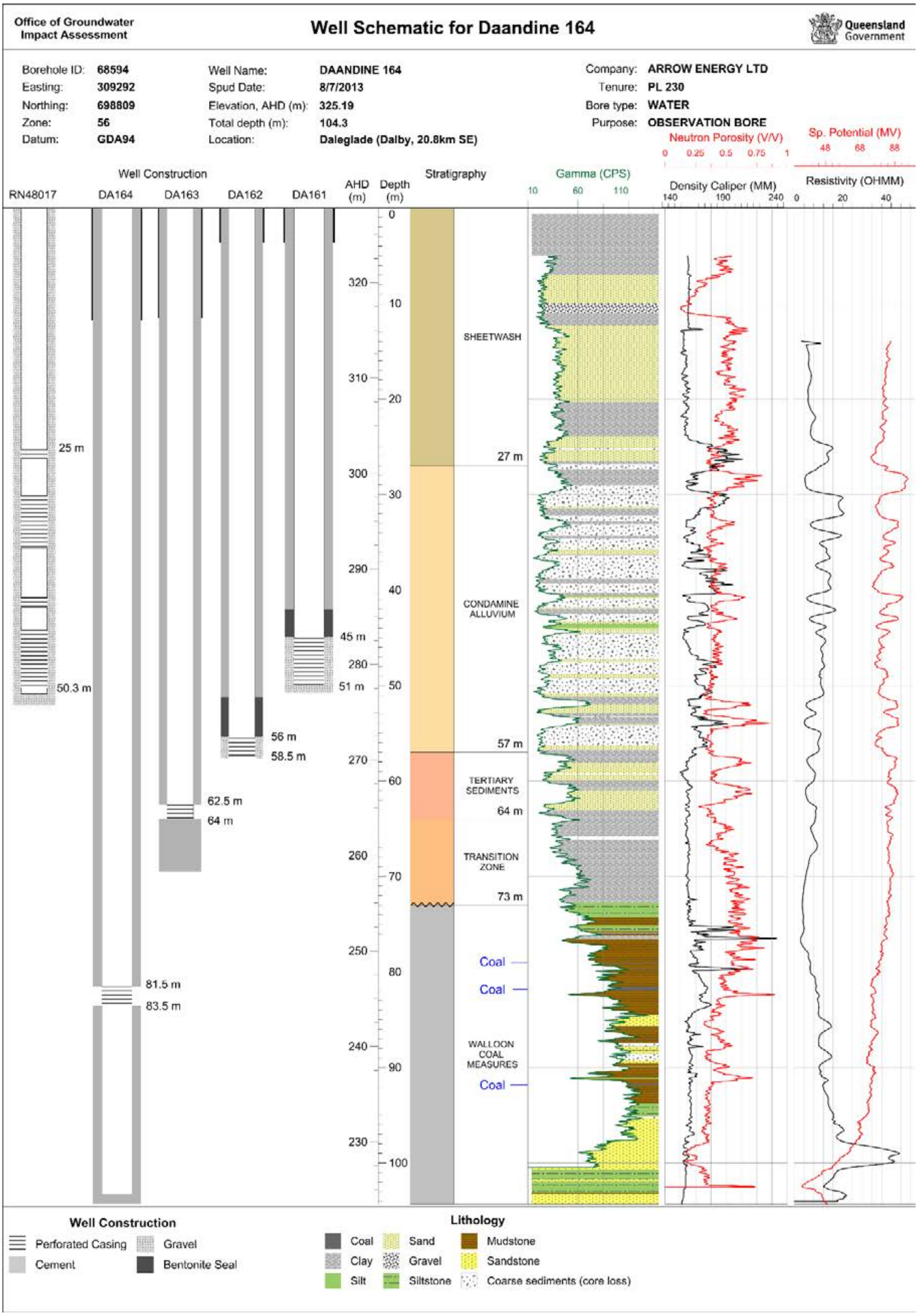

Figure 7-4 Composite bore log for DA-164 with nested observation bores (Daleglade)

Site geology is best represented by the cored and geophysically logged bore DA-164 (Figure 7-4). Interpretation is based on a combination of factors including geophysical signatures (such as gamma, resistivity and induction log), recorded lithology and visual inspection of core logs. Based on the interpreted lithology, the bore encountered topsoil and sheetwash to a depth of 27 metres, underlain by an alternating sequence of unconsolidated clay, silt, sand and coarse sand of the Condamine Alluvium to 57 metres. The lower portion of this unit, from 57 metres to 64 metres, is characterised by grey-coloured coarse sand bounded by clay layers, collectively interpreted as Tertiary Sediments. This Tertiary Sediments unit may not be laterally extensive. The unit overlies coloured clay from 64 metres to 73 metres. From the core and geophysical logs, it appears to be weathered and gradually transitioning to firm mudstone. This unit is interpreted as the transition zone at this site, containing primarily the weathered mudstone and siltstone. The Walloon Coal Measures, comprising interbedded siltstone, mudstone, sandstone and coal seams, lies directly under this transition zone, from 73 metres to the bottom of the bore at 104 metres. The first substantial coal seam is recorded around 82 metres. The Walloon Coal Measures sequence is characterised by gradually increasing gamma count and increasing resistivity from below the interpreted top of the Walloon Coal Measures at 73 metres.

Bores DA-161, DA-162 and DA-163 each encountered geology similar to DA-164, with minor variations in depth of contacts. Pumping bore RN 48017 is completed in the Condamine Alluvium to a total depth of 52 metres and is screened intermittently from 25 metres to 50 metres.

Regionally, groundwater flow in the Condamine Alluvium in the area is towards the northwest, roughly parallel to the Condamine River. Before pumping, the groundwater level in the Condamine Alluvium at the site was at an elevation of about 314 metres, although it fluctuates regularly in response to groundwater pumping. The Condamine Alluvium at this site is physically under confined conditions because the groundwater level in Condamine Alluvium is above the interpreted base of sheetwash. Unconfined conditions may occur at some locations during periods of heavy local groundwater pumping. Below the Condamine Alluvium, pre-testing groundwater levels—at the base of the granular alluvium, or Tertiary Sediments, and in the Walloon Coal Measures coal seam—were all within 40 centimetres of each other.

7.4.4 Pumping test

A schematic of the Daleglade monitoring bores and pumping test layout is shown in Figure 7-5. The pumping bore is screened at various intervals from 27 metres to 51 metres across the sandy units of the Condamine Alluvium. Two other observation bores, at 31 metres (DA-162) and 179 metres (DA-161), are also screened in the lower part of the alluvium across two separate sand units, to observe lateral propagation of the cone of depression. Another observation bore, DA-163, is screened in what is believed to be the lowermost sand unit of the Condamine Alluvium or Tertiary Sediments, from 62 metres to 64 metres, to test the hydraulic connectivity with the overlying part of the Condamine Alluvium. Observation bore DA-164 is screened in a coal seam about 14 metres below the hydraulic basement of the Condamine Alluvium.

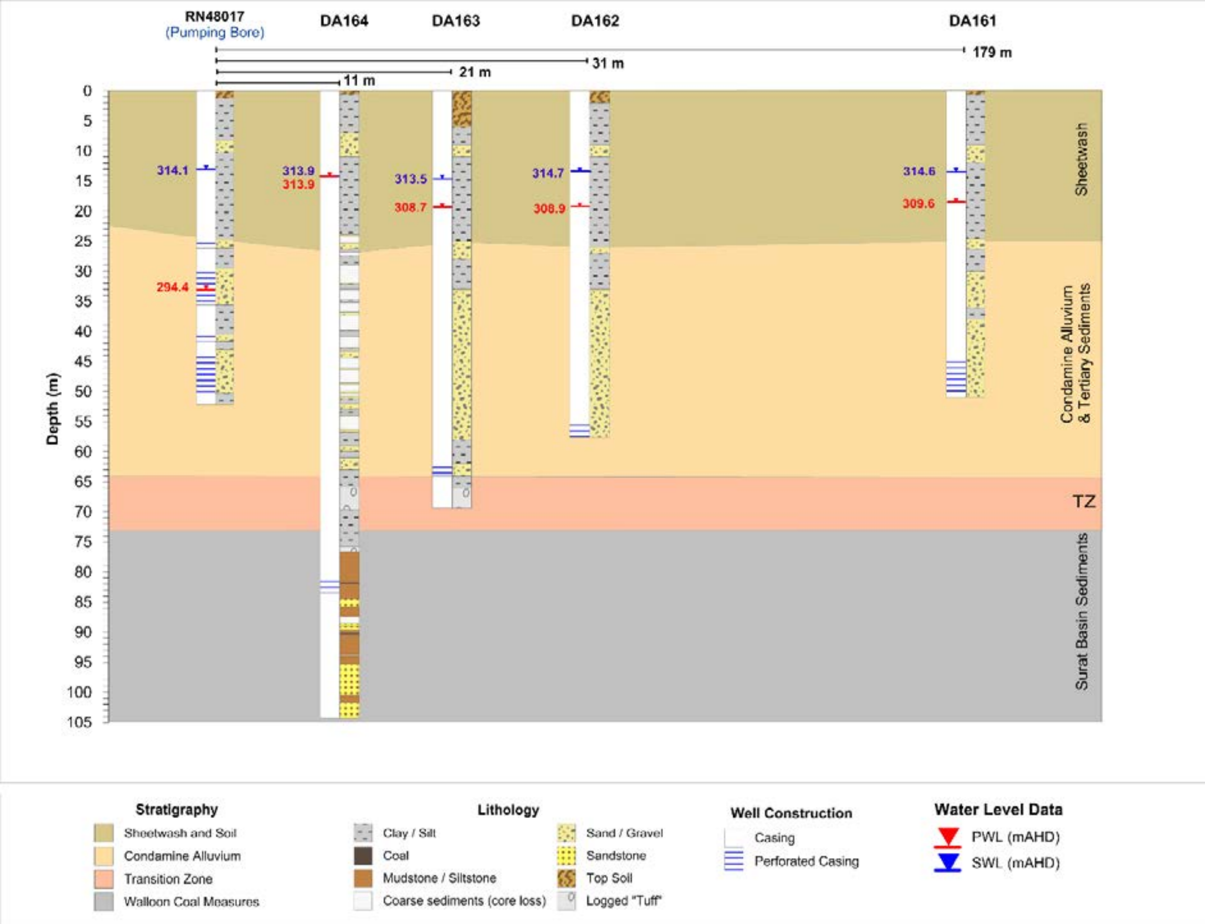

Figure 7-5 Layout of the observation bores at the Daleglade test site

A 30-day constant-rate test was carried out from 2 September 2013 to 2 October 2013. The pumping rate from bore RN 48017 varied between 56 litres per second (L/s) and 60 L/s throughout the test. Pumped water was discharged to a nearby ring tank. Groundwater levels in RN 48017 and the four observation bores were recorded automatically using pressure transducers throughout the test, as well as in the months leading up to the test and following the test.

7.4.5 Interpreting the pumping test results

In response to the pumping of RN 48017 during the test period, groundwater levels for the pumping bore and each of the observation bores are shown in Figure 7-6. The timeframe (July–December) includes the period of preparing the tests, pumping, recovery and ongoing monitoring. For reference purposes, barometric pressure changes and rainfall in the corresponding period is also shown. The response in bore DA-164 is also shown separately at a smaller scale.

