Department of Natural Resources, Mines and Energy
Office of Groundwater Impact Assessment

Underground Water Impact Report for the Surat Cumulative Management Area

July 2019

Queensland Government

This publication has been compiled by the Office of Groundwater Impact Assessment, Department of Natural Resources, Mines and Energy.

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Key summary

- This is the third Underground Water Impact Report (UWIR) since the Surat Cumulative Management Area (CMA) was declared in 2011.
- The report is prepared by the independent Office of Groundwater Impact Assessment and provides for ongoing assessment and management of cumulative impacts from coal seam gas (CSG) development in the Surat and southern Bowen basins
- The report is underpinned by a redeveloped geological model, groundwater flow model and detailed scientific assessments using additional data that has become available since 2016.
- The existing and planned CSG production area has increased by 17% since 2016 with projection of about 21,000 CSG wells. This is around two-thirds of the wells proposed when the projects were approved.
- In two important aquifers, the Hutton Sandstone and the Condamine Alluvium, predicted impacts are less than those predicted in 2016. In contrast, greater impacts are predicted in the Walloon Coal Measures and the Springbok Sandstone.
- Predicted impacts are different from 2016 due to changes in the industry's planned development, improvements in modelling and new knowledge about aquifer connectivity.
- A total of 571 water bores are predicted to be impacted in the long term of which 80% are in the CSG target formations. This is an increase of about 10% compared to 2016 predictions.
- Over the next three years, 100 water bores are predicted to be impacted, for which responsible tenure holders are identified for follow-up make good arrangements.
- Of the 122 bores identified as affected until 2018 through the previous UWIRs, as of mid-2019, make good agreements have been concluded for 99 bores and 71 have been decommissioned.
- Current CSG water extraction is about 60,000 ML/year from 6,800 wells. Average CSG water extraction over the life of the industry is predicted to be around 51,000 ML/year with a peak of about 100,000 ML/year.
- Estimated non-CSG groundwater extraction is about 164,000 ML/year, of which 41,000 ML/year is from the Great Artesian Basin and largely unmetered.
- Analysis of monitoring data suggests that there is evidence of CSG impacts occurring in the Springbok Sandstone, which overlies the CSG target formation. However, there is no evidence of CSG impact in the underlying Hutton Sandstone, even though groundwater levels are generally declining in that formation.
- The monitoring network is to be strengthened from the current operational network of around 600 monitoring points to 622 groundwater level and 103 water chemistry monitoring points. This is an increase of about 10% compared to the network specified in 2016.
- Eight groups of springs are predicted to be impacted by more than 0.2 m of pressure decline in their source aquifers. Of these sites, six are assessed as high risk and require the development of mitigation plans, which are assigned to responsible tenure holders.
- An assessment of the cumulative impacts on environmental values, such as terrestrial groundwater-dependent ecosystems, is included for the first time. Minor areas of risk are identified, mostly associated with impacts in the outcrop of the Walloon Coal Measures.

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Table of contents

List of figures

List of tables

Appendices

Abbreviations

°C ....degrees Celsius

3D....................three-dimensional

AGL ....AGL Energy Ltd (including subsidiaries and joint venture partners)

APLNG ....Australia Pacific LNG (including subsidiaries and joint venture partners)

Armour.............Armour Energy Ltd (including subsidiaries and joint venture partners)

Arrow ....Arrow Energy Ltd (including subsidiaries and joint venture partners)

ATP ....authority to prospect

CDMMR...........cumulative deviation from mean monthly rainfall

CMA ....cumulative management area

CSG ....coal seam gas

DES ....Department of Environment and Science (Queensland)

DNRME ....Department of Natural Resources, Mines and Energy (Queensland)

EA....................environmental authority

EIS....................environmental impact statement

EP Act ....*Environmental Protection Act 1994*

EPBC Act ....*Environment Protection and Biodiversity Conservation Act 1999*

EV....................environmental value

GAB ....Great Artesian Basin

GDE..................groundwater-dependent ecosystem

GWDB ....DNRME's groundwater database

IAA....................immediately affected area

IESC ....Independent Expert Scientific Panel on Coal Seam Gas and Large Coal Mining Development

km ....kilometres

L ....litres

L/s....................litres per second

LAA..................long-term affected area

LNG.................liquefied natural gas

m ....metres

mD...................milliDarcy

MERLIN...........Mineral and Energy Resources Location and Information Network

mg/L ....milligrams per litre

ML ....megalitres

ML/year ....megalitres per year

mm ....millimetres

MNES..............matters of national environmental significance

OGIA ....Office of Groundwater Impact Assessment

Origin ....Origin Energy Ltd (including subsidiaries and joint venture partners)

P&G.................petroleum and gas

P&G Acts.........*Petroleum and Gas (Production and Safety) Act 2004* and *Petroleum Act 1923*

PEST ....model-independent parameter estimation and uncertainty analysis software

PL....................petroleum lease

PLA ....petroleum lease area

psi....................pressure, pound-force per square inch

QDEX..............Queensland Digital Exploration Reports System

QGC ....Queensland Gas Company Pty Ltd (including subsidiaries and joint venture partners)

the Range.........the Great Dividing Range

RE ....regional ecosystem

RTH.................responsible tenure holder

S&D.................stock and domestic

Santos ....Santos Ltd (including subsidiaries and joint venture partners)

SAR..................sodium adsorption ratio

Senex ....Senex Energy Ltd (including subsidiaries and joint venture partners)

SIMS.................Spring Impact Management Strategy

TDS ....total dissolved solids

UWIR................Underground Water Impact Report

Water Act..........*Water Act 2000*

Water EPP........Environmental Protection (Water) Policy 2009

WMS.................Water Monitoring Strategy

Executive summary

Context

This report is the third Underground Water Impact Report (UWIR) for the Surat Cumulative Management Area (CMA) since declaration of the CMA in 2011. The report provides an up-to-date assessment of cumulative groundwater impacts from petroleum and gas (P&G) development in the Surat and southern Bowen basins, and strategies for managing those impacts. The predominant P&G development is for coal seam gas (CSG).

Under the Queensland regulatory framework, a CMA may be declared where groundwater impacts from more than one resource development overlap. Within a CMA, the independent Office of Groundwater Impact Assessment (OGIA) is responsible for assessing cumulative impacts and establishing integrated management arrangements through a UWIR. The assessment is completed every three years in order to accommodate changes to industry development plans and new information about the groundwater flow system.

P&G tenure holders have a statutory right to extract groundwater that is unavoidably taken during production. This extraction is subject to a range of obligations for managing groundwater impacts arising from exercising this right, including monitoring and ‘make good’ of affected water supply bores.

The current UWIR 2019 supersedes the previous two UWIRs, prepared in 2012 and 2016. Preparation of the UWIR 2019 is informed by data from an expanded groundwater monitoring network, recently constructed CSG wells, revised geological mapping, a comprehensive seismic dataset and the outcomes of a significant research program to improve understanding of groundwater systems operating in the area. This new information has been used to redevelop the regional groundwater flow model and improve prediction of impacts from P&G water extraction.

Petroleum and gas development in the Surat CMA

There are two primary target formations for CSG production in the Surat CMA – the Walloon Coal Measures in the Surat Basin and the Permian coal measures (mainly the Bandanna Formation) in the Bowen Basin. The current total CSG tenure footprint is about 26,000 km^2.

Since 2016, the area of existing and planned CSG production in the Surat CMA has expanded by about 17%. Currently, there are approximately 6,800 CSG wells within existing production areas. This is projected to increase to around 21,000 wells based on current industry development plans. Overall, this is about two-thirds of the number originally proposed in Environmental Impact Statements.

OGIA requires tenure holders in the Surat CMA to submit their latest development plans every 12 months. In the recent period, future development plans have generally shifted towards later commencement dates than provided for in previous UWIRs. There are some areas where planned commencement has been brought forward, while some new areas of development have been added within the existing leases.

There are also conventional oil and gas fields within the Surat CMA, but most are towards the end of their production life. Moonie is the major field, accounting for more than half the oil production within the CMA.

Groundwater flow systems and aquifer connectivity

There are aquifers that lie immediately above and below the CSG target formations, particularly in the Surat Basin which is also part of the Great Artesian Basin (GAB). Another major aquifer system, the

Condamine Alluvium, also sits above the coal formation. Understanding the potential for connectivity between the target coal formations and those aquifers is therefore a major focus for OGIA.

Ongoing research by OGIA and others, using new data, has improved the collective understanding of the geology and groundwater flow systems in the Surat CMA. OGIA has also redeveloped the geological model using additional datasets to support research and underpin the construction of the regional groundwater flow model.

The potential for geological faulting to increase connectivity between the coal formations and overlying and underlying aquifers has been further assessed. A total of 32 faults are now explicitly represented in the geological model and 22 of those in the groundwater flow model. In parallel, further analysis of smaller faults indicates that although there is potential to increase connectivity with overlying aquifers at some locations, widespread connectivity is not expected.

Emerging data from CSG well completions has revealed that around 16% of CSG wells may be partially completed into the overlying Springbok Sandstone. This has the potential to induce direct connectivity with the underlying Walloon Coal Measures, although separate analysis suggests that the amount of water being contributed from the Springbok Sandstone is minor. Regardless, the partial completion of CSG wells into the Springbok Sandstone is now explicitly represented in the regional groundwater flow model.

An assessment of the potential for connectivity between the Condamine Alluvium and underlying Walloon Coal Measures has continued, with more recent data reaffirming previous findings that suggested low connectivity.

Groundwater extraction and use

There are approximately 22,500 water bores in the Surat CMA. Of these, around 8,100 access the formations in the GAB, predominantly for stock and domestic (S&D), stock intensive, industrial and town water supply purposes. About 13,500 bores access the overlying alluvium (mainly the Condamine Alluvium) and tertiary basalts for irrigation and S&D purposes. The remaining bores access the underlying Bowen Basin.

The majority of non-CSG groundwater extraction is not metered, resulting in a high degree of uncertainty in relation to actual use. The approach initially developed for the UWIR 2016 for estimating unmetered groundwater is now further improved. Based on this refined approach and new data, current non-CSG groundwater extraction in the CMA is estimated to be around 164,000 ML/year – 20% less than previous estimates. Of this, about 25% is from the GAB formations.

CSG groundwater extraction has been relatively steady over the last three years at around 60,000 ML/year. This is likely due to a combination of declining water extraction from maturing fields and an increasing number of CSG wells in nearby areas. Extracted water is treated and primarily used for beneficial purposes or reinjected into aquifers. One reinjection scheme is currently operational, injecting around 5,000 ML/year into the Precipice Sandstone.

Trends in groundwater level

Observed trends in groundwater levels are used to build and validate the conceptualisation of the groundwater flow system and to identify impacts that may have occurred. Importantly, monitoring data is also used to calibrate the groundwater flow model, together with estimates of CSG and non-CSG groundwater extraction.

Observed groundwater levels from monitoring in formations surrounding the CSG reservoir may show a combined effect of CSG and non-CSG impacts. Separating the two influences from observed groundwater levels is challenging because, in most circumstances, neither impact can be measured directly. Therefore, a multiple-lines-of-investigation approach is applied to establish if CSG impacts have contributed to observed trends.

CSG groundwater extraction from the Walloon Coal Measures increased rapidly from late 2013 to mid-2015. In some areas, water levels have declined by up to 250 m in the immediate vicinity of CSG production in response. The level of decline is greater in the lower part of the formation compared to the upper part. However, available data indicates impacts are confined to within 10-15 km of the CSG fields.

Groundwater level monitoring data for the Springbok Sandstone, which overlies the Walloon Coal Measures, shows evidence of CSG impacts in at least three of the monitoring points within the CSG production area.

The Hutton Sandstone aquifer, which underlies the Walloon Coal Measures, is separated from the coal reservoir by the Durabilla Formation – an extensive aquitard. Groundwater level trends in the Hutton Sandstone are of particular interest because it is a major water supply aquifer in the GAB and declines of up to 1.5 to 2 metres per year have been observed recently at some locations. Analysis indicates that at this stage, there is no evidence to suggest that these declines are due to CSG water extraction from the overlying Walloon Coal Measures. Non-CSG groundwater extraction from the Hutton Sandstone aquifer itself is likely to be the primary cause of the declining trends. CSG depressurisation may be a contributing factor in some areas, but there is no evidence to support this. Some minor impacts are predicted in the longer term and the findings are largely consistent with predictions reported in the previous UWIR.

There is also no evidence of CSG impacts in the Precipice Sandstone from CSG development. Reinjection is the dominant positive effect on water levels in these areas. Similarly, there is no evidence of CSG-related impacts in the Condamine Alluvium.

Available water chemistry data from all formations is assessed to understand the long-term movement of water through the groundwater system. At this stage, other than in isolated areas of the Walloon Coal Measures, no significant changes in water chemistry are observed that could be related to CSG groundwater extraction.

Modelling of impacts

The regional groundwater flow model has been redeveloped to assess the impacts on water levels from current and proposed P&G development activities. New techniques developed for the previous UWIR model are further enhanced and significantly more monitoring data, which has become available since 2016, has now been used to calibrate the model. The groundwater model is also based upon a revised geological model that incorporates up-to-date mapping and recent CSG well and geophysical data.

The groundwater flow model is constructed using MODFLOW USG. It is a complex model, as it simulates 34 layers of geological strata over a large area – about 450 x 650 km. The model accounts for dual phase flow (the movement of gas and water together) in coal seams, faults and the partial completion of CSG wells into the Springbok Sandstone. Detailed individual models, known as numerical permeameters, were also constructed to develop formation-scale permeability values from the extensive available lithological and geophysical data.

To account for ambiguities associated with simplifications used in model construction and inaccuracies in source data, an uncertainty analysis is also completed. This effectively involves generating hundreds of different versions of the model that are consistent with the data and then using these models to generate a range of predictions.

Prediction of groundwater impacts

The groundwater flow model is used to predict short-term and long-term pressure impacts in aquifers due to existing and planned CSG development. Short-term impacts are presented as the Immediately Affected Area (IAA) for each aquifer, which is an area where a decline in groundwater levels of more than five metres is predicted within the following three years. Water supply bores accessing water in an aquifer within its IAA are known as IAA bores. These predictions underpin proactive make good arrangements.

Long-term impacts are presented as the Long-term Affected Area (LAA), which is the area of an aquifer where a decline in water levels of more than five metres is predicted at any time in the future. In addition, patterns of long-term impacts are also presented together with a range of predictions from the uncertainty analysis to underpin the assessment of risk to springs and other management strategies.

In the short term, there are two formations where IAA bores are identified – the Walloon Coal Measures and the Springbok Sandstone. There are 100 bores identified as IAA bores for the first time, of which 91 are in the Walloon Coal Measures. This reflects the continued expansion of the existing CSG production area and further propagation of impacts over time.

A total of 122 bores have been effectively identified as IAA bores from the previous UWIRs. Of those bores, 88 bore assessments have been completed as of March 2019 and 99 make good arrangements have been concluded so far.

The prediction of the total number of LAA bores has increased from 518, in the UWIR 2016, to 571 – an increase of about 10%, although 122 of those bores have already been decommissioned or are in the process of being decommissioned. The most significant changes to the predictions of LAA bores relate to the Walloon Coal Measures and the Springbok Sandstone where impacts are greater than previously predicted in the UWIR 2016. In contrast, the long-term impacts in the Hutton Sandstone, the Precipice Sandstone and the Condamine Alluvium are less compared to those previous predictions.

The most change is seen in the Springbok Sandstone. This is due to the improved representation of the upper part of the Walloon Coal Measures and the partial completion of CSG wells into the lower part of the Springbok Sandstone. In contrast, predictions of less extensive impacts in the Hutton Sandstone and the Condamine Alluvium relate to lower vertical permeability for the aquitard that separates these formations from the Walloon Coal Measures.

CSG groundwater extraction over the life of the industry is now predicted to average about 51,000 ML/year with a peak of about 100 ML/year.

Water Monitoring Strategy

Water monitoring requirements are outlined in the Water Monitoring Strategy (WMS), which has three main components: the specification of groundwater monitoring points and monitoring parameters that comprise the network; tenure holder obligations for installing and operating the network; and tenure holder obligations for the provision of data collected from the network.

Since the UWIR 2012, a substantial groundwater monitoring network has been built across the Surat CMA, resulting in the installation of around 600 monitoring points. The WMS in UWIR 2019 has now expanded to include 622 water pressure and 103 water chemistry monitoring points – an increase in the network of 10%. The strategy also provides for the progressive replacement of monitoring points that are considered unsuitable for ongoing monitoring. Around half of the pressure monitoring network points are within the CSG target formations.

There are also complementary networks including DNRME's networks, Groundwater Online and Groundwater Net, which provide bore owners with information about the condition of their bores and trends in water levels. These networks also provide additional data to support OGIA's assessment.

Spring Impact Management Strategy

There are 52 spring complexes and 78 watercourses that overlie aquifers predicted to be affected by more than 0.2 m as a result of CSG water extraction. Most of these sites are located within the outcrop areas of GAB aquifers, towards the north of the Surat CMA. In most cases, the affected aquifer is not the source aquifer for the spring of watercourse.

Eight sites are identified where impact of more than 0.2 m as a result of CSG water extraction is predicted in a spring's source aquifer. Predicted impacts are typically less than a metre. At six of these sites, relatively high risks have been identified. At these sites, tenure holders are required to further investigate the local hydrogeology to improve the assessment of risk, and develop mitigation actions.

At this stage, impacts on springs from CSG development are not observed at any site. Most will not be impacted because their source aquifers are not affected, or the predicted impact is small.

The risk of changes to the hydrology and ecology of springs is reassessed in each UWIR cycle on the basis of improved knowledge about local hydrogeology and the current impact predictions. The risk assessment informs the design of future research, adjustment to the monitoring program and, where necessary, development of mitigation actions.

Environmental values and environmental assets

Legislative changes in late 2016 extended the scope of the environmental values (EVs) to be assessed as part of the UWIR. In this report, OGIA has characterised and assessed the risk to terrestrial groundwater-dependent ecosystems (GDEs) and the risk of subsidence on the broader suite of EVs.

Potential terrestrial GDEs are mapped and risk is assessed. In most cases, the risk is low, but some limited areas of higher risk are identified. Further research is required to verify whether groundwater is supporting individual terrestrial GDEs and clarify their resilience to groundwater drawdown. A risk-based assessment has also been completed on the likelihood of subsidence occurring as a result of CSG extraction. The risk to EVs is low or moderate with the exception of one reach of Woleebee Creek near Wandoan, where the risk is relatively high.

Responsible tenure holder obligations

In a CMA, where a number of petroleum tenure holders operate, there are overlapping impacts.

The UWIR sets out management actions and assigns responsibilities for individual tenure holders. These include the requirement to complete bore assessments at water supply bores identified as IAA bores, implementing make good measures where bores are likely to be impaired, as well as implementing actions under the WMS and SIMS.

Since the impacts from tenure holders may overlap in a CMA, clarity is provided in assigning individual responsible tenure holders for the management obligations, through rules specified in the UWIR. The rules were established initially in the first UWIR in 2012 and are refined to provide increased clarity for both tenure holders and affected landholders.

Periodic reporting and research

OGIA will continue to provide the Department of Environment and Science with annual reports on the implementation of the UWIR. Annual reports describe any changes to circumstances that may affect the predictions of impact made in the UWIR, and updates on the implementation of management actions specified in the UWIR.

OGIA will continue to implement an independent multidisciplinary research program focussing on ongoing improvement in groundwater modelling, analysis and re-evaluation of trends in monitoring data as more data becomes available.

Chapter 1 Introduction

1.1 Water rights of petroleum tenure holders

In Queensland, the *Petroleum and Gas (Production and Safety) Act 2004* and the *Petroleum Act 1923* (collectively referred to here as the P&G Acts) authorise petroleum tenure holders to undertake activities related to petroleum exploration and production. Petroleum tenure holders have a statutory right to take or interfere with underground water (or groundwater). Water taken under this right is referred to as ***associated water***[1], and the right to take the water is referred to as an ***underground water right***. This right has existed for petroleum and gas (P&G) activities since 1923 to provide for safe operating conditions and to achieve the pressure necessary to extract petroleum and gas.

Since 2010, under the Queensland *Water Act 2000* (Water Act), tenure holders are subject to a number of responsibilities to manage groundwater impacts arising from the exercise of underground water rights. These responsibilities, collectively referred to as the ***underground water management framework***, include the requirement to assess, monitor and manage impacts on water bores caused by the exercise of underground water rights, and to enter into 'make good' agreements with the owners of impacted water bores.

Recent changes to legislation that commenced in late 2016 now apply the same underground water management framework to most mining activities. The changes have also rationalised P&G tenure holders' rights to non-associated water, such as for the construction of roads and camps, for which water licences are now required.

1.2 Underground water management framework

The underground water management framework under Chapter 3 of the Water Act provides for:

- periodic assessment of groundwater impacts on aquifers, including predictions of impacts on water bores and environmental values
- a baseline survey of all water bores in and around the tenures
- detailed assessment of potentially affected water bores to establish whether their capacity to supply water will be impaired
- an obligation for tenure holders to put measures in place to make-good affected water bores
- development and implementation of a groundwater monitoring network
- development and implementation of a strategy for managing impacts on environmental assets and values
- preparation of an **Underground Water Impact Report (UWIR)** every three years to report the outcomes of the assessment and management arrangements outlined above.

A draft UWIR must be released for public consultation prior to being finalised. After consideration of issues raised through submissions, the report is submitted to the Queensland Department of Environment and Science (DES) for approval. Once approved, the report becomes a statutory instrument and provides a basis for ongoing management of groundwater impacts in line with the

[1] Terms in bold and italics are listed in the Glossary

strategies outlined in the report. Annual reporting is required to provide an update on any changes in circumstances that would affect impact predictions in the UWIR.

1.3 Assessment and management of cumulative impacts

Impacts on groundwater pressure from two or more resource development activities can overlap. In these situations, it is difficult for individual tenure holders to assess cumulative groundwater impacts and to determine individual tenure holder responsibilities for monitoring and make-good obligations. Therefore, to ensure that a comprehensive cumulative groundwater assessment is completed and to provide clarity on management responsibilities of the involved tenure holders, an area containing projects with overlapping impacts can be declared a **cumulative management area (CMA)** under Chapter 3 of the Water Act.

When a CMA is established, tenure holders' responsibilities for preparing the UWIR are displaced. In a CMA, the **Office of Groundwater Impact Assessment (OGIA)** – an independent statutory entity – becomes responsible for preparing a single UWIR for the whole area and undertaking assessments, establishing management arrangements and identifying responsible tenure holders to implement specific aspects of those management arrangements. Responsible tenure holders have a legal obligation to implement management activities assigned in the UWIR. OGIA oversees the implementation of those arrangements while DES remains the regulatory agency for compliance with those obligations.

1.4 The Surat CMA

Established in 2011 in response to coal seam gas (CSG) development, the Surat CMA (Figure 1-1) covers the area of current and planned CSG development in the Surat Basin and the southern Bowen Basin, described in detail in the next chapter. Thus far, no other CMAs have been established.

The Surat CMA straddles the Great Dividing Range (the Range) and falls within a region covering various catchments of both the southern Fitzroy River Basin and the northern Murray-Darling Basin.

The Range divides the Murray-Darling Basin river systems, which are dominated by the Condamine and Balonne rivers, from the northerly and easterly flowing Nogoa, Comet, Dawson and Boyne river systems. The Condamine-Balonne river system is the dominant surface drainage system in the south of the region. The Condamine River originates in elevated areas south of Warwick and flows north-west towards Chinchilla where it then turns westward towards Roma and becomes part of the Balonne River, draining towards the south-west across the border into the Darling River system.

The climate of the area is sub-tropical with most rainfall occurring in summer, between November and February. Rainfall and runoff are highly variable and evaporation rates are high. Consequently, many of the rivers and streams in the area are ephemeral.

The predominant land use in the region is agriculture, including broadacre cropping, horticulture, grazing and lot feeding. Other land uses include urban, industrial, CSG and conventional P&G extraction, mining (mainly coal) and conservation.

1.5 Previous UWIRs for the Surat CMA

The first Surat UWIR was prepared by OGIA (then part of the Queensland Water Commission) in 2012, followed by a second UWIR that came into effect in September 2016. Those are now superseded by this UWIR 2019. The UWIR 2019 was finalised following the release of a consultation draft in May 2019.

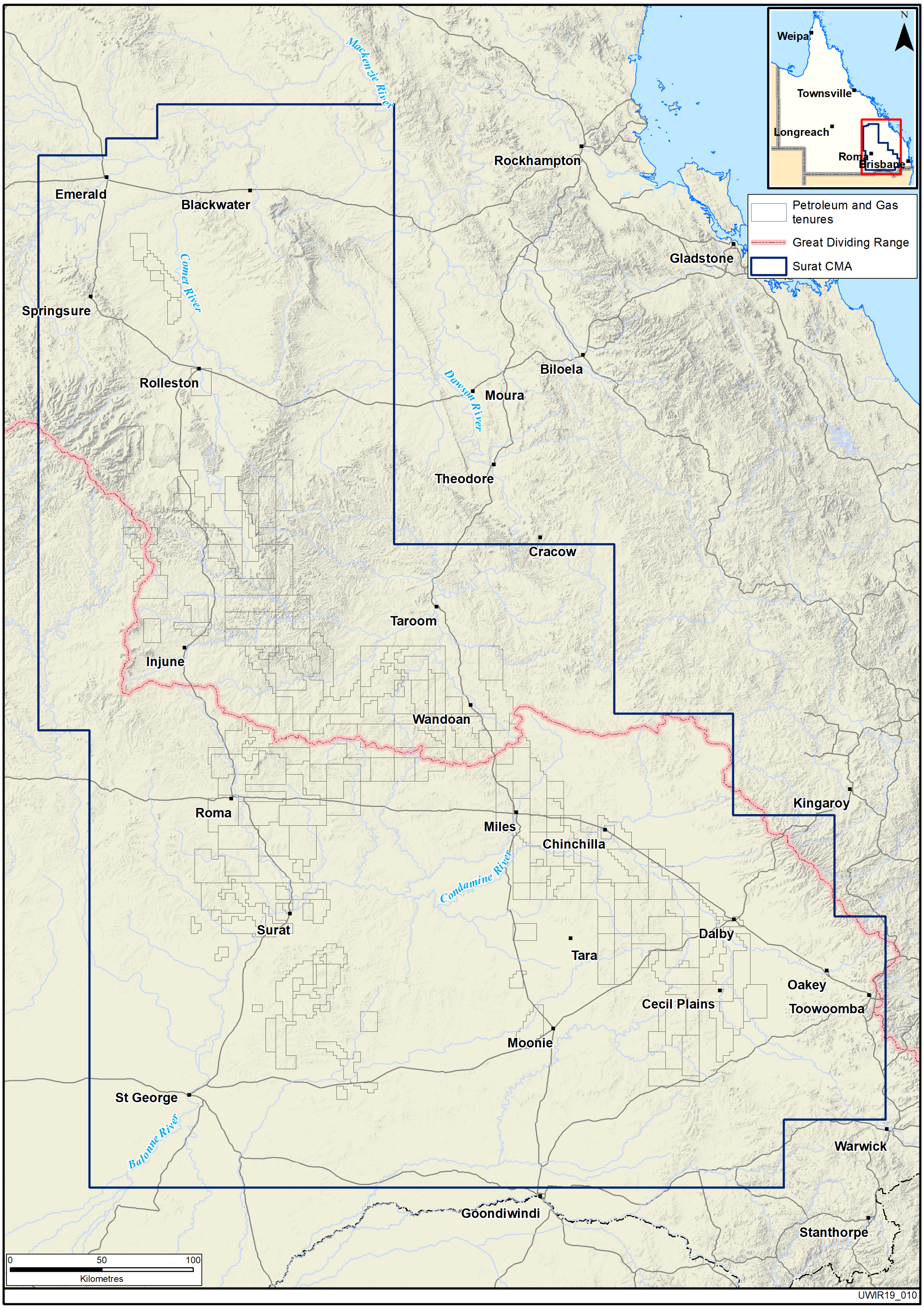

Figure 1-1 The Surat Cumulative Management Area (Surat CMA)

1.6 Scientific assessment underpinning the UWIR

For the first UWIR, OGIA's approach was to rely on pre-existing information and secondary interpretation of datasets to build a regional conceptualisation and a numerical groundwater flow model. The next UWIR cycle involved additional primary data analysis, hydrogeological investigation, conceptualisation and development of innovative modelling approaches.

Since the UWIR 2016, a range of additional datasets has become available including: geological and hydrogeological properties from additional CSG wells; groundwater monitoring data from a network of about 600 monitoring points established through the UWIR obligations; and a range of other monitoring data. This updated data and information were used in the current third cycle of UWIR development. Research focused on three areas:

- improving regional-scale conceptualisation and modelling, e.g. revising the geological model, analysing regional trends in groundwater levels, updating the groundwater flow model, analysing hydrochemistry and verifying baseflow-fed watercourses
- sub-regional-scale hydrogeological assessments around CSG gas fields that have been in production for some time and where significant new monitoring data is now available
- improving methods and tools for assessment, such as estimation of non-P&G water use, modelling techniques, uncertainties due to bore connectivity and geological faults and spring monitoring.

The research is detailed in a number of technical reports by OGIA. A list of these reports is provided in Appendix A and they are also available on OGIA's website.

1.7 Structure of the report

The report is broadly structured in three parts – contextual background on existing and proposed P&G development and groundwater assets (Chapters 1 to 4); assessment of impacts on groundwater assets (Chapters 5 to 7); and strategies for managing those impacts (Chapters 8 to 12).

Chapter 2 provides an overview of petroleum and gas tenures and associated activities in the Surat CMA. Chapter 3 summarises the geology and groundwater systems. Historical and current groundwater extraction in the CMA is summarised in Chapter 4.

A summary of current conditions and trends in groundwater pressure monitoring data including analysis of the potential CSG impacts that may have occurred so far is presented in Chapter 5. Chapter 6 describes the techniques and methods used for predicting groundwater impacts, and important aspects of the construction of the regional groundwater flow model. Chapter 7 sets out the predictions of impacts on aquifers, water bores and environmental assets.

Chapter 8 specifies the water monitoring strategy, which is the regional network of monitoring points used for assessing water pressure trends. Chapter 9 specifies the strategy for managing impacts on springs in the area. Chapter 10 describes other environmental values – a new scope for this UWIR. Chapter 11 details the rules for assigning responsibilities to individual petroleum tenure holders for strategies and other reporting obligations identified in the report. Finally, Chapter 12 lays out requirements for reporting on the implementation of actions specified in the UWIR.

Chapter 2 Petroleum and gas development in the Surat CMA

This chapter provides contextual information about petroleum and gas (P&G) development activities in the Surat CMA, production methods, as well as current and proposed production footprints. This information was used to prepare an industry development scenario for input to the regional groundwater flow model for predicting impacts of P&G development on groundwater.

In the P&G Acts, ***petroleum*** includes naturally occurring hydrocarbons such as oil, gas and CSG. These are collectively referred to as P&G.

2.1 Petroleum and gas production methods

Naturally occurring P&G is extracted from geological formations using conventional and unconventional methods. Conventional methods refer to the direct extraction of P&G residing in porous rock formations such as sandstone and are termed ***conventional petroleum and gas***. In recent decades, unconventional methods have been developed to extract gas (***unconventional gas***) from other formations including coal formations (CSG) and low-porosity rock formations such as shale (shale gas) or low-permeability sandstone/siltstone (tight gas). CSG is typically extracted from relatively shallower depths of 200 to 1000 m, while shale gas and tight gas are extracted from depths of 1,000 to 5,000 m.

In the Surat CMA, conventional production dates back to the 1960s and is now approaching end of life. The predominance of CSG is evident from total reported gas production in the Surat and Bowen basins (Figure 2-1) which shows a sharp rise in CSG production since around 2005 and a steady decline in conventional oil and gas production since 1995. Currently, there are no existing or proposed shale gas or tight gas developments in the Surat CMA except a single instance of a recent exploration well south of Roma.

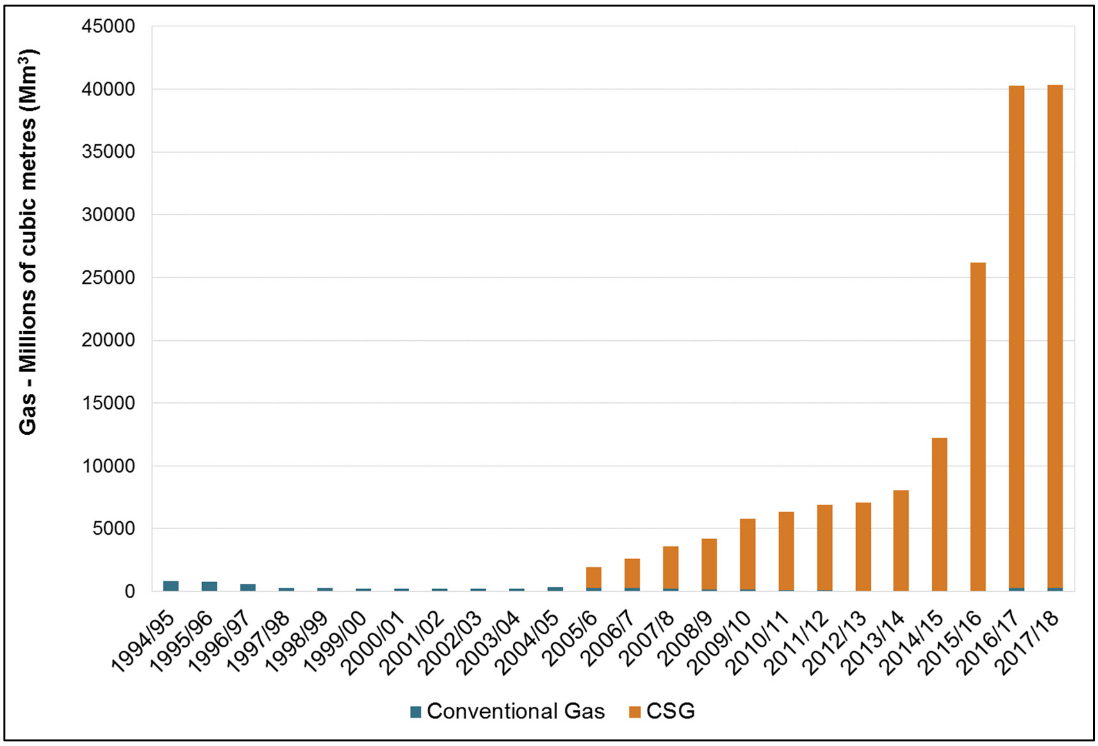

Figure 2-1 Trends in total conventional gas and CSG production in the Surat CMA

In the context of groundwater, there are some fundamental differences between conventional and unconventional methods:

- The volume of associated water extracted using conventional production methods is much less than the volume of water extracted during CSG production.
- Unlike P&G in conventional reservoirs, CSG is distributed over a relatively large area and requires a large number of production wells to extract gas.
- In the life of a CSG production well, water extraction peaks early, while for conventional production, water extraction increases over time before declining again in mature stages of development.