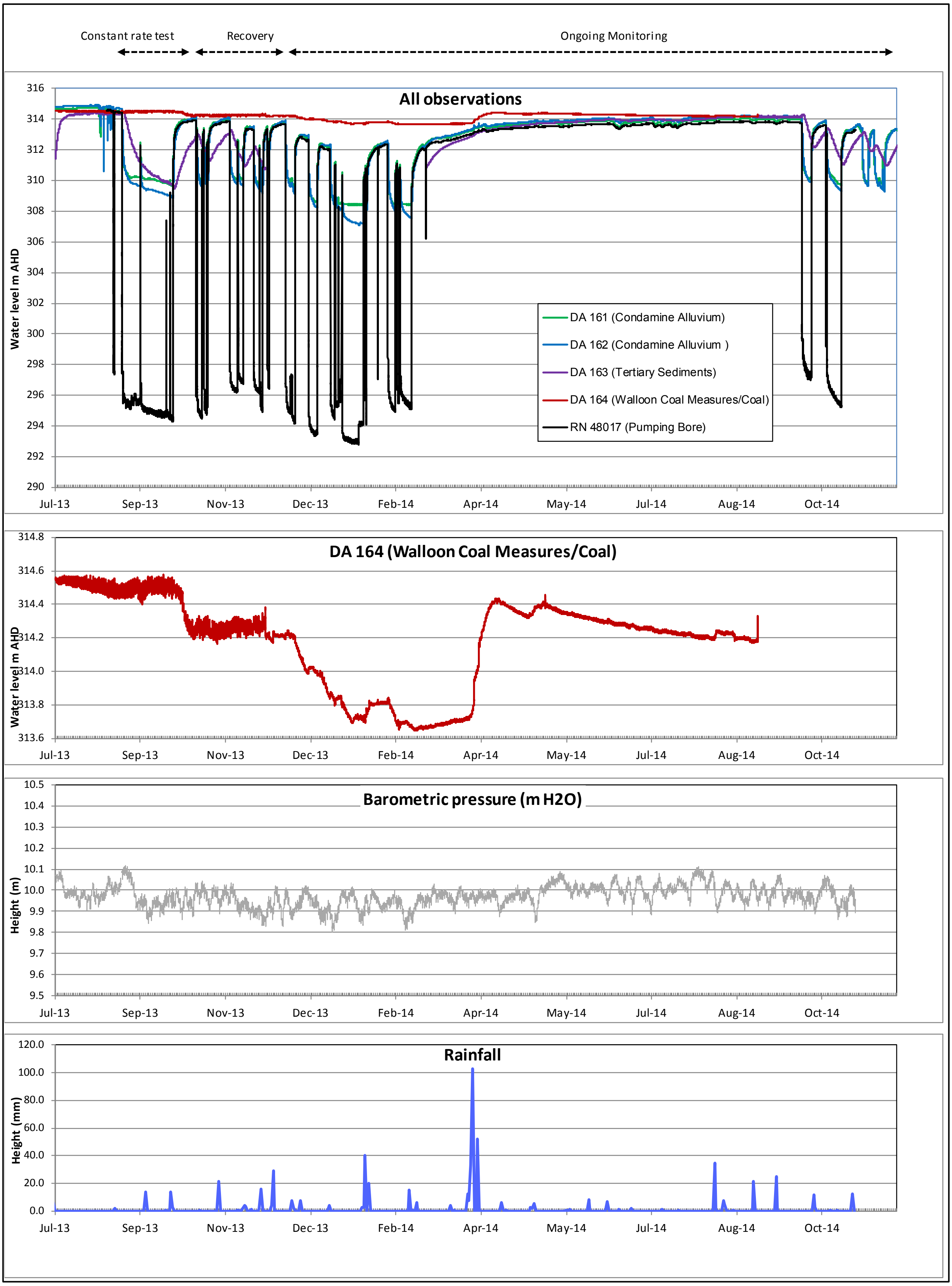

Figure 7-6 Groundwater level response to pumping test in Daleglade

A number of methods were used to interpret the groundwater level response during the pumping and recovery periods, and to estimate the hydraulic parameters of the Condamine Alluvium, the transition zone and the Walloon Coal Measures as follows.

- **Qualitative interpretation** was performed to assess the groundwater level response in the pumping bore and observation bores.
- **Analytical interpretation** was performed to estimate hydraulic parameters, using simplified analytical models of groundwater flow for generic hydrogeological conditions at the pumping test site.
- **Numerical interpretation** was performed to simulate three-dimensional flow conditions at the pumping test site, using a numerical groundwater flow model to estimate the range of hydraulic parameters that could cause the observed groundwater level response in the pumping bore and observation bores.

The use of multiple interpretation methods maximises confidence in the interpretation of the test response and in the assessment of hydraulic parameter values.

7.4.5.1 Qualitative interpretation

At the end of the 30-day pumping period, groundwater levels in response to pumping showed that a vertical groundwater head difference of about six metres was created between the Condamine Alluvium and the underlying Walloon Coal Measures around the site. The drawdown in the pumping bore (about 20 metres) suggests a greater head difference, but a significant part of the drawdown in the pumping bore would have been due to well losses.

All bores in the Condamine Alluvium showed similar drawdown and recovery trends, as observed in pumped bore RN 48017. DA-161 responded first to pumping stress, despite being farthest (179 metres) from the pumping bore. This is because the screen on this bore is positioned at a similar elevation to that of the pumping bore and it is likely that the two are well connected through a continuous sand body, resulting in very high permeability along that direction. DA-162 showed a slightly delayed response, with the screen location in this bore lower than that of the pumping bore creating a vertical flow pathway through a relatively lower-permeability material. Bore DA-163, with screen placement in the lowermost part of the sand-dominated Tertiary Sediments, showed a far more delayed response to pumping but reached a magnitude of drawdown similar to DA-161 at the end of the 30-day pumping period.

These responses indicate a definite hydraulic connection of the Tertiary Sediments with the other parts of the Condamine Alluvium through preferential flow pathways, indicating that, hydrogeologically, the Tertiary Sediments are effectively part of the Condamine Alluvium aquifer. The recovery of DA-163 was also delayed relative to DA-161 and DA-162. Monitoring of the observation bores continued after the test and the delayed drawdown and recovery observed during the test occurred during irrigation pumping cycles after the test.

There was a slight inverse response of about 0.2 metres in DA-163 each time pumping started or stopped. This is characteristic of the Noordbergum/Rhade effect, which is common in semi-confined or confined systems, and is related to poroelastic effects not involving the flow of groundwater (Berg, et al., 2011).

Bore DA-164, which is screened in the coal, showed little or no correlation with the pumping cycles. Groundwater level in DA-164 rose by about 0.05 metres during the pumping period, then dropped by about one metre over the period of various pumping cycles before starting to recover at the end of the pumping period, in February 2014. Although there is a general drop and then recovery in groundwater levels corresponding roughly to the pumping period, it is unlikely that the response is mainly a result of the vertical leakage of water from the Walloon Coal Measures to the Condamine Alluvium. The following factors may be relevant to the observed response:

- Groundwater level trends of the Condamine Alluvium and the Walloon Coal Measures are poorly correlated. If the delayed response in the Walloon Coal Measures was due to slow leakage, a similar delayed response should have been observed during the recovery; however, this did not occur.

- There are sudden changes in groundwater levels in the Walloon Coal Measures as observed at the end of January 2014 and March 2014. These changes correspond directly to major rainfall events and, considering the depth of the aquifers, are unlikely to be inflow-related. These changes are likely to be the result of mechanical loading due to the additional weight of water in the Condamine Alluvium and saturation of the soil horizon which exerts increased pressure and causes the groundwater level—under confined condition in the Walloon Coal Measures—to rise rapidly. The responses also suggest that the saturation level in the Condamine Alluvium would have dropped during the pumping cycle, causing unloading and, in turn, causing the groundwater level to drop in the Walloon Coal Measures.

- There is a general declining trend in the groundwater level in the Walloon Coal Measures, as observed from March 2014 to September 2014—a period when the groundwater level in the Condamine Alluvium had recovered gradually. This trend is likely to be a result of a general drop in the regional Walloon Coal Measures groundwater level over the period.

In summary, the drop in groundwater level in the Walloon Coal Measures during the test is very small. If any of this small change is due to pumping from the Condamine Alluvium, it is masked by the combined effects of mechanical loading and regional trends. Nevertheless, in subsequent quantitative analysis it is assumed that all the observed change in groundwater level is due to vertical movement of water in response to pumping. This assumption results in an overestimation of connectivity rather than underestimation.

7.4.5.2 Analytical interpretation

To interpret pumping test results, the following analytical methods were used:

- curve matching interpretation of the transient response during the pumping period

- analytical modelling of the transient response during the full pumping, recovery and ongoing monitoring periods, using MLU (Multi-Layer Unsteady state) software (Hemker & Post, 2014).

Curve matching

A best-fit gradient of drawdown versus distance was estimated using only drawdown at bores RN 48017, DA-161 and DA-162. Drawdown from bores DA-163 and DA-164 was omitted from this interpretation, as these bores are not in the same lateral lithological unit. The Cooper-Jacob method (Cooper & Jacob, 1946) for a confined aquifer system was used in interpreting the transmissivity value for the Condamine Alluvium.

Analysis of the transient groundwater level response in the Condamine Alluvium pumping bore and observation bores, during the pumping period and the recovery period, was performed using curve matching techniques (Hantush, 1962), (Cooper & Jacob, 1946), (Theis, 1935) and with AQTESOLV software (Duffield, 2007). The resulting estimates of transmissivity (T) and hydraulic conductivity (K) are summarised in Table 7-2. Hydraulic conductivity estimates are based on an aquifer thickness of 42 metres. The vertical hydraulic conductivity (Kv) value was also obtained for the aquitard, using the Hantush solution. The unrealistically high storativity (S) value for DA-163 reflects the delayed response to pumping and possible over-compensation of this parameter due to the incomplete understanding of the stratification effects of the overall aquifer.

Bore DA-164 was not interpreted using curve matching because the underlying assumptions in the methods did not apply.

Table 7-2 Estimated parameters from curve matching at Daleglade

Bore (Aquifer)	Hantush: Drawdown and Recovery				Cooper-Jacob method			Theis method		
	T (m^2/d)	K (m/d)	K_v	S	T (m^2/d)	K (m/d)	S	T (m^2/d)	K (m/d)	S
RN 48017 (Condamine Alluvium)	333	7.9	1.2×10^{-3}	3.5×10^{-4}	471	11.2				
DA-161 (Condamine Alluvium)	224	5.3	2.5×10^{-4}	8×10^{-4}	482	11.5	4.5×10^{-4}	423	10.1	4.9×10^{-4}
DA-162 (Condamine Alluvium)	263	6.3	6.6×10^{-2}	1.2×10^{-2}	337	8	4.4×10^{-2}	263	6.3	1.1×10^{-3}
DA-163 (Tertiary Sediments)	34	0.8	0.1	0.2						
DA-164	N/A									

MLU analysis

Multi-Layer Unsteady state (MLU) is an analytical modelling package for analysing pumping test data for layered aquifer systems (Hemker & Post, 2014). It allows each layer to be populated with parameter values (Kh for aquifers, Kv for aquitards, and S). An MLU analytical model was set up by Jacobs, on behalf of Arrow Energy, and a combination of manual adjustment and model optimisation was used to achieve a fit to the observed drawdown data for the observation bores. Multiple runs were undertaken. An example of one of the runs for the observed and simulated data using MLU is shown in Figure 7-7.

A total of four aquifer units and five aquitards were simulated using a range of hydraulic parameter values to yield the best fit to observed levels in the four observation bores. The simulation yielded a good fit to groundwater levels in the Condamine Alluvium bores, and was able to match the general observed trend of the response in DA-164 (Walloon Coal Measures) as shown in Figure 7-7. As described earlier in Section 7.4.5.1, the response in DA-164 is affected by a number of factors. Nevertheless, the data has been fitted to the curve based on the conservative assumption that the groundwater level response is mainly a result of leakage from the Walloon Coal Measures to the Condamine Alluvium. Estimated parameters for the aquifer and aquitard layers are summarised in Table 7-3.

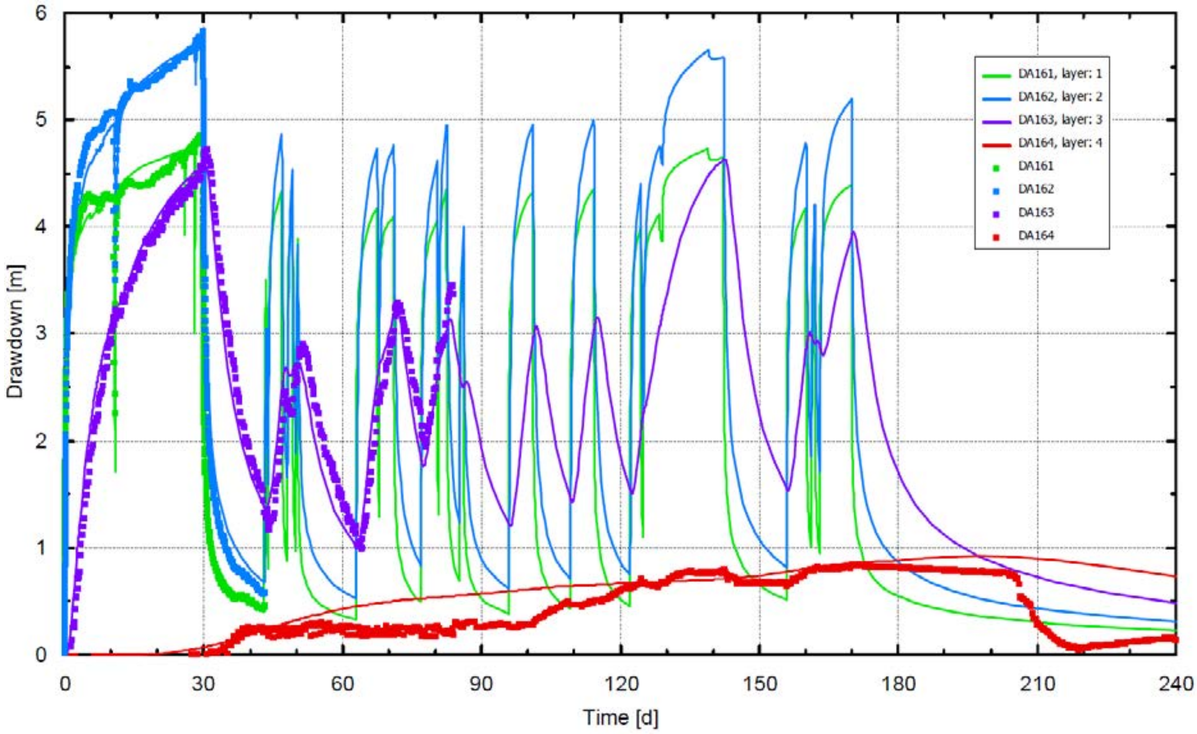

Figure 7-7 Observed drawdown (dots) vs simulated drawdown (solid lines) from one of the MLU model runs (Daleglade)

Table 7-3 Estimated parameters from MLU analysis at Daleglade

Aquifer / Aquitard layer	Thickness (metres)	K_v (m/day)	K_h (m/day)	S*
Sheetwash	24	3 x 10^{-3}	-	1 x 10^{-5}
DA-161 (Condamine Alluvium)	27	-	20 to 25	1 x 10^{-4}
DA-162 (Condamine Alluvium)	2.9	-	0.3 to 0.5	1 x 10^{-4}
DA-163 (Tertiary Sediments)	1.4	-	3 x 10^{-3} to 0.1	1 x 10^{-5}
Transition zone and Upper Walloon Coal Measures	18.6	1 x 10^{-5} to 3 x 10^{-4}	-	5 x 10^{-5}
Coal Seams (DA-164)	0.2	-	1	5 x 10^{-5}
Underlying Walloon Coal Measures (Interburden)	2	2 x 10^{-6} to 4 x 10^{-5}	-	1 x 10^{-5}

* Estimated storage values are lower than expected, likely due to simplification involved in analytical solutions for multilayered systems.

7.4.5.3 Numerical analysis

A 3-D numerical groundwater flow model of the Daleglade site was constructed using MODFLOW-USG to simulate the pumping test response over a period of 144 days from 2 September 2013 to 24 January 2014. The model covered a five-kilometre by five-kilometre grid and included seven layers to represent various units. A time-varying specified head boundary condition was assigned to the outer boundary of the model domain to simulate groundwater level fluctuations over the modelled period. The model was calibrated using the PEST software package, allowing hydraulic parameters to vary within specified ranges to yield a best fit between simulated and observed groundwater levels. The model did not simulate the period after 24 January 2014, as the rapid increase in DA-164 groundwater level after this date would have led to instability in the PEST calibration, which is also an indication that the rapid rise is not related to groundwater flow. A plot of observed versus simulated data for DA-162 (Condamine Alluvium), DA-163 (Tertiary Sediments) and DA-164 (Walloon Coal Measures) is presented in Figure 7-8.

Much like the MLU analysis, the calibrated model yielded a good fit to groundwater levels in the Condamine Alluvium bores and was able to roughly match the general trend of the response in DA-164. It was not able to predict the more rapid fluctuations observed in DA-164, again suggesting that the response in DA-164 was not induced by the pumping from RN 48017. Also, similar to the MLU analysis, fitting with general trend carries an underlying assumption that the main cause for the drop in groundwater level in the Walloon Coal Measures is the induced leakage of water from the Walloon Coal Measures to the Condamine Alluvium—a conservative assumption about estimating vertical hydraulic conductivity, which is likely to result in an overestimation of connectivity than underestimation. Calibrated parameter values are summarised in Table 7-4. Differences in parameter values obtained from numerical and analytical methods are noted. These differences are attributed to the fact that a number of complexities associated with the sub-regional system and spatial parameter variations could not be represented in analytical assessments. In relative terms, values from the numerical method are considered more reliable than values from other methods.

Table 7-4 Estimated parameters from numerical analysis at Daleglade

Unit	Calibrated parameter values		
	K_h (m/d)	K_v (m/d)	S
Condamine Alluvium	0.63 to 75	0.03 to 1.0	6.25×10^{-4} to 3.3×10^{-3}
Tertiary Sediments	0.19 to 0.40	0.04 to 0.09	8.8×10^{-4} to 4.1×10^{-3}
Transition zone and Upper Walloon Coal Measures	2.5×10^{-5} to 5.4×10^{-3}	2.9×10^{-6} to 6.2×10^{-4}	4.7×10^{-5}
Coal seams	3.3×10^{-3}	3.2×10^{-4}	6.1×10^{-4}
Underlying Walloon Coal Measures (interburden)	7.5×10^{-6}	7.3×10^{-7}	4.8×10^{-5}

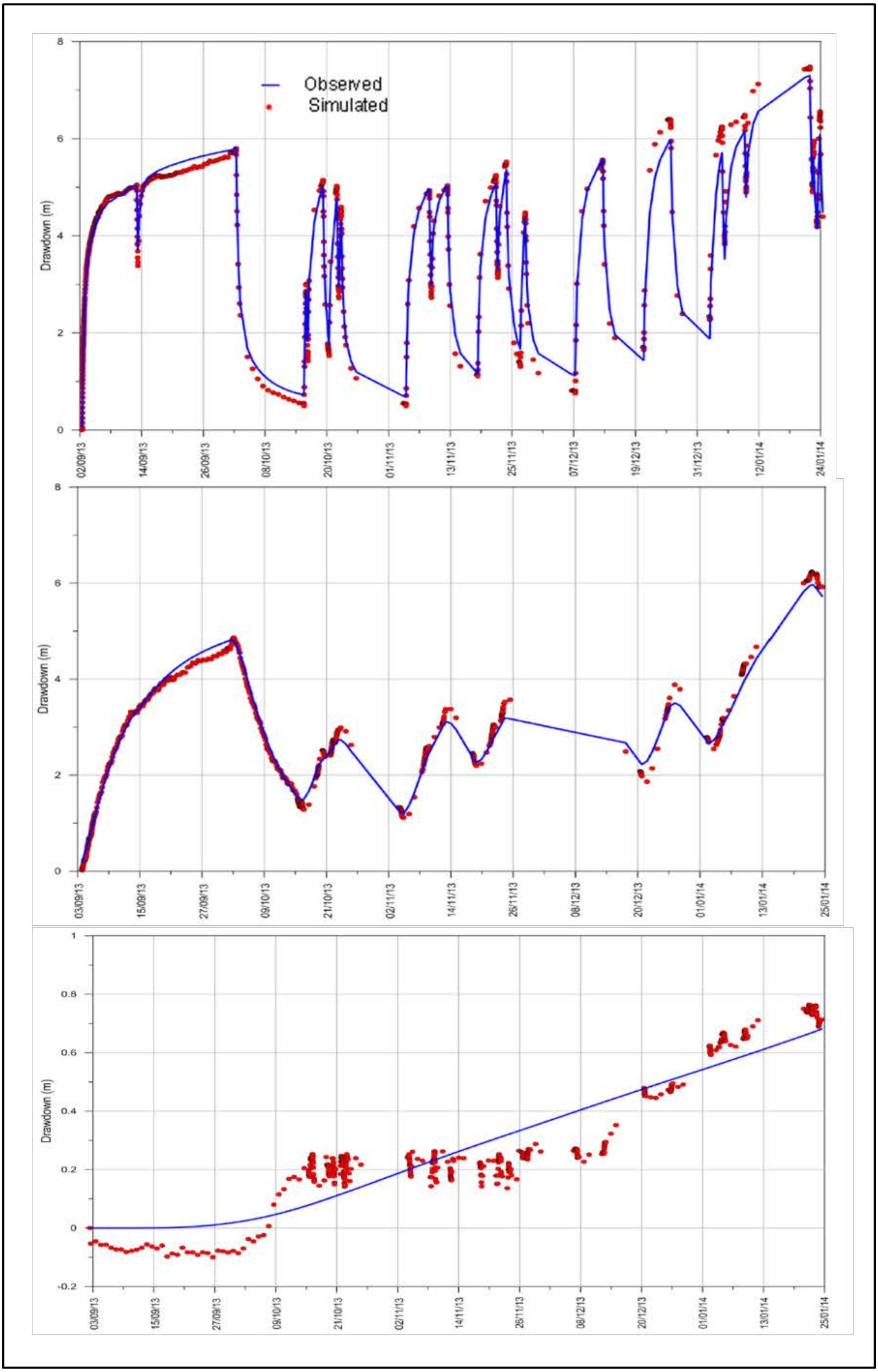

Figure 7-8 Observed vs simulated drawdown in response to pumping in Daleglade bores DA-162, DA-163 and DA-164, using numerical analysis

7.4.6 Complementary investigations and analysis

In addition to the pumping test, other complementary investigations were also carried, out including:

- a laboratory analysis of core samples for testing vertical permeability
- water chemistry and isotopic analysis of samples collected from the observation bores.