2.1.1 Conventional petroleum and gas

Conventional P&G is found in porous rock formations such as sandstone. Gas and other petroleum products, formed over millions of years, move through the porous rock in a generally upward direction until a trap stops the movement and concentrates the hydrocarbons. The trap could be dome-shaped at the boundary between the permeable formation and the overlying impermeable formation, or it could be a faulted structure in the rock, having the same effect. As the gas concentrates, the porous rock becomes a gas reservoir.

Traps are formed either by folds and other structures in sedimentary layers (structural traps) or where more permeable formations transition into impermeable formations (stratigraphic traps). While both structural and stratigraphic traps are found within the Surat CMA, stratigraphic traps are more prevalent. The Moonie oil field and the Peat and Scotia gas fields are examples of structural traps (Department of Natural Resources and Mines 2017), whereas the Roma and Surat gas fields are typical of stratigraphic traps on the western limb of the Taroom Trough. A schematic diagram of oil and gas accumulation types is shown in Figure 2-2.

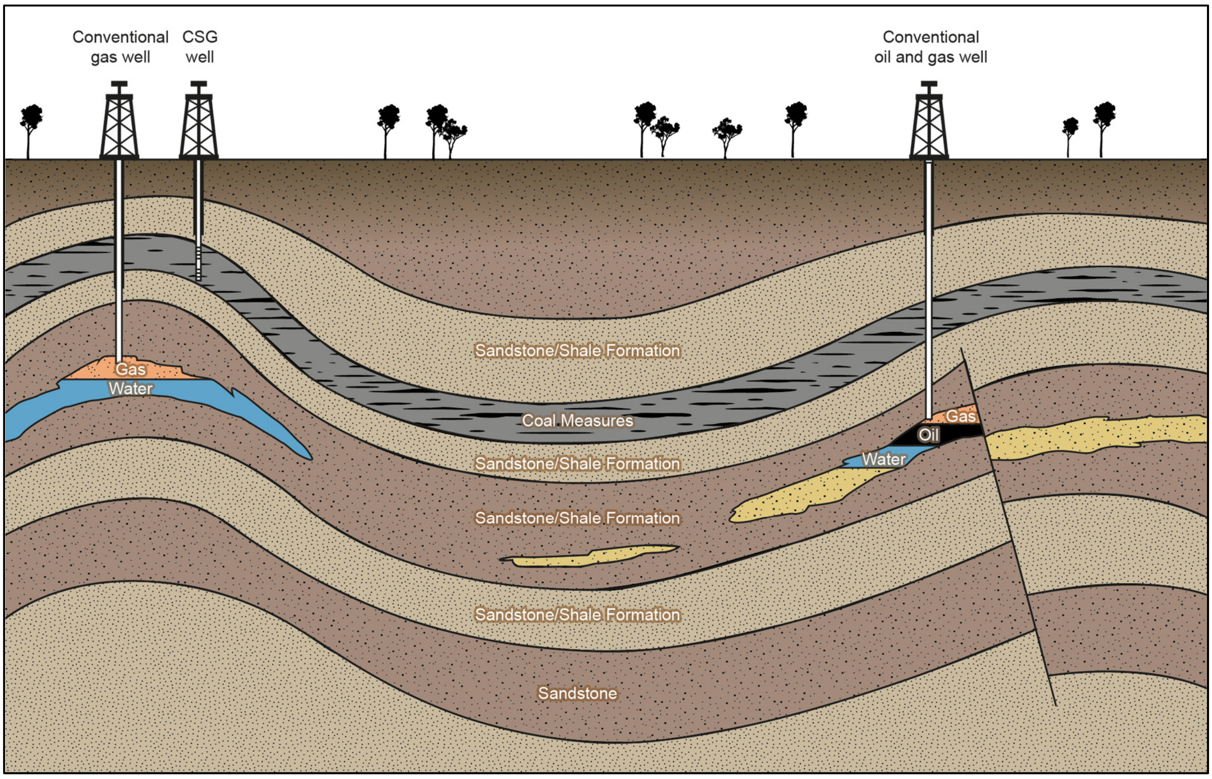

Figure 2-2 Schematic of oil and gas accumulation types

Extraction of gas from conventional reservoirs requires a relatively small number of production wells compared to CSG reservoirs, because the gas tends to be localised and can move relatively easily though the porous rock towards the well. Although water is extracted along with the gas, there is no need to lower water pressure over large areas to produce the gas. The volume of water extracted varies, but is generally much less than for CSG.

2.1.2 Coal seam gas

CSG is a natural gas – typically methane with small percentages of other gases such as ethane, butane, propane and pentane. It is attached to the surface of coal particles, along fractures and cleats, and is held in place by water pressure. The coal is both the source and the reservoir of the gas. The gas is extracted by drilling a well into the coal formation and pumping groundwater out of the well to depressurise the formation. The volume of water that needs to be pumped to achieve the pressure reduction varies from well to well and is highly dependent on the geology intersected by the well.

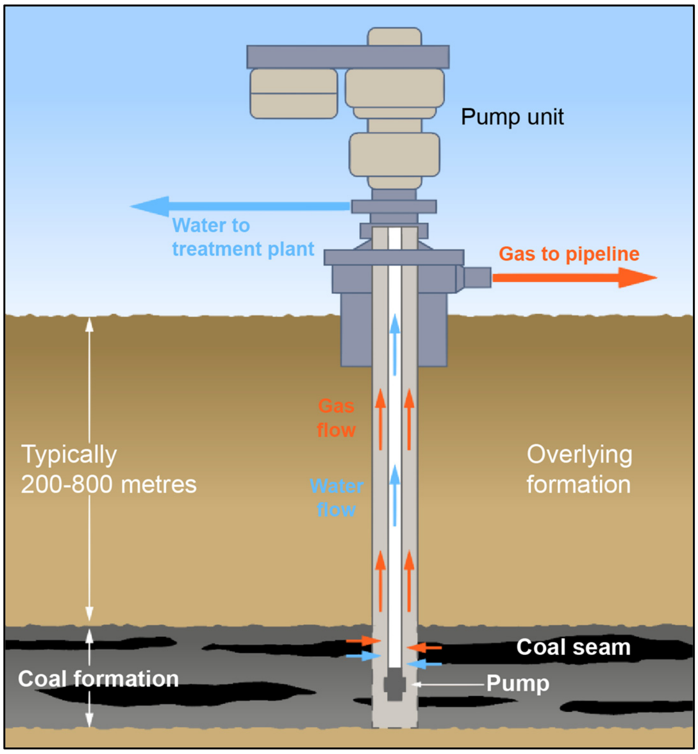

Figure 2-3 Typical layout of a CSG well

A typical layout of a CSG well is shown in Figure 2-3. To produce gas, the water pressure in the well is reduced to 35–120 psi, which is equivalent to 25–80 metres head of water. Once the desired pressure is reached, pumping continues at the rate necessary to maintain the pressure, until gas production becomes uneconomical. Initially, as shown Figure 2-4, groundwater alone is extracted, but as the pressure drops, more and more gas is released and extracted together with water, leading to an increasing ratio of gas to water over time. The flow of water and gas together is known as 'dual phase flow' (Morad, Mireault & Dean 2008).

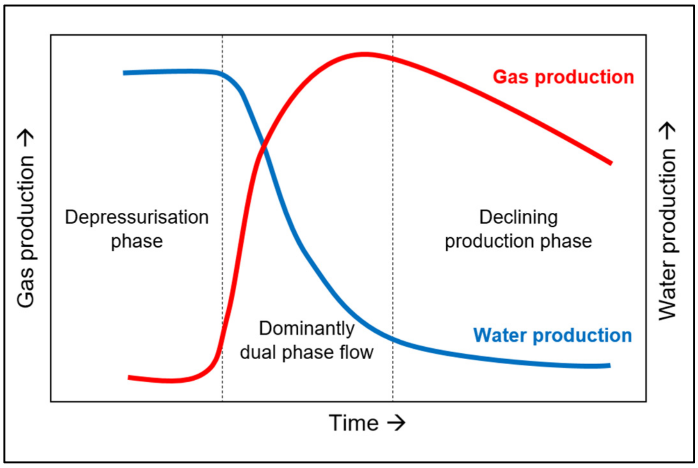

Figure 2-4 Typical gas and water flow profile during CSG production

2.2 Tenure and authorities

2.2.1 Tenure system

The Queensland P&G Acts specify authorities that can be granted for activities related to petroleum and gas exploration and production. The two authorities of relevance to this report are those that provide associated water rights to the tenure holders; namely, an authority to prospect (ATP) and an authority to operate a petroleum lease (PL). These authorities are referred to collectively in this report as **petroleum tenures**. Petroleum tenures provide rights in relation to gas as well as other petroleum products, such as oil.

There is no distinction between a petroleum tenure that supports conventional P&G production and a petroleum tenure that supports CSG production. However, the use of the tenure is usually constrained by the environmental authorities granted under Queensland's *Environmental Protection Act 1994* (the EP Act) or the development plans for the tenure approved under the P&G Acts. Petroleum tenures relate to specific areas of land which are generally described in terms of blocks and sub-blocks. Each block is about 75 km^2 and each sub-block is about 3 km^2.

An ATP gives the tenure holder the right to explore (or prospect) for petroleum resources. That right includes drilling test wells to evaluate petroleum resources, carrying out test production and taking groundwater in the course of carrying out those activities. A tenure holder may relinquish all or a part of a tenure at any time.

The holder of an ATP may apply for a PL if a commercially viable petroleum resource is discovered. The application must be accompanied by an initial development plan that details the nature and extent of the proposed activities. Once granted, a PL authorises the holder to carry out production testing, produce petroleum within the tenure area and take groundwater in the course of carrying out these activities. A PL can be granted for up to 30 years, with potential for renewal. All water extraction must be reported to the Department of Natural Resources, Mines and Energy (DNRME).

The entities that hold petroleum tenures are referred to as ***petroleum tenure holders***. As tenures are often held as joint ventures, when DNRME grants an ATP or PL, it assigns a single entity as the **authorised holder**. The authorised holder is the primary contact for the petroleum tenure and is legally responsible for dealing with served notices and other documents. All references to tenure holders in this report refer to the authorised holders.

DNRME records all mining and petroleum tenure information in the MyMinesOnline system. General petroleum tenure holder information stored in this database is publicly accessible. Information about petroleum wells (test and production) and water extraction is recorded in the Queensland Digital Exploration Reports System (QDEX).

2.2.2 Recent changes to petroleum tenure holders' water rights

As stated in section 1.1, petroleum tenure holders' statutory right to take or interfere with groundwater has existed since 1923. Recent changes to legislation, which commenced on 6 December 2016, rationalised these rights – by making a distinction between the rights associated with 'associated water' and 'non-associated water' – and also applied the same rights to the mining sector.

Associated water is groundwater[2] that is taken, or interfered with, as a result of carrying out an authorised activity for the tenure[3], such as groundwater extraction to depressurise the reservoir for gas production or drilling of a petroleum well. Tenure holders have a statutory right to take this water, subject to a range of obligations relating to impact assessment and management arrangements.

Non-associated water is any extracted groundwater that is not associated water. This typically includes groundwater extraction by tenure holders for consumptive purposes such as construction activities or camp supplies. For non-associated water take, tenure holders now require water licences, or similar authorisation under the Water Act. On 6 December 2016, transition periods for existing operations commenced, during which water licences need to be obtained – within five years for tenures inside a CMA and within two years for tenures outside a CMA.

2.2.3 Linkages to environmental approvals

An environmental authority (EA) under the EP Act is required before a tenure can be granted. A single EA can apply to multiple petroleum tenures. In relation to water, the EA primarily deals with the management of surface water and contamination issues relating to surface and groundwater. Groundwater impact assessment and management obligations are adaptively managed in Queensland through the UWIR, under Chapter 3 of the Water Act.

The broad impacts of a major P&G project on groundwater resources are considered through the environmental impact assessment process prior to the granting of environmental authorities and tenure. A prospective PL holder is required to develop an environmental management plan to support an application for an EA. An environmental management plan identifies the environmental values, potential impacts and actions to protect environmental values. An environmental impact statement (EIS) prepared for a declared 'coordinated project' under the Queensland *State Development and Public Works Organisation Act 1971* requires the Coordinator-General’s report for the project before a tenure can be granted. The tenure conditions must be consistent with the Coordinator-General’s conditions.

In relation to the management of extracted CSG water on the surface, the Queensland Government CSG water management policy encourages the beneficial use of CSG water in a way that protects the environment and maximises its productive use. CSG water must be used beneficially first before treating and disposing in a way that avoids, and then minimises and mitigates, impacts on environmental values.

The Australian Government *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act) identifies matters of national environmental significance (MNES) that are to be protected, including a number of springs in the Surat CMA. The EPBC Act also establishes water resources in relation to CSG developments as MNES. As a result, all proposals for CSG developments that are likely to have significant impacts on water resources require approval under the EPBC Act. This requirement is known as the ‘water trigger’. Such approvals are typically subject to a range of conditions for the assessment and management of impacts. The Australian Government also seeks advice from the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the IESC) in the process of making decisions about the projects.

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[2] In this report, reference to groundwater is the same as ‘underground water’.
[3] As defined in section 185 of the *Petroleum and Gas (Production and Safety) Act 2004*.

2.3 Petroleum and gas tenures in the Surat CMA

The locations of all P&G tenures in the Surat CMA as of February 2019 are shown in Figure 2-5. Three types of tenures are presented: ATPs or exploration tenures; PLs, which authorise production; and petroleum lease applications (PLA), which are ATPs under application to become PLs, on which production testing can therefore occur.

Close to 20% of the CMA is covered by ATPs that have little or no activity in relation to water extraction. In the context of this report, the term ***relevant tenures*** is therefore used to refer to all tenures that are either PLs or PLAs. PLAs are included because they are part of ATPs for which tenure holders have firm proposals for production and have applied for EAs. There are other ATPs where EAs have been applied for, or where EISs have been completed or submitted but application for PLs have not yet been lodged. These are referred to as ***potential relevant tenures*** because, in the future, they may be subject to PL applications. There are also some ATPs or areas where tenure holders have indicated an intention to apply for EAs or produce EISs in the more immediate future. These are referred to as **other relevant tenures**.

The distribution of relevant tenures, potential relevant tenures and other tenures is shown in Figure 2-6. These relevant tenures are grouped in different colours in the figure to show major authorised holders for those respective tenures, representing:

- AGL, its subsidiaries and joint venture partners (collectively referred to as **AGL**)
- Armour Energy, its subsidiaries and joint venture partners (collectively referred to as **Armour**)
- Arrow Energy, its subsidiaries and joint venture partners (collectively referred to as **Arrow**)
- Bridgeport, its subsidiaries and joint venture partners (collectively referred to as **Bridgeport**)
- Origin Energy, its subsidiaries and joint venture partners including Australia Pacific LNG (collectively referred to as **Origin**)
- Queensland Gas Company, its subsidiaries and joint venture partners (collectively referred to as **QGC**)
- Santos, its subsidiaries and joint venture partners (collectively referred to as **Santos**)
- Senex Energy, its subsidiaries and joint venture partners (collectively referred to as **Senex**)
- **other** authorised holders.

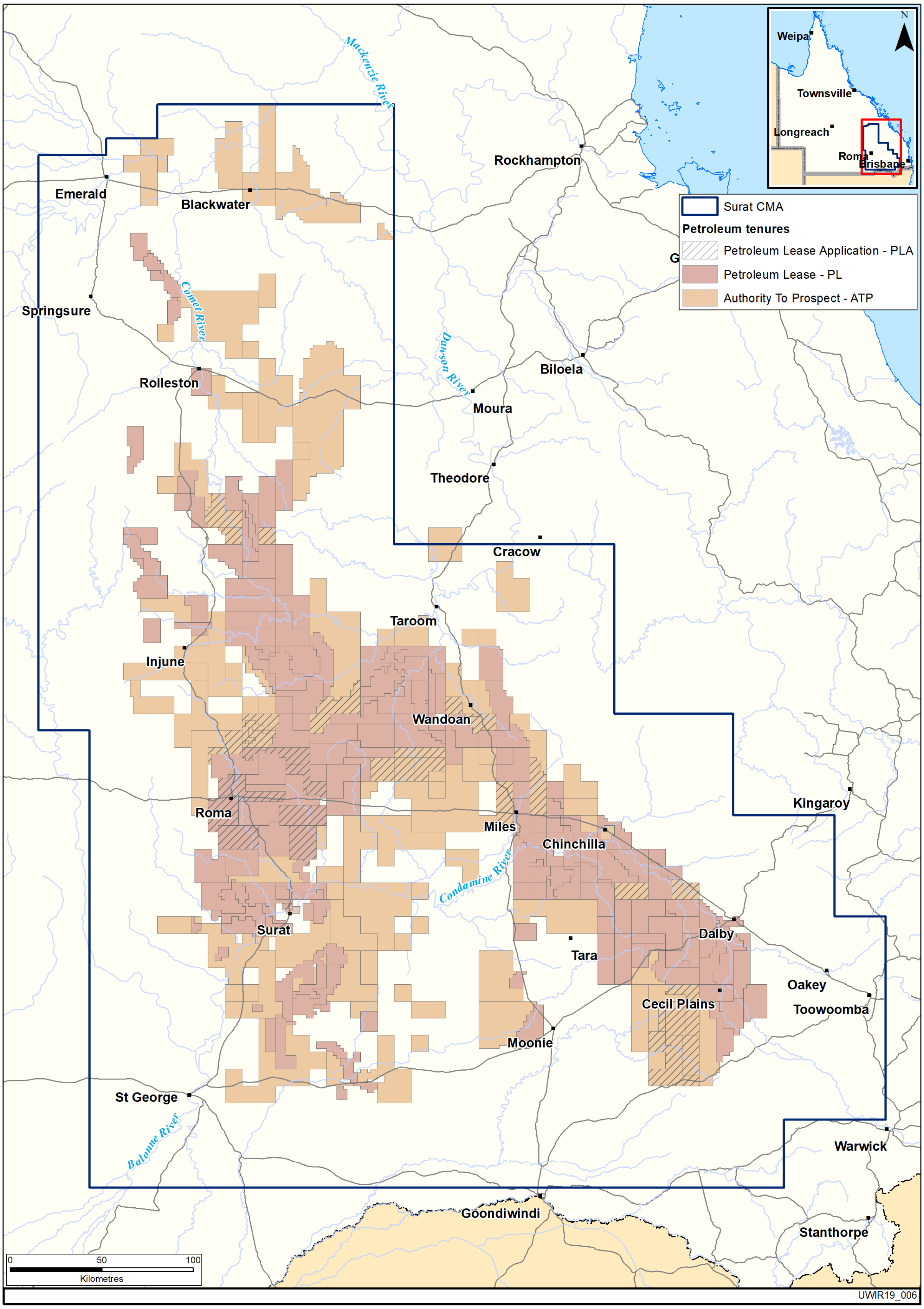

Figure 2-5 Distribution of petroleum and gas tenures in the Surat CMA

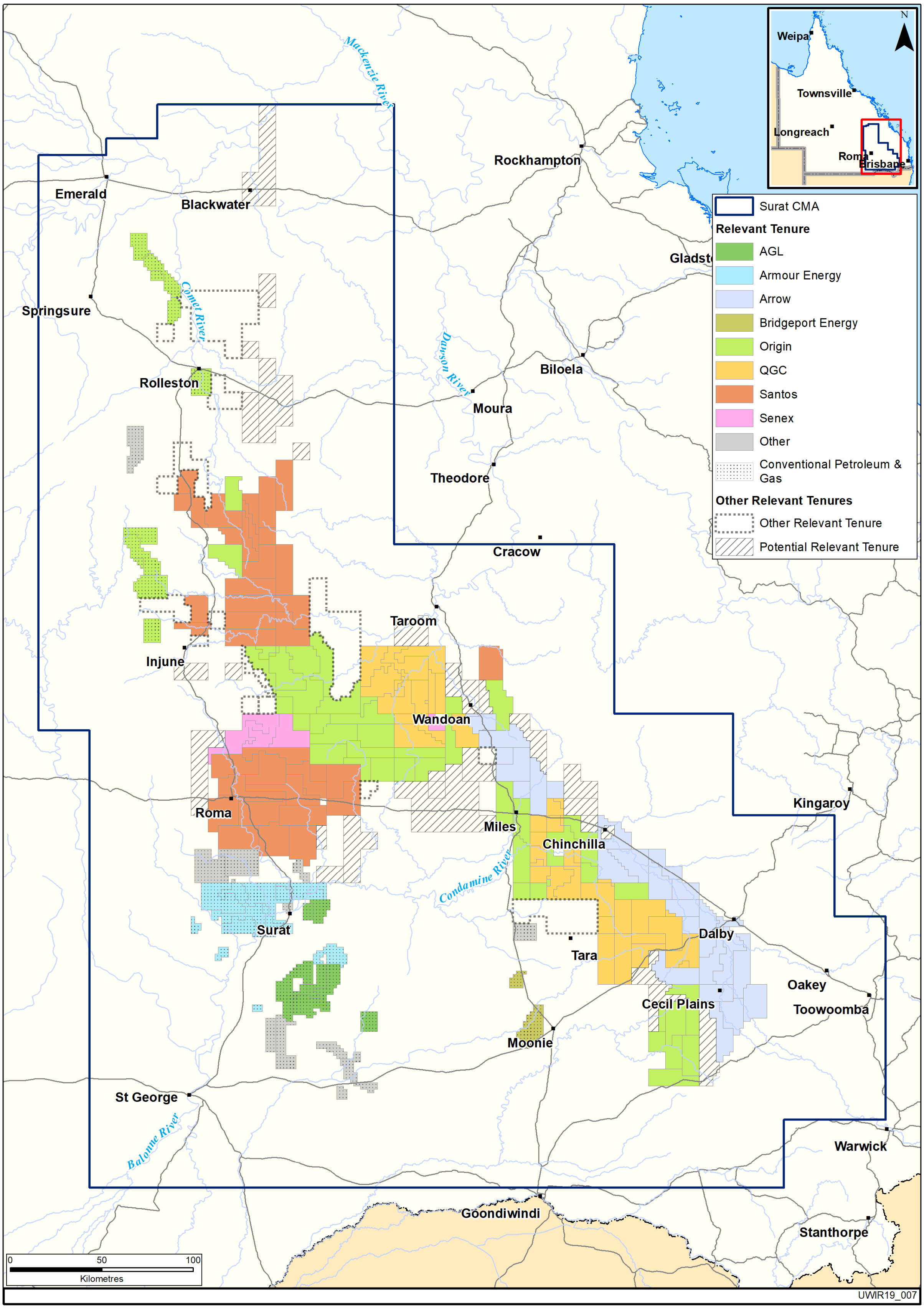

Figure 2-6 Distribution of relevant tenures and authorised tenure holders in the Surat CMA

2.4 Current status of petroleum and gas production

2.4.1 Production areas

A tenure area may be utilised by the tenure holder for production purposes and/or gas field development. A tenure holder's plan for developing production fields in a tenure may vary over time due to emerging information about reservoir dynamics, availability of reserves and changing market conditions. Those changes to plans may affect the proposed development footprint, as well as the timing of production commencement and cessation. Some of the tenure area may never be developed. Typically, about 50 to 70% of the total tenure area is used for production purposes (Appendix B). In the context of this report, the part of the relevant tenures where production is occurring or proposed is therefore referred to as the ***production area***. The production footprint, with associated planned commencement, development sequencing and cessation, is collectively referred to as the ***development profile***.

On an annual basis, OGIA compiles a whole-of-life cumulative **industry development profile** at the sub-block level, based on information received directly from tenure holders and verified information available to DNRME through various reporting arrangements. The development profile is used as the input scenario for the regional groundwater flow model for impact predictions and development of various impact-management strategies. The development profile presented and used in this report is based on the information available as at late 2018.

Figure 2-7 shows the distribution of the production area as of late 2018, together with a similar distribution as of 2015 that was used in the previous UWIR. Three categories are shown:

- **existing CSG production area:** land footprint on which CSG production was occurring at the end of 2018
- **planned CSG production area:** land footprint on which CSG production is proposed at some point in the future
- **active conventional petroleum and gas production area:** land footprint where conventional petroleum and gas production is still occurring.

The spatial distribution of planned commencement and cessation timing for production areas is presented in Appendix B. Details of each of the production tenures, their current status, target formation, the existing and proposed CSG wells in those tenures and planned commencement timing are provided on OGIA's website. This information is compiled by OGIA from various sources and is used in this report for impact predictions.

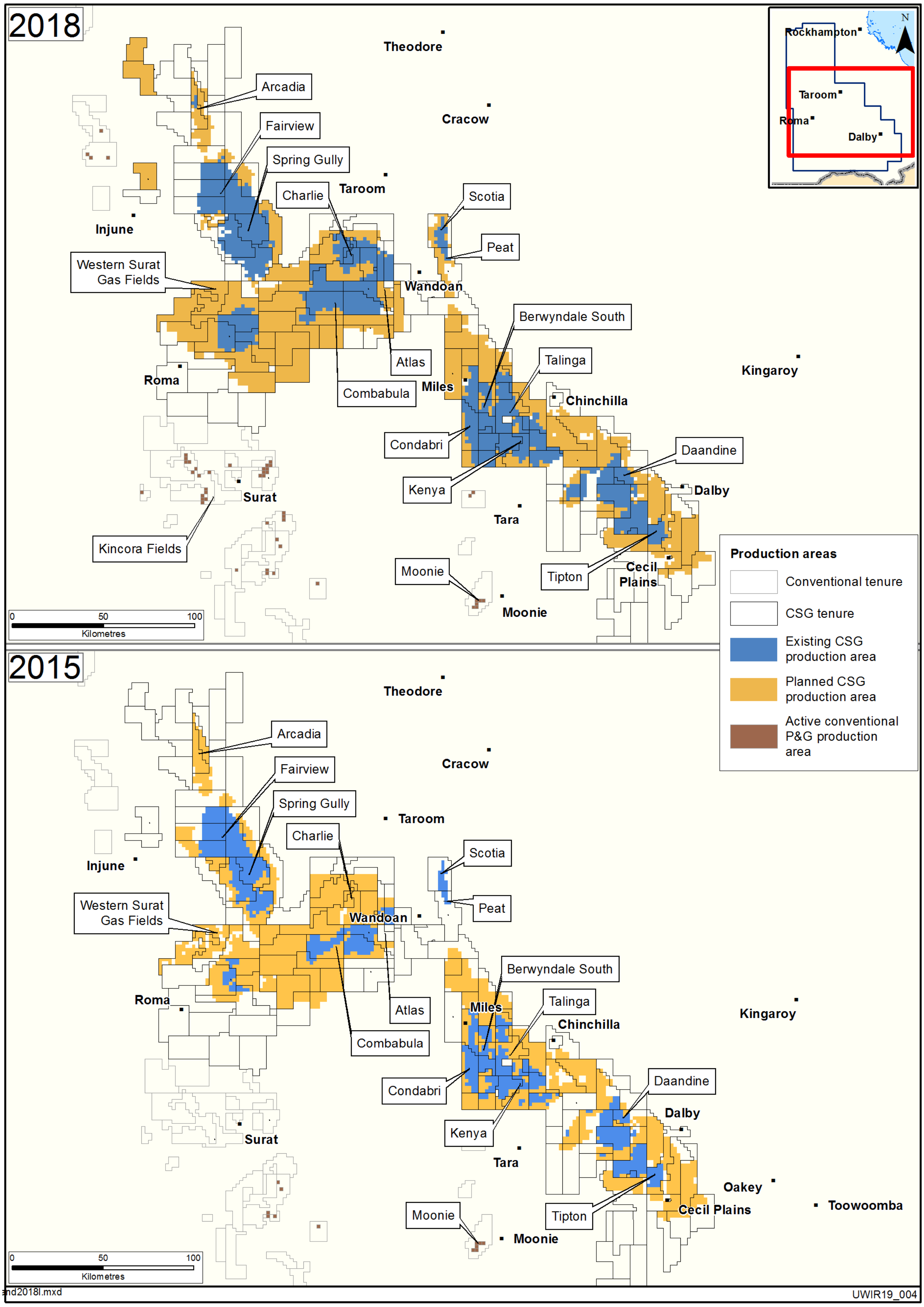

Figure 2-7 Distribution of production areas and their status (2018 and 2015)

2.4.2 Current trends

CSG projects providing gas for the domestic market have been in operation in the southern Bowen Basin since 1995 and in the Surat Basin since 2004. With the proposal for using CSG to produce liquefied natural gas (LNG) for the export market, four major projects were proposed in the last decade, representing a large expansion in CSG development in the Surat CMA. Three of these projects are already delivering gas and LNG to domestic and international markets. Specific project status details are presented in Appendix B.

As at late 2018, approximately 10,000 P&G wells within the Surat CMA are recorded in the Queensland Government Mineral and Energy Resources Location and Information Network database (MERLIN). Since the status of a well is dynamic and subject to change, however, the information on bore type, subtype and status provided and stored in DNRME databases may not always be current.

To account for potential status changes, OGIA runs further verification of the location, depth, purpose and status of these wells, based on up-to-date geological information and groundwater extraction records. This process suggests that an estimated 6,800 CSG wells in the Surat CMA are either producing gas or have been completed as production wells. Of these, 84% are in the Surat Basin and the rest are in the southern Bowen Basin. There are also an additional 500 wells outside CSG production areas for exploration or testing purposes.

There has been a sharp rise in the completion of CSG wells from 2012 onward, with about 1,000 to 1,500 wells completed annually. This trend is expected to continue until about 2023. Based on the current development profile, OGIA estimates that if all production areas are developed as currently planned, an estimated 21,000 CSG wells will be completed by the end of 2050 (Figure 2-8).

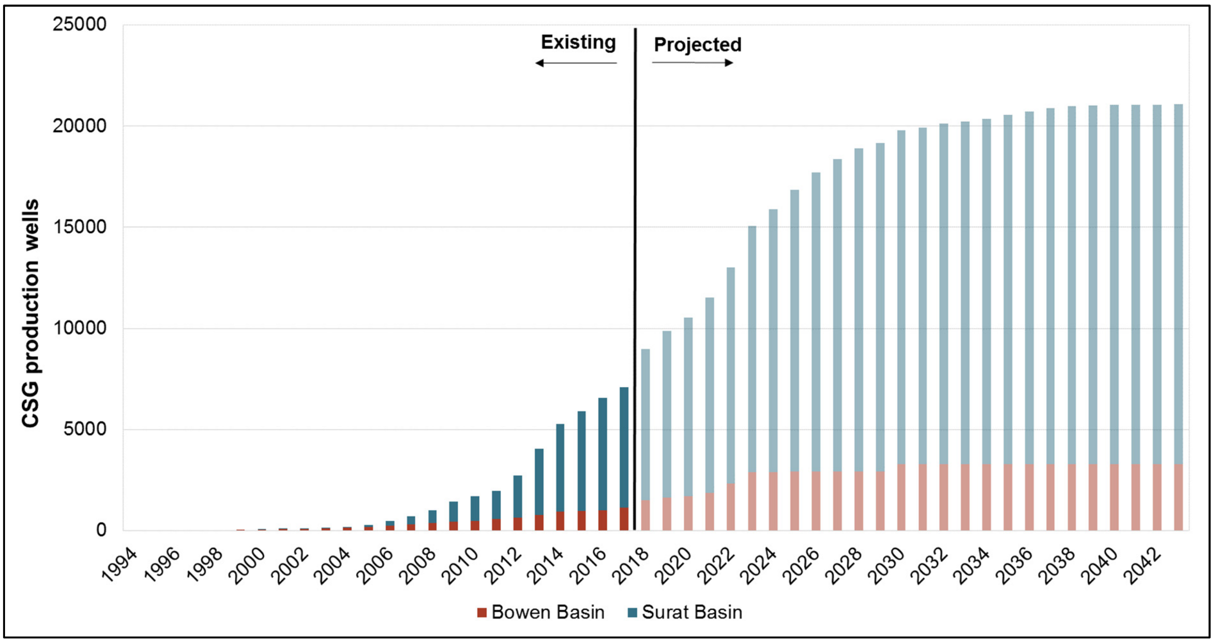

Figure 2-8 Existing and projected CSG wells in production areas

The majority of the conventional petroleum fields exclusively produce either gas or oil; very few fields produce both gas and oil. Fields north of Roma are primarily gas fields; those further south, from Roma to Moonie, tend to be either oil or gas, while Bridgeport's Moonie field, further south, is exclusively an oil field. Although there are about 30 oil fields that have recorded some production in recent years, Moonie is the major field, accounting for over half the oil production within the CMA. Moonie's production is in a declining trend, as is the case for all conventional petroleum fields in the

Surat CMA. This includes Armour's nearby Myall Creek gas fields and AGL's Churchie gas fields, located approximately 15 km east of Surat. These two fields produced almost 50% of the total conventional gas production from the Surat CMA during the period 2005-2016. Verification of the status of conventional wells suggests that of the 10,000 wells in the Surat CMA recorded as P&G wells in MERLIN, there are currently only about 70 active conventional oil and gas production wells.

2.4.3 Changes since the UWIR 2016

The cumulative industry development profile presented in the UWIR 2016 was based on information available as of late 2015. A number of changes have occurred since then in terms of the CSG production footprint and planned timing of commencement. A comparison of the current and previous planned development footprints is shown in Figure 2-7. Planned commencement date changes that have occurred between UWIR 2016 and UWIR 2019 are shown in Figure 2-9.