Five core samples from DA-164 were selected from different lithologies across the Condamine Alluvium and the upper Walloon Coal Measures. These were submitted to the Water Research Laboratory's centrifuge permeameter facility at UNSW for permeability testing. Very low vertical hydraulic conductivity (Kv) values were observed from the core samples tested, ranging from about 10^{-4} m/day to 10^{-6} m/day for material in and around the transition zone depth. Specific results from all core samples are shown in Appendix 5.

Vertical hydraulic conductivity (Kv) values obtained from numerical methods are considered more reliable than those from analytical methods because the numerical methods take into account complexities that cannot be accounted for in analytical methods. Estimates from core material are less reliable than either analytical or numerical methods for estimating Kv at a formation scale because unbiased sampling of the variable lithology is impracticable and cannot account for the complexity of groundwater flow paths. Typically, for a set of Kv values from a series of core samples across a formation, the lowest Kv material tends to most influence the formation-scale Kv.

Groundwater samples were collected several times, from the pumping bore and four observation bores, and analysed at ALS laboratories for hydrochemical and isotope composition. Results indicate that water chemistry is similar in all bores, with slightly lower concentrations of Ca^{2+} and Mg^{2+} and slightly higher concentrations of Na^{+}, K^{+}, CO_3^{2-} and HCO_3^{-} in the Walloon Coal Measures bore compared to the Condamine Alluvium bores. The SAR value is very high compared to other bores in the area, with the Walloon Coal Measures bore having the lowest SO_4 (2 mg/L), Ca^{2+} (17 mg/L) and Mg^{2+} (23 mg/L). The salinity level is generally lower in all the Condamine Alluvium observation bores (1,000 to 1,700 mg/L) compared to the Walloon Coal Measures bore and tends to increase with depth. Age dating from radioisotope analysis also suggests that the age increases with depth, with the youngest water (about 4,500 years old) in the pumping bore and the oldest water (25,500 years old) in the Walloon Coal Measures. The age of water for the Walloon Coal Measures is similar to that recorded elsewhere in the Surat Basin for comparable hydrogeological conditions.

In general, water quality signatures are consistent with the conclusions drawn from the hydraulic responses.

7.5 The Cecil Plains site

7.5.1 Site overview

The Cecil Plains site (also known as the 'Lone Pine' site) is located east of the town of Cecil Plains in an area of high groundwater extraction, as shown in Figure 7-1. Water was pumped from Condamine Alluvium bore RN 119784 for 46 days; groundwater levels were monitored in the pumping bore and in a number of nearby Condamine Alluvium and Walloon Coal Measures observation bores.

This test site was selected because:

- there is a large long-term groundwater level depression in the Condamine Alluvium due to high groundwater extraction for irrigation, resulting in about 20 metres of groundwater level difference from the Walloon Coal Measures to the Condamine Alluvium
- the Condamine Alluvium has high transmissivity compared to other parts of the aquifer
- the transition zone was mapped to be relatively thin (less than 10 metres)
- CSG production is planned in the vicinity.

7.5.2 Drilling and installing the observation bores

For the dual purposes of pumping tests and long-term monitoring, in mid-2014 Arrow Energy drilled and installed three observation bores—LP-14, LP-15 and LP-16—at the Cecil Plains site, and an investigation bore, LP-17. All are within 33 metres of the pumping bore, RN 119784. The location of these bores is shown in Figure 7-9. Details of screened depth and target formations are shown in Table 7-5.

Bore LP-17 was drilled 13 metres west of RN 119784 for initial investigative purposes. The bore was cored from 36 metres to 150 metres with a core diameter of 85 mm for detailed geological logging; core sampling was done at specific depths for assessing mineralogy and lab testing for permeability. The bore was also originally intended to be used for observation, but was later decommissioned due to technical difficulties arising from the bore completion. Images of cores from selected depths in this bore are shown in Appendix 4.

A suite of geophysical logs was run at LP-17. The gamma logs could only be run to 134 metres due to bore collapse. Some of the gamma signatures are subdued, but still provide a useful relative response that is representative of the site. A full suite of logs including gamma, resistivity and self-potential, was run at LP-14 on the eastern side of the pumping bore, as shown in Appendix 6. There is some minor shift in geophysical signatures between the two bores due to lateral lithological variation.

All observation bores were drilled to 215-mm diameters and installed with 115-mm steel casing, except LP-15 which was installed with 50-mm PVC casing and screen. LP-15 was screened with gravel pack and bentonite plugs above and below. LP-14 and LP-16 were cased and cemented to their entire lengths and then perforated to desired depth intervals.

Observation bore LP-17 is representative of the site geology; a composite geophysical and lithological log from this bore, together with screened parts of other observation bores in the cluster, is shown in Figure 7-10.

Figure 7-9 Cecil Plains site – location of pumping bore and observation bores

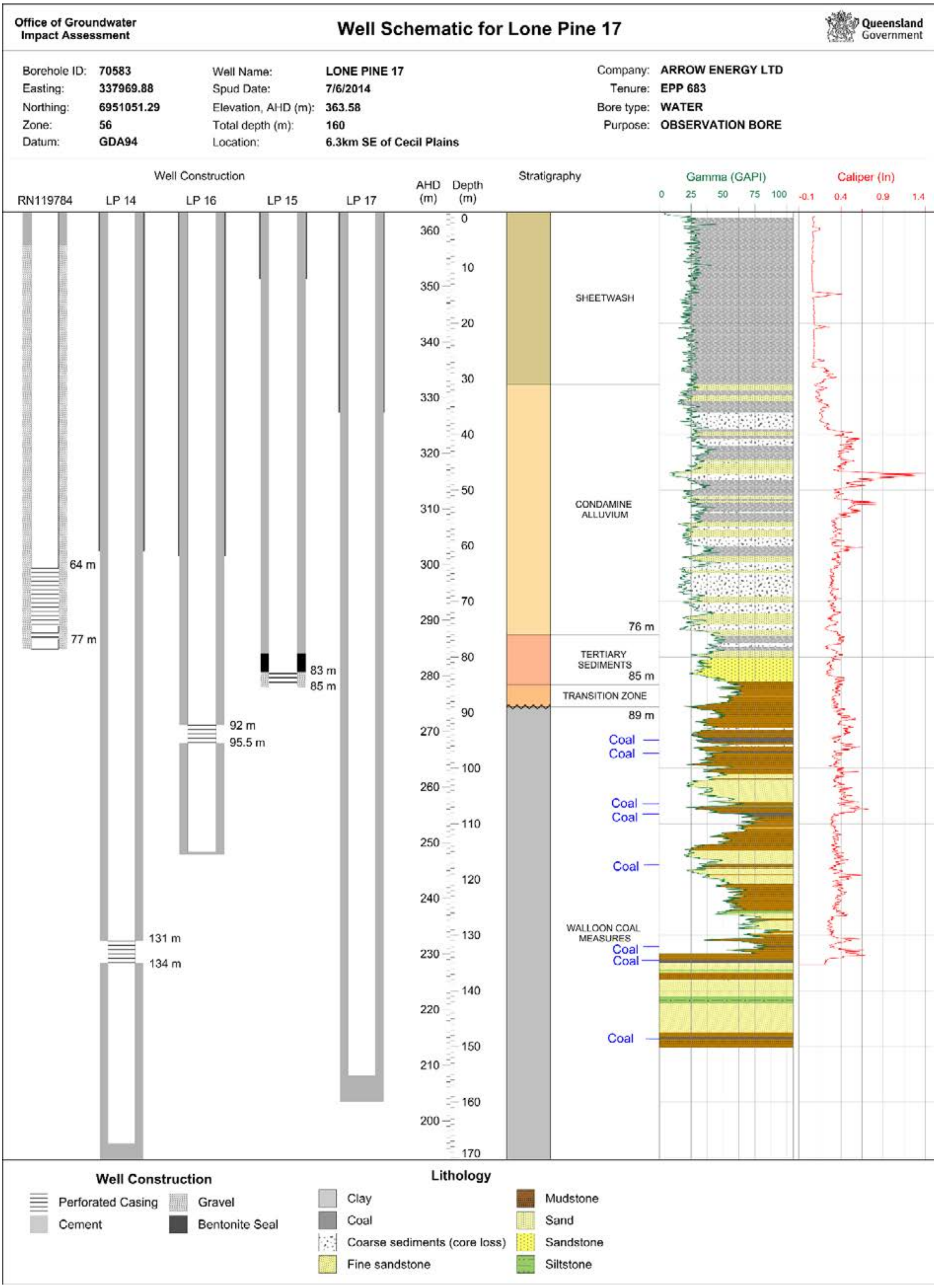

Figure 7-10 Composite bore log for LP-17 with nested observation bores (Cecil Plains)

Table 7-5 Cecil Plains observation bores details

Bore ID	Total depth (mBGL)	Screen top (mBGL)	Screen bottom (mBGL)	Screened unit	Distance from pumping bore (metres)
RN 119784 (pumping bore)	78.6	64	76.8	Condamine Alluvium	-
LP-14	170.4	131.0	135.0	Walloon Coal Measures	13
LP-15	85.7	82.9	84.9	Tertiary Sediments	33
LP-16	117.0	92.2	95.5	Walloon Coal Measures	23
LP-17	160.0	n/a	n/a	Pilot hole	13
RN 42231373	83	57	65	Condamine Alluvium	1,980
RN 42231465	102.4	69	84	Condamine Alluvium	1,280
CB-17	90.0	76.0	90.0	Condamine Alluvium	2,520

mBGL = metres below ground level

7.5.3 Geological and hydrogeological conditions

The Cecil Plains site is located near the deepest part of the Condamine Alluvium and is underlain by the Upper Jundah Coal Measures, the uppermost units of the Walloon Coal Measures. The Springbok Sandstone wedges out, separating the Condamine Alluvium and the Walloon Coal Measures in the immediate vicinity of the site, towards the west. A regional cross-section (section H) about two kilometres south of pumping bore RN 119784, along the east-west direction, is shown in Figure 4-2. This section is representative of the Condamine Alluvium and bedrock geology in this area.

Site geology is best represented by the core and geophysical log from bore LP-17, shown in Figure 7-10. The top 30 metres consists primarily of clay and silt which are sheetwash deposits. The sheetwash is underlain by about 46 metres of thick granular alluvial deposits from 30 metres to 76 metres, consisting of several horizons of medium-to-coarse, mostly grey-coloured unconsolidated sand alternating with layers of clay and silt. Sandy units are well sorted and are comprised primarily of quartz grains with some lithic fragments. These sandy units are characterised by lower gamma count and very poor core recovery.

The bottom of the granular alluvium deposits forms the base of the Condamine Alluvium. There is four metres of clay underlying this granular alluvium. Similar to the Daleglade site, a five-metre unit of pale white to grey-coloured medium-to-coarse friable sandstone also exists below this clay. This sandstone unit is characterised by a lower gamma count and has a brecciated appearance in places. From 76 metres to 85 metres, it is interpreted as the Tertiary Sediments. Underlying the Tertiary Sediments is another four-metre-thick horizon of clay material, representing the transition zone. The transition zone more generally can comprise alluvial or weathered mudstone, but at this site is likely to be weathered mudstone (85 metres to 89 metres) which has a distinctively high gamma count.

The transition zone grades into grey-to-brown, fine-to-medium sandstone typical of the Walloon Coal Measures[5]. With increasing depth, there is a gradual transition to carbonaceous mudstone before the first coal is encountered at a depth of 93 metres, about 17 metres below the base of the granular alluvium. Below this depth, a sequence of firm mudstone, carbonaceous mudstone with traces of coal, siltstone, and fine sandstone represents the Walloon Coal Measures. Further coal seams were encountered at about 97 metres, 108 metres and 135 metres. The Walloon Coal Measures sequence represents the Upper Jundah Coal Measures, with shallower coal (93 metres to 108 metres) belonging to the Macallister Seams and deeper coal (135 metres) belonging to the Wambo Seams. It is this lower seam that is anticipated to be the target for coal seam gas in the area.

Groundwater levels in the Condamine Alluvium vary significantly in the area of the Cecil Plains site, as it is an area of high groundwater extraction for agriculture. Typically, groundwater levels range from 314 metres to 320 metres, with the groundwater level near RN 119784 at about 314 metres. The westerly thinning confining wedge formed by the sheetwash, and the groundwater level fluctuations from water extraction in this area, cause a mix of confined and unconfined conditions, depending on local hydrogeological controls.

Regionally, Condamine Alluvium groundwater across this area flows to the groundwater depression centred in the vicinity of RN 119784. The static groundwater level in the Walloon Coal Measures is about 334 metres at the site and about 342 metres further north (Carn Brea, CB-18). Although limited information has been available about the Tertiary Sediments in the area, it is anticipated that the unit is in hydraulic connection with the Condamine Alluvium and, for all practical purposes, is considered part of the Condamine Alluvium aquifer.

The groundwater level difference of about 20 metres between the Walloon Coal Measures and the Condamine Alluvium suggests a significant impediment to flow across the two formations.

7.5.4 Pumping test

The layout of the three observation bores constructed at the Cecil Plains site, the pumping bore, and some surrounding bores used for observations during the pumping test, are shown with their corresponding hydrogeological units in Figure 7-11. Details of the observation bores are shown in Table 7-5. The pumping bore is screened in the lowermost part of the Condamine Alluvium and three dedicated observation bores are screened in:

- sandy units of the Tertiary Sediments immediately below the alluvium (LP-15)
- the uppermost coal unit below the transition zone (LP-16)
- the lower coal unit (LP-14).

[5] An alternative conceptualisation that does not use the concept of a transition zone could also be conceived wherein the Condamine Alluvium and the Tertiary Sediments are underlain by the Walloon Coal Measures with a decreasing weathering of the Walloon Coal Measures with depth. Three units would be recognised i.e. the Condamine Alluvium, an effective aquitard and a connected coal matrix. However, in this case, most of the transition zone clays would be mapped together with the upper weathered Walloon Coal Measures and, hence, in practical terms, there is little difference between the two conceptualisations.

The observation bores are installed specifically to monitor hydraulic response in various units across the Condamine Alluvium and the Walloon Coal Measures interface.

A 46-day pumping test was carried out at the Cecil Plains site from 17 October 2014 to 2 December 2014. The pumping rate from RN 119784 varied between 45 and 60 L/s throughout the test, with some intermittent short stops due to power failures. Pumped water was discharged to a nearby ring tank. Groundwater levels in RN 119784 and the five observation bores were recorded automatically using pressure transducers throughout the test, as well as in the weeks leading up to the test and following the test.

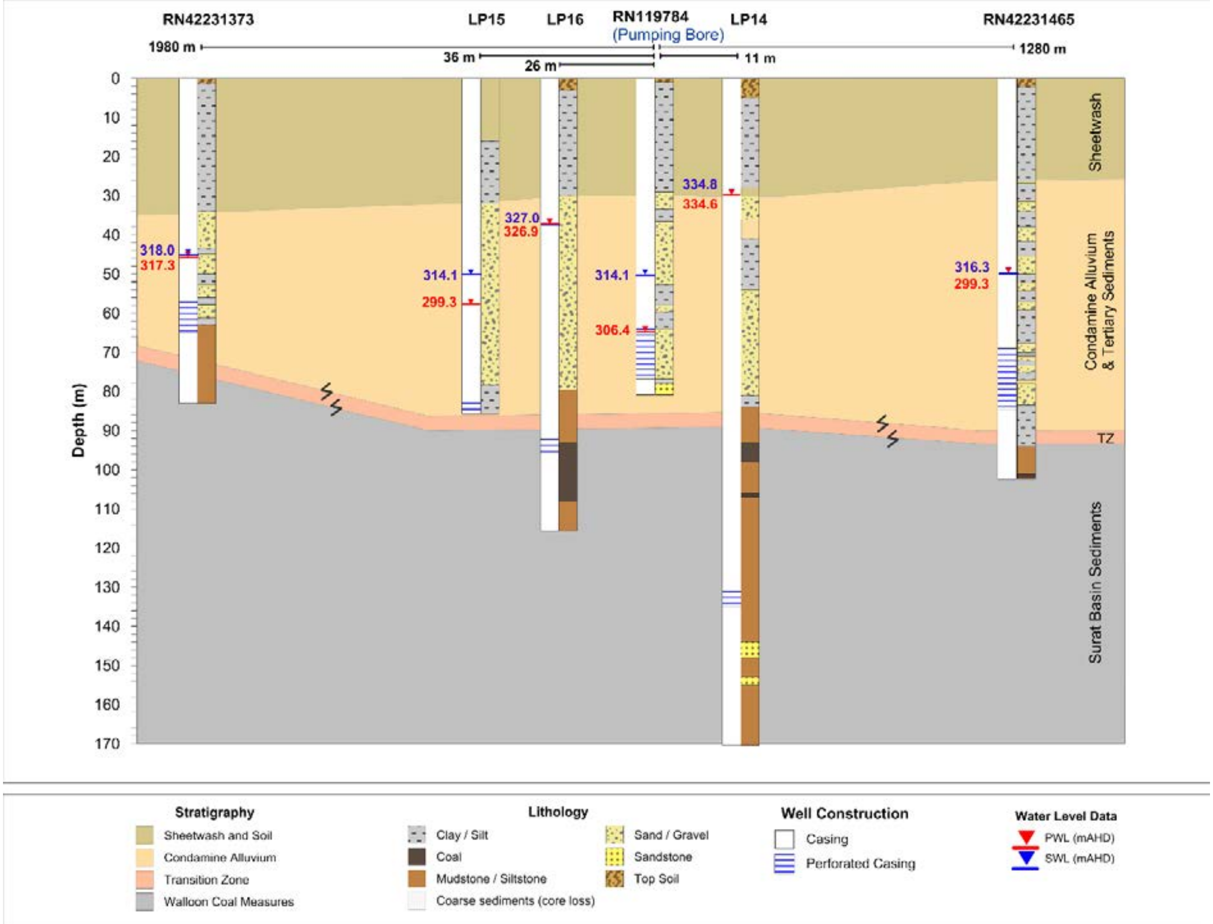

Figure 7-11 Layout of the observation bores at the Cecil Plains pumping test site

7.5.5 Interpreting the pumping test results

Groundwater levels in pumping bore RN 119784 and all observations bores, covering the pumping test period and the recovery period immediately following the test, are shown in Figure 7-12. Data for LP-16 is corrected for barometric efficiency.

To understand groundwater level response during the pumping and recovery periods, and to estimate the hydraulic parameters of materials in the Condamine Alluvium, the transition zone and the Walloon Coal Measures, a number of methods were used:

- **Qualitative interpretation** was performed to assess the groundwater level response in the pumping bore and observation bores.

- **Analytical interpretation** was performed to estimate hydraulic parameters using simplified analytical models of groundwater flow for generic hydrogeological conditions at the pumping test site.

- **Numerical interpretation** was performed to simulate three-dimensional flow conditions at the pumping test site using a numerical groundwater flow model to estimate the range of hydraulic parameters that could cause the observed groundwater level response in the pumping bore and observation bores.

The use of multiple interpretation methods maximises confidence in the interpretation of the test response and assessment of hydraulic parameter values.

7.5.5.1 Qualitative interpretation

The groundwater level in the Condamine Alluvium bore RN 119784 at the site before the start of the test was 314.1 metres, while the level in other observation bores in the Condamine Alluvium 1–3 kilometres away from the site was 2–3 metres higher. This difference suggests a pre-existing hydraulic gradient towards the pumping bore. Groundwater level at LP-15, screened in the Tertiary Sediments six metres below the base of the Condamine Alluvium, was also 314.1 metres—the same depth as that of the Condamine Alluvium pumping bore—suggesting the two units have a strong hydraulic connection with each other.

LP-16, the observation bore screened in the first coal (92.2 metres to 95.5 metres) of the Walloon Coal Measures, which is about seven metres below the screened Tertiary Sediments (LP-15), had a pre-test level of 327.0 metres. This head difference of about 13 metres results in a relatively strong upwards hydraulic gradient and indicates that, in the test area, the transition zone and the upper part of the Walloon Coal Measures act as a confining layer for the Walloon Coal Measures, and that vertical flow is inhibited under natural conditions. Also, the groundwater level in the deeper coal seam 40 metres below the first coal, recorded in LP-14, is 334 metres, resulting in an even stronger upward gradient. The significant difference in groundwater levels between the two coal seams suggests that they are hydraulically isolated from each other in general.

The maximum drawdown in the pumping bore was 18 metres after about 14 days of pumping. Over the next 32 days of pumping, the groundwater levels tended to rise to a residual drawdown of 15 metres, in an apparent response to a background rise in groundwater levels in the areas that was unrelated to the test. It recovered to its pre-pumping level five days after pumping stopped, and continued to recover, reflecting a general regional groundwater level trend in the Condamine Alluvium.