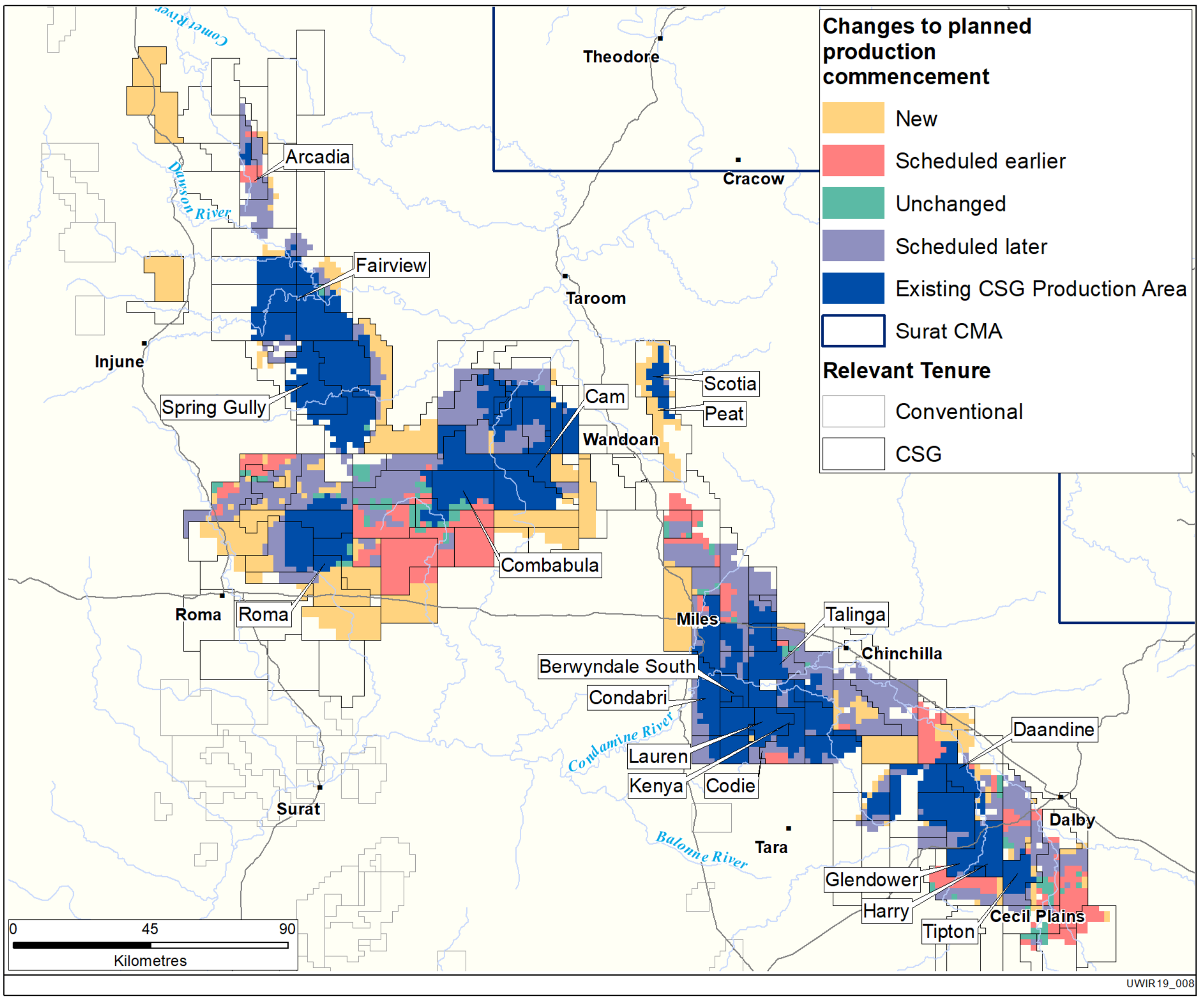

Figure 2-9 Changes in planned commencement timing of production areas from 2015 to 2018

Key observations from the comparison are summarised below:

- The area that is currently in production (Existing CSG Production Area) has increased by 40% (approximately 2,000 km^2) since the UWIR 2016. This aligns with the LNG plants being commissioned and requiring gas supply from the gas fields.
- The total production area (existing and planned) has increased by 17% to approximately 14,000 km^2; however, the total area is still only around half of the total area collectively proposed in various EISs between 2009 and 2013.
- The expansion of the existing CSG production area is noticeable across most development areas of the CMA; however, it is particularly noticeable in QGC's Charlie project area, west of Wandoan and the area around Santos's Roma gas field.
- The expansion of the planned CSG production area is in localised areas across the CMA. There are new gas fields included in the current development plans, such as Origin's Ramyard, Dalwogan, Kainama and Clifford gas fields, and Santos's Kia Ora and Arcadia West gas fields. Arrow plans expansion in Development Area 5, located between Dalby and Chinchilla. Santos plans expansion of its Scotia gas field, located east of Wandoan. Origin plans expansion of its Peat gas field, directly south of Scotia.
- Other than in a small number of gas fields, there is a general shifting of planned production to later years, some by up to 10 years.
- Santos has brought forward plans for expansion of the gas fields 50 km east of Roma by up to 10 years. Conversely, the majority of its Arcadia gas field, 50 km north-east of Injune, has been delayed by up to three years.
- Senex has slightly delayed planned commencement for the majority of its Western Surat Gas Project, except the north-west corner, where plans have generally been brought forward by three years.
- The south-eastern extent of Arrow's planned production area has been significantly brought forward. Arrow has reversed its development direction for Development Area 5, progressively bringing wells online from the south-east to the north-west, along the Dalby to Chinchilla development path.
- Origin has rescheduled development of its Reedy Creek gas fields, bringing forward production in some areas by up to six years.

Since 2016, a number of tenure transactions in the Surat CMA have seen the acquisition of conventional petroleum and gas tenures by new operators. For example, Bridgeport took over the operation of the Moonie oil field from Santos, and Armour has taken over from Origin as the operator of the Kincora Gas Facility and associated fields east of Surat.

The Queensland Government has also released tenures with conditions requiring that they be developed as domestic-only projects. The first of these was awarded for Senex's Atlas project. Other such tenure areas have been released; however, the relevant approvals required to progress to production have not yet been obtained.

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Chapter 3 Groundwater flow systems

This chapter presents an overview of the current understanding of the geology and hydrogeology in the Surat CMA, incorporating additional data and information that has become available since the UWIR 2016. This information forms the basis for the conceptual understanding of groundwater flow that is used for impact assessment and development of the management strategies presented in later chapters. Additional details are provided in separate technical reports listed in Appendix A.

3.1 Geological context

3.1.1 Evolution of geological knowledge

The understanding of the geology and structural framework of the Surat and Bowen basins continues to evolve. A detailed description of the geological understanding as at 2015 was provided in OGIA (2016a). A range of additional data and knowledge has become available since then, which OGIA has used to develop a revised regional geological model (OGIA 2019a), a key input to support impact assessment in the UWIR 2019. Key improvements compared to the previous UWIR are:

- refinement of the spatial extent of formations using new geological surface mapping and interpretation of 2,700 additional wireline-logged wells
- revised representation of outcrop geology using new surface mapping by the Geological Survey of Queensland (Cranfield 2017)
- remapping of the extent and thickness of the shallow Cenozoic units using information from water bore records
- revised mapping and understanding of the structure of faults – particularly within the Surat Basin – from seismic interpretation, incorporating a comprehensive seismic dataset maintained by GSQ and compiled by the University of Queensland (Copley et al. 2017)
- revised mapping of the contact zones between the Bowen and Surat basins from seismic interpretation
- enhanced understanding of the lithological variations within and between formations, from new wireline data supplemented by logging of core and chip samples.

These ongoing improvements further enhance the understanding of groundwater flow presented in subsequent sections of this report and used in the interpretation of groundwater trends (Chapter 5) and development of a revised groundwater flow model used for prediction of impacts (Chapter 6).

3.1.2 Geological basins

The Surat CMA incorporates parts of three large sedimentary basins: the southern part of the **Bowen Basin**, the **Surat Basin** and the western part of the **Clarence-Moreton Basin**. Geologic formations within the three basins mainly comprise various layers of sandstone, siltstone and mudstone that were primarily deposited by rivers and lakes, with occasional marine influences.

A map showing geological basins and major structural elements in the Surat CMA is shown in Figure 3-1. The Bowen Basin is the deepest and oldest of the three basins, running north–south through the centre of the region. Overlying this is the Surat Basin, covering most of the central and southern parts of the Surat CMA. The sediments of the Clarence-Moreton Basin interfinger with those of the Surat Basin west of Dalby and Cecil Plains. Overlying these basins are extensive areas of unconsolidated younger alluvial sediments and volcanic basalts.

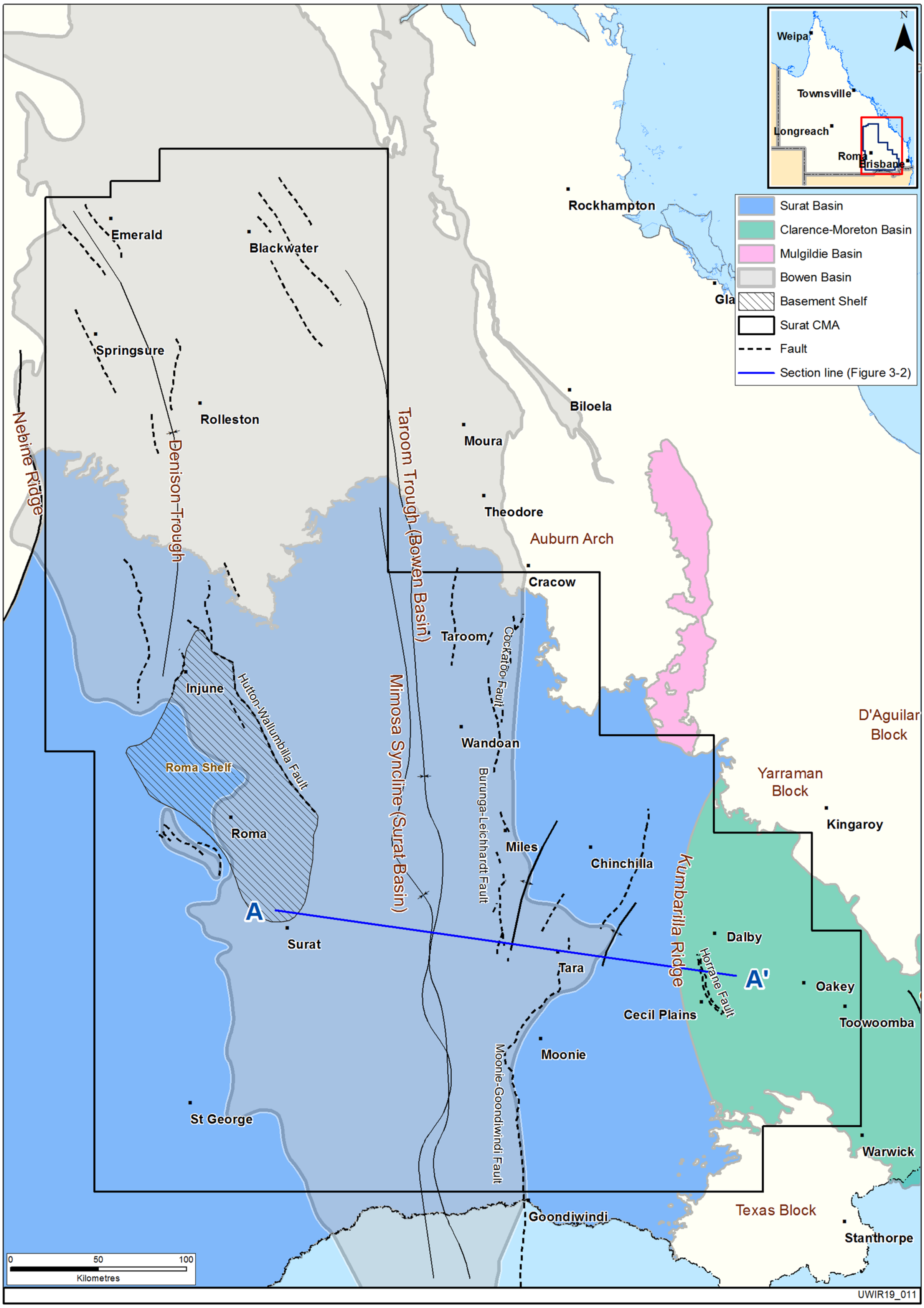

Figure 3-1 Geological basins and major structural elements in the Surat CMA

A simplified geological cross-section across the basins is shown in Figure 3-2 with a corresponding seismic section to demonstrate: major geological boundaries between the Surat and Bowen basins; coal formations; and major geological faults.

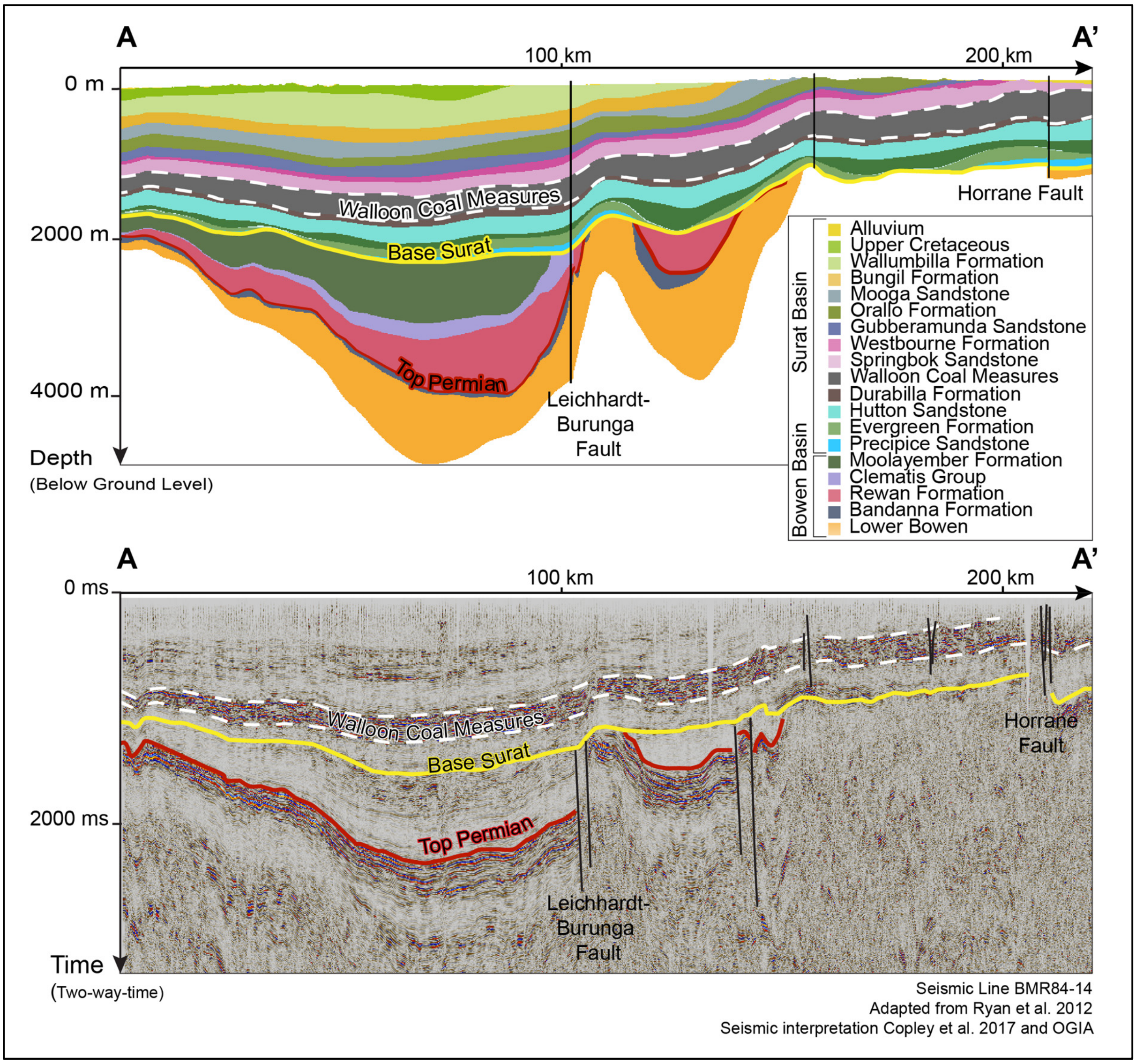

Figure 3-2 Generalised geologic cross-section of the Surat and Bowen basins with corresponding seismic section

The **Bowen Basin** is an elongated, Permo-Triassic basin trending north–south, extending from central Queensland, south beneath the Surat Basin and into New South Wales where it connects with the Gunnedah and Sydney basins. This basin contains broadly folded Permian to Triassic sediments, with a maximum thickness of approximately 9,000 m in the Taroom Trough.

The **Surat Basin** is filled by Jurassic and Early Cretaceous sedimentary rock units which attain a maximum thickness of 2,500 m (Hoffmann et al. 2009; Babaahmadi, Sliwa & Esterle 2015). It sits unconformably over the Bowen Basin in the Taroom Trough towards the centre of the basin, and basement rocks on the margins. The basin is a highly heterogeneous mix of alternating layers of sandstones, siltstones, mudstones and coal.

The Kumbarilla Ridge has traditionally been considered the boundary between the Surat and Clarence-Moreton basins to the east, but Ransley and Smerdon (2012) suggest a clear lithostratigraphic correlation between the sediments of the Surat Basin and the Cecil Plains Sub-basin. This correlation was also evident when OGIA undertook the lithostratigraphic interpretation of geophysical wireline data and prepared the 2018 geological model. Therefore for all practical purposes in this report, the Clarence-Moreton Basin is considered an extension of the Surat Basin.

The Walloon Coal Measures, the target for CSG, is present in both the Surat and Clarence-Moreton basins, representing a widespread episode of deposition of river, lake, swamp and marsh sediments. The formation has been partly eroded, or exposed, over much of the eastern part of the Clarence-Moreton Basin (Goscombe & Coxhead 1995). More details about the coal formations are presented in section 3.4.3.

Generally relatively thin accumulations of unconsolidated alluvial sediments (**Cenozoic sediments**) also cover much of the Surat CMA. These sediments typically comprise sand, silt and clay deposited along pre-existing streams and drainage lines. The Condamine Alluvium is one of the more significant accumulations of alluvial sediments in the region, with a thickness of up to 130 m in the central floodplain near Dalby. The Main Range Volcanics, to the east, comprises mostly basalt and overlies the eroded surface of the Clarence-Moreton Basin and some older basement rocks. Most of the volcanics are extensively eroded and covered in part with alluvium. Recent geological mapping of the area east of the Condamine Alluvium suggests that the Main Range Volcanics is less extensive than previously assessed.

3.1.3 Geological formations

The main stratigraphic units comprising the Surat and Bowen basins and the overlying Cenozoic sediments are presented in detail in Appendix C and shown more generally in Figure 3-6. The solid geology, i.e. distribution of formations outcropping at the surface or sub-cropping underneath the unconsolidated or Cenozoic cover – as derived from the updated OGIA geological model – is mapped in Figure 3-3. A summary of the geological model is provided in section 6.2. Up-to-date lithology and geological characteristics of the stratigraphic formations are detailed in a separate report (OGIA 2019a). Summary information relating to the average lithological composition of the main relevant formations, as derived from wireline data interpretation, is presented Figure 3-4. Detailed lithological information is also used in parametrisation of the groundwater flow model using an innovative method (***numerical permeameter***) developed by OGIA as described in Chapter 6.

Lithological composition data suggests that the upper Hutton Sandstone, Precipice Sandstone and lower Springbok Sandstone contain much higher sandstone proportions than the other formations. There is clear distinction between the upper Hutton Sandstone, which contains a higher sandstone proportion, and the lower Hutton Sandstone, which has a lower sandstone proportion. A similar pattern is noted in the Springbok Sandstone. However, the characteristics of sandstone bodies (including the degree of cementation, particle size, swelling clay content, thickness and continuity) within different formations can vary significantly.

All formations, including those which are sandstone dominated, show significant proportions of fine-grained strata (mudstone, siltstones and carbonaceous shale) indicating a high degree of heterogeneity both spatially and vertically. The presence of these fine sediment layers has a significant influence on vertical permeability as detailed further in section 3.4.2.

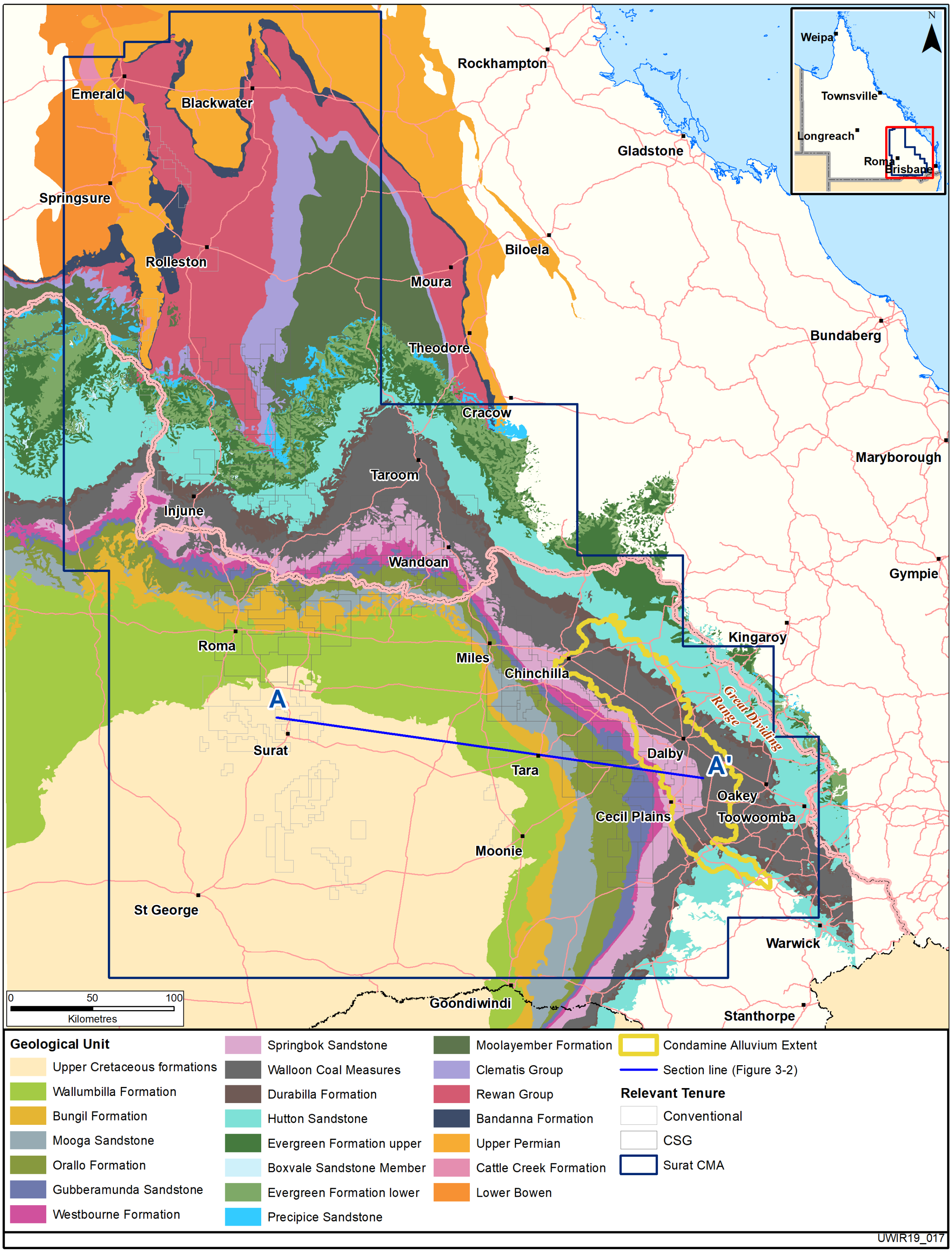

Figure 3-3 Solid geology in the model domain (Cenozoic cover removed)

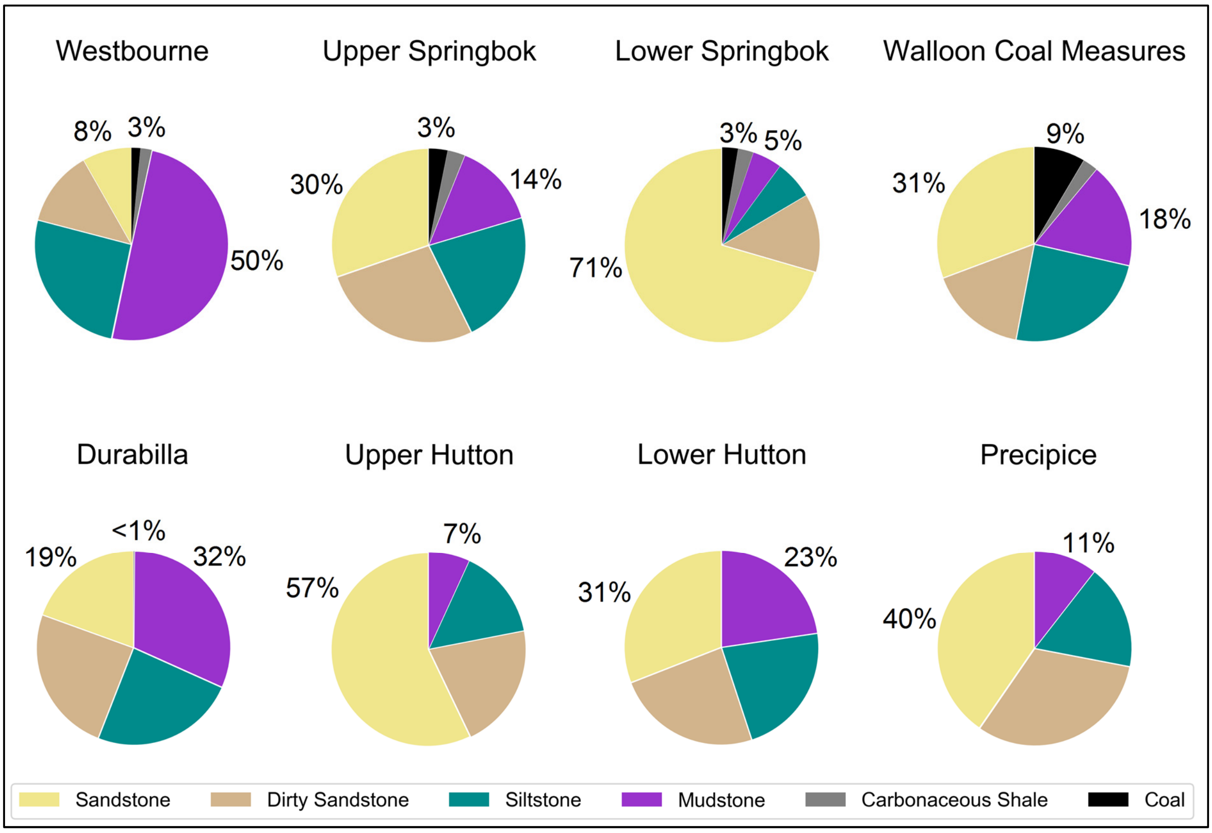

Figure 3-4 Lithological composition of relevant formations in the Surat CMA

In the Walloon Coal Measures, coal represents about 9% of the overall thickness of the formation. Siltstone, sandstone and mudstone form the matrix within which the coal lenses exist. There are also coal lenses in the Springbok Sandstone, comprising about 3% of the total formation thickness.

The Westbourne Formation contains the highest proportion of mudstone. This reaffirms its status as one of the major aquitards.

3.2 Groundwater systems

There are four primary groundwater systems in the Surat CMA, each comprising one or more aquifers:

- **Great Artesian Basin (GAB):** a Jurassic to Cretaceous age hydrogeological basin comprising alternating aquifers and aquitards of various geologic formations of Surat Basin sediments and their equivalents.
- **Bowen Basin:** Permian to Triassic aquifers and aquitards of the Bowen Basin formations underlying the Surat Basin.
- **Basalt:** Cenozoic consolidated surficial aquifer that mainly caps the Clarence-Moreton Basin along the Great Dividing Range (the Range).
- **Alluvium:** Quaternary unconsolidated surficial aquifers; mainly the Condamine and St. George alluviums.

In terms of productive groundwater supplies, the GAB and the Condamine Alluvium are the two most significant groundwater systems in the Surat CMA. Generalised groundwater movement in these systems is shown in Figure 3-5.

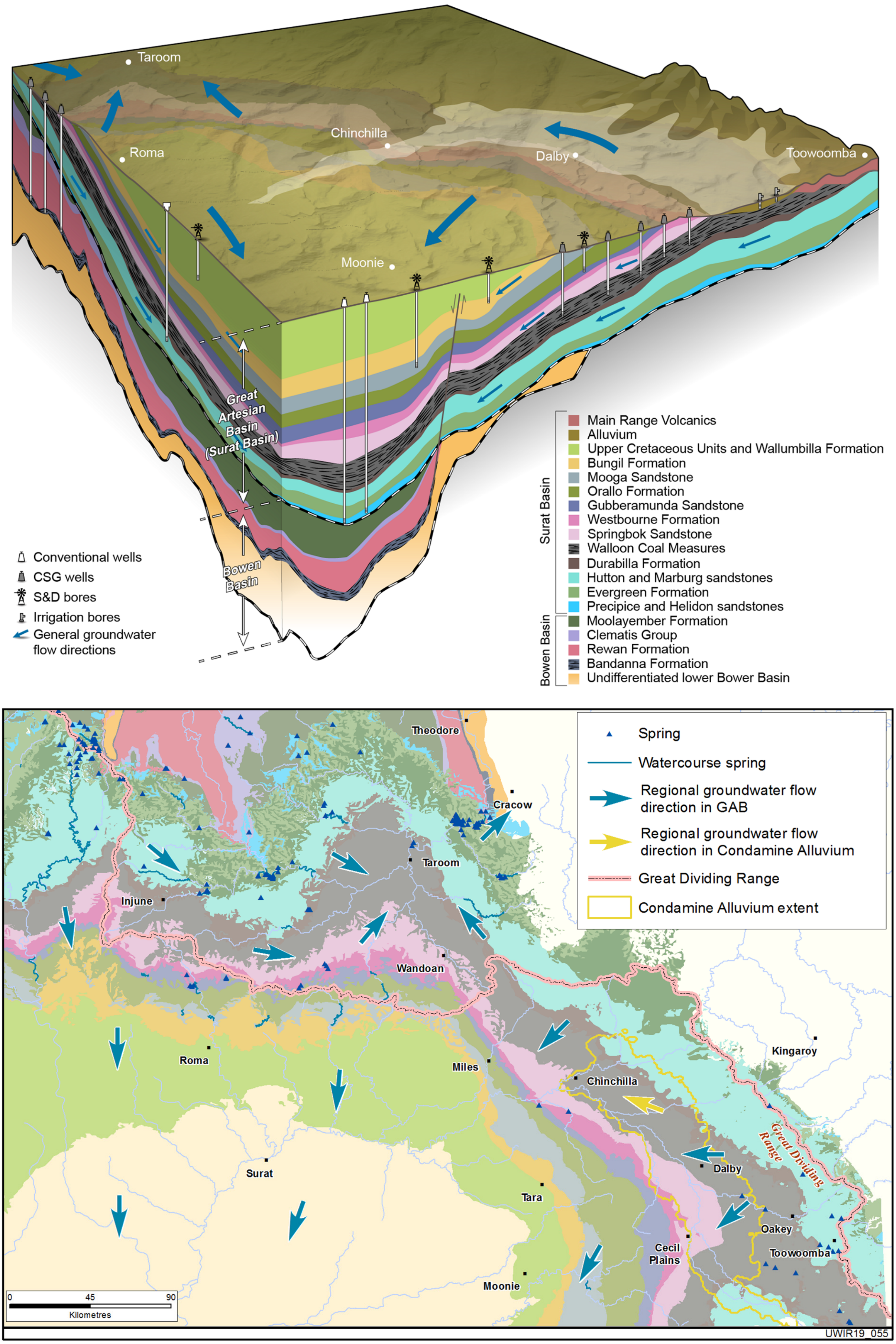

Figure 3-5 Representation of the main groundwater systems in the Surat CMA

3.2.1 The Great Artesian Basin

The GAB is the largest and deepest artesian basins in the world, comprising multiple layers of alternating sandstone, siltstone and mudstone that form sequences of aquifers and aquitards. Rather than being a single geologic basin, the GAB instead comprises a number of component basins. These are collectively spread across 1.7 million km^2, covering four states and nearly one-fifth of Australia (Ransley & Smerdon 2012).

In Queensland, the GAB covers about 65% of the state and ranges in thickness from less than 100 m, close to the basin margins, to more than 3,000 m in the central parts of the basin. Groundwater movement is very slow, estimated at about 1–5 metres per year. For the most part, the GAB is under artesian pressure. Recent validation of groundwater flow conceptualisation from isotopic data by CSIRO, using the OGIA 2016 groundwater flow model (Siade et al. 2018), suggests groundwater ages in excess of 1 million years over most of the Surat CMA.

In the Surat CMA, two geological basins – the Surat Basin and its equivalent the Clarence-Moreton Basin – form sub-basins of the GAB and are considered as a single connected hydrogeological system. The boundary between the Surat Basin and the Eromanga Basin to the west is the Eulo / Nebine Ridge. To the north-east, the boundary between the Surat and Mulgildie basins is defined by a basement high, over which the Evergreen Formation thins out. This forms a natural hydrogeological divide between these basins.

The main aquifers are the Precipice Sandstone, Hutton Sandstone, Gubberamunda Sandstone, Mooga Sandstone, Bungil Formation and their equivalents. These aquifers are generally laterally continuous, have significant water storage and permeability and are extensively developed for groundwater use. Aquifers are recharged by infiltration of rainfall and leakage from streams into outcropping sandstone, mainly on the eastern margins of the basin, close to the Range.

In the classical conceptual model of the GAB, groundwater recharge was understood to occur in outcrop areas, where formations were exposed to the surface. Water then flowed primarily along the formation towards the south, south-west and west, discharging naturally via springs and watercourses in some cases, with the remaining water flowing into the GAB to the south-west. More recent studies by Geoscience Australia (GA), OGIA and other research organisations such as the University of Queensland (UQ) suggest that groundwater flow dynamics in the eastern parts of the GAB are more complex and do not necessarily conform to this simple classical model. For example, in the Surat Basin, north of the Range, groundwater flow appears to be towards the north-east, suggesting discharge into the Dawson River catchment. This flow direction is consistent with the topography, but not with the dip of the stratigraphic sequence, which is generally towards the south-west. This pattern of flow continues to be represented in OGIA's groundwater flow model.

Water quality in most aquifers is generally fresh to brackish and suitable for stock, with salinity averaging 1,900 milligrams per litre (mg/L). The Walloon Coal Measures generally has higher salinity, averaging 3,000 mg/L and ranging from about 150 mg/L to more than 18,000 mg/L. Water quality is spatially variable, due to: the lateral and vertical variability in the lithology of the formation; variations in groundwater recharge; and variations in the length of time the water has resided in the formation (refer to section 4.1.4 for more details).

3.2.2 The Bowen Basin system

There is limited data available on the groundwater conditions within the deeper Bowen Basin sediments underlying the Bandanna Formation (from which CSG is produced in the Bowen Basin). In general, however, these formations are fine-grained, well cemented, and have little permeability. These sediments include the coal-bearing Cattle Creek Formation, which has been the target of recent CSG exploration activities.

The Triassic sandstone aquifers of the Clematis Group are the main aquifers used for water supply purposes in the Bowen Basin. The Moolayember Formation is primarily a fine-grained siltstone and mudstone formation which generally hydraulically separates the Bowen Basin sediments from the Surat Basin sediments above. The Triassic aquifers of the Bowen Basin (predominantly the Clematis Sandstone) were historically recognised as aquifers of the GAB, due to their artesian pressure and potential for connection with Jurassic aquifers. More recently, these aquifers tend no longer to be seen as part of the GAB (Smerdon & Ransley 2012; Ransley et al. 2015). The interconnection of these aquifers with the overlying GAB aquifers is nevertheless recognised and in Queensland, the Surat and Bowen basins are managed together under the *Water (Great Artesian Basin and Other Regional Aquifers) Plan 2018* (GABORA).

Across most of the Bowen Basin, the Clematis Sandstone aquifer is separated from the Bandanna Formation by a thick sequence of fine-grained, low-permeability siltstones and mudstones of the Rewan Group.

3.2.3 Alluvial systems

Shallow alluvial groundwater systems have been variably developed for irrigation, stock and domestic (S&D) and town water supplies. The most significant and highly developed system is the alluvium associated with the Condamine River, used for irrigation and town water supply with minor use for domestic and other purposes. Bore yields range up to 60 litres a second (L/s), although most are less than 10 L/s (Department of Environment and Resource Management 2009; KCB 2010a).

The Condamine Alluvium is incised into the underlying Surat and Clarence-Moreton basin sediments by up to 120 m in the central area and comprises gravels and fine to coarse-grained channel sands interbedded with clays. The productive part of the alluvium comprises individual channel sand and gravel units that are typically less than 20 m thick. A thick, clayey sequence of sheetwash deposits overlies the productive granular alluvium in the east, causing the aquifer to be semi-confined in nature.

The Condamine Alluvium is primarily recharged from infiltration through the bed of the Condamine River. Minor recharge occurs laterally from the surrounding bedrock and alluvium of the tributaries of the Condamine River. The consistent layer of low-permeability black soil over most of the Condamine Alluvium (up to 10 m thick) restricts direct rainfall recharge.

Groundwater quality within the Condamine Alluvium is generally good; however, salinity is higher towards the margins of the alluvium in areas that are more distant from the river and in the down-valley direction, where permeability is lower. In these areas, groundwater has resided in the aquifer for longer and there is more potential for the alluvium to interact with the basement (KCB 2010b). The salinity in the aquifer ranges from about 40 mg/L to more than 16,000 mg/L, with an average of about 1,500 mg/L.

The St. George Alluvium is an unconsolidated to semi-consolidated formation occurring west of St. George, extending over 25,000 km^2 with a maximum thickness of over 200 m. The deeper parts of the aquifer consist of unconsolidated coarse sand with gravel layers covered by silt, clay, siltstone and mudstone layers. The upper part is more laterally extensive and consists of unconsolidated fine to very coarse sand beds, up to 4 m thick.

3.2.4 Basalts

The Tertiary basalts of the Main Range Volcanics contain significant aquifers used for irrigation, S&D and town water supplies. The aquifers are typically 10 to 30 m thick. Bore yields are highly variable, ranging from 5 to 50 L/s, with an average of about 20 L/s. Water quality is generally good, with salinity averaging 900 mg/L and ranging from 50 to 4,000 mg/L. Tertiary basalts also occur in the north of the area, overlying the Bowen Basin sediments. In general, the aquifers in these basalts are not as high-yielding as those of the Main Range Volcanics.

3.3 Hydrostratigraphic units and classification

The formations in the Surat CMA have long been classified as aquifers and aquitards. A compilation of the geological descriptions (nomenclature, age, distribution, rock types, and hydrological properties) for all formations in the GAB was developed as part of the GAB Water Resource Assessment (Ransley & Smerdon 2012). All formations were reclassified to recognise the variability in properties of hydrostratigraphic units, providing a gradational classification that includes 'aquifer', 'partial aquifer', 'leaky aquitard', 'tight aquitard' and 'aquiclude' (Ransley, Radke & O'Brien 2012). This classification system was further refined by Ransley et al. (2015).

Recent studies in the Surat Basin (Ransley et al. 2015) suggest that within most of the formations, there is a greater degree of heterogeneity and spatial variability, both vertically and laterally, than previously acknowledged. As a result, a single formation may show characteristics of all five classes at different locations and depths. Nevertheless, the gradational system is considered useful for regional conceptualisation and has been used as a basis for further classification of the formations in the Surat CMA (Figure 3-6). The proposed definitions for those classes are:

- **regional aquifer:** high transmissivity, bore yields that are vertically and laterally consistent at a regional scale, e.g. Precipice Sandstone
- **partial aquifer:** medium transmissivity, bore yields that are vertically and laterally inconsistent at a regional scale and exhibiting a high degree of heterogeneity, e.g. Hutton Sandstone
- **tight aquifer:** medium to low transmissivity, bore yields that are regionally inconsistent and exhibiting a high degree of heterogeneity e.g. Springbok Sandstone
- **interbedded aquitard:** similar to a tight aquifer but with thin, spatially limited water-yielding zones are interbedded in an otherwise tight aquitard, e.g. Walloon Coal Measures
- **tight aquitard:** predominantly low permeability, regionally extensive and thick formations.

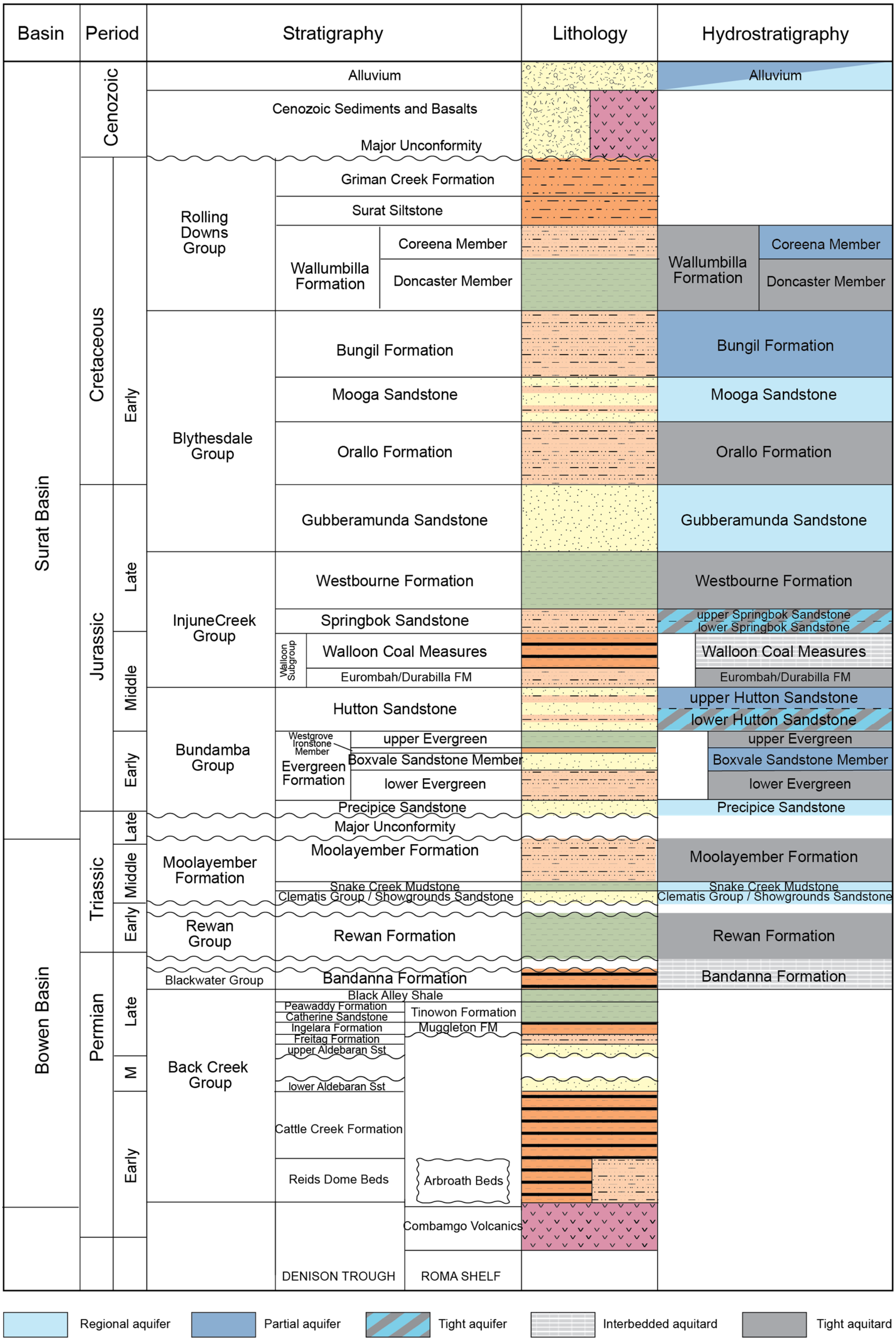

Figure 3-6 Generalised hydrostratigraphic classification in the Surat CMA

3.4 Key characteristics of groundwater systems

There is a growing body of data and information about the hydrogeological characteristics of the geological formations present within the Surat CMA and their responses to hydrogeological stresses. A number of ongoing assessments by OGIA and other research organisations have informed a progressive evolution of the collective understanding of groundwater systems and their functioning in the Surat CMA. In addition to the geological assessment detailed earlier, these include:

- sub-regional hydrogeological assessments in and around the CSG fields, involving a detailed assessment of groundwater level trends (OGIA)
- validation of watercourses connected to groundwater (OGIA 2017a)
- permeability profiling in the Hutton Sandstone (OGIA)
- refinement of non-CSG water use estimation (OGIA, UQ)
- collection and analysis of additional hydrochemistry data from wells and bores, to investigate the potential for aquifer interconnectivity (OGIA)
- assessment of hydrogeological characteristics of geological faults (OGIA 2019b)
- hydrochemical sampling, analysis and modelling of the Precipice and Hutton sandstones north of the Range (Raiber & Suckow 2017; Siade et al. 2018)
- numerical modelling of the Precipice Sandstone and review of data relating to the Moonie oil field as part of the Surat Deep Aquifer Appraisal Project (University of Queensland)
- revision of recharge estimates (OGIA, UQ-CCSG).

Findings and outcomes of the OGIA assessments listed above are documented in separate technical reports (Appendix A). In the context of CSG impact assessment, key elements and characteristics relating to groundwater systems updated by outcomes of the above research are summarised in the following section.

3.4.1 Groundwater recharge

There are three dominant recharge mechanisms in the Surat CMA: localised recharge, preferential pathway flow and diffuse recharge (OGIA 2016a; Kellett et al. 2003). Localised recharge occurs beneath drainage features including rivers and free-draining unconsolidated sedimentary cover such as alluvium. Preferential pathway flow occurs where zones of increased permeability – such as fractures and permeable beds – allow rapid inflow to a deeper aquifer. This is understood to be the dominant recharge mechanism in the GAB (Kellett et al. 2003). Rainfall events high in intensity and volume are required to provide sufficient saturation of the surficial sediments for effective diffuse recharge to occur.

Kellett et al. (2003) also used a chloride mass balance approach to estimate recharge for selected aquifers. In 2016, OGIA applied this approach to chloride data for all units present in the Surat CMA. For the current UWIR, OGIA has re-run this analysis based on an updated chloride data set.

Preliminary results from an ongoing study by UQ (West et al. 2018) concludes that the chloride mass balance method used by OGIA is an appropriate method for estimating mean recharge to the outcrop areas of the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone. The method provides estimates of recharge at the surface in most cases; however, numerical modelling work suggests that the majority of this surficial recharge discharges locally to streams and rivers such that less than 10% of this recharge reaches the deeper confined aquifers. Recent work completed by CSIRO (Suckow et al. 2016) using geochemical methods reaches a similar conclusion suggesting that actual recharge to the deeper confined parts of the Hutton Sandstone in the north of the Surat Basin is approximately 3% of the chloride mass balance recharge calculated in the outcrop area.

Revised chloride mass balance calculations undertaken by OGIA for the current UWIR suggest total recharge of around 297 GL/year – equivalent to around 9 mm/year on average – marginally higher than previously estimated in 2016. This estimate was applied in OGIA's groundwater flow model prior to calibration. Post calibration water balance suggests that most of this recharge is rejected locally through streams, creeks and tree evapotranspiration and only around 18 GL/year makes it way to the deeper formations as net recharge.

3.4.2 Hydraulic properties and formation anisotropy

The two key hydraulic parameters that influence groundwater flow are hydraulic conductivity (k), also referred to more generally as ***permeability***, and ***storativity*** (S). Permeability reflects the ease with which water or another fluid can flow through a medium such as a consolidated rock or unconsolidated sediment. Storativity reflects the capacity of the medium to store water that can be released when the medium is depressurised or desaturated.

Estimating these two parameters is essential for developing an understanding of groundwater flow and building a groundwater flow model. In groundwater flow modelling the values of these parameters are changed iteratively during calibration to match observed groundwater responses from monitoring data. However, in areas where there is no monitoring data, initial estimates are maintained and used in predicting groundwater level changes. For these reasons, OGIA has developed an innovative parameterisation technique that uses lithology data from thousands of CSG wells as described below.

Estimates of these hydraulic parameters are generally derived using hydraulic tests, which can be undertaken at various scales, both in the field (such as pumping tests) and in the laboratory. In the Surat Basin, the majority of hydraulic tests undertaken are either laboratory core tests or drill stem tests. Data is available for only a relatively small number of formal pumping tests.

Permeability measurements are influenced by the scale of the hydraulic tests. Core tests are typically undertaken on samples which are only around 0.1 m in length, drill stem tests estimate permeability over a test section of a few metres, and pumping tests may in some cases be run in bores which are open to hundreds of metres of formation. Generally, the greater the scale, the higher the probability of encountering a more permeable zone.

A comprehensive review of permeability was undertaken by OGIA (2016a) for the conceptualisation underpinning the UWIR 2016 groundwater model. That analysis focussed on formation-scale statistics to compare and contrast aquifers and aquitards across the Surat CMA. Important relationships between permeability and depth were developed and used in setting initial numerical parameters for the model.

Since the UWIR 2016, new data has become available on hydraulic properties. An up-to-date compilation of hydraulic properties now includes results for some 8,100 core tests, 7,700 drill stem tests and more than 100 aquifer pumping tests. Ranges of horizontal permeability values from these tests, together with model calibrated values (Figure 3-7), indicate that the Gubberamunda and Precipice sandstones are the most permeable consolidated formations in the Surat CMA.

There is wider variability in permeabilities across a number of regional aquifers, particularly in the Hutton and Springbok sandstones, reflecting a higher level of heterogeneity for those formations.

Despite the relatively large amount of permeability data available for the CMA, there are measurement-scale biases and coverage is limited to some locations. Estimating suitable values for vertical permeability at the formation scale is particularly problematic. In order to fill these critical gaps, OGIA developed an innovative numerical permeameter based workflow (OGIA 2016b) to generate formation-scale aquifer properties using lithology data derived from about 8,000 CSG wells in the Surat CMA and adjusted to the available permeability measurements. This was used as an input into the groundwater flow model and is detailed further in section 6.5.3.

At the formation scale, each formation includes mixed assemblages of sandstone, siltstone, mudstone, coal and shale, configured in a complex three-dimensional arrangement. This results in much lower effective permeabilities in the vertical direction than the horizontal direction. The ratio between vertical and horizontal permeability is referred to as the anisotropy. This vertical variation in permeability is demonstrated best using permeability profiling data for the Walloon Coal Measures and the Hutton Sandstone commissioned by OGIA in 2018, in a newly drilled water bore east of Chinchilla. Figure 3-8 shows a permeability trace for this bore, together with interpreted lithology. As shown in the plot, the median permeability values for the upper and lower Hutton are much higher, due to higher sandstone proportions (yellow bands) compared to the overlying Durabilla and Walloon Coal Measures which contain higher proportions of mudstone and siltstone (purple and green bands). Layering of lower-permeability mudstone and siltstone also significantly reduces the effective vertical permeability. Calculations based on data for this bore suggest an anisotropy of around 1000 for the Hutton Sandstone, further validating the model-derived values that are of the same order of magnitude.

While relatively few actual measurements of storativity (or specific storage) are available, estimates of storage parameters can typically be derived from porosity data derived from wireline logs and standard equations. As theoretical ranges of storage parameters are much smaller than ranges of permeability, indirect estimates of storage are not subject to the same degree of potential error as similar estimates of permeability.

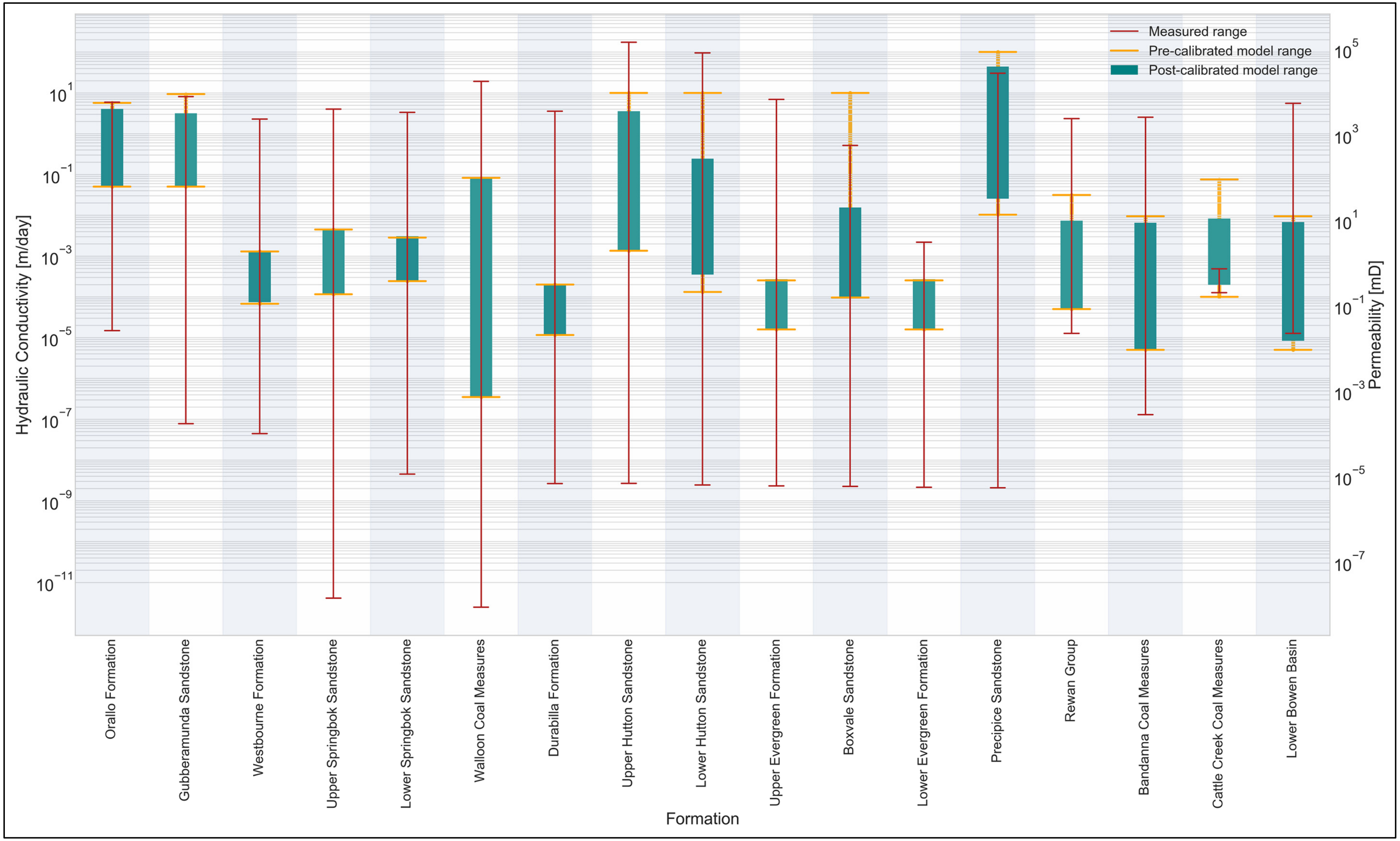

Figure 3-7 Horizontal permeability ranges in the Surat CMA – pre- and post-calibrated estimates

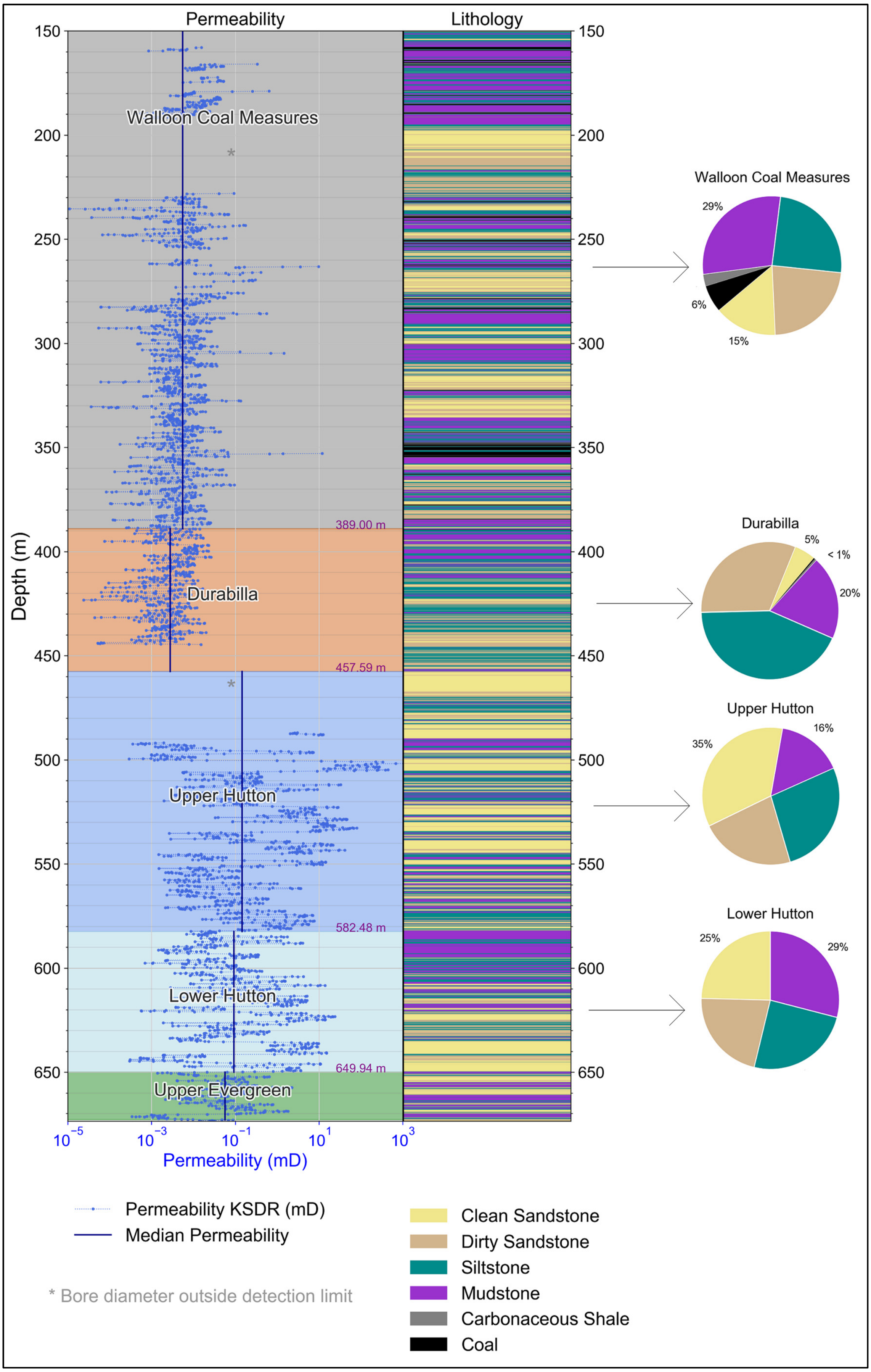

Figure 3-8 Continuous permeability profile from a water bore east of Chinchilla

3.4.3 Groundwater flow in the coal measures

The Walloon Coal Measures, the Bandanna Formation and the Cattle Creek Formation are the relevant coal sequences for CSG production in the Surat CMA.

The Walloon Coal Measures comprises siltstone, mudstone, fine to medium-grained lithic sandstone and coal, deposited over millions of years from rivers and in lakes and swamps across the Surat and Clarence-Moreton basins (Scott et al. 2004). The two coal-dominated formations within the Walloon Coal Measures are the Juandah Coal Measures in the upper part and the Taroom Coal Measures in the lower part. These coal measure units are separated by the Tangalooma Sandstone. At the base of the Walloon Coal Measures is the Durabilla Formation, which primarily contains low-permeability sandstone, siltstone and mudstone and is devoid of coal.

The geology of the Walloon Coal Measures is complex, comprising mostly thin, discontinuous coal seam layers (Scott et al. 2004). This is demonstrated in Figure 3-9 which presents a visualisation of the Walloon Coal Measures from detailed geophysical log data for the eastern gas fields. Most of the coal seams comprise numerous thin, non-continuous stringers or lenses (up to 45 individual coal seams can be recognised in places) separated by bands of low-permeability sediments often referred to as the interburden. Coal typically makes up less than 9% of the total thickness of the Walloon Coal Measures.

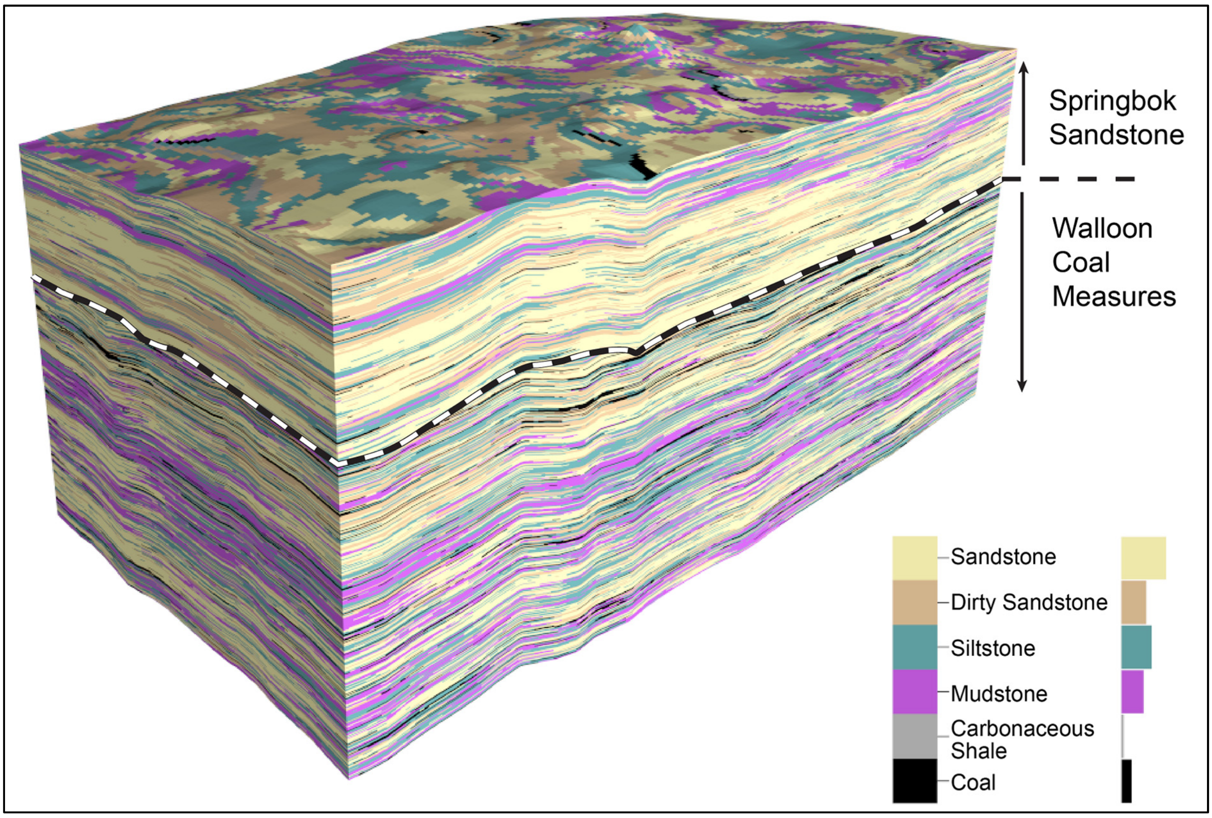

Figure 3-9 Walloon Coal Measures visualisation showing the complexity of the geology

The coal seams are generally the more permeable units, with permeabilities in the range of 1 to 1,000 mD (equivalent to a hydraulic conductivity of $1x10^{-3}$–1 m/d). They sit within a sequence of mainly mudstones, siltstones or fine-grained sandstones, which typically have lower permeabilities in the range of 0.0001–0.01 mD (equivalent to a hydraulic conductivity of $1x10^{-7}$–$1x10^{-5}$ m/d). Permeability also reduces with depth in the Walloon Coal Measures, as the cleats and fractures within the coal seams – which provide most of the permeability in the formation – close up due to the weight of the overlying material. For every 300 m increase in depth, the coal permeability is expected to decline by about one order of magnitude. For other lithologies, it typically takes the weight of 1300 m of overlying material to cause a similar reduction in permeability.

A CSG well tapping the coal measures will initially draw water primarily from high-permeability coal seams, creating a pressure difference with the surrounding interburden, which will also contribute a small amount of water inflow to the well, particularly over the long term. This implies that during the initial stages of well development, the groundwater pressure in the coal seams will drop, while in the interburden the pressure may remain largely unaffected. As extraction continues, the pressures of the two units will gradually equilibrate over the lifetime of the well until they are the same. For CSG wells in the Surat CMA, this process is expected to take around 20 to 25 years to complete.

Another factor affecting groundwater flow in coal measures is the release of gas in response to depressurisation. As the coal seams are depressurised, both gas and water are released and dual phase flow occurs within the coal seam (section 2.1.2). The presence of gas within the coal seam provides additional resistance to the flow of water and effectively reduces the water permeability, compared to if water alone was present in the coal seam. As a result, the effective permeability also tends to reduce over time as depressurisation continues and more gas flows with the water. This contributes to the reduction in associated groundwater extraction over time (Figure 2-4). During the latter stages of development, coal seams may become completely depressurised, such that the only source of water entering the well is a small amount of inflow from the surrounding interburden and slow recharge from outside the wellfield.

Once dewatered, it is anticipated that the coal seams will be particularly prone to compression, which may cause some minor compaction and subsidence (section 10.3). Where this does occur, re-wetting of the coal seams is likely to occur more slowly than did the initial desaturation.

Even though the water quality in the Walloon Coal Measures is relatively poor in many areas (section 3.2.1), the formation is used for S&D, stock-intensive, industrial and urban purposes, where permeable strata within the formation can be accessed at shallow depths near the outcrop areas. Groundwater is encountered typically from around 20 m below the ground, with most supplies being deeper than 30 m. Groundwater generally flows from higher elevations in the north and east, toward the west and south-west.

The groundwater flow characteristics of the Bandanna Formation are similar to those of the Walloon Coal Measures, although the thickness and distribution of coal is somewhat different. The thickness of the Bandanna Formation varies from 70 to 250 m. Ten individual coal seams can be identified. They tend to be slightly thicker (typically less than two metres) and therefore more continuous than the coal seams in the Walloon Coal Measures. Coal seams typically comprise less than 15% of total thickness of the Bandanna Formation. Very little groundwater is extracted for agricultural or other purposes from this formation. Water quality is variable, with salinity ranging from about 200 to 9,000 mg/L.

The Cattle Creek Formation is present at depths of up to 1,800 metres below ground and about 500 m below the base of the Bandanna Formation. Since only a few CSG exploration wells have extended into this formation, little is known at this stage about the nature, thickness and distribution of coal seams in this unit.

This detailed understanding of groundwater flow in the coal measures has supported the design of the regional groundwater flow model in which dual phase flow, the discontinuous nature of coal seams and the separate pressure regime in the upper and lower parts of the Walloon Coal Measures are all represented. Additionally, the understanding has also contributed to interpretation of monitoring trends (Chapter 5) and design of monitoring network (Chapter 8).

3.5 Inter-aquifer connectivity

In terms of groundwater movement, the connectivity between two geological formations is the ease of, or resistance to, groundwater flow between the formations. All geologic materials are permeable to some extent and all adjacent geologic formations are therefore connected to each other to some extent. It is the degree of connectivity that varies.

Where no material separates formations, connectivity depends on the vertical permeabilities of the formations. Where geological material separates two formations, connectivity depends on the thickness and vertical permeability of the intervening material. As an example, weathered clay and silt provide more resistance to flow than a sandstone layer. Similarly, a thick layer of silt provides more resistance to flow than a thin layer of the same material. Improperly constructed wells and bores and geological faults can additionally affect connectivity.

Connectivity is an inherent characteristic of the formations. A good hydraulic connection is not in itself sufficient to induce groundwater flow between two formations. A difference in water pressure (or groundwater level) between the formations is necessary for flow to occur. While there will be no flow between well-connected formations if there is no pressure difference, there will be some flow between even poorly connected formations if there is a large pressure difference.

3.5.1 Influence of faults on connectivity

A geological fault is a break along which rock formations have moved past each other by a distance - referred to as the fault throw or displacement. Faults have the potential to affect aquifer connectivity and groundwater flow. Therefore, an understanding of their location, impact on groundwater flow and the way they are represented in the groundwater flow model are important considerations. Seismic survey data, supplemented with knowledge about the formation materials from well log data, provides a useful insight into the location and displacement of faults at a local and regional scale.

Since the UWIR 2016, a fault characterisation study undertaken by OGIA has led to improved representation of regional faults in the groundwater flow model (section 6.5.4.3). The work has also provided new insights into smaller faults, not yet directly represented in the model, but considered in assessing aquifer connectivity and analysing groundwater level trends (Chapter 5).