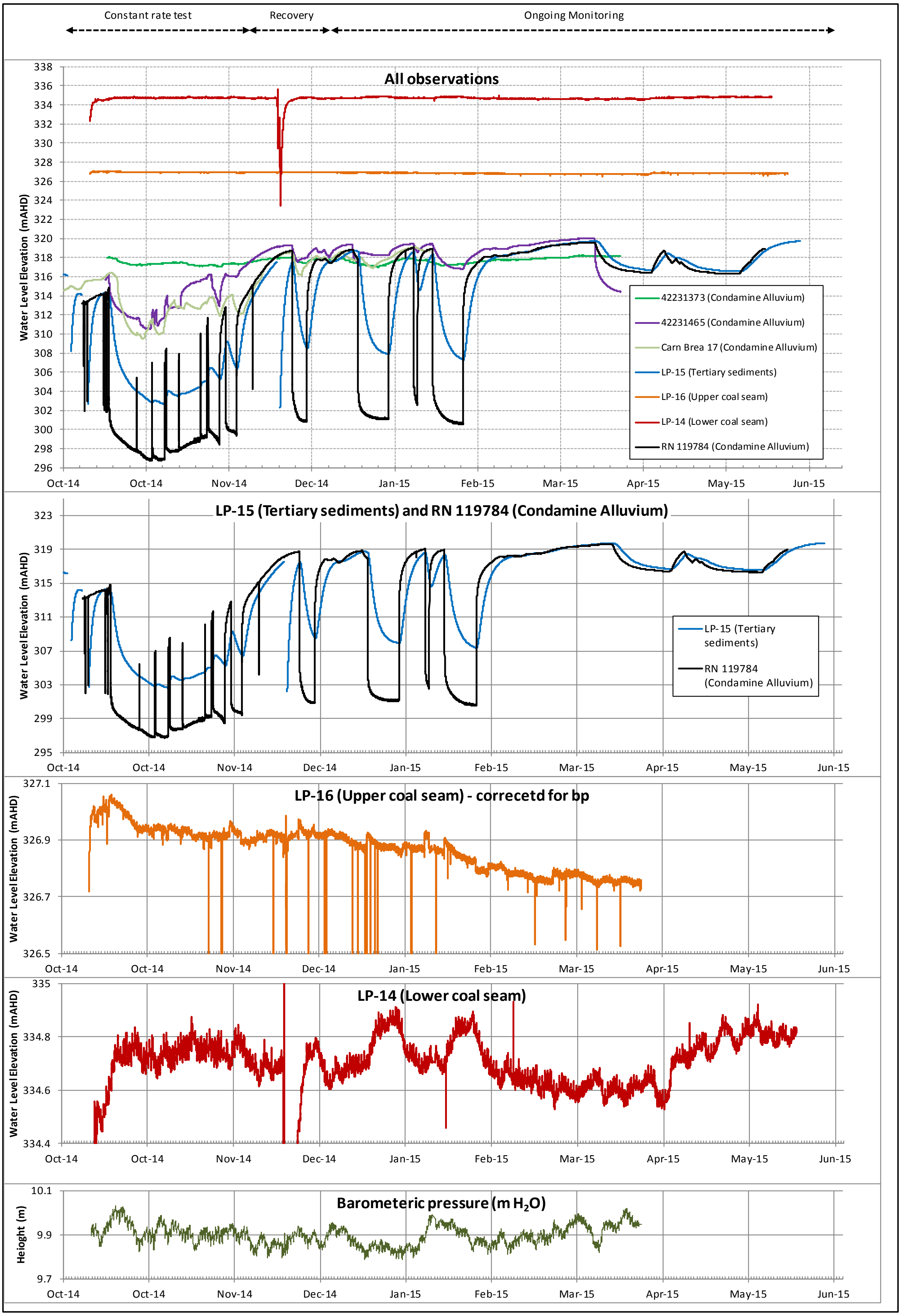

Figure 7-12 Groundwater level response to pumping test in Cecil Plains

Observation bore LP-15, in the Tertiary Sediments six metres below the interpreted base of the Condamine Alluvium, shows a similar but delayed response with lesser magnitude than the pumping bore. It recovered to its pre-pumping level five days after pumping stopped. There is a slight inverse response of about 0.1 metres in this bore each time pumping started or stopped, which is characteristic of the Noordbergum/Rhade effect (Berg, et al., 2011). Overall, groundwater level response in the Tertiary Sediments suggests a strong vertical and lateral hydraulic connection with the Condamine Alluvium and, hence, it is concluded that the Tertiary Sediments is effectively part of the Condamine Alluvium aquifer.

In the context of vertical connectivity across the transition zone, the response in the shallower coal seam (LP-16) about 10 metres below the Condamine Alluvium is important. Although a gradual drawdown of about 0.15 metres developed over about 45 days of pumping, there was little or no recovery after pumping stopped. Superimposed on this trend are spikes caused by mechanical loading and unloading effects each time that pumping starts or stops, causing an inverse groundwater level response. The initial response of this bore, coupled with the small total drawdown and lack of recovery after pumping, suggests that the observed response is likely a combination of mechanical loading and regional trend rather than a direct response to pumping in the Condamine Alluvium.

A hydraulic head gradient exists between the Condamine Alluvium (LP-15) and the first coal of the Walloon Coal Measures (LP-16). It is reasonable to assume that if there is a hydraulic connection across the two, then inflow of water from the Walloon Coal Measures to the Condamine Alluvium due to this head difference would cause a long-term downward trend in groundwater level in coal, which would be exacerbated by pumping in the Condamine Alluvium. Although unlikely, some minor inflow from the Walloon Coal Measures to the Condamine Alluvium cannot be completely ruled out.

No discernible drawdown was observed in the deeper coal seam (LP-14) over the pumping period. The groundwater level trend is similar to that in the upper coal unit, but somewhat subdued. There was a sudden drop in groundwater level of about 10 metres, followed by a slow recovery on 17–18 December 2014. This was in response to pumping a small volume of water (120 litres) from this observation bore in the process of water quality sampling. The response suggests that the coal seam has a very low permeability and storativity.

The three more distant bores screened in the Condamine Alluvium showed some response to pumping, but drawdown and recovery trends in those bores do not strongly correlate with the pumping test bore. This indicates that they may have been influenced by pumping from other nearby pumping bores and/or changes in the regional groundwater level.

Collectively, the responses indicate that the Condamine Alluvium at the Cecil Plains site is highly permeable and that the hydraulic connection between the Condamine Alluvium and Walloon Coal Measures coal seams is low.

7.5.5.2 Analytical interpretation

Similar to the Daleglade test site, the following analytical methods were used to interpret pumping test results:

- curve matching interpretation of the transient response during the pumping period

- analytical modelling of the transient response during the full pumping, recovery and ongoing monitoring periods, using MLU software (Hemker & Post, 2014).

Curve matching

Distance-drawdown analysis was not performed for this test site because interference from other pumping bores made it impossible to accurately determine the magnitude of drawdown in the Condamine Alluvium observation bores in response to pumping at RN 119784 alone.

Analysis of the transient response in the Condamine Alluvium pumping bore and the Tertiary Sediments observation bore, using the Cooper-Jacob method (Cooper & Jacob, 1946) and the Theis method (Theis, 1935), provides a reasonable fit to observed drawdown over the first week of the test. Fit to the later part of the time-drawdown is poor, but this may be the result of regional groundwater level fluctuations or changes in pumping rate. Aquifer storage estimates are not reliable for this bore, due to wellbore storage and skin effects. Estimates of aquifer parameters are summarised in Table 7-6.

Data from the Condamine Alluvium observation bores RN 42231373, RN 42231465 and CB-17 could not be accurately assessed as interference from other irrigation bores made it impossible to accurately determine the magnitude of drawdown due to pumping at RN 119784.

Table 7-6 Estimated parameters from curve matching at Cecil Plains

(Bore) Aquifer	Cooper-Jacob method			Theis method		
	T (m^2/day)	K (m/day)	S	T (m^2/day)	K (m/day)	S
(RN 119784) Condamine Alluvium	530	16.6	n/a	650	20.3	0.12
(LP-15) Tertiary Sediments	160	5	0.05	100	3.1	0.15

MLU analysis

An MLU analytical model was set up and a combination of manual adjustment and model optimisation was used to achieve a fit to the observed drawdown data for the observation bores. A fit between the observed and simulated data using the MLU method is shown in Figure 7-13 and the corresponding estimates of parameters are shown in Table 7-7.

The MLU analysis for the pumping bore and for LP-15 considers the first 13 days of data, which appear to be free of interference signals from the other Condamine Alluvium irrigation bores. After this time, other influences external to the test became very apparent and accurate curve matching became impractical. A very conservative approach is used to estimate vertical hydraulic conductivity for the overlying Walloon Coal Measures from LP-16; the estimate for this layer is therefore likely to represent the upper limit. For LP-14, no impact was apparent by the end of the monitoring period, so this bore was not used in the analysis.

Table 7-7 Estimated parameters from MLU analysis at Cecil Plains

Aquifer / Aquitard layer	Thickness (metres)	Kv (m/d)	Kh (m/d)	T (m^2/d)	S
Sheetwash	30.5	1 x 10^{-6}			0.0001
Condamine Alluvium (RN 119784)	45.7		4.7	215	5 x 10^{-5}
Tertiary Sediments (basal clay part)	7.8	1.2 x 10^{-4}			6 x 10^{-5}
Tertiary Sediments (sandy part) LP-15	0.5		1	0.5	1.5 x 10^{-5}
Transition zone	8.5	5 x 10^{-7}			1 x 10^{-6}
Upper coal seam (LP-16)	2.2		5	11	4 x 10^{-5}
Walloon Coal Measures: interbedded mudstone, siltstone, fine sandstone, with coal bands and tuff	36.6	1 x 10^{-7}			1 x 10^{-6}
Lower coal seam (LP-14)	3.2		0.1	0.32	1 x 10^{-6}
Lower aquitard representing a very limited flow basal layer	30	1 x 10^{-7}			1 x 10^{-6}

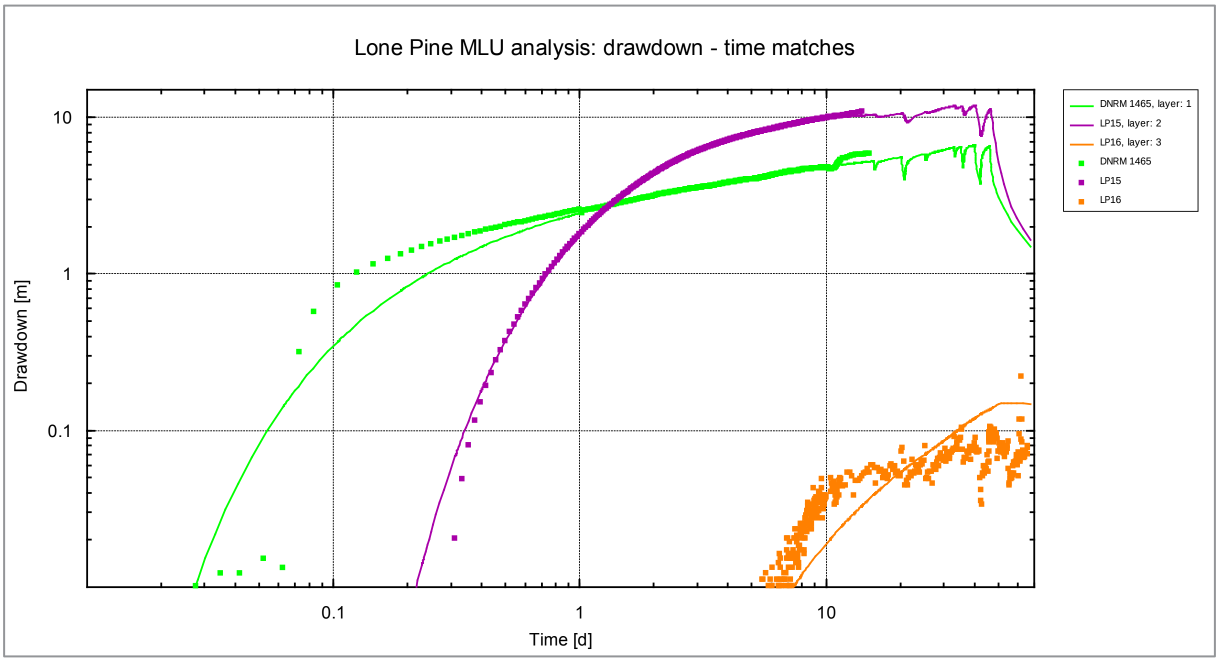

Figure 7-13 Observed drawdown (dots) vs simulated drawdown (lines) for one of the MLU model runs (Cecil Plains)

7.5.5.3 Numerical interpretation

A three-dimensional numerical groundwater flow model of the Cecil Plains site was constructed in MODFLOW 2000 and calibrated using the PEST software package. This model was constructed by Arrow Energy with support and oversight from OGIA's modelling team. The model domain was about eight kilometres wide and nine kilometres long, with a grid spacing of 250 metres. Nine uniform elevation model layers were represented, based on interpreted thickness from drilling and logging results. The transition zone and the upper weathered Walloon Coal Measures were initially represented as a single layer between the Tertiary Sediments and the coal layer, but were later subdivided into three layers. Steady state and manual transient calibrations were undertaken. More than 3,000 pilot points were used in the calibration by Arrow Energy.

A good calibration was achieved with a mass balance error of less than one per cent and an RMS value of less than 0.16 per cent. A plot of observed versus simulated data for the pumping bore and observation bores in the Tertiary Sediments (LP-15) and in the upper Walloon Coal Measures (LP-16) is shown in Figure 7-14. Reasonable matches were obtained from the pumping bore and LP-15. As detailed earlier in the qualitative analysis section, the groundwater level pattern in LP-16 is affected by a range of factors and the numerical simulation therefore could not reproduce the observed data by simulating lateral and vertical flow alone. However, the model calibration achieved the observed groundwater level difference between the formations and, as a result, the estimates of vertical hydraulic conductivity are more likely to represent the upper bound of possible values. Calibrated parameter values are summarised in Table 7-8.