3.5.1.1 General characteristics of faults

The majority of the previously mapped regional scale fault systems within the Surat CMA have displacement in excess of several hundred metres and predominantly only affect the Bowen Basin sediments. Although faults affecting the Surat Basin sediments often occur close to the large Bowen Basin fault systems they have much smaller displacement of generally less than 50 m. In terms of their influence on inter-aquifer connectivity, faults in the Surat CMA may affect:

- vertical connectivity predominantly by increasing the vertical permeability of the host rock due to fracturing in the damage zone
- horizontal connectivity by juxtaposing aquifers which would not otherwise be in direct contact.

A generalised representation of a fault zone – including a highly fractured damage zone, movement along the fault and juxtaposition of formations – is shown in Figure 3-10. Several factors govern the degree to which individual faults affect connectivity. In terms of vertical connectivity, key controls on the effective permeability of the damage zone include type of fracturing around the fault, the presence or absence of swelling clays within the host rock, and the degree of mineralisation.

With regard to horizontal connectivity, the smearing of clay within the fault core can limit flow across the fault even when two permeable strata are placed in direct contact. In the context of CSG impact assessment within the Surat CMA, faults are of most significance where there is sufficient displacement to connect permeable coal seams with adjacent aquifer units (OGIA 2019b).

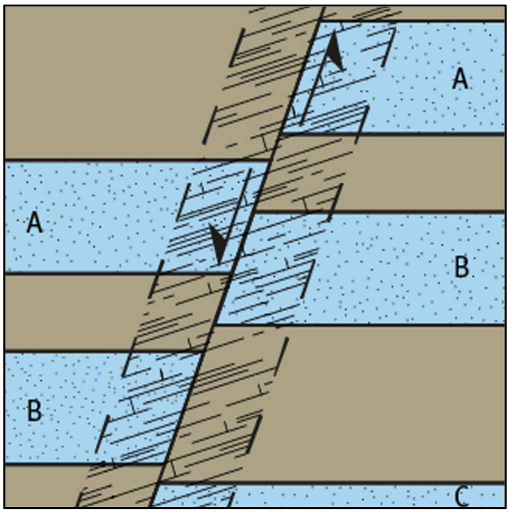

Figure 3-10 Schematic showing a generalised representation of a fault zone

3.5.1.2 OGIA's approach to fault characterisation

Building on previous mapping of faults, some additional mapping by UQ, seismic interpretation and geophysical survey at selected spring sites, a total of 32 major mappable faults are incorporated into the geological model, 22 of which were subsequently explicitly represented in the groundwater flow model for UWIR 2019 (section 6.5.4.3). Faults are represented in a way that accounts for the juxtaposition of the formations based on estimated fault displacement, and variations in permeability along the fault plane because of potential clay smearing. Clay smearing is assessed on the basis of interpreted lithology from geophysical logs around the faulted formations.

Representation of faults in the groundwater flow model allows for flow from one aquifer to another if the displacement is greater than the intervening aquitard. For example if the displacement in the CSG target formation – the Walloon Coal Measures – is greater than the thickness of the material separating the upper most coal seam from the Springbok Sandstone, then the Springbok Sandstone is put in direct contact with the CSG reservoir. Similarly, if the fault displacement is greater than the underlying thickness of the Durabilla Formation, then this creates a connection between the Hutton Sandstone and the Walloon Coal Measures.

In addition to the faults explicitly represented in the groundwater flow models, there are many other smaller faults in the area. Although it is not yet possible to incorporate these faults into the regional groundwater flow model, OGIA has analysed the potential for these smaller faults to increase connectivity, and has used the outcomes of the analysis when assessing trends in groundwater monitoring data (Chapter 5).

The analysis involved mapping small faults affecting either the upper or lower boundary of the Walloon Coal Measures from seismic data interpretation and estimating fault displacement. A total of 61 mappable faults and numerous fault intersections were identified through this process in and around the CSG fields.

The estimates of fault displacement were then used to identify faults where this could result in the juxtaposition of the coal formation against permeable aquifers above or below the Walloon Coal Measures. The degree of clay smearing was also assessed from the lithology data to determine the capacity for a fault to seal. Further hydrogeological analyses followed this in focus areas.

3.5.1.3 Conceptual assessment of fault connectivity

The displacement of faults affecting the contact between the Springbok Sandstone and the Walloon Coal Measures was typically found to be in the range of 10-20 m, but displacement of up to 60 m was estimated in some instances. Since the material separating the upper most coal seam in the Walloon Coal Measures from the overlying Springbok Sandstone is typically less than 10 m, the majority of these faults have sufficient throw to place coal seams against the Springbok Sandstone and increase potential connectivity. For example, two faults in the Kenya East gas field located between Chinchilla and Tara are likely to have brought the coal seams of the Walloon Coal Measures into direct contact with the lower Springbok Sandstone. Analysis of groundwater level and chemistry trends, and numerical testing at this location suggest that these faults are likely to be contributing to propagation of impacts from the Walloon Coal Measures into the Springbok Sandstone (section 5.4.2). However, only a small proportion of faults have similar overall characteristics to those observed at Kenya East.

In relation to the connectivity between the Walloon Coal Measures with the underlying Hutton Sandstone, only two locations have been identified where faults have sufficient displacement to bring the two formations into contact. They are sections of the Horrane Fault near Cecil Plains, and a small Surat basin fault close to the location of the Hutton-Wallumbilla Fault, north of Roma. The Horrane Fault is 40 km long trending south to north with a maximum estimated displacement of 108 m (Figure 3-11). Reservoir pressure monitoring data shows that a large pressure difference exists across this fault suggesting that it represents a barrier to horizontal flow within the Walloon Coal Measures.

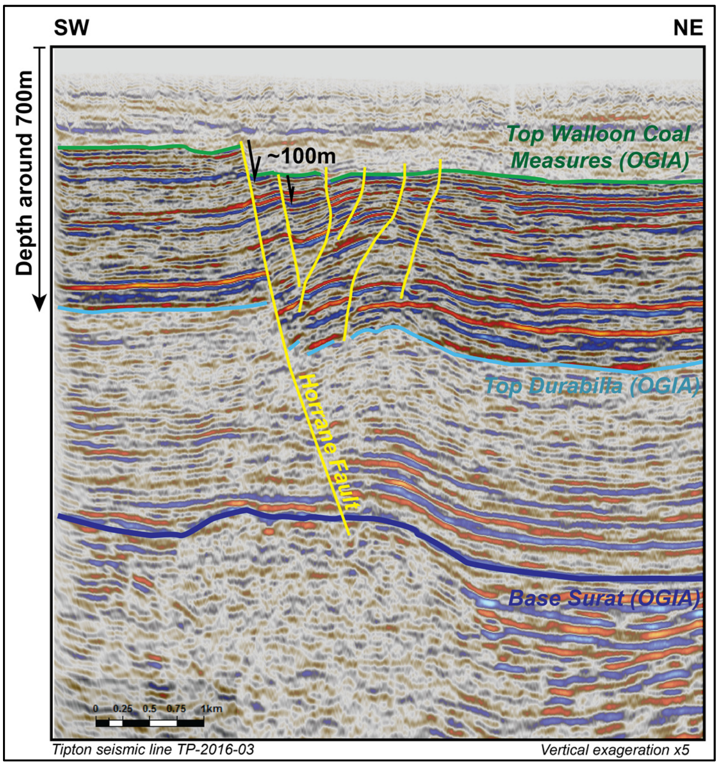

Figure 3-11 Seismic section through the Horrane fault *(sesimic data sourced from Arrow Energy)*

Arrow instigated an investigation in the Horrane Fault and concluded that the fault is likely a barrier based on interference tests and coring. This is consistent with the high degree of clay smearing that is likely to exist because of the high clay content of the Walloon Coal Measures and Durabilla Formation, inferred from nearby well lithological data. However, until further investigations are conducted to confirm these findings, OGIA has conservatively represented this fault in the groundwater flow model in such a way that flow can occur from the Hutton Sandstone into the Walloon Coal Measures via the fault plane.

The Hutton-Wallumbilla Fault in the Bowen Basin has a displacement in excess of 1,000 metres. The geological formations to the east of the Hutton-Wallumbilla Fault were uplifted and subsequently eroded away prior to the deposition of the Precipice Sandstone, bringing the Precipice Sandstone into direct contact with the Bandanna and Cattle Creek formations in this area (section 3.5.6).

Vertical connectivity through faults in the Surat Basin is limited by the presence of swelling clays and depth below ground, both of which tend to reduce fracture permeability in the damage zone. Mineralisation of fractures may further reduce vertical connectivity. The exception to this is in some shallow areas where geological conditions may be more conducive to vertical propagation. For example, there are only four known instances of faults creating vertical pathways for groundwater flow to the surface. Three of these are at springs including the Lucky Last and Abyss springs, and one is the Condamine River gas seeps. In all these cases, the source aquifer is within 100 m of the surface.

3.5.1.4 Summary

Since the 2016 UWIR, an additional seven major faults have been incorporated into the regional groundwater flow model. As a result, 22 major faults are now represented in the model. In addition, further mapping and characterisation of a large number of small faults have improved OGIA's conceptual understanding of groundwater flow, aquifer connectivity and analysis of monitoring trends. Overall there are some faults that are likely to affect aquifer connectivity particularly between the Springbok Sandstone and the Walloon Coal Measures. However, the assessment so far provides no basis to expect that faulting will have implications for the propagation of impacts at a regional scale. OGIA is continuing to investigate this further.

3.5.2 Implications of well construction and abandonment

CSG well construction and physical integrity have the potential to influence the transmission of groundwater impacts from CSG reservoirs to surrounding aquifers. This may occur in two ways: through the direct extraction of water, where CSG wells are open to adjacent formations; and through induced connectivity across formations, in the event that well integrity is compromised. Similar circumstances may also occur for improperly constructed water bores or abandoned coal exploration holes.

In Queensland, a code of practice (Department of Natural Resources Mines and Energy 2018) applies to the construction and abandonment of P&G wells and conversion of P&G wells to water bores. The code primarily addresses safety and environmental issues and identifies measures to prevent cross-flow contamination between hydrocarbon-bearing formations and aquifers.

CSG wells in the CMA are generally constructed as traditional vertical wells that are screened into the coal formations across the productive coal seams. However, directional or horizontal wells designed to reduce the surface footprint and optimise production where coal seams are favourably disposed are becoming increasingly common, particularly in the Bandanna Coal Measures.

Vertical wells are constructed to a finished diameter of 5 to 7 inches with a production casing that is typically opened through the production zone within the coal formation, accessed either through pre-perforated casing across the coal seams or by shooting holes through the casing and cement grout across the productive coal seams (Figure 3-12). Both construction types result in effective inlet intervals to provide access to formation fluids (water and gas).

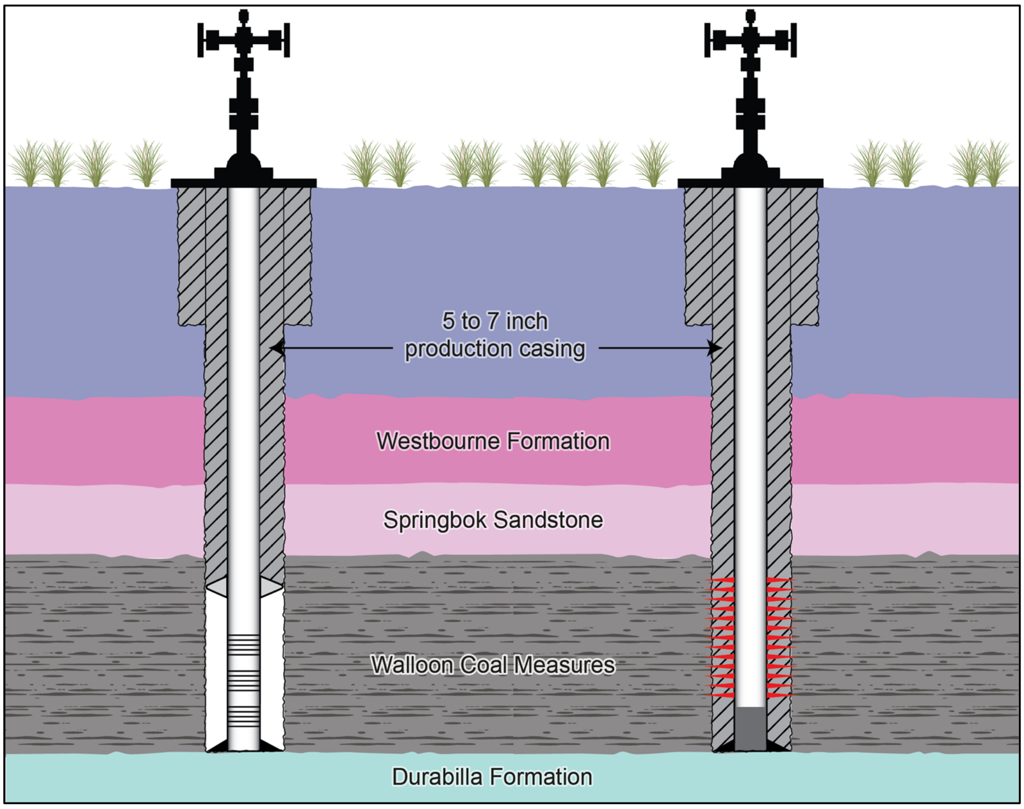

Figure 3-12 Typical construction of a CSG well

General industry practice for well construction is to establish a 'set-back' distance of at least about 30 m between permeable water-bearing zones and the top of the CSG production zone This also suggests that in instances where coal seams or gas flows are encountered in less permeable parts of the Springbok Sandstone, wells may be completed to access those zones.

OGIA has compiled information about the inlet intervals of about 5,600 existing CSG wells in the Surat Basin, to assess if water may be directly accessed from the Springbok Sandstone during gas production. Analysis suggests that after taking into account the uncertainties in interpreted contact between the Walloon Coal Measures and the Springbok Sandstone, about 16% of wells may still be partially completed into the Springbok Sandstone. The number of CSG wells partially completed into Springbok Sandstone since 2005 are shown in Figure 3-13. The practice varies across the tenure holders and at this stage, the data suggests that Arrow has not completed wells this way.

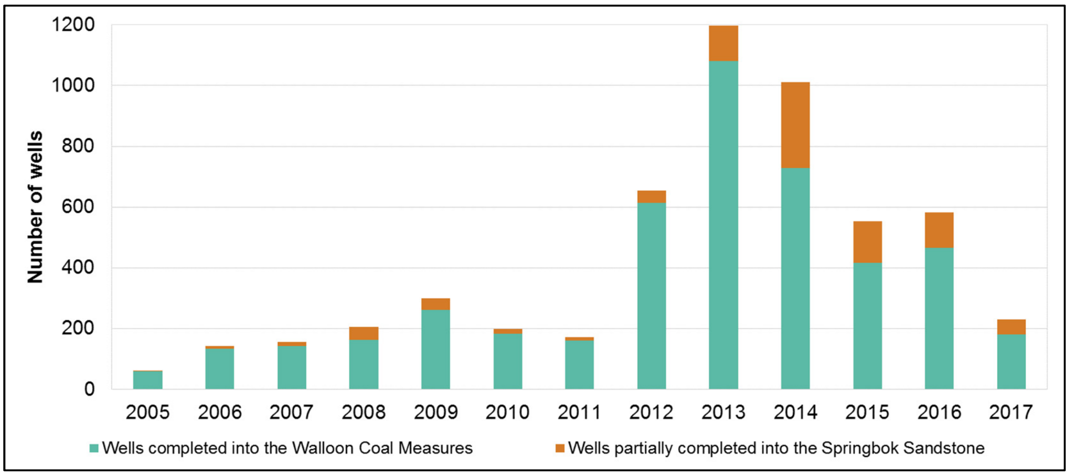

Figure 3-13 Proportion of CSG wells partially completed into the Springbok Sandstone

CSG wells that are partially completed into the Springbok Sandstone will, to some extent, extract water directly from the part of the formation where the screens are placed. The amount of water extracted, and the magnitude of the resulting pressure drop in the Springbok Sandstone, will depend upon the permeability of the formation and the length of well screen installed above the top of the Walloon Coal Measures.

OGIA compared water production profiles and water chemistry changes of wells that are exclusively completed into the Walloon Coal Measures, with wells completed both into the Walloon Coal Measures and partially into the Springbok Sandstone. This comparison indicates that 97% of wells partially completed into the Springbok Sandstone do not extract a materially higher volume of water than wells in the same gas fields that are exclusively completed into the Walloon Coal Measures. This finding is also supported by a separate analysis of water chemistry data. These investigations tend to confirm that where CSG wells are completed into the lower Springbok Sandstone, the permeability of the formation is for the most part low.

Partial completion of wells into the Springbok Sandstone is accounted for – in the groundwater flow model construction, calibration and predictions – by allowing such wells to extract water directly from the screened portions of the Springbok Sandstone (section 6.5.4.7).

As reported in the UWIR 2016, coal exploration holes drilled prior to 2002 may not have been abandoned properly and have the potential to affect connectivity. However, the majority of these bores are located in or near the outcrop areas of the Walloon Coal Measures on the margin of the basin and would have no effect on groundwater connectivity. On the other hand coal exploration holes in Springbok Sandstone outcrop areas could potentially increase connectivity between the Walloon Coal Measures and the Springbok Sandstone if they remain open over a longer period of time.

Since 2016, OGIA has further explored the potential effects of coal exploration holes, P&G wells and water bores on aquifer interconnectivity. Initial investigations reaffirmed the previous understanding that older exploration holes are likely to have partially collapsed over time and may not induce connectivity. A new methodology using machine learning techniques is being piloted to identify regional signatures of potential connectivity from hydrochemistry data. This work is expected to continue in the future.

3.5.3 The Walloon Coal Measures and the Condamine Alluvium

The Condamine Alluvium is an important groundwater resource that overlies the Walloon Coal Measures. Since 2012, OGIA has led a research project into the connectivity between the two formations using multiple lines of investigation: reinterpreting geology with a particular focus on the contact between the two systems; mapping regional groundwater level differences between the two systems; analysing the hydrochemistry of the two systems; drilling, coring and running pumping tests at representative sites; and numerically analysing the test data. Details of the investigations, approach and outcomes were compiled in an investigation report (OGIA 2016c).

The project concluded that there was a low level of connectivity between the Condamine Alluvium and the Walloon Coal Measures. It was conceptualised that vertical flow and interaction between the Condamine Alluvium and the upper parts of the Walloon Coal Measures is impeded by a combination of the undifferentiated clay transition zone at the base of the alluvium and the firm mudstone/siltstone interburden of the Walloon Coal Measures, in which its coal seams are embedded (Figure 3-14). The degree to which flow is impeded therefore depends upon the combined thickness and vertical hydraulic conductivity of these two units.

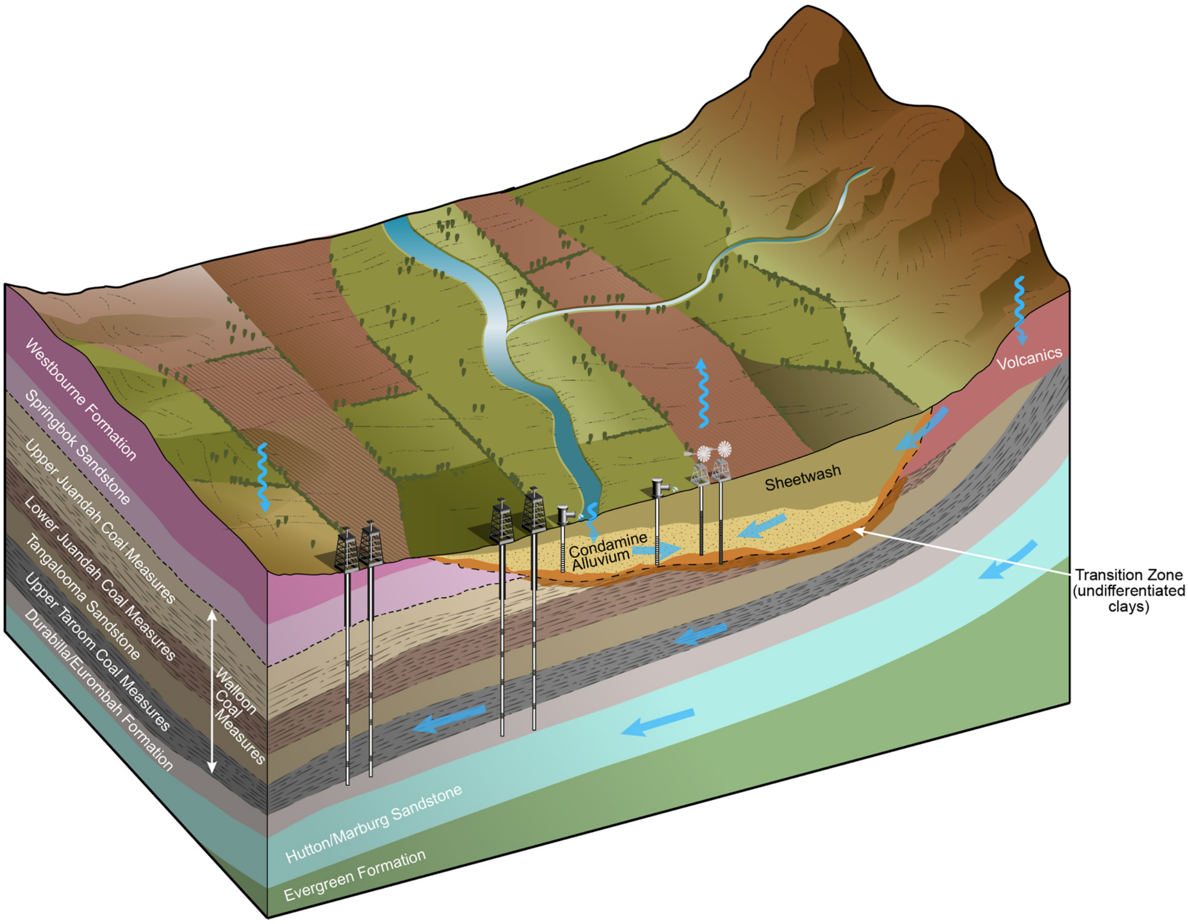

Figure 3-14 Schematic of the regional hydrogeological setting around the Condamine Alluvium

Since the last connectivity investigation in 2015, the following additional data and information have reaffirmed the findings that the degree of connectivity is low:

- New mapping of the contact between the Walloon Coal Measures and the Condamine Alluvium in the 2018 geological model (from additional wireline and bore data) reaffirms that understanding of the geology is consistent with the previous investigations.
- Updated mapping of the groundwater level difference between the Condamine Alluvium and the Walloon Coal Measures also reaffirms that there is a significant impediment to flow between the two formations. This is described further in section 5.4.4.
- About three years of additional data from ongoing monitoring at the two pump test sites (OGIA 2016c) has become available since the UWIR 2016 and supports earlier conclusions that the level of connectivity at these sites is low.
- Based on a detailed review of available seismic surveys, there is now better mapping of the Horrane Fault within the western margins of the Condamine Alluvium (section 3.1.1).

3.5.4 The Walloon Coal Measures and the Springbok Sandstone

As part of the revised conceptualisation for this report, OGIA reviewed a number of additional datasets and information to improve understanding of the connectivity between the Walloon Coal Measures and the Springbok Sandstone including: more detailed geological datasets in and around areas of current CSG development; improved definition of the geological contact between the formations; more detailed characterisation of individual faults that offset the contact; a review of bore construction issues and the influence of hydraulic stimulation activities; and revised hydrochemical analyses.

The lower part of the Springbok Sandstone contains more sandstone (71% on average) than the upper part (30% on average) (section 3.1.3) due to a change in depositional environments from higher to lower energy; however, this difference in composition is not always reflected in the permeability data. As shown in Figure 3-7, both the upper and lower parts of the Springbok Sandstone are characterised by relatively low horizontal permeability. This may be related to the relatively high percentage of swelling clays commonly found in particular in the matrix of sandstones encountered in the Springbok Sandstone and Walloon Coal Measures. Furthermore, both the Walloon Coal Measures and the Springbok Sandstone tend to be highly stratified and include significant proportions of siltstone and mudstone. As a result, the estimated vertical permeability based on core permeability tests and formation-scale numerical permeameter results is much lower than in the horizontal direction. Interconnectivity between these two units is therefore considered likely to be low despite the direct erosional contact between the units (i.e. the absence of an intervening aquitard).

However, since the contact between the two formations is erosional, there are areas where the Springbok Sandstone is in contact with the productive coal seams (i.e. the upper aquitard shown in Figure 3-15 is thin or absent). A higher degree of interconnectivity is expected in these areas.

As discussed in previous sections, connectivity may be enhanced by a number of other features, including CSG wells partially completed into the Springbok Sandstone and wells and bores that may be opened to multiple formations. At many locations, faults also exceed the upper aquitard thickness, potentially bringing some coal seams into contact with the Springbok Sandstone.

CSG water extraction has reduced pressures in the upper parts of the Walloon Coal Measures and induced a groundwater level difference of up to 185 m with the overlying Springbok Sandstone; however, data for the majority of Springbok monitoring points located close to active CSG production areas shows little or no significant drawdown in response to the pressure difference, although a number of sites are beginning to show possible CSG impacts. Groundwater level trends in the Springbok Sandstone are discussed further in section 5.4.2.

Reference to the available hydrochemistry data suggests that the Springbok Sandstone is also distinctly less saline and less chemically evolved than the Walloon Coal Measures and that few CSG production wells show improving water quality trends, suggesting that interaction with the overlying Springbok Sandstone is limited.

3.5.5 The Walloon Coal Measures and the Hutton Sandstone

The Hutton Sandstone is physically separated from the Walloon Coal Measures by the Durabilla Formation, a unit commonly regarded as a major aquitard of the GAB (Ransley & Smerdon 2012).

Interconnectivity between the Walloon Coal Measures and the underlying Hutton Sandstone will be largely controlled by the thickness and properties of the intervening Durabilla Formation (or lower Walloon Coal Measures) aquitard. As shown in Figure 3-15, the Durabilla Formation is continuous across the current and proposed CSG footprint, with an average thickness of about 55 m across most of the area, although there are areas with less than 10 m thickness.

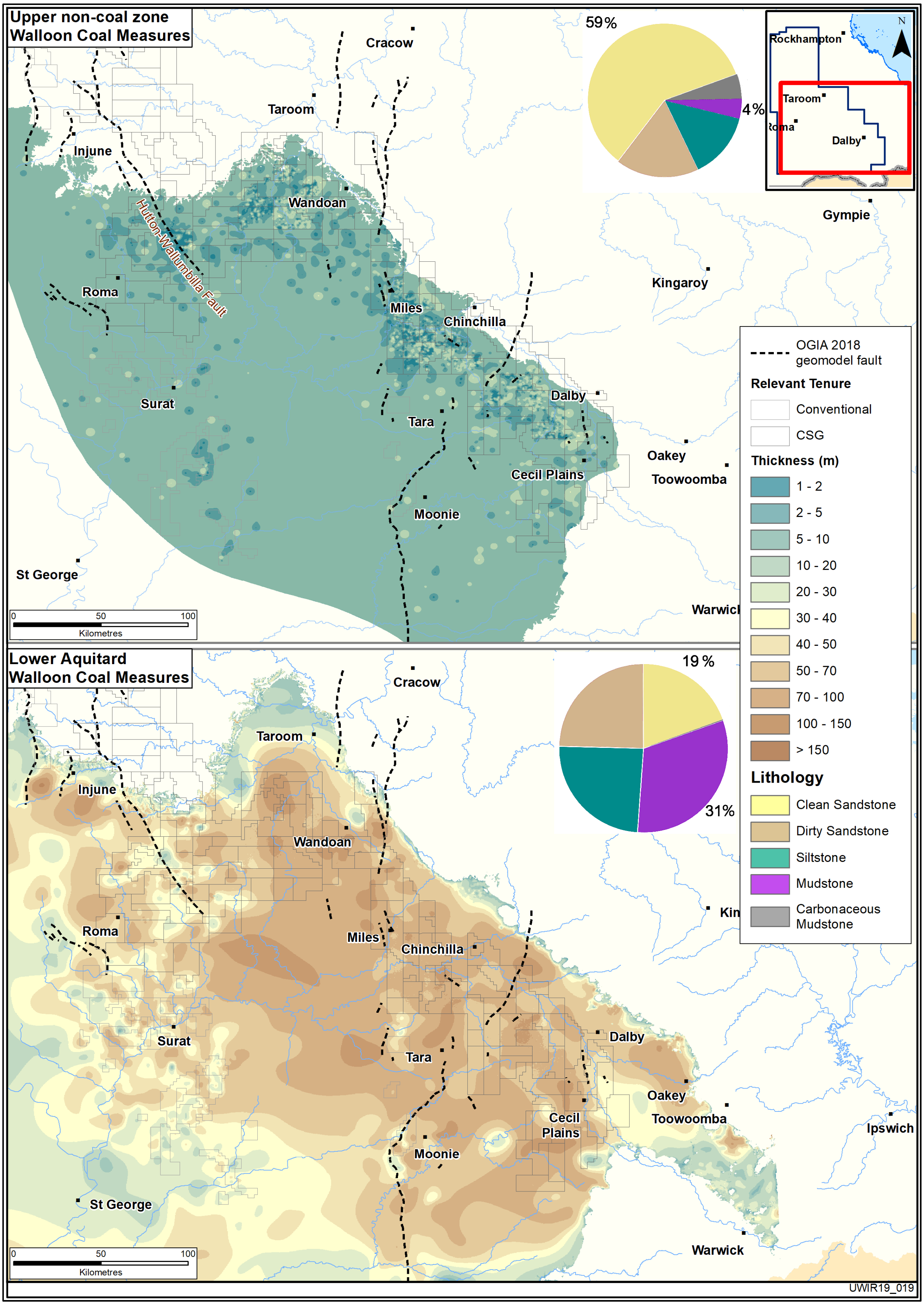

Figure 3-15 Thickness of the upper and lower aquitards in the Walloon Coal Measures

The Durabilla Formation predominantly comprises siltstone, mudstone and fine to medium-grained poorly sorted sandstones with almost no coal and consequently little permeability. Numerical permeameter results which provide the most reliable formation-scale effective vertical hydraulic conductivity estimates for the Durabilla Formation suggest vertical permeabilities in the10^{-6} to 10^{-7} m/day range – typical of a very effective aquitard that would provide significant resistance to vertical flow.

In the same way that pressure differences now exist between the Walloon Coal Measures and the Springbok Sandstone, pressure differences of up to 300 m now exist between the Walloon Coal Measures and the Hutton Sandstone with no discernible influence in observed groundwater levels in the Hutton Sandstone, further indicating a very low level of connectivity. This is detailed further in trend analysis presented in section 5.4.3.

Whilst the major ion chemistry of water drawn from CSG wells in some parts of the CMA is similar to that in the Hutton Sandstone, this is not considered to be indicative of significant inter-aquifer flow predominantly since there is little evidence of improving water quality in CSG wells. The fresher character of some of the Walloon Coal Measures CSG samples is most likely due to relatively high recharge and through-flow in the formation in areas where the coal is more permeable.

Unlike the Springbok Sandstone, there are relatively few features which could affect connectivity between the Walloon Coal Measures and Hutton Sandstone across the Durabilla Formation, since there are no coal exploration holes extending to the Hutton Sandstone. An evaluation of CSG well intake and down-hole wireline logs also suggests that of the thousands of CSG production wells, only one may be partially screened into the Hutton Sandstone.

With the exception of Surat Basin faults in the vicinity of the Horrane and Hutton-Wallumbilla fault systems, the faults intersecting the Hutton Sandstone have no apparent potential to juxtapose coal seams at the base of the Walloon Coal Measures against sandstones in the upper parts of the Hutton Sandstone. Fault-induced lateral connectivity between these two formations is therefore expected to be very low.

Overall interconnectivity between the Walloon Coal Measures and the underlying Hutton Sandstone is therefore considered low.

3.5.6 Permian coal measures and surrounding aquifers

The Bandanna Formation is the main productive CSG formation within the Bowen Basin. It is laterally isolated from the Rangal Coal Measures in the north due to erosion, and the Baralaba Coal Measures in the east due to faulting. Depressurisation of the Bandanna Formation is therefore unlikely to affect aquifers to the north around Clermont and to the east around Biloela.

The deeper Permian formations underlying the Bandanna Formation have extremely low permeability. It is therefore unlikely that depressurisation of the Bandanna Formation will affect the underlying formations. In addition, the Bandanna Formation is generally isolated from the overlying major aquifers by the thick, very low-permeability mudstones of the Rewan Group. For the most part, therefore, depressurisation of the Bandanna Formation will not affect overlying aquifers; however, since the Surat Basin sediments were deposited over the erosional surface of the Bowen Basin, there is potential for the coal formations of the Bowen Basin to come in contact with the Precipice Sandstone (the basal unit of the Surat Basin) where faulting has caused uplifting of the coal formation to the erosional surface of the Bowen Basin.

Since 2016, there has been a substantial increase in the volume of seismic survey and drilling data available to OGIA around two areas where the Bandanna Formation is in contact with the Precipice Sandstone. Revised interpretation of the seismic data for the 2018 geology model (OGIA 2019a) has improved the mapping of the contact zones shown in Figure 3-16:

- an area immediately east of Injune near the Fairview and Spring Gully fields, in the vicinity of the Hutton-Wallumbilla Fault (the **western contact zone**)
- an area 5 km south of the Peat gas field, near the Burunga Fault (the **eastern contact zone**).

In the western contact zone, the geological formations to the east of the Hutton-Wallumbilla Fault were uplifted and subsequently eroded away prior to the deposition of the Precipice Sandstone, bringing the Precipice Sandstone into direct contact with the Bandanna and Cattle Creek formations in this area. As a result, there is potential for a high degree of interaction between both of these coal-bearing formations and the Precipice Sandstone in this area.

Some of the earliest CSG fields were developed in the Bandanna Formation. Fairview was developed in 1996 and Spring Gully in 2005. Water pressures have fallen in the Bandanna Formation by more than 200 m due to depressurisation for CSG production, with no discernible effect to date on water levels within the Precipice Sandstone (section 5.4.5).

The eastern contact zone occurs adjacent to the Burunga Fault. At this location, similar to the western contact zone, the Bandanna Formation is overlain by the Precipice Sandstone. This area of potential connectivity is much smaller compared to the western contact zone. However, there is minimal data available on groundwater pressure or chemistry at this location from which to assess the degree of connectivity. Further monitoring is required to understand the potential for impacts at this location.

3.5.7 Summary of connectivity

Overall, the understanding of inter-aquifer connectivity has improved since 2016. Additional major faults have been mapped and added to the groundwater flow model. Detailed analysis suggests that there is some potential for faults to enhance connectivity through displacement that may place the Springbok Sandstone in contact with the Walloon Coal Measures in some areas. However, because of the partial completion of CSG wells into the Springbok Sandstone and new analysis that shows that the non-productive upper part of the Walloon Coal Measures is thinner than previously assessed, connectivity between the two formations is also higher than previously assessed. In contrast, all the data and evidence suggests that connectivity across the Walloon Coal Measures and the Hutton Sandstone is lower than previously assessed. Similar conclusions are also drawn for lower connectivity between the Condamine Alluvium and the Walloon Coal Measures.

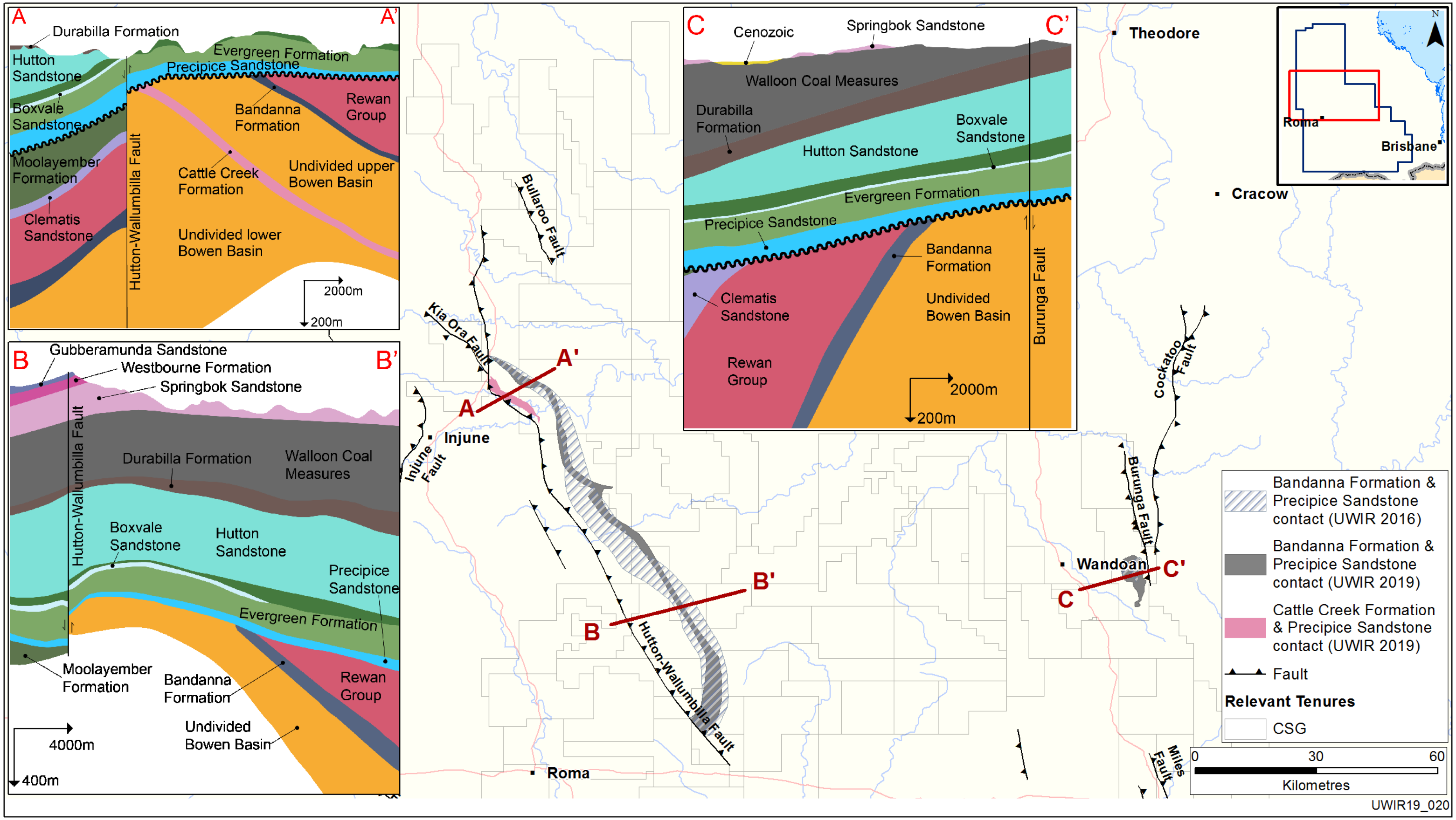

Figure 3-16 Contact zones between the Bandanna Formation and overlying Surat Basin

Chapter 4 Groundwater extraction and use

This chapter provides a summary of groundwater extraction and use in the Surat CMA, including a summary of water supply bores and P&G wells across the area.

Groundwater resources in the Surat CMA are developed for a range of consumptive purposes including agricultural, industrial, town water supply and stock and domestic (S&D) use. Groundwater use from the GAB is primarily for grazing, stock-intensive and town water supply purposes. The overlying Condamine Alluvium is primarily developed for irrigation.

Non-consumptive groundwater extraction ('associated water') by the P&G industry is primarily from the coal measures, where it is extracted to depressurise coal measures during CSG production. The mining industry also extracts groundwater to dewater some coal mines, but the scale of extraction is much smaller compared to CSG.

Information about water bores and estimated groundwater use from those bores is directly used in groundwater flow modelling for calibration purposes (Chapter 6). The information is also used in building an understanding of aquifer responses to this water extraction in terms of analysing trends in groundwater level and water chemistry (Chapter 5).

4.1 Groundwater use for non-P&G purposes

For this report, the term 'water use' is applied to the extraction of groundwater for consumptive use in agriculture, irrigation, town water supply, industrial, and stock and domestic purposes. This excludes the extraction of associated and non-associated water by the P&G industry (see section 4.2).

To provide context for later parts of this chapter, this first section includes a summary of authorisations required for drilling and accessing groundwater for consumptive use and the distribution of water bores in the Surat CMA.

4.1.1 Water licensing and reporting

Under the Water Act, a water licence or entitlement is generally required for the take of groundwater for consumptive purposes. Licensing requirements and conditions about the volume of water that can be taken under a licence depend upon the purpose of groundwater use and the level of management required for the aquifer system. Specific requirements are established in relevant water plans, which seek to balance the needs of water users and the environment. There are four water plans applying to different parts of the Surat CMA: the GAB; Condamine and Balonne; Burnett Basin; and the Border Rivers and Moonie catchments.

The majority of water take in the Surat CMA is in accordance with the water plans applying to the GAB and Condamine and Balonne catchment. General licensing requirements for accessing groundwater in these plans are summarised below:

- A water licence is required to take groundwater in the Surat and Bowen basins for all purposes excluding domestic use and some stock use in some areas.
- Where a water licence is required for S&D purposes, a volumetric limit is not specified on the licence, because take is limited by the amount of stock that may be pastured on the property.
- A water licence is required for all other purposes, including stock-intensive and town water supply, and includes a specified annual volumetric limit.

- Within the Condamine Alluvium and Main Range Volcanics, water licences are required for all purposes excluding S&D purposes.

Within the GAB aquifers, a development permit is also generally required for the construction of a water supply bore for any purpose. The exception is the Eastern Downs where bores constructed for S&D purposes are exempt. Similarly, within the Condamine Alluvium, water bores for all purposes other than S&D require development permits under the Planning Act.

For each water bore, regardless of its purposes, a licensed driller must be used for construction. All bores must be completed in accordance with the minimum construction standards, which specify both construction materials and minimum design standards (Department of Natural Resources Mines and Energy 2017). This ensures water bores are constructed to the highest standard and protective of the groundwater resource.

DNRME administers the licensing provisions of the Water Act. Information about water licences, authorised volumetric limits and purposes are recorded in DNRME's Water Management System. Information about water bores and their construction is maintained in DNRME's Groundwater Database (GWDB), including bores that may not require a water licence.

4.1.2 Water bores, their purposes and status

There are approximately 22,500 water bores in the Surat CMA. Around 8,100 of these water bores access GAB formations in the Surat Basin, approximately 600 access the underlying Bowen Basin and the remaining bores (around 13,800) access the overlying shallow alluvium and tertiary basalts (Table 4-1). The distribution of water supply bores in the CMA primarily reflects the availability of reliable groundwater supplies at the shallowest possible depths and the location of key regional development areas such as Toowoomba, Dalby and Roma (Figure 4-1).

The majority (approximately 90%) of bores are constructed to depths of less than 200 m and are predominantly (84%) for S&D purposes, requiring comparatively smaller volumes and lower yields. In some instances, bores are completed to depths of up to about 1,000 m. The majority of water bores are subartesian, meaning that the water level in the bores is below the ground surface. Only 14% of bores in the Surat Basin are recorded as artesian. These are generally located away from CSG production areas, in the south-western and northern parts of the CMA.

Bore data and records in the GWDB are generally from the time of drilling, as submitted by the water bore drillers. Information on bores attached to water licences may be updated following discussions between the landholders and DRNME.

More recent information on water bores within the tenure footprint is also collected as part of ***baseline assessments***. These are undertaken by tenure holders in advance of development commencing (see section 8.7). Thus far, more than 3,500 baseline assessments have been completed for water bores in the Surat CMA. However, there are some challenges in directly linking the baseline assessment data with records on the GWDB. In particular, the unique bore identifier (Registered Number or RN) linked as part of the baseline assessment may differ from that recorded in the GWDB. OGIA has undertaken an extensive manual review of this dataset (see section 8.2.4), focusing on assessments completed within the short-term and long-term impacted areas. Through this process, OGIA has identified around 250 new bores not previously recorded in the GWDB and additional up-to-date information for bores that had been recorded in the GWDB. This information will be progressively uploaded to the GWDB.

Table 4-1 Estimated water use in the Surat CMA

Formation	Number of bores			Water use (ML/year)*		
	Non S&D	S&D	Total	Non-S&D	S&D	Total
Alluvium and Basalt						
Condamine Alluvium	1,366	3,278	**4,644**	67,324	2,436	**69,760**
Other Alluvium and Basalts	1,524	7,451	**8,975**	42,617	7,253	**49,870**
Upper Cretaceous	9	123	**132**	526	414	**940**
Alluvium and Basalt subtotal	*2,899*	*10,852*	***13,751***	*110,466*	*10,103*	***120,570***
Surat Basin (GAB)						
Wallumbilla Formation	2	122	**124**	18	339	**357**
Bungil Formation	1	235	**236**	3	634	**638**
Mooga Sandstone	13	625	**638**	259	1,713	**1,971**
Orallo Formation	33	736	**769**	1,669	1,861	**3,530**
Gubberamunda Sandstone	78	685	**763**	4,305	1,858	**6,162**
Westbourne Formation	2	59	**61**	547	122	**669**
Springbok Sandstone	13	194	**207**	150	364	**515**
Walloon Coal Measures	124	1,008	**1,132**	3,398	1,215	**4,614**
Durabilla Formation	10	101	**111**	182	162	**345**
Hutton Sandstone	348	2,697	**3,045**	10,159	3,596	**13,755**
Boxvale Formation		44	**44**	0	143	**143**
Evergreen Formation	21	443	**464**	646	802	**1,448**
Precipice Sandstone	45	289	**334**	5,578	547	**6,125**
Moolayember Formation	2	156	**158**	60	450	**510**
Surat Basin (GAB) subtotal	*692*	*7,394*	***8,086***	*26,973*	*13,808*	***40,781***
Bowen Basin						
Clematis Sandstone	6	126	**132**	232	319	**551**
Rewan Group	3	60	**63**	20	111	**131**
Bandanna Formation	4	62	**66**	169	112	**280**
Bowen Basin Sediments	27	336	**363**	993	447	**1,440**
Cattle Creek Formation		10	**10**	0	10	**10**
Bowen Basin subtotal	*40*	*594*	***634***	*1,414*	*999*	***2,413***
TOTAL	3,631	18,840	**22,471**	138,854	24,910	**163,764**

** The numbers may not add up exactly in these columns due to rounding off errors*

The status of water bores in the GWDB is recorded as either 'existing', 'abandoned and destroyed' or 'abandoned but usable'. In some instances, there are inconsistencies in the recorded status between the GWDB and the baseline assessment. Therefore, OGIA has developed a workflow to determine water bores that are likely to be abandoned or decommissioned – including those that could not be found during baseline assessments – or where tenure holders have reached an agreement to decommission water bores. All bores not recorded as decommissioned are considered existing and usable, regardless of whether the water bores are currently in use. These existing water bores are also considered further for the purpose of identifying impacted bores under the UWIR (Chapter 7).

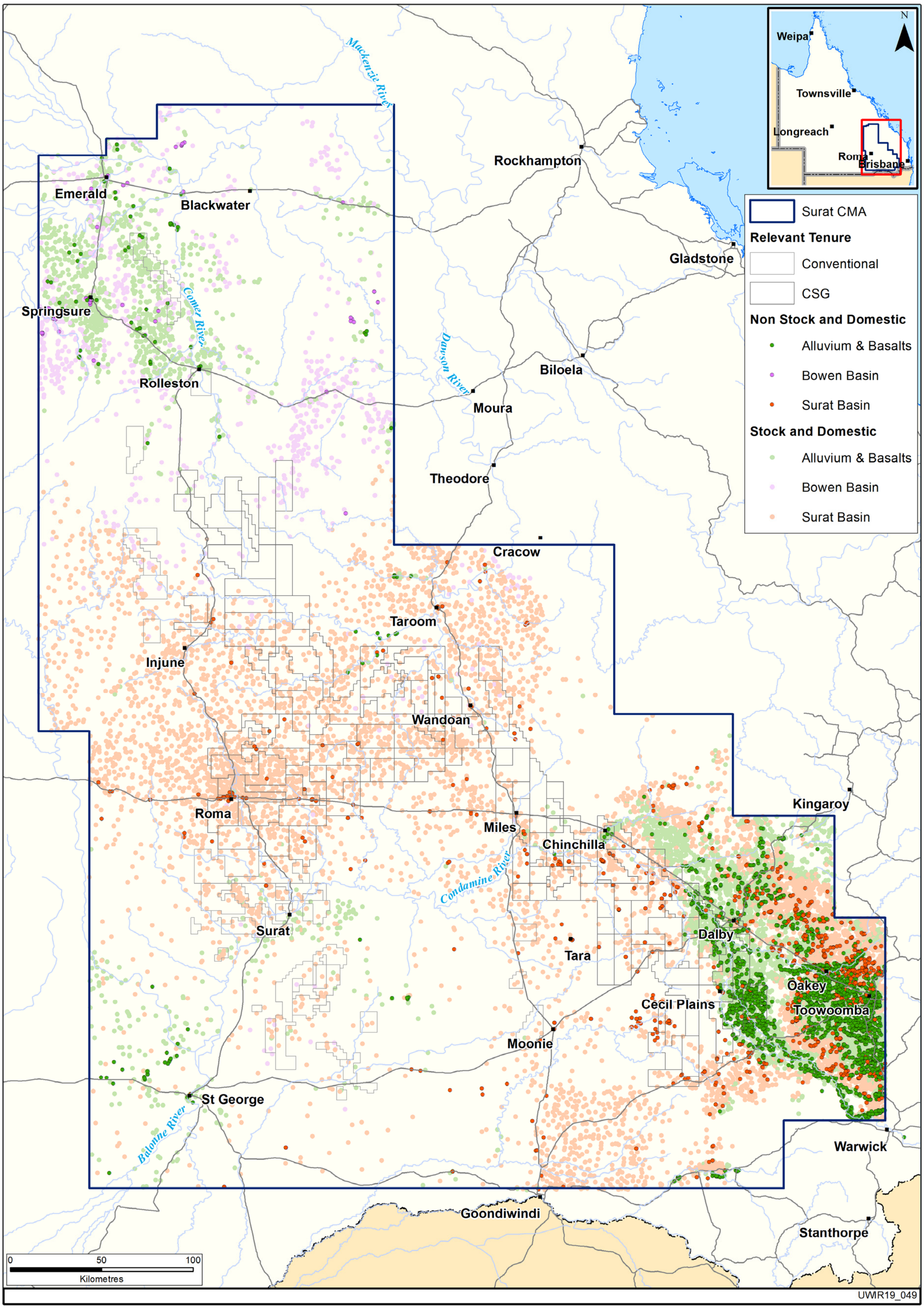

Figure 4-1 Distribution of water bores in the Surat CMA

4.1.3 Estimated water use

4.1.3.1 Context and approach

Reliable measurement of water use is necessary for model calibration and analysis of trends in monitoring data. The requirement to measure and report groundwater extraction in the Surat CMA varies. S&D water use does not require metering. For other purposes, there is limited (less than 1%) metering of water use outside of the Condamine Alluvium and Main Range Volcanics.

In the absence of metering data, indirect methods are required to estimate groundwater use. A method was first developed by OGIA in 2012 and has since been refined based on additional data and information. Some sporadic metered data is now also becoming available which has helped in reconciling water use estimates and building uncertainty bounds around the estimates. This data was largely not available in 2012 or 2016.

For S&D water use, the underlying principle of the method for estimation is that the deficit between the water supply demand and availability of surface water supply sources is met by groundwater. Demand is estimated based on grazing potential (stock-carrying capacity), property size and climatic variability.

For non-S&D use, in instances where metered data is available, that data is used – particularly in the Condamine Alluvium. In the case of the GAB however, metered data is generally not available and water use is estimated by applying a percentage to the licenced annual volumetric limit (entitlement volume) for specific purposes. In the GAB a review of the limited available metering data indicates that irrigation, agricultural and town water supply use is generally 70–90% of the entitlement volume, industrial is about 50% of the entitlement volume and groundwater use for feedlot purposes varies with the number of cattle in the feedlot.

Estimated volumes for individual bores are assigned to the aquifers into which the bores are interpreted to be screened. This process is referred to as the ***aquifer attribution*** and is based on available bore construction information, geological formation depths from the OGIA 2019 geological model, bore assessments, site verification where available and further desktop verification of bores in priority areas (OGIA 2019c). In some cases, OGIA's aquifer attribution may differ from the formation assigned in a water licence.

Where a bore is screened across more than one formation, water use has been distributed to the intersected formations relative to their permeabilities. For example, a water bore screened across the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone is likely to be accessing most of the water from the Hutton Sandstone because the permeability is higher in that formation.

4.1.3.2 Results

Estimated water use for S&D and non-S&D purposes in the Surat CMA is summarised in Table 4-1. The bore numbers presented are for existing water supply bores only (see section 4.1.2). The formations assigned to bores are based on the formations from which bores are accessing most of the water. Spatial distribution of current water use is presented in Figure 4-2. Growth in estimated water use over historical period is presented in Figure 4-3 while a further breakdown of water bores and estimated use is provided in Appendix D.1.

The current estimated water use in the Surat CMA is about 164,000 ML/year. Of this, about 41,000 ML/year (25%) is estimated to be from the GAB (i.e. the Surat Basin).

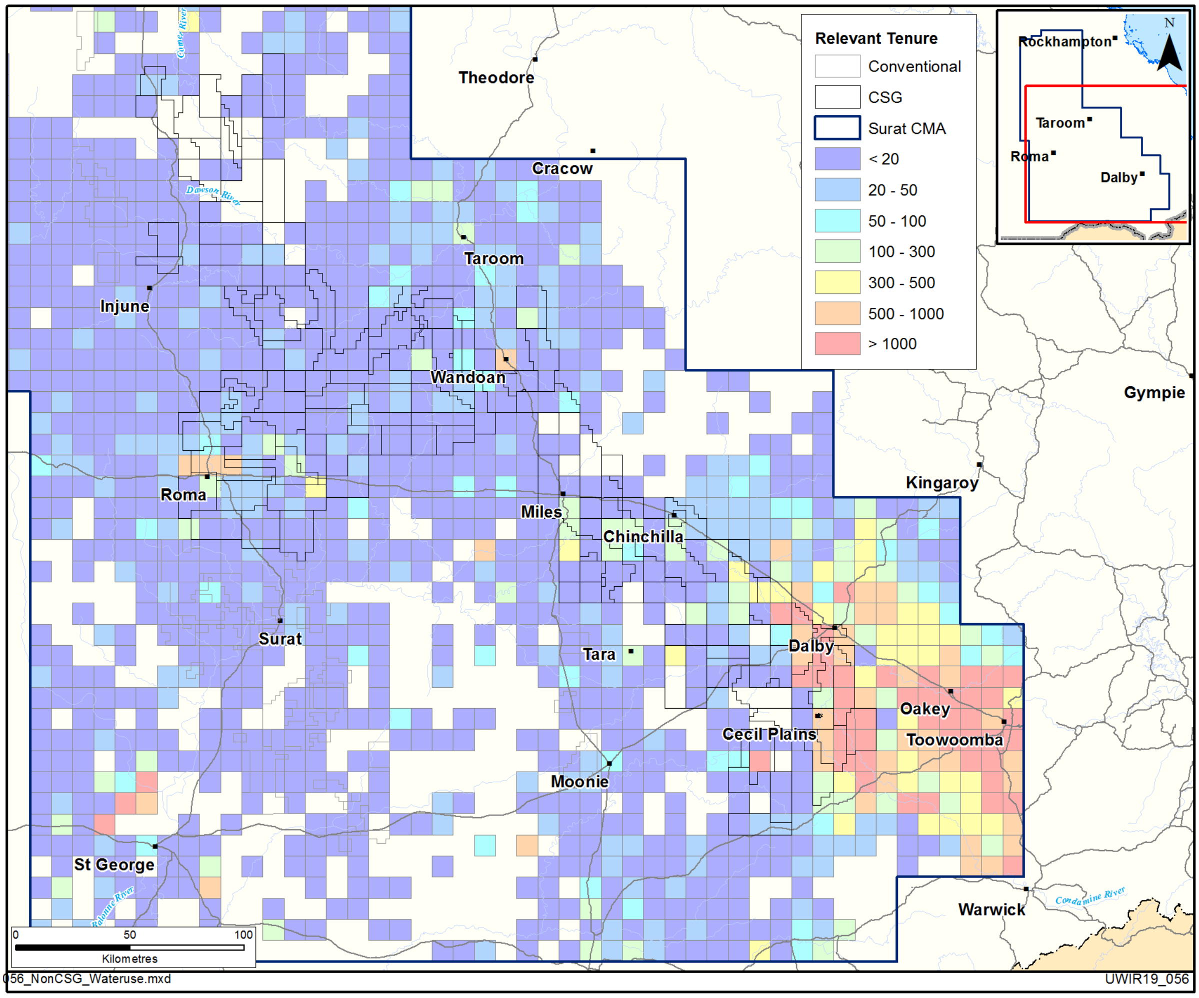

Figure 4-2 Spatial distribution of water use

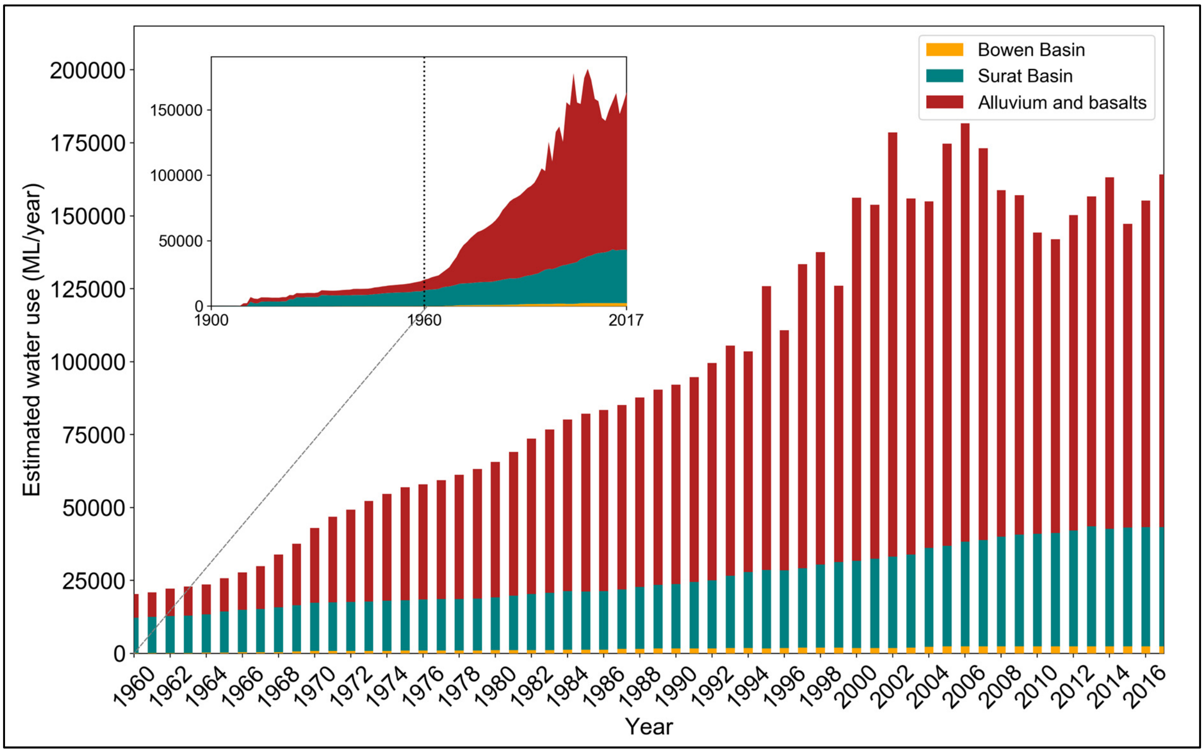

Figure 4-3 Growth in consumptive water use by major groundwater systems

Around 90% of water bores in the GAB are for S&D purposes, accounting for around 34% of the total water use. Water use has been gradually increasing since 1910 but has been stabilising since about 2000, which corresponds with the commencement of major water planning initiatives in Queensland.

In the absence of metering data, and due to underlying assumptions involved in estimating water use, there is significant uncertainty with this estimate. Further analysis of this uncertainty indicates that water use could be around 10% lower or up to 40% higher than estimated. This wide variation in estimates remains a key challenge for model calibration and interpretation of groundwater system responses to extraction. OGIA will continue to develop the method to refine estimated water use and thereby improve future modelling.

There has been a significant reduction in the overall water use estimate since the UWIR 2016. The main change relates to the estimation of non-S&D water use where, instead of the full entitlement volume, only a proportion of that volume is now applied in the estimated use.

Estimated water use was applied as input in the groundwater model calibration (section 6.5.5). Overall the model calibrated to lower volumes of water use than the estimated use.

4.1.4 Water quality

Groundwater is accessed from most formations across the Surat CMA. Water quality within the major water supply formations varies. The primary factors which influence water quality are formation mineralogy, proximity to areas where the formation is recharged and groundwater flow dynamics within the formation.

Groundwater within the recharge areas is generally fresh, characterised by lower salinity as represented through total dissolved solids (TDS). As groundwater moves through formations, its water chemistry evolves differently for different formations. A summary of the water chemistry for the major water supply formations across the Surat CMA is provided in Table 4-2, with a more extensive list of analytes and formations included in Appendix D.2.

Table 4-2 Median values of analytes for major aquifers in the Surat CMA

Formation	Samples	Concentration (mg/L)					pH	SAR
		Calcium	Sodium	Chloride	Fluoride	TDS		
Alluvium	4,814	46	205	250	0.2	1,064	7.9	5.4
Basalt	2,932	46	106	170	0.2	825	7.9	2.7
Mooga Sandstone	269	3	462	210	0.9	1,558	8.4	57.8
Gubberamunda Sandstone	369	3	350	150	0.3	1,126	8.4	46.3
Springbok Sandstone	250	11	653.5	844	0.7	1,970	8.3	64.1
Walloon Coal Measures	624	34	550	597	0.4	1,877	8.0	18.6
Hutton Sandstone	913	29	321	310	0.3	1,297	8.0	12.8
Precipice Sandstone	248	3	45	16	0.2	184	7.3	7.8
Clematis Sandstone	182	23	76	50	0.2	522	7.8	2.3
Bandanna Formation	26	6	498	177	1.4	1,576	8.1	44.5

Sandstone dominated or permeable formations such as the Precipice, Clematis and Hutton sandstones, the Condamine Alluvium and the Main Range Volcanics generally contain better water quality compared to other formations – TDS of around 1000 mg/L and sodium adsorption ratio (SAR) of around 10.

For human drinking purposes, a TDS of less than 1000 mg/L is required, whereas up to 4000 mg/L TDS is acceptable for stock purposes. These key formations are more suitable for drinking and/or irrigation purposes and account for more than 90% of non-S&D water use in these units.

4.2 Groundwater extraction by the P&G industry

Groundwater extraction by the P&G industry is primarily for non-consumptive purposes – the incidental taking of groundwater during oil and gas production. Water extracted in the process is referred to as ***associated water***. There are two types of associated water extraction in the CMA:

- groundwater extracted during the depressurisation of coal formations for CSG production
- groundwater extracted as part of conventional oil and gas production.

In addition, P&G tenure holders extract a small amount of non-associated water for consumptive purposes including construction, dust suppression and camp water supplies.

4.2.1 Associated water extraction

Under the P&G Regulation, tenure holders are required to report volumes of associated water produced on a six-monthly basis. In parallel, under the UWIR Water Monitoring Strategy (see Chapter 8), tenure holders are also required to provide monthly water production data per well. OGIA reconciles the two datasets to compile monthly water production volumes for each well. This information is used for various hydrogeological assessments, trend analysis and groundwater flow model calibration.

As detailed in section 2.4.2, there are currently around 6,800 CSG wells and 70 conventional oil and gas production wells in the Surat CMA. Total water production from those wells over time is shown in Figure 4-4. Volumes are shown as rates in ML/year, as derived from monthly volumes submitted to OGIA (see section 8.3).

As shown in Figure 4-4, there has been a significant increase in associated water extraction since 2014 to the current level of around 60,000 ML but the extraction rate appears to be stabilising – partially due to reduction in extracted water over time from existing wells and infilling of new wells in areas where partial depressurisation has already occurred. The majority (50,000 ML/year) of extracted water is associated with CSG production in the Surat Basin. CSG water extraction in the Bowen Basin has remained relatively stable in recent years at around 9,000 ML/year.

The spatial distribution of CSG water extraction in 2017 across the CSG fields is presented in Figure 4-5. This suggests that, overall, the largest associated water extraction occurs from the Fairview, Talinga, Daandine, Kenya and Berwyndale production fields.

Graphs showing trends in bulked-up CSG water extraction and corresponding gas production over time for three representative fields – Talinga, Daandine and Spring Gully are also presented in Figure 4-5. The trends reaffirm the relative gas and water production in various phases of development (section 2.1.2) i.e. a declining trend in water production with corresponding rise in gas production over time. This also partially explains the stabilisation of overall associated water extraction despite an increase in the number of production wells at new fields between 2014 and 2018 (Figure 2-8).

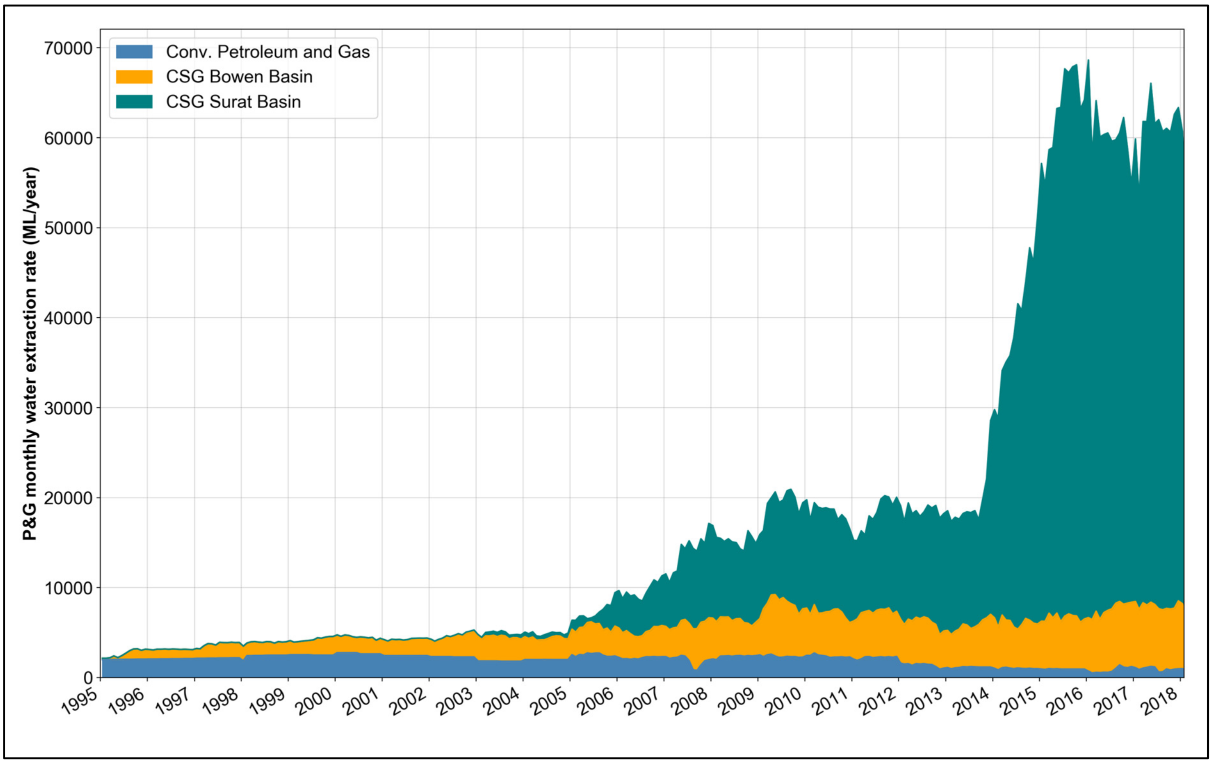

Figure 4-4 Historical groundwater extraction by the P&G industry in the Surat CMA

The conventional P&G industry is in a mature phase in the Surat CMA, with water extraction declining significantly since 2011 to the current level of around 1,000 ML/year. This also corresponds to declining oil production. The majority of conventional associated water extraction is from the Precipice Sandstone in the Moonie oil field. There is also some minor extraction from the Evergreen Formation and the Clematis Sandstone.

4.2.2 Non-associated water extraction by CSG tenure holders

Non-associated water is groundwater extracted by P&G tenure holders for consumptive purposes such as camp supplies and construction. From 2021 onwards, a water licence will be required for this non-associated water extraction in the CMA.