Table 7-8 Estimated parameters from numerical analysis at Cecil Plains

Unit	Calibrated parameter values		
	K_h (m/d)	K_v (m/d)	Specific Storage (S_s)
Condamine Alluvium	1.4 to 40	0.1 to 1.4	8.9×10^{-5} to 1.8×10^{-3}
Tertiary Sediments	6.3×10^{-4} to 6.5×10^{-2}	7×10^{-5} to 0.1	1.2×10^{-7} to 4.3×10^{-5}
Transition zone and Upper Walloon Coal Measures	4.9×10^{-7} to 2×10^{-2}	5.7×10^{-10} to 7×10^{-7} *	9.2×10^{-9} to 2.9×10^{-4}
Coal seams	2.9×10^{-4} to 0.1	7.3×10^{-5} to 7.1×10^{-3}	1.9×10^{-5} to 1.1×10^{-2}
Underlying Walloon Coal Measures (interburden)	6.5×10^{-5} to 1×10^{-2}	3.8×10^{-9} to 5.8×10^{-6}	2.2×10^{-4} to 3.5×10^{-4}

* The range is from calibrated values in three layers from two different versions of model.

7.5.6 Complementary investigations and analysis

Complementary investigations were carried out, including:

- a laboratory analysis of core samples for testing vertical permeability
- water chemistry and isotopic analysis of samples collected from the observation bores.

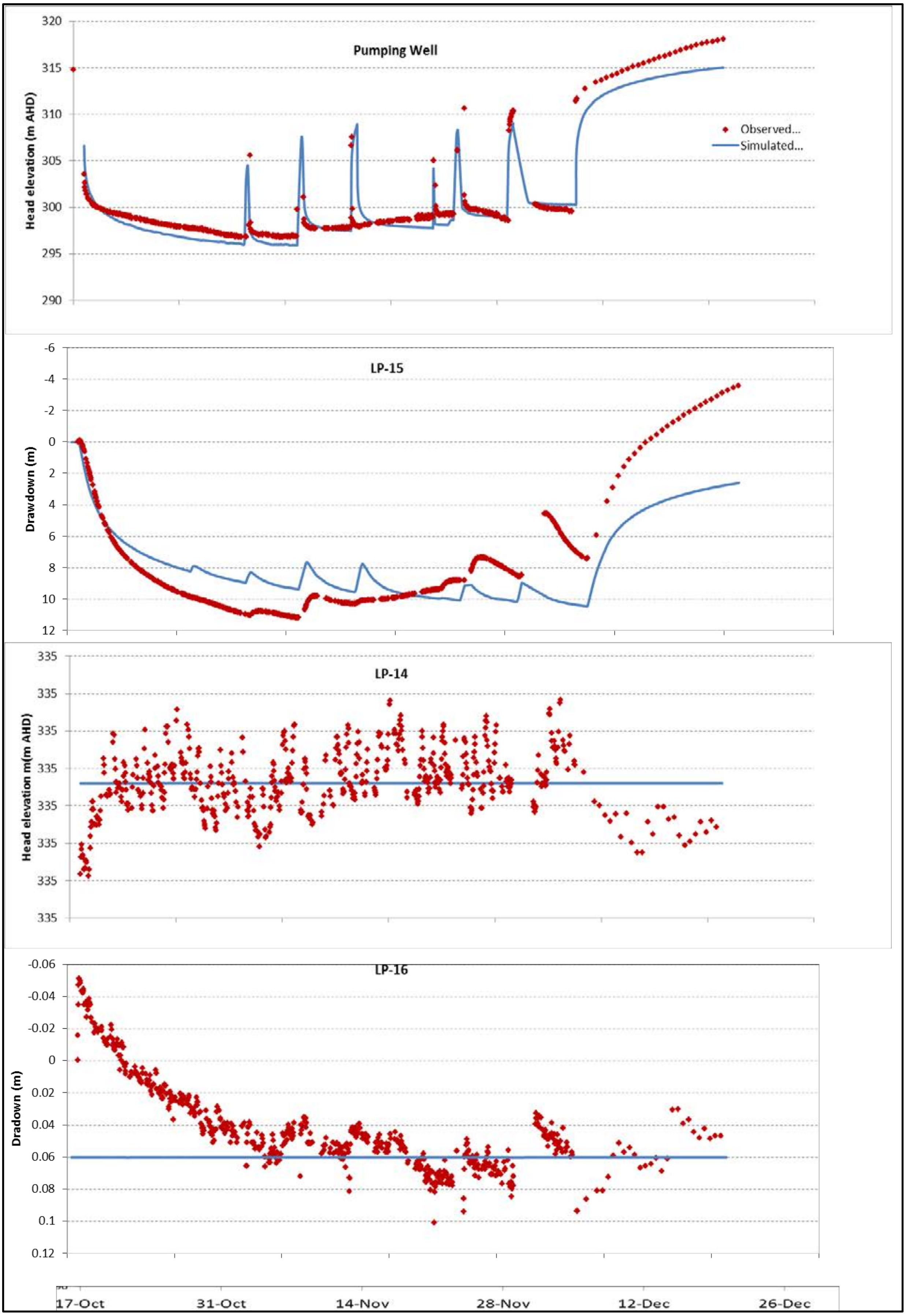

Figure 7-14 Observed vs simulated drawdown response to pumping in bores RN 119784 (pumping well), LP-15, LP-14 and LP16

Fourteen core samples were selected from different lithologies across the Condamine Alluvium and the upper Walloon Coal Measures from LP-17. Laboratory analysis was undertaken by Weatherford Laboratories on behalf of Arrow Energy and results of the individual tests are shown in Appendix 5. For the depth range between the lower part of the Tertiary Sediments and the coal seams of the Walloon Coal Measures (76 to 95 metres), very low vertical hydraulic conductivity values (Kv) were observed, ranging from about 1.5 x 10^{-4} m/day to 2 x 10^{-7} m/day. For a number of samples from the Walloon Coal Measures interburden mudstone and siltstone, the values are less than the measurement limit of 9.5 x 10^{-8} m/day.

Water chemistry indicates that salinity levels at the Cecil Plains site are lower than at the Daleglade site, with increasing salinity with depth (from 390 to 790 mg/L). Measured salinity in the Walloon Coal Measures is lower than typical Walloon Coal Measures water, but consistent with nearby bores. However, the Condamine Alluvium pumping bore has lower salinity than the coals (TDS of 390 mg/L for the alluvium versus 790 mg/L for LP-14 and 670 mg/L for LP-16) and significantly lower pH, EC, TDS, Na, Cl, F and SAR compared to LP-14 and LP-16. Compared with the pumping bore (and LP-14 and LP-16), LP-15 has very high SO_4 (125 mg/L versus 10 mg/L), indicating sulphate-rich minerals in the LP-15 zone.

Hydrochemistry of nearby Condamine Alluvium and Walloon Coal Measures bores in Cecil Plains shows groundwater quality similar to that reported at the pumping test site. For example, nearby Condamine Alluvium bores have average TDS of 400–500 mg/L, whereas Walloon Coal Measures bores have average TDS of 800–900 mg/L. Similarly, SAR values for nearby bores are 2.5 for the Condamine Alluvium and 7.5–15 for the Walloon Coal Measures.

Isotopic compositions indicate different origins of water between the pumping bore and LP-14 and LP-16, both of which plotted to the right of the global meteoric water line (GWML). This indicates evaporative enrichment and is related to an increased chloride concentration. On the other hand, the pumping bore plotted above the GWML, indicating recent recharge with lighter isotopes. There was no difference between pre- and post-test isotopic combinations for any water type.

Age of water estimated from C^{14} and percent modern carbon was higher for shallower bores than deeper bores, ranging from 5,800 years old (pumping bore) to 30,000 years old (deeper coal seams of the Walloon Coal Measures). This is similar to the trend noted at the Daleglade site.

In general, water quality signatures are consistent with the conclusions drawn from the hydraulic responses.

7.6 Conclusions

A comprehensive pumping test program was undertaken at two representative sites, together with drilling and coring of observation bores and complementary laboratory analyses of samples. A range of qualitative and quantitative analyses of pumping test data was undertaken to estimate the hydraulic parameters relevant to hydraulic connectivity between the Condamine Alluvium and the Walloon Coal Measures. The resulting estimates of hydraulic parameters from the different methods are summarised in Appendix 7.

The test results indicate low vertical hydraulic conductivity (Kv) values suggesting limited connectivity between the Walloon Coal Measures and the Condamine Alluvium. Qualitative interpretation of the pumping test data, hydrochemistry and lithology at the two test sites is consistent with this conclusion.

8 Conceptualisation of connectivity

8.1 General

The preceding chapters have presented the approach and results of multiple lines of investigation carried out on various aspects of groundwater flow systems relevant to the connectivity between the Walloon Coal Measures and the Condamine Alluvium. This chapter presents a synthesis of the findings of the investigations.

8.2 Groundwater flow systems

A representative 3-D schematic of the regional geological and hydrogeological setting in and around Condamine Alluvium is shown in Figure 8-1.

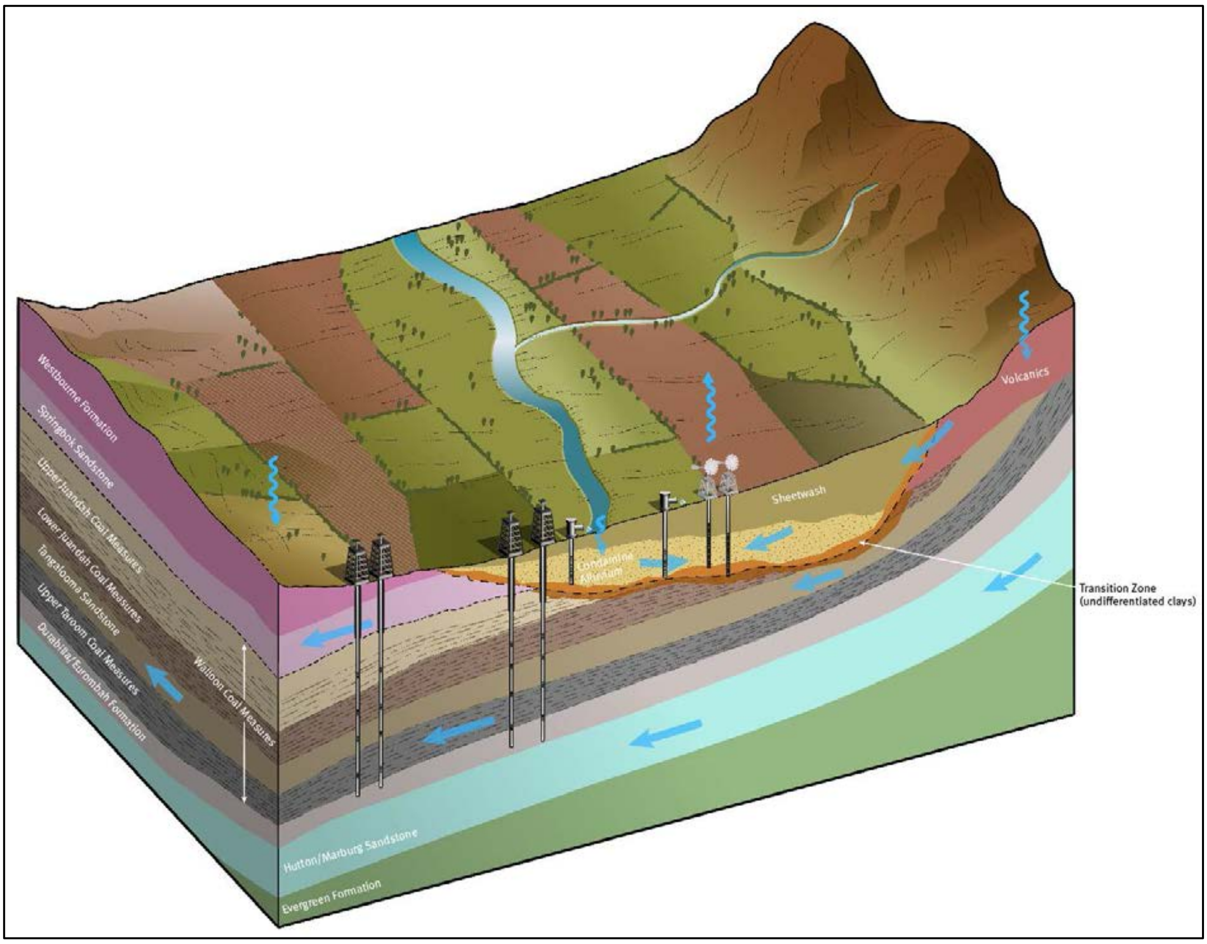

Figure 8-1 Schematic of the regional hydrogeological setting around the Condamine Alluvium