QGC, Origin and Santos have reported non-associated take within the Surat CMA. The total volume of extraction currently is around 500 ML/year, having peaked at around 1,700 ML/year in 2013. The recent reduction is due to declining exploration and construction activities by the tenure holders. Most of this water is extracted from the Precipice and Gubberamunda sandstones.

4.2.3 Reinjection

Associated water is treated by tenure holders to an appropriate standard and then used for consumptive purposes or reinjected into the aquifer system. Santos and Origin have established reinjection facilities to inject treated associated water into aquifers in accordance with the conditions of the relevant environmental authorities.

Santos's reinjection facilities target the Gubberamunda Sandstone at the Roma gas field. Origin targets the Precipice Sandstone at Spring Gully and Reedy Creek/Combabula gas fields.

At this stage, only the Origin facilities are operational. Since commencement of the scheme in January 2015, Origin's facilities have injected more than 20,000 ML into the Precipice Sandstone, currently averaging around 5,000 ML/year.

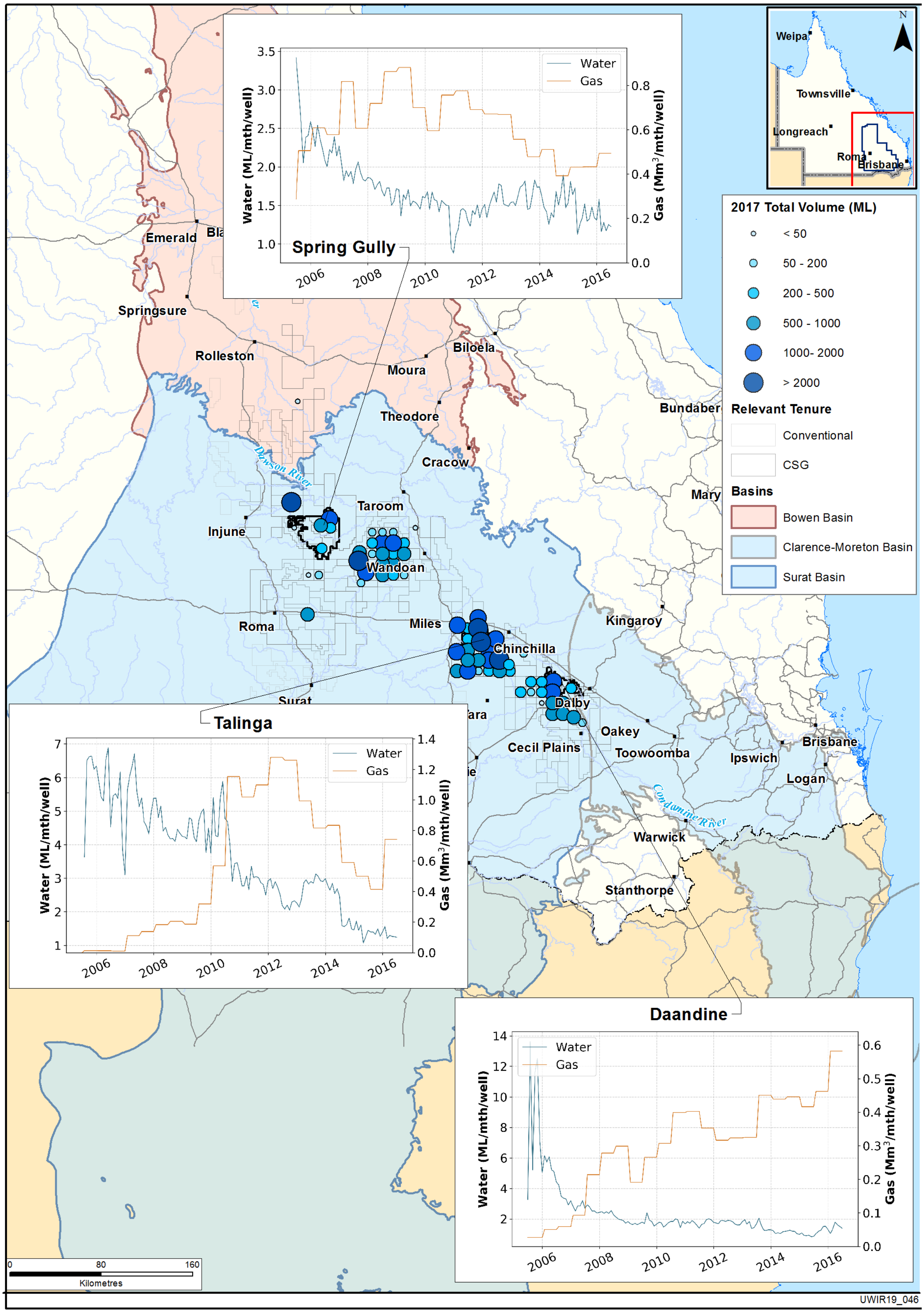

Figure 4-5 Spatial distribution of CSG water extraction with profiles for selected fields

4.3 Water extraction by mining

Coal mining is the dominant resource activity of significance in the Surat CMA. In the Surat Basin, coal is extracted from the Walloon Coal Measures and in the Bowen Basin from the Permian coal measures, outside the CSG production areas.

Coal mining in the Surat Basin commenced in the 1990s. There are four operational mines (Cameby Downs, Commodore, Kogan Creek and New Acland) and eight proposed mines that have development approval.

All current and proposed coal mines in the Surat Basin are surface mining operations within the outcrop of the Walloon Coal Measures and Springbok Sandstone. Extraction of groundwater is typically for dewatering of seepage into the mine pits. In most instances, the magnitude of drawdown caused by this seepage is in the order of tens of metres and decreases with distance away from the mine pit.

The total reported associated water use by coal tenure holders in the CMA is approximately 8,500 ML for the 2016/17 reporting period. The vast majority (more than 95%) of the associated water extraction occurs in formations of the Bowen Basin at the Kestrel, Ensham and Curragh coal mines in the northern part of the Surat CMA.

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Chapter 5 Trends in groundwater level

Considerably more monitoring data has become available in the Surat CMA since the UWIR 2016. A major research focus for OGIA during the current UWIR cycle has been on identifying ***groundwater level trends*** from this data and establishing potential causes for those trends, particularly in relation to identifying impacts that may have occurred from CSG depressurisation. Details of the assessment are provided in a separate report (see Appendix A). This chapter provides a summary of key conclusions drawn from the assessment.

The first part of this chapter presents general influences that affect groundwater level trends and the scientific approach that has been applied to analyse trends. This is followed by an overview of observed groundwater level trends in the main Surat Basin coal seam gas reservoir (the Walloon Coal Measures) and the formations immediately overlying (the Springbok Sandstone and the Condamine Alluvium) and underlying (the Hutton Sandstone) the reservoir. Observed groundwater level trends in the Precipice Sandstone are also discussed. The chapter concludes with a summary of the application of the approach to establishing potential causes of those trends, and key conclusions from the analysis.

A generic term – ***groundwater level*** or water level – is used here to refer to water pressure in an aquifer. This is generally the level to which groundwater rises in a monitoring bore. In unconfined aquifers in outcrop areas, this is the level below which aquifers are saturated with water. In confined areas where a low-permeability clay or mudstone formation sits above an aquifer, the water pressure in the aquifer causes the water level in the bore to rise above the top of the aquifer. Groundwater level trend is a term used to describe changes in water level or water pressure over a specific period of time. A trend can be rising or falling.

The term ***drawdown*** is also used extensively in this report and generally refers to a decline in water level due to groundwater extraction, with reference to some pre-development level. Drawdown may occur because of CSG and/or non-CSG water extraction. All or part of the drawdown caused by CSG water extraction is referred as CSG **impact** in this report.

5.1 General influences on groundwater levels

At any given point in time, a number of factors may influence the water level in a bore. In an undeveloped aquifer, the water level represents a balance between natural recharge and discharge, or input and output. When the rate of recharge to an aquifer exceeds the rate of discharge, the groundwater level will rise. Conversely, when the rate of groundwater discharge is greater than the rate of groundwater recharge, groundwater storage is depleted and water levels will decline.

In an undeveloped aquifer, the primary groundwater input is through rainfall or leakage from rivers. This typically occurs in outcrop areas where the aquifer is exposed at the surface. Once recharge water enters the aquifer system, it flows down-gradient from areas of higher groundwater elevation to areas of lower elevation and may flow out to rivers, streams and springs. All other factors being equal, if average recharge is maintained then there would be little or no variation in water level. However, during extended periods of above-average rainfall, the water level would gradually rise; similarly, below-average rainfall will tend to result in a declining groundwater level trend. Monitoring points closer to recharge areas typically show more immediate and clearer responses to variations in rainfall. Monitoring points further away from recharge areas typically show subdued and delayed responses. A large groundwater system such as the GAB therefore responds slowly to changes in recharge compared to smaller systems such as the Condamine Alluvium.

Groundwater extraction from water bores will cause the water level to gradually decline until a new balance is reached between extraction (or discharge) and recharge. For the same amount of water extracted, the magnitude and extent of decline will be influenced by aquifer permeability. In more permeable aquifers, such as the Precipice Sandstone, declines would be lesser but more widespread, compared to low-permeability formations, such as the Springbok Sandstone, where the decline at the bore will be much greater but less widespread.

Direct extraction of water from confined CSG target formations tends to create immediate and large declines in reservoir water levels. Depending on the degree of connectivity with adjacent formations, this may induce additional recharge from the surrounding aquifer formations in the form of vertical flow. Where this occurs, the rate of drawdown will be reduced.

There are a number of other factors unrelated to recharge or discharge that can also influence changes in water levels. These include loading and unloading effects – created by water being withdrawn from overlying formations (depressurisation) or added to overlying formations (rainfall) – and changes in atmospheric pressure. In most cases, these other factors are relatively minor components of water level change.

5.2 Overall approach to analysis of trends

In the context of this report, the primary focus of the trend analysis is to understand the extent to which the observed trends reflect impacts from CSG depressurisation.

Observed groundwater levels in formations surrounding the CSG reservoir may show a combined effect of non-CSG groundwater extraction from water bores in those aquifers (non-CSG impact) as well as induced flow from the aquifers to CSG reservoirs (CSG impact) (Figure 5-1). Separating the two impacts in time series of observed groundwater levels is challenging because neither impact can be measured directly.

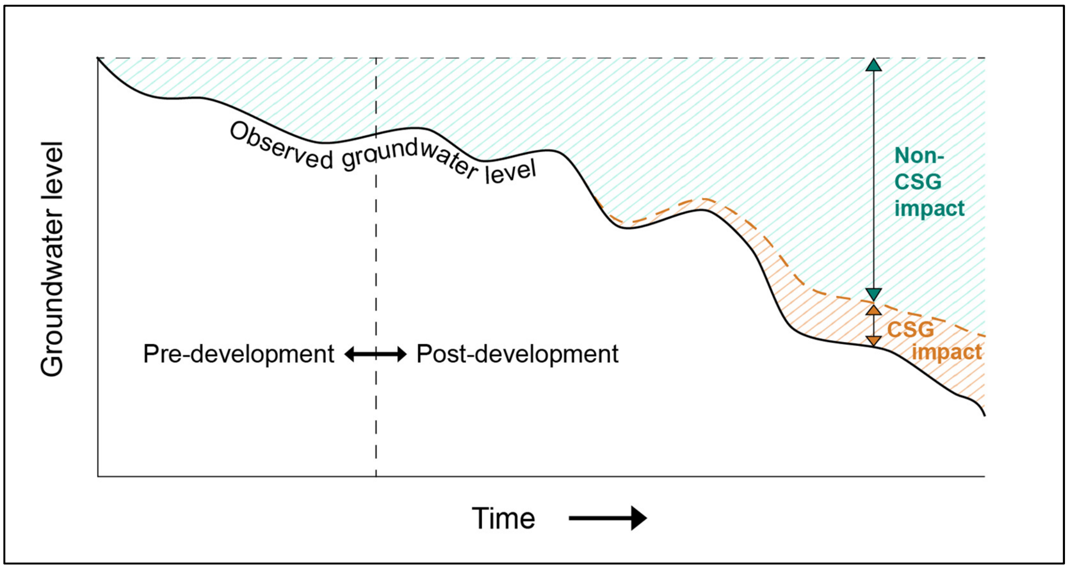

Figure 5-1 Schematic showing the combined effect of CSG and non-CSG development on groundwater levels

One method for separating CSG impacts is to establish a pre-CSG background trend in groundwater level (i.e. the trend resulting from all non-CSG influences including climate). If these non-CSG factors remain largely stable before and after CSG development and there is sufficient monitoring data during that period, then CSG impacts can be identified as a deviation from the background trend. This approach requires both pre-CSG time series water level data and reliable estimates of non-CSG groundwater extraction to separate these influences. Unfortunately, at most locations, there is neither sufficient groundwater level data nor reliable estimates of non-CSG water use to establish pre-CSG development background trends.

Therefore, OGIA has by necessity relied on indirect methods for the analysis of trends. Building upon previous analysis in 2016 (OGIA 2016d, 2016a) a multiple-lines-of-evidence approach is applied. This has included both statistical and visual correlation of observed trends with a range of factors such as estimated rainfall recharge, estimates of non-CSG water use and measured CSG water extraction. This is further supported by hydrochemistry analysis, updated geological knowledge, structural characterisation, understanding of aquifer interconnectivity and numerical testing through modelling. Importantly, the outcomes from the trend analysis has informed the refinement of the Water Monitoring Strategy (Chapter 8).

5.3 Data availability

Prior to CSG development, the majority of the monitoring infrastructure in the GAB was established by DNRME for managing consumptive water use. As a result, the pre-CSG infrastructure was largely limited to outcrop areas away from CSG development, where groundwater was generally accessed at shallower depths for consumptive purposes.

Since 2010, there has been a significant increase in monitoring infrastructure in deeper formations around the CSG development areas, where tenure holders have established monitoring points in response to previous UWIR requirements or for their own specific purposes (Chapter 8).

OGIA has considered all available data from various sources, including:

- monitoring data derived from the monitoring network established under the UWIR (Chapter 8)
- additional monitoring undertaken by tenure holders for which data was made available to OGIA
- DNRME monitoring including Groundwater Online and Groundwater Net bores (section 0)
- water supply bores with multiple water level measurements.

The tenure holder and DNRME networks largely comprise dedicated monitoring infrastructure, i.e. the purpose of the bore is for monitoring and the bore is not also used for water supply. Dedicated monitoring points are important because the data is generally not directly influenced by pumping effects.

Collectively, there are around 830 locations where water level monitoring data is available from the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone. Of these, about 40% are from formations other than the CSG target formation – the Walloon Coal Measures.

Prior to analysis, groundwater level data is checked for errors, properly referenced and corrected for variations in temperature and salinity. Corrections are necessary because, compared to fresh water, higher salinity will result in lower measured groundwater levels. The quality of the data also varies. There are some monitoring points, generally older installations, that show erroneous or unreliable records. In some cases, groundwater levels may be affected by the presence of gas in the bore, or are yet to stabilise (e.g. some low-permeability Springbok Sandstone monitoring points). There are also monitoring points that are not representative of the formation, because they either are screened across multiple formations, or have doubtful construction. These monitoring points are gradually being phased out or replaced as part of the WMS (refer to Chapter 8).

Groundwater chemistry data is also available from UWIR and non-UWIR monitoring points, including a large number of CSG production wells. In total, water chemistry data is available from about 1,200 CSG wells and other monitoring points in the Walloon Coal Measures and about 170 monitoring bores in the Springbok and Hutton sandstones. The data generally includes major cations and anions, and occasionally some trace elements and isotopes.

To support the analysis of trends, maps showing the interpreted groundwater flow directions for the Springbok Sandstone, Upper Juandah Coal Measures, Taroom Coal Measures, Hutton Sandstone and Precipice Sandstone have been prepared using the available data (Appendix E).

5.4 Analysis

5.4.1 Walloon Coal Measures

The Walloon Coal Measures is an interbedded aquifer comprising the Upper and Lower Juandah Coal Measures, the Tangalooma Sandstone and the Taroom Coal Measures (section 3.4.3). In some areas, tenure holders have further subdivided the Juandah Coal Measures to also include a middle coal seam. The two dominant target formations are the Upper Juandah Coal Measures – the topmost unit in the Walloon Coal Measures – and the Taroom Coal Measures, which is the bottommost unit. Groundwater levels in these units are important because they affect potential groundwater flow from the overlying Springbok Sandstone and the underlying Hutton Sandstone respectively.

Similar to other Surat Basin formations, north of the Range regional groundwater flow is generally northward, suggesting discharge into the Dawson River catchment (Figure 3-5). South of the Range, groundwater flow directions are generally southward, broadly consistent with the dip of the formation.

Regional groundwater levels in the Upper Juandah and Taroom coal measures show extensive CSG-induced decline around some of the oldest producing fields – Talinga, Kenya and Daandine (Figure 2-7). In comparison in the northern gas fields – where CSG development is more recent – declines are less pronounced.

The spatial distribution and magnitude of observed drawdown at various monitoring locations for the Upper Juandah and Taroom coal measures are shown in Figure 5-2. Examples of groundwater level response to CSG development over time within the Walloon Coal Measures is shown for four representative locations in Figure 5-3. At these locations, groundwater levels are recorded at multiple depths within the formation (nested sites), providing valuable information on how changes in groundwater level occur vertically within different parts of the Walloon Coal Measures. For comparison total CSG water extraction over time is also shown on the same figures for two distances from each monitoring location: 0–1 km and 1–5 km.

Across the development area, there are broadly consistent trends in groundwater level response to CSG development. The magnitude of drawdown within each of the sub-units within the Walloon Coal Measures generally increases with depth. In the lower part of the Walloon Coal Measures – the Taroom Coal Measures – declines tend to be greater, up to 250 m. In comparison, in the shallower Upper Juandah Coal Measures, the observed declines are typically 100 m or less. In part this reflects the disconnected nature of the coal seams due to the intervening low permeability interburden (section 3.4.3).

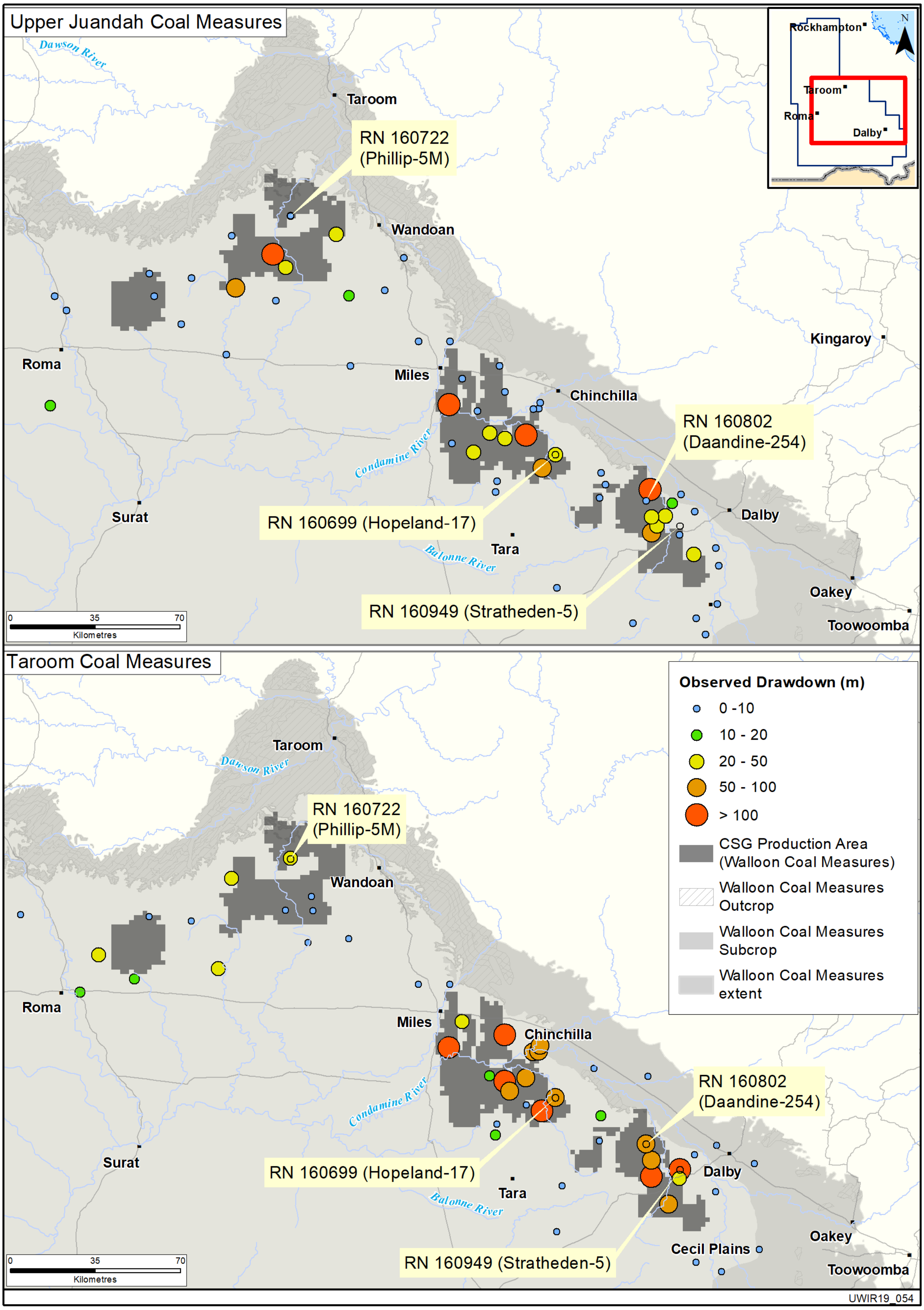

Figure 5-2 Observed drawdown in the Upper Juandah and Taroom coal measures

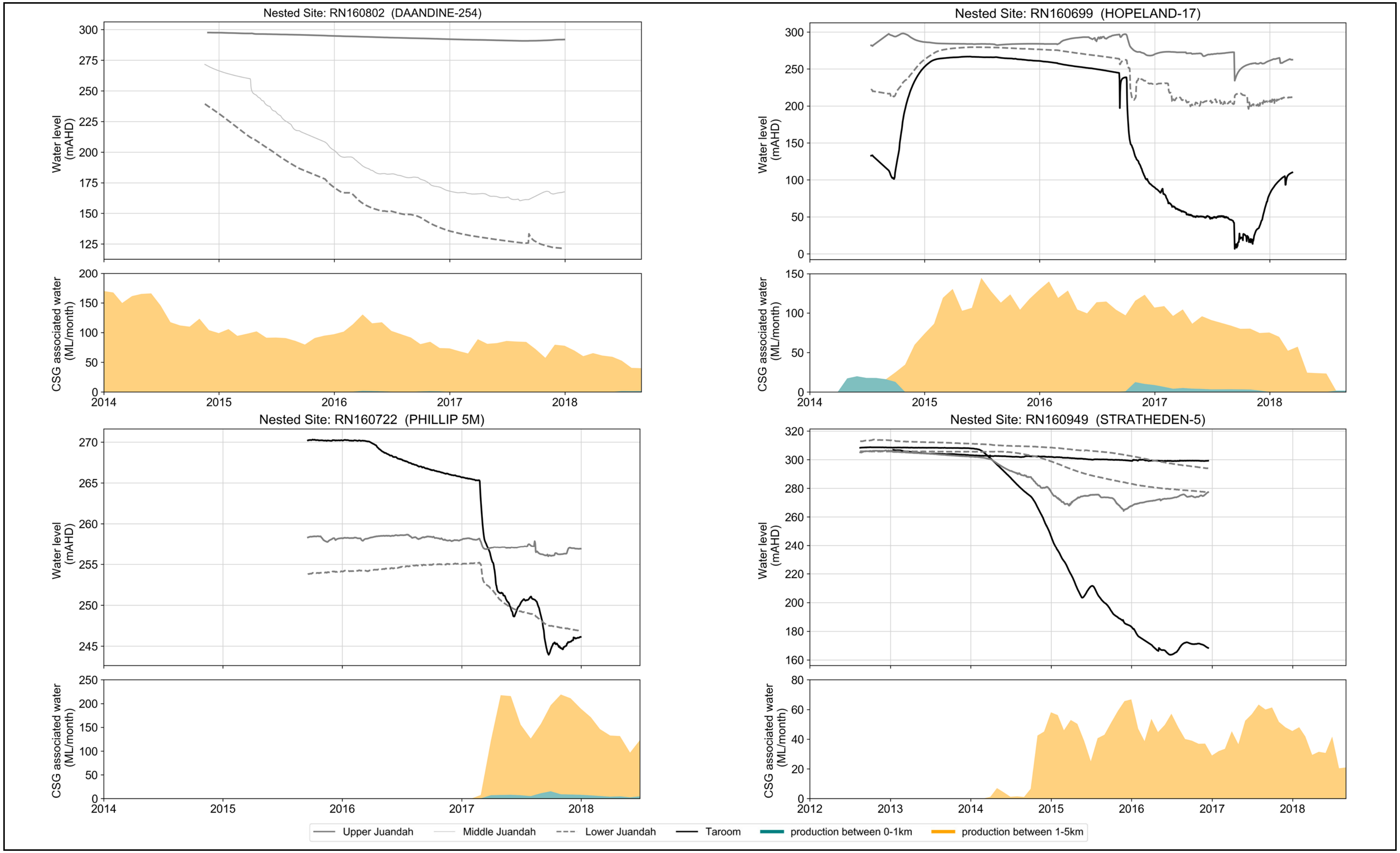

Figure 5-3 Groundwater level trends at selected sites in the Walloon Coal Measures

As shown in Figure 5-3, at Daandine-254 (RN160802) located west of Dalby, a significant gradual decline in groundwater level of close to 200 m is observed in the lower part of the Walloon Coal Measures compared to the upper part where little decline is observed. Hopeland 17 (RN160699) is located approximately 30 km south of Chinchilla (Figure 5-2). At this location, local CSG development commenced in late 2016. As shown in Figure 5-3, all three sub-units of the Walloon Coal Measures responded rapidly to the commencement of CSG production with a 200 m decline observed in the Taroom Coal Measures. Stratheden 5 (RN160949) is located approximately 30 km west of Dalby. At this location, a gradual decline of about 150 m is observed in the Taroom Coal Measures with only minor drawdown in shallower units, consistent with observations at Hopeland 17. In the northern area south of Wandoan where CSG production has started more recently, there is sharp decline of about 35 m (Phillip 5M, RN160722) corresponding with the commencement of nearby CSG water extraction.

In all cases there is a strong correlation of water level decline in the Walloon Coal Measures with CSG water extraction - which has increased considerably since 2014 (Figure 4-4). In comparison, non-CSG groundwater use from the Walloon Coal Measures within the active development area is negligible. Comparison within 5 km of the production area suggests that non-CSG water use is less than 5 ML/year compared to typically about 100 ML/year by the CSG extraction from the same area. Therefore, almost all the decline in the Walloon Coal Measures in and around the CSG fields is considered primarily to be related to CSG extraction.

A comparison of observed groundwater level decline in all monitoring points in the Walloon Coal Measures, with distance to nearest active CSG well, is shown in Figure 5-4. This is to assess how far these impacts have propagated to date. The plot indicates declines of more than 10 m are limited to areas within 10 km of CSG production wells. This also suggests that although declines of 200–300 m are observed closer to CSG wells, the cone of groundwater level decline (or impact) around the CSG field is steep and generally confined to within 10–15 km. Although not conclusive, there is also an indication of a flatter cone of depression in the lower part of the Walloon Coal Measures.

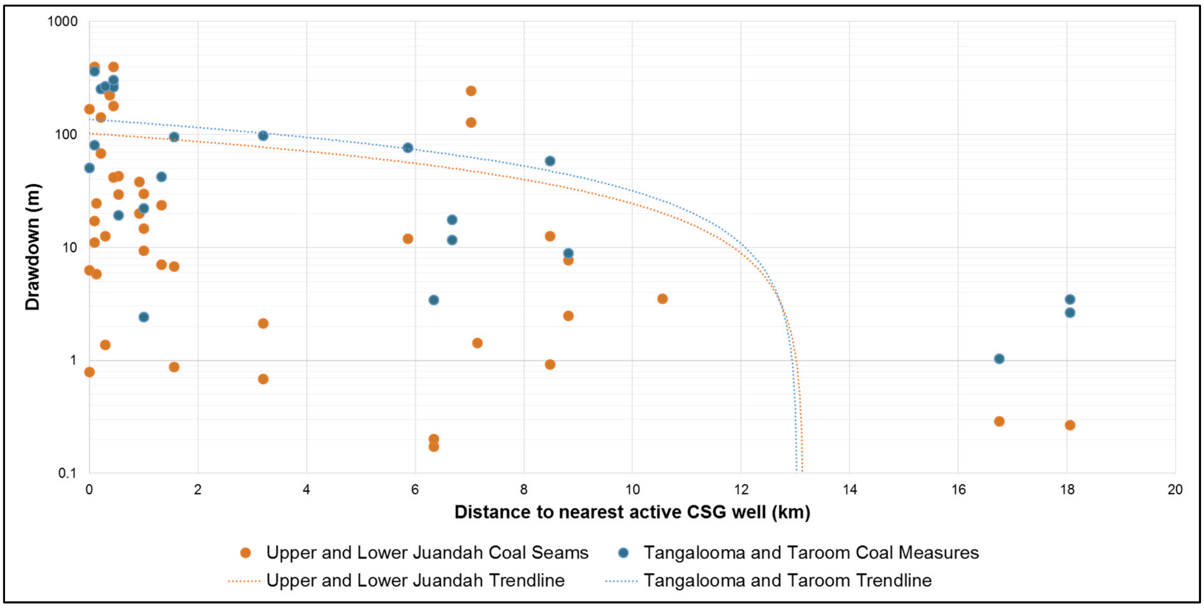

Figure 5-4 Groundwater level decline in the Walloon Coal Measures with distance to nearest active CSG field

5.4.2 Springbok Sandstone

Given the scale of the proposed CSG development area and the magnitude of observed drawdown in the Walloon Coal Measures, there is the potential for significant drawdown in both overlying and underlying aquifers. The Springbok Sandstone immediately overlies the Walloon Coal Measures in the Surat Basin. However, the formation is considered a tight aquifer and has a very low estimated water use and permeability compared to other aquifers (section 4.1.3).

There are 129 groundwater level monitoring points completed in the Springbok Sandstone across the Surat CMA. Of these locations, only six sites have at least one year of continuous data prior to 2010 – the length of record necessary for trend analysis. In the post-2010 period, there are 91 sites that have at least one year of continuous data, of which 50 are suitable for establishing trends and further analysis. Sites with unreliable data, or where drawdown in the underlying Walloon Coal Measures is not known, were not used for trend analysis purposes.

The rate of decline during the period before and after 2010 is shown in Figure 5-5. Hydrographs for the four representative sites marked in Figure 5-5 are presented in Figure 5-6. To establish the factors that may influence the observed groundwater levels, the following is also presented with corresponding groundwater levels:

- cumulative deviation from mean monthly rainfall (CDMMR, because long-term variations in rainfall are a useful proxy for groundwater recharge)
- total CSG water extraction within 10 km of the monitoring location
- estimated non-CSG water use within 25 km of the monitoring location.

Additional selected groundwater level hydrographs for the Springbok Sandstone are also presented in Appendix E.

Groundwater flow directions in the Springbok Sandstone are similar to other formations (Appendix E). North of the Range, although somewhat limited, the available data suggests possible northward groundwater flow and discharge to the upper tributaries of the Dawson River and associated minor alluvium (Figure 3-5). South of the Range, groundwater level flow is generally south and south-west, consistent with the dip of the formation.

Monitoring points show highly variable trends with an even representation of rising, falling and flat trends. There are a number of monitoring points that show sustained drawdown from at least the 1960s through to late 2010 (RN13989, Figure 5-6). This drawdown correlates primarily with non-CSG water use and to a lesser extent with rainfall patterns. More rapid drawdown is often noted during extended drier periods and in late 2010, which is likely to be due to the combination of lower recharge and increased groundwater extraction during these periods.

In deeper parts of the system in and around the CSG fields, impacts from CSG water extraction are most apparent in Kenya East GW4 (RN160525A, Figure 5-6), located 30 km south of Chinchilla. This monitoring site shows relatively static water levels until late 2014, after which there is a sharp change in trend, leading to an 18 m decline over the next three years. This change corresponds with the commencement of CSG production within 10 km of this site. Mapping and analysis of faults (section 3.5.1) suggest the presence of a nearby fault, where the Walloon Coal Measures is juxtaposed against the Springbok Sandstone, which may allow direct groundwater flow between the two formations. Additionally, water chemistry for a number of CSG wells in this area indicates potential mixing of water between the two formations.