The Condamine Alluvium functions as a single regional aquifer system of connected sand bodies within a skeleton of clay layers. The system is recharged primarily by leakage from the Condamine River and its tributaries in the east and southeast, particularly during periods of flood. Diffuse rainfall recharge is limited by the high clay content of near-surface soils and sheetwash. Some lateral inflow from bounding aquifers in the northeast is also acknowledged (Huxley, 1982) (KCB, 2010b). Natural discharge is mainly through the narrow alluvial section at the downstream end although currently the majority of the discharge from the system is via groundwater extraction from private water bores. Prior to groundwater development, flow in the Condamine Alluvium system was mainly southeast to northeast; however, in recent decades, the flow direction has changed, with groundwater now flowing toward groundwater depressions that have developed as a result of groundwater extraction.

Tertiary Sediments occur along some relict drainage features at the base of the Condamine Alluvium and include reworked sediments in some instances. Investigations (Chapter 7) have revealed that these Tertiary Sediments are hydraulically well connected to the Condamine Alluvium and are, therefore, effectively part of the Condamine Alluvium aquifer.

The Walloon Coal Measures is a formation of the GAB system which underlies the Condamine Alluvium. Regionally, the Walloon Coal Measures is generally considered to be an aquitard (Ransley & Smerdon, 2012) but in places it also serves as an aquifer, particularly at shallow depths where it is used for stock and domestic water supplies. Locally, around the Condamine Alluvium, the GAB is recharged through the Main Range Volcanics and outcropping sandstone units along the eastern and south-eastern margins. Groundwater flow is generally to the northwest.

The Walloon Coal Measures is an extremely heterogeneous formation, both laterally and vertically. Permeable coal seams tend to occur in discontinuous lenses up to one metre thick, although typically less than 0.4 metres thick. The lateral extent of individual coal plies (lenses) typically ranges from 500 metres to about 3,000 metres (Ryan, et al., 2012), (Hamilton, et al., 2014). The coal seams are imbedded within a very low-permeability matrix of mainly mudstone, siltstone and fine sandstone, which is often referred to as interburden. As a result, under natural conditions (i.e. pre-development), groundwater in the coal seams and the matrix would be in a near-equilibrium condition, moving very slowly through the coal and the matrix along the bedding planes with very limited vertical flow. The upper and lower parts of the Walloon Coal Measures can therefore have significantly different hydraulic heads, as is observed in the Cecil Plains area.

Extraction of groundwater from the Walloon Coal Measures underneath most of the central part of the Condamine Alluvium is limited because of the generally high salinity and low yields. There is some extraction along the eastern margin where groundwater is available at shallower depths and the quality of water is better. On the western margins, the underlying Springbok Sandstone supplies groundwater in smaller quantities and the quality is also poorer than the groundwater of the Condamine Alluvium.

8.3 Hydraulic connectivity between the Condamine Alluvium and the Walloon Coal Measures

A conceptual schematic showing the characteristics of the interface between the Condamine Alluvium and the Walloon Coal Measures is shown in Figure 8-2.

Four representative hydrostratigraphic units can be identified:

- the Condamine Alluvium (an aquifer), which is taken to include Tertiary Sediments where present
- a low-permeability transition zone of undifferentiated clay (an aquitard) between the base of the Condamine Alluvium and the un-weathered Walloon Coal Measures

- firm mudstone/siltstone above the uppermost coal seams of the Walloon Coal Measures (an aquitard)
- the part of the Walloon Coal Measures that has largely connected coal seams in a matrix of mudstone, siltstone and fine sandstone and which may be the target for CSG production.

Tertiary Sediments occur in places on the relict erosional surface of the Walloon Coal Measures. These deposits are hydraulically well connected to the Condamine Alluvium and are, therefore, considered to be hydrogeologically a part of the Condamine Alluvium.

The flow in the Condamine Alluvium aquifer and the transition zone is mainly horizontal. Vertical flow and interaction between the Condamine Alluvium and the Walloon Coal Measures is impeded by a combination of the transition zone and firm mudstone/siltstone of the uppermost Walloon Coal Measures. The degree to which the flow is impeded depends upon the combined thickness and vertical hydraulic conductivity of these two layers.

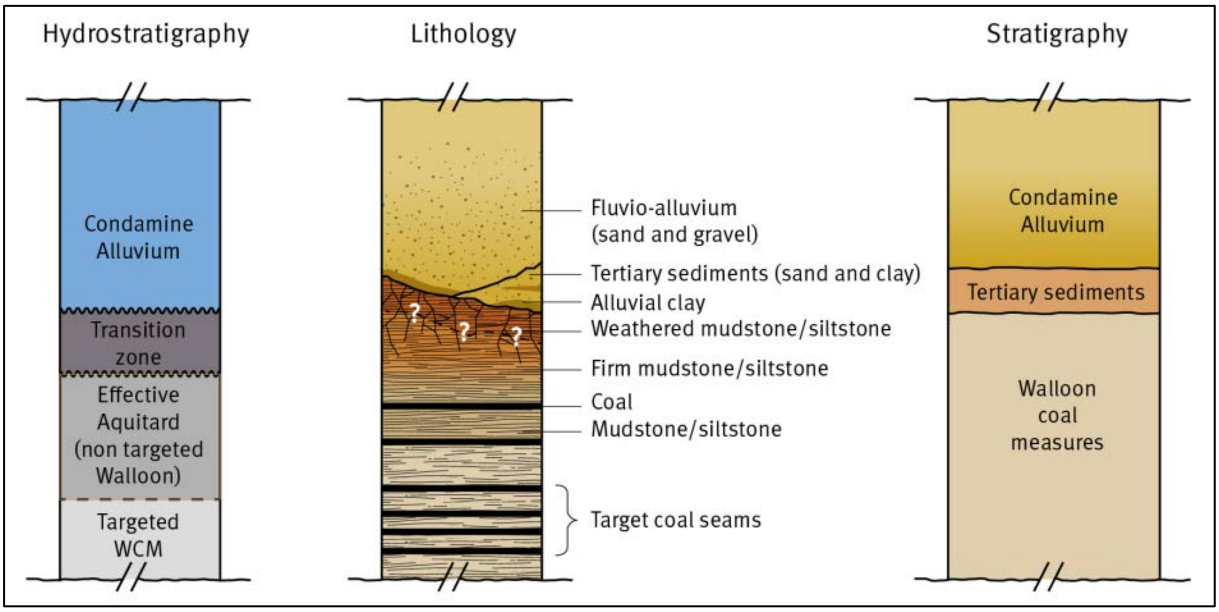

Figure 8-2 Conceptual schematic representation of the interface between the Walloon Coal Measures and the Condamine Alluvium

The transition zone is not a continuous layer. Where the transition zone is absent and the Springbok Sandstone is not interposed between the Condamine Alluvium and the Walloon Coal Measures, the coal seams of the Walloon Coal Measures may come into direct contact with the overlying granular alluvium. There is potential for this connectivity pathway to occur over a small strip on the western side of the Condamine Alluvium. However, given the dip of the Walloon Coal Measures, the general absence of coal seam gas within 150 m of the surface, the proposed 30 m minimum separation of CSG well screens from the base of the alluvium (section 2.8) and the discontinuous nature of the coal seams, it is considered that the potential for this pathway to contribute significantly to connectivity between the formations is low.

Records suggest that a small proportion of water bores (perhaps three per cent) accessing the Condamine Alluvium are likely to have been drilled into the top of the Walloon Coal Measures largely since it is often difficult to distinguish between basal alluvial clay and the upper weathered mudstone of the Walloon Coal Measures. However, due to the limited penetration of these bores into the Walloon Coal Measures and the likely collapse of any open annular space, these bores are unlikely to significantly affect the connectivity between the formations.

8.4 Aquifer/Aquitard hydraulic parameters

The factors that determine the level of connectivity between the Condamine Alluvium and the Walloon Coal Measures are the thickness and vertical hydraulic conductivity of the transition zone and the upper part of the Walloon Coal Measures. Measurements of vertical hydraulic conductivity are available from two pumping test sites which provide indicative values over the area influenced by pumping tests. Laboratory test data from core samples is also available, but relates to point-scale values for materials rather than for the effective vertical hydraulic conductivity of the aquitard layer as a whole.

On this basis, the vertical hydraulic conductivity for the transition zone and the upper Walloon Coal Measures is expected to range from 10^{-9} to 10^{-4} m/day across the Condamine Alluvium footprint.

9 Overall Conclusions

The Condamine Connectivity project pursued several lines of investigation resulting in the following conclusions:

- The geologic data shows that a clay-rich or mudstone horizon at the base of the Condamine Alluvium and the top of the Walloon Coal Measures acts as a physical barrier that impedes flow between the formations.
- Persistent differences in groundwater levels between the formations, and the flow patterns within the formations, demonstrate that impediments to flow exist between the formations.
- Hydrochemical data suggests that there has been little past movement of water between the formations, even in areas where significant groundwater level differences have existed over a prolonged period.
- Detailed aquifer pumping tests at two sites found no significant flow of water between the formations in response to pumping tests around those sites. The tests show that the vertical hydraulic conductivity for the material between the formations is consistent with that of a highly effective aquitard.

It is concluded that the level of hydraulic connectivity between the Condamine Alluvium and the Walloon Coal Measures is low.

Detailed information and data generated from the project has been incorporated into the regional groundwater flow model developed by OGIA to support preparation of the Surat UWIR 2016.

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Appendices

Appendix 1: Reported water balance components in Condamine Alluvium – an extract from Dafny & Silburn (2013)

Appendix 2: Bores surveyed for mapping groundwater levels in the Condamine Alluvium footprint (2013)

Appendix 3: A list of Walloon Coal Measures bores used for groundwater level mapping

Appendix 4: Images of core samples from selected depths at Daleglade and Cecil Plains

Appendix 5: Laboratory test results of core permeability at Daleglade and Cecil Plains

Appendix 6: Composite bore log for LP-14 (Cecil Plains)

Appendix 7: Summary of hydraulic parameters from pump testing at Daleglade and Cecil Plains