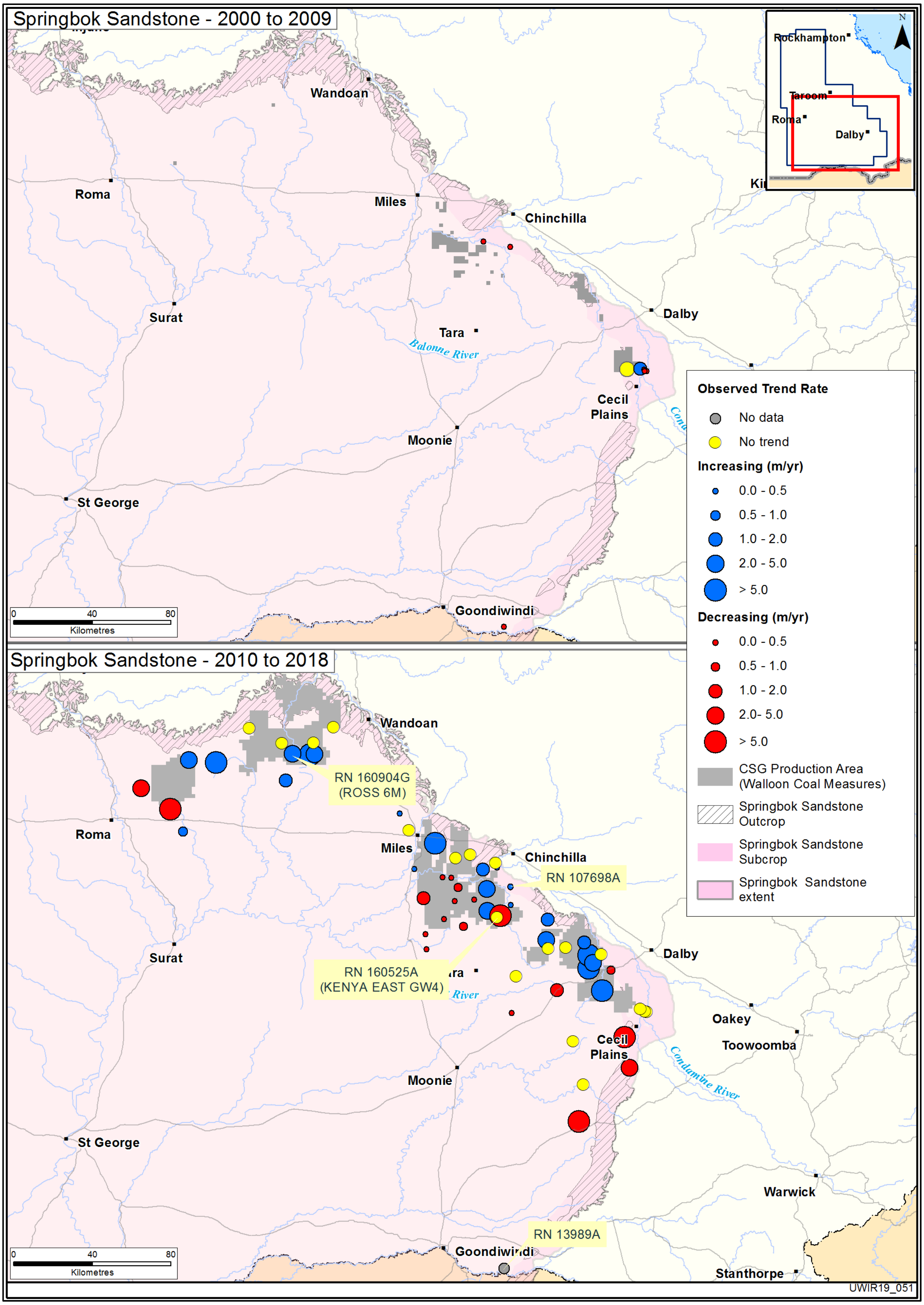

Figure 5-5 Summary of observed groundwater level change in the Springbok Sandstone

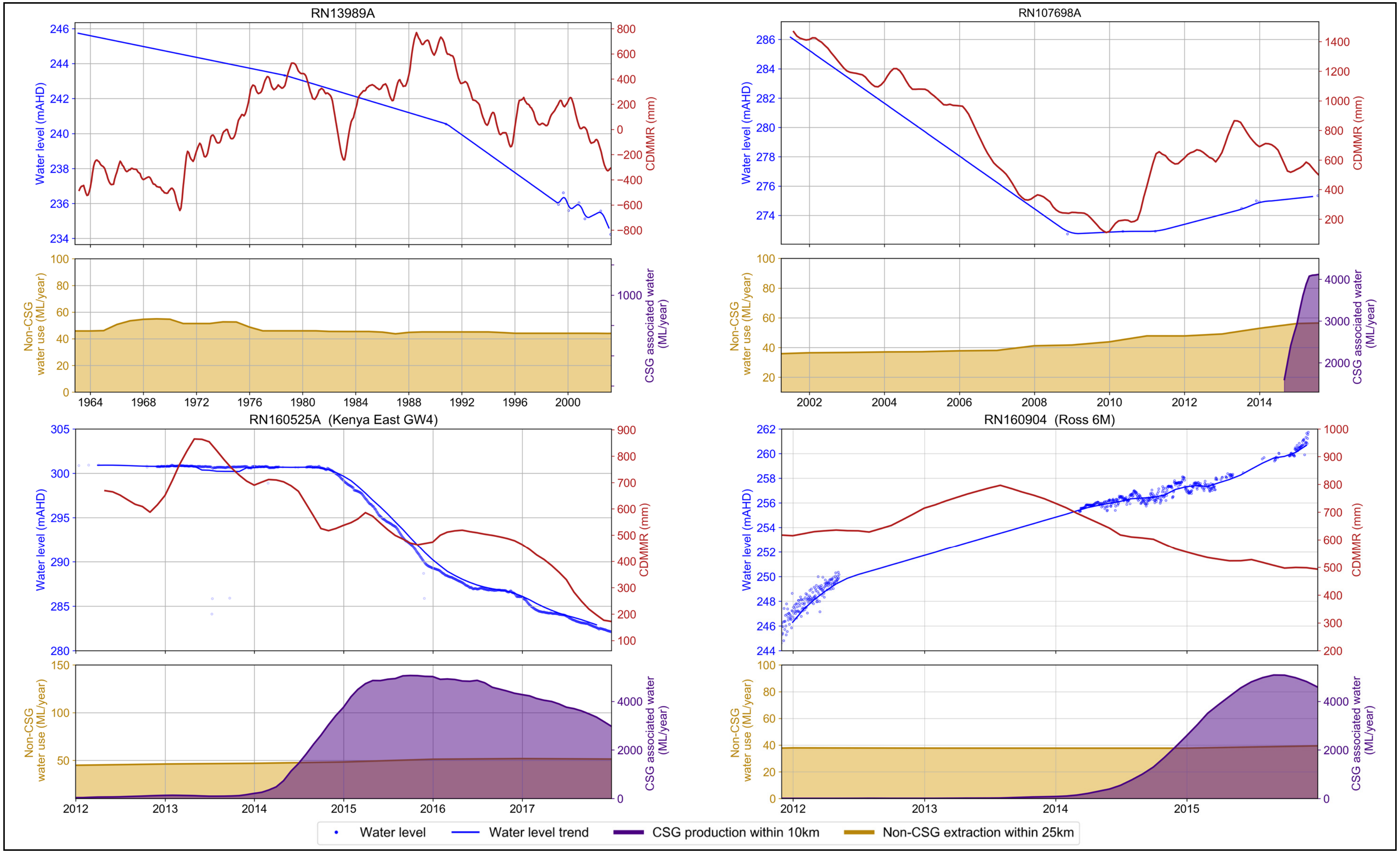

Figure 5-6 Example hydrographs showing trends in the Springbok Sandstone

A similar pattern to Kenya East may also be emerging at other Springbok Sandstone monitoring points within development areas (e.g. Broadwater GW11 and Isabella 7M) although data at this early stage is somewhat inconclusive. OGIA will continue to evaluate these sites as more data becomes available. In terms of water chemistry, the Walloon Coal Measures and Springbok Sandstone are significantly different – the coal seams are considerably more saline. Regionally, there are no systematic decreasing trends in chloride, which is the primary indicator of salinity change, in the Walloon Coal Measures. However, there are some local areas including the Kenya East field where water quality trends can be observed, which may indicate local connectivity.

In addition to declining water level trends, rising trends are also observed at a number of locations following CSG commencement (Figure 5-5). For example, at the Ross 6M monitoring points (RN160904, Figure 5-6) completed into the lower Springbok Sandstone, observations indicate a rising trend during a period when rainfall has, for the most part, been below average. The cause has not yet been established but may include the presence of gas or gradual equilibration in water level due to low permeability.

Overall, there are variable trends in the Springbok Sandstone. Consistent with previous predictions, there is evidence of CSG impacts at some locations, particularly where connectivity may be enhanced due to local geological features such as faults. There is also limited non-CSG water use from the formation, although this may still be sufficient to cause localised groundwater level declines, particularly outside of CSG production areas. Rising groundwater level trends in CSG production areas could be related to low permeabilities or other non-groundwater-related factors.

5.4.3 Hutton Sandstone

The Hutton Sandstone underlies the Walloon Coal Measures in the Surat Basin, with the Durabilla Formation aquitard separating the aquifer from the CSG reservoir. Water level trends in the Hutton Sandstone are of particular interest because it is a major water supply source in the Surat Basin (section 4.1) and recent reported declining trends have caused some concerns for water users.

There are 191 groundwater level data points in the Hutton Sandstone. Of these, only 28 sites have at least one year of continuous data prior to 2010. In the post-2010 period, there are 98 sites where similar data is available, of which 87 sites have data that is suitable for trend analysis.

The location and trends for the periods before and after 2010 are shown in Figure 5-7 with example hydrographs shown in Figure 5-8. CDMMR, CSG water extraction within 10 km of the monitoring location, and estimated non-CSG water use for the corresponding period are also shown in the hydrographs to show correlation with recharge and groundwater extraction. Additional selected groundwater level hydrographs for the Hutton Sandstone are presented in Appendix E.

Groundwater flow directions in the Hutton Sandstone are similar to other Surat Basin formations, with local variations (Appendix E). There is an interpreted groundwater divide around the Range, resulting in two dominant flow directions. North of the Range, groundwater flows towards the northeast, suggesting discharge to the Dawson River. South of the Range, groundwater flows south and southwest, consistent with the dip of the formation. The groundwater level maps are generally consistent with earlier findings (Hodgkinson, Hortle & McKillop 2010; Ransley & Smerdon 2012; OGIA 2016a).

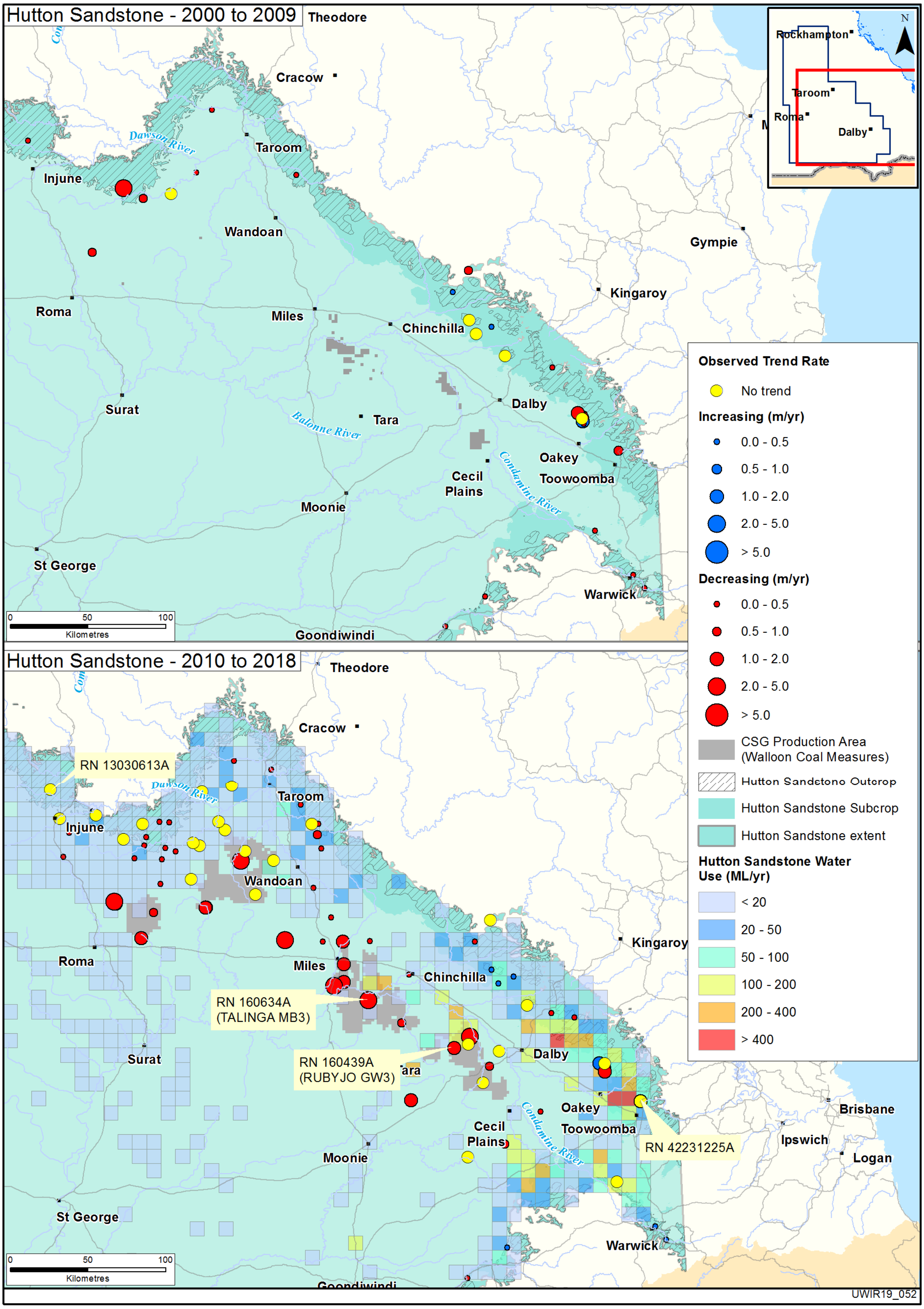

Figure 5-7 Summary of observed groundwater level changes in the Hutton Sandstone

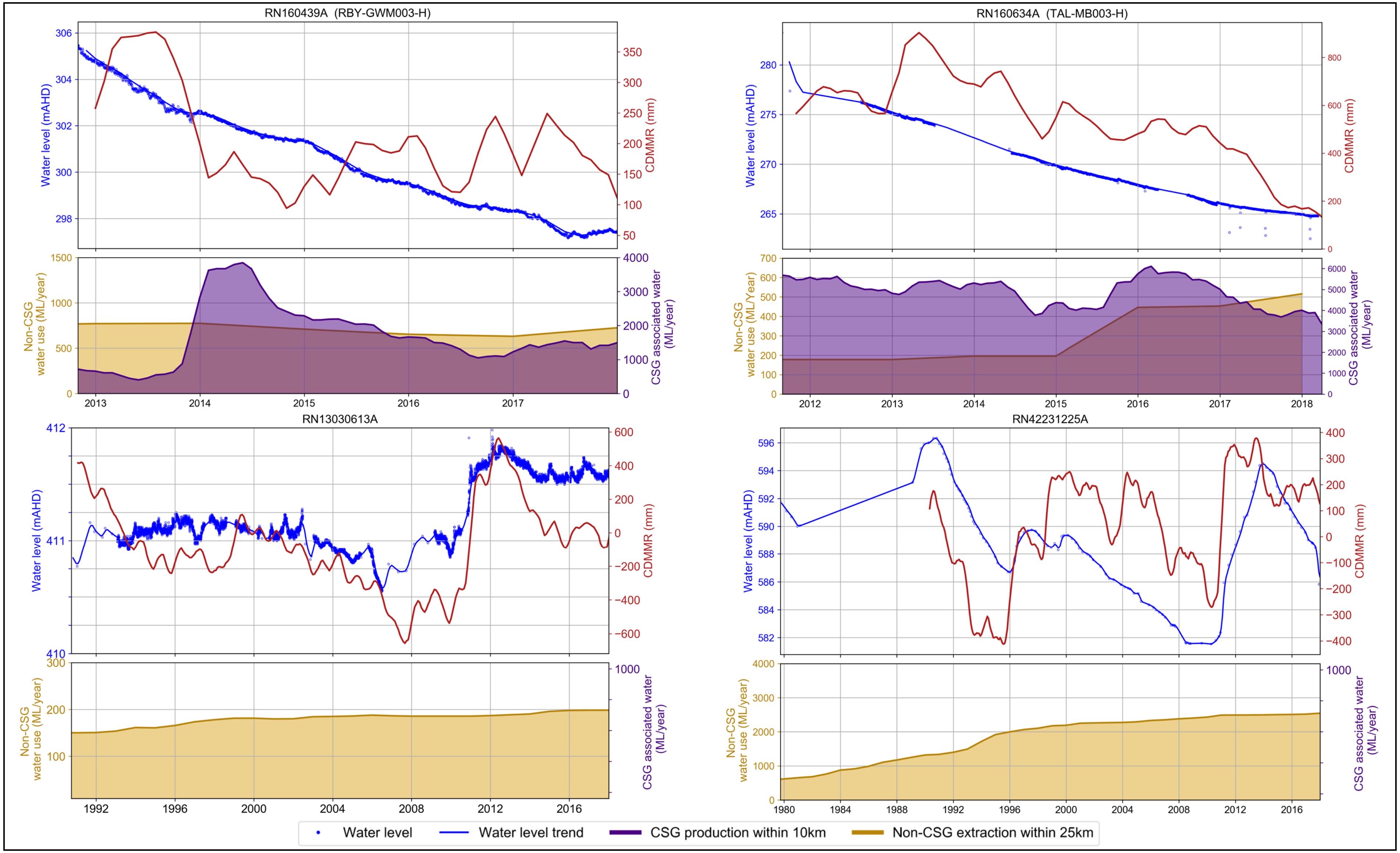

Figure 5-8 Example hydrographs showing trends in the Hutton Sandstone

Within and adjacent to the outcrop areas, groundwater levels in the Hutton Sandstone are relatively stable and show a strong correlation with rainfall. Examples of this correlation are shown at RN13030613A near Injune and at RN42231225A near Toowoomba (Figure 5-8), although there is some ambiguity about the RN42231225A which may be representing Main Range Volcanics. In areas away from the outcrop areas and closer to the CSG fields (e.g. RN160439A and RN160634A, Figure 5-8) there is no obvious correlation with rainfall.

As shown in Figure 5-7, generally declining trends during the pre-CSG development period are noted from the available data closer to outcrop areas. However, there is very limited data to establish trends in and around the CSG development areas for the same period.

In the post-development period, the majority of sites particularly deeper in the basin show generally declining trends with rate between around 0.5 and 2 m per year. Declining trends are noted both inside and outside CSG production areas. In the vicinity of CSG development areas, two-thirds of the points show a declining trend and the remainder show no trend. The majority of sites north of the Range, where the groundwater flow direction is northward away from the GAB, show no trend for the same period.

The spatial distribution of non-CSG water use for the Hutton Sandstone is shown in Figure 5-7. Generally, there is extensive non-CSG groundwater development in areas where the formation is either at outcrop or at depths of less than 500 m. The majority of groundwater use north of the Range is for S&D purposes while further south between Toowoomba and Miles, there are areas of significant groundwater use for industrial, stock intensive and irrigation purposes coinciding, in some places, with active CSG development. Spatially, declining trends are observed in areas where there is significant localised non-CSG water use, indicating potential correlation. There is also correlation between non-CSG water use and observed groundwater levels over time, such as RN160634A (Figure 5-8).

In relation to correlation with CSG water extraction, there is no discernible change in the rate of groundwater level decline corresponding to the onset of CSG water extraction, although the pre-development data is limited. For example, at RN160439A (Figure 5-8), the observed rate of decline in water levels appears to stabilise in the recent period when local CSG extraction is increasing rapidly.

Unlike the Springbok Sandstone, CSG wells are not completed into the Hutton Sandstone and the likelihood of enhanced connectivity through bores and wells is considered to be low (section 3.5.5).

Given the limited historical data, a sub-regional-scale groundwater model was developed to further evaluate whether CSG impacts may have occurred in the Hutton Sandstone. The purpose of the model was to test different hypotheses that may explain the observed drawdown at RN160634A (Figure 5-8) in the vicinity of Talinga and Condabri gas fields. The results suggest that CSG impacts are unlikely to propagate to the Hutton Sandstone, unless the vertical permeabilities are unrealistically high in the Durabilla Formation that separates the Hutton Sandstone from the overlying Walloon Coal Measures.

As noted in section 3.5.5, the Durabilla Formation is about 55 m thick and comprises siltstone, mudstone and fine to medium grained sandstone, which is likely to result in very low vertical permeability. Analysis of faults suggests that other than in the vicinity of the Horrane and Hutton Wallumbilla faults, faulting does not cause juxtaposition of Walloon Coal Measures with the Hutton Sandstone and the potential for connectivity is therefore low.

Overall, the widespread declining trends in available data correlate well with rainfall patterns, particularly in outcrop areas, and with non-CSG related groundwater use in the aquifer, both inside and outside CSG production areas. There are no discernible changes in the rate of decline that could correlate with CSG water extraction. There is a reasonably thick aquitard separating the aquifer from the CSG reservoir and connectivity is unlikely to be significantly influenced by geological faults or poorly constructed bores and wells.

Therefore, at this stage, there is no evidence to suggest that declining trends in the Hutton Sandstone are due to CSG water extraction in the overlying Walloon Coal Measures. Non-CSG water extraction for the aquifer itself is likely to be the primary cause of the declining trends. CSG depressurisation may be a contributing factor in some areas, but there is no definitive evidence at this stage to support this. Minor CSG impacts are predicted in the longer term and the findings are largely consistent with predictions reported in the previous UWIR.

5.4.4 Condamine Alluvium

Groundwater use for irrigation purposes has lowered the groundwater level in the more developed parts of the Condamine Alluvium by up to 26 m over the past 60 years, significantly altering the flow pattern in the formation. Until recently, groundwater levels in the Walloon Coal Measures have not materially changed, resulting in a difference of 5–20 m between the formations across much of the central part of the Condamine Alluvium (OGIA 2016c).

OGIA has updated mapping of groundwater level difference along the western flank, where CSG development has occurred and the Walloon Coal Measures is depressurised (Figure 5-9). The pattern of groundwater level differences shown is comparable to those reported in the UWIR 2016 and continues to suggest overall low connectivity between the two formation (section 3.5.3).

Groundwater level trends in the Condamine Alluvium have remained stable in recent time. Along the western flank, in close proximity to areas of current CSG development, general trends are demonstrated through two monitoring sites – RN42230159A east of the Condamine River away from CSG fields, and RN42230165A west of the river and in the proximity of Daandine gas field (Figure 5-10). Trends in both monitoring points correlate reasonably well with longer-term dry and wet periods in the CDMMR. Both also show a correlation with long-term non-CSG water use within 25 km, particularly in the period 1990 to 2005. Nearby monitoring in the Walloon Coal Measures, e.g. RN42231390A and RN160678A, shows clear declining trends that are not observed in the Condamine Alluvium, although the length of record is short.

In close proximity, at the Broadwater GW11 and Stratheden 4 sites, significant drawdown due to CSG extraction is observed in the Walloon Coal Measures. This drawdown has resulted in groundwater level difference of up to 30 m from the Condamine Alluvium to the underlying Upper Juandah Coal Measures. However, there has been no detectable response in the Condamine Alluvium at either location. This is consistent with observations made at the Daandine 164 site, one of two pumping test sites investigated as part of the Condamine Connectivity study (OGIA 2016a). The fluctuations in groundwater levels observed near Daandine 164 during the testing period were instead attributed to the combined effects of mechanical loading and regional trends in the Walloon Coal Measures (OGIA 2016a).

Consistent with previously reported findings, it is considered unlikely that the trends in the Condamine Alluvium are influenced by CSG water extraction in the Walloon Coal Measures.

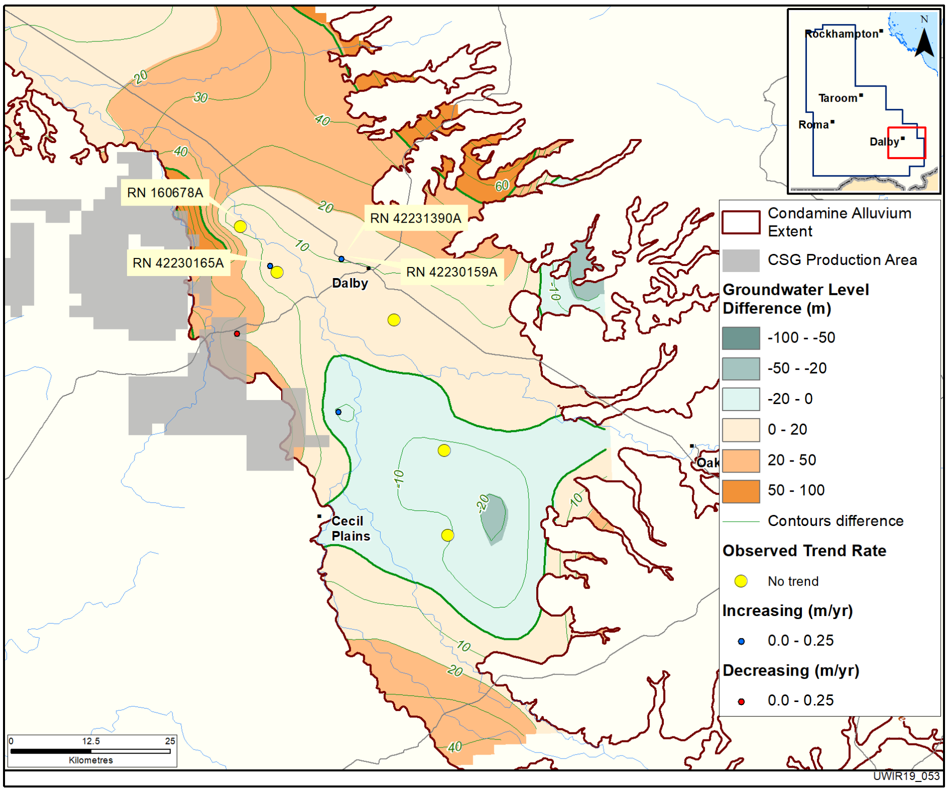

Figure 5-9 Groundwater level difference - Condamine Alluvium to the Walloon Coal Measures

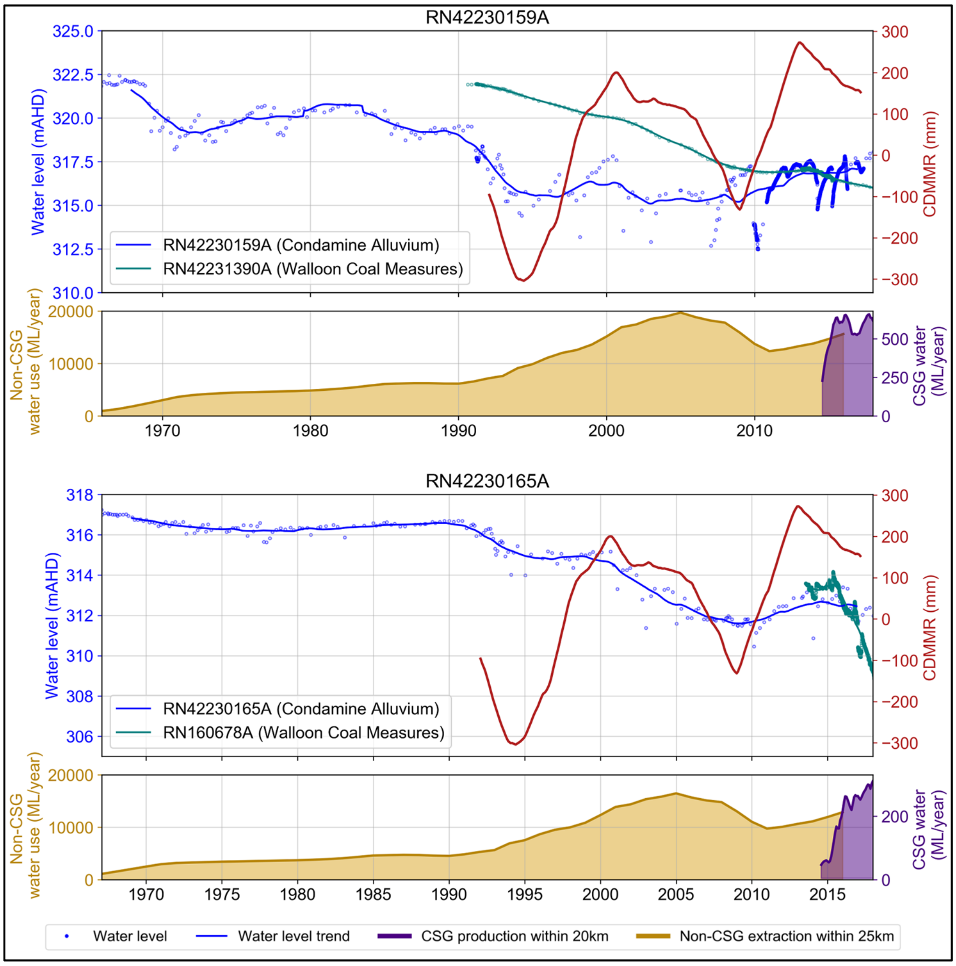

Figure 5-10 Example hydrograph showing trends in the Condamine Alluvium

5.4.5 Precipice Sandstone

The Bandanna Formation is generally isolated from overlying aquifers by the Rewan Formation, limiting any impact propagation from CSG development. However, as reported in 2016, there are two locations where the Precipice Sandstone is interpreted to be in direct contact with the Bandanna Formation – in the western and eastern contact zones (Figure 3-16). These two zones are in close proximity to existing CSG production fields and represent areas of potential connectivity.

There is also conventional oil production from the Moonie field in the southern part of the CMA, in which some extraction of associated water has been directly from the Precipice Sandstone (Figure 2-6) since 1963. At this location, oil has formed within a structural trap within the Precipice Sandstone and Evergreen Formation (Figure 2-2).

There are 125 monitoring points in the Precipice Sandstone. Of these, only 58 have at least one year of continuous data prior to 2015, while 73 have at least one year of continuous data post-2015; 24 representative sites with continuous data were selected for trend analysis. The location and estimated water level trends for these monitoring points are shown in Figure 5-11, with example hydrographs shown in Figure 5-12. CSG and non-CSG water extraction is also shown, along with the reinjection profile from Reedy Creek and Spring Gully sites.

As for the Hutton Sandstone, the available data for the Precipice Sandstone indicates two dominant groundwater flow directions either side of the Range (Appendix E). In terms of trends, there is a mix of stable to moderately declining trends observed prior to 2015 in the Precipice Sandstone and generally increasing trends thereafter (Figure 5-11).

The Precipice Sandstone is a regional aquifer, with the highest horizontal permeability of all aquifers in the Surat Basin (Figure 3-7). Changes in water levels in response to recharge or extraction are consequently generally smaller in magnitude and more laterally extensive, compared to other units. Peaks and troughs associated with recharge events are therefore also less pronounced compared to lower-permeability formations, such as the Hutton Sandstone (RN13030613A, Figure 5-8).

Potential CSG impacts on the Precipice Sandstone relate to extraction from the Bandanna Formation in and around two areas where the two formations are in direct contact. CSG production from the Bandanna Formation commenced in the late 1990s. There is no time series data available prior to commencement, with the majority of monitoring commencing in the late 2000s.

Adjacent to the two contact zones with the Precipice Sandstone, the available data for the pre-2015 period shows a mix of trends from slightly increasing (RN160925 and RN160736) to slightly decreasing (RN160737). In the post-2015 period, moderately increasing trends (RN160925 and RN160737) to stable trends (RN160736A) are observed. Further north, closer to outcrop and adjacent to the western contact zone, slightly rising trends are observed in RN160927, RN160650, and RN160649 (Figure 5-11). During this period, there are no discernable impacts from CSG or non-CSG extraction at this location.

In the southern Surat Basin around Miles and Chinchilla, the available data across both time periods indicates declining trends in the Precipice Sandstone (RN160672, Figure 5-12). In this area, there is extensive non-CSG development. In parallel, the Moonie oil field commenced in the 1960s. The regionally observed declines in groundwater pressure are therefore likely to reflect a combination of non-CSG and historical P&G development.

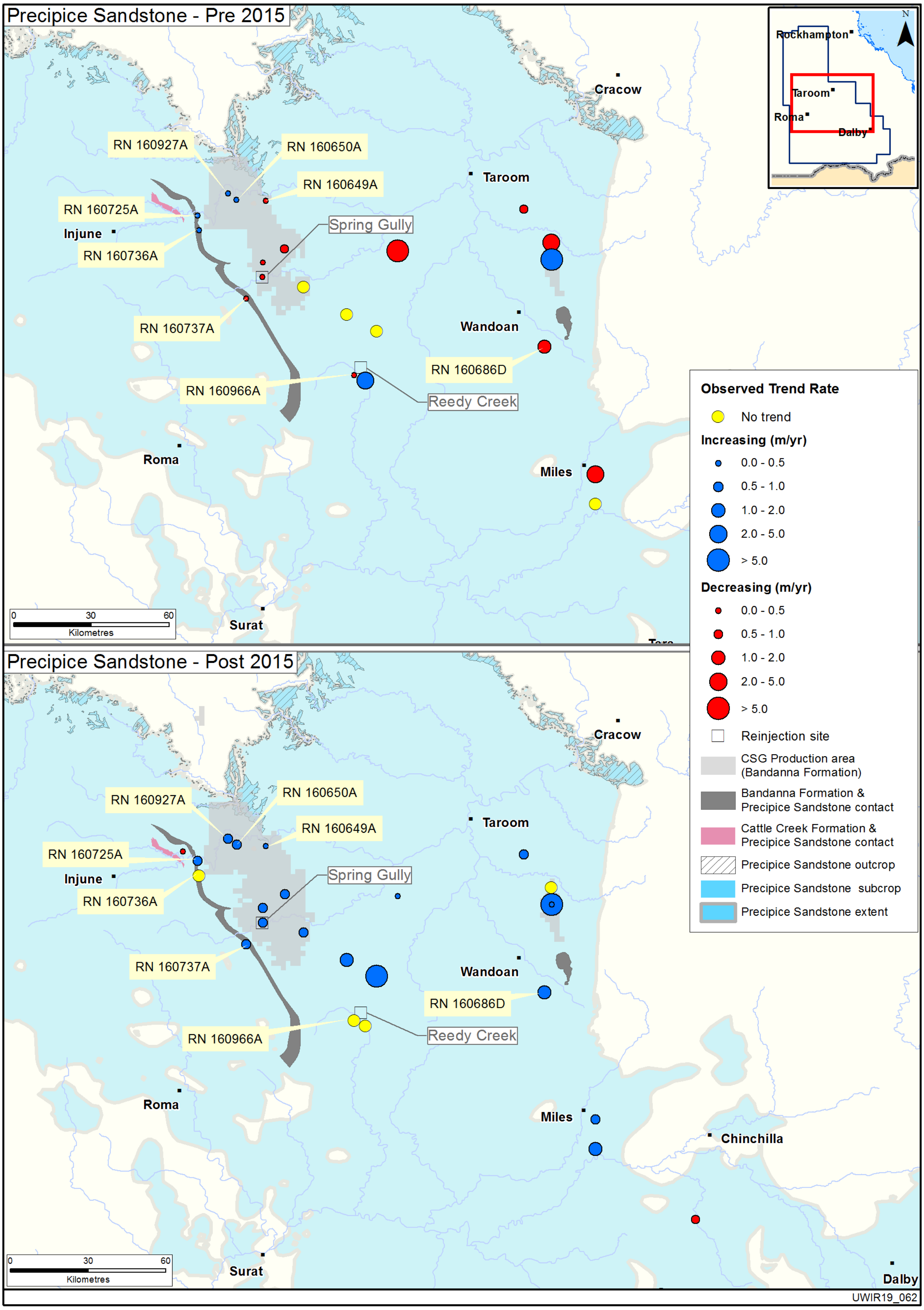

Figure 5-11 Summary of observed groundwater level changes in the Precipice Sandstone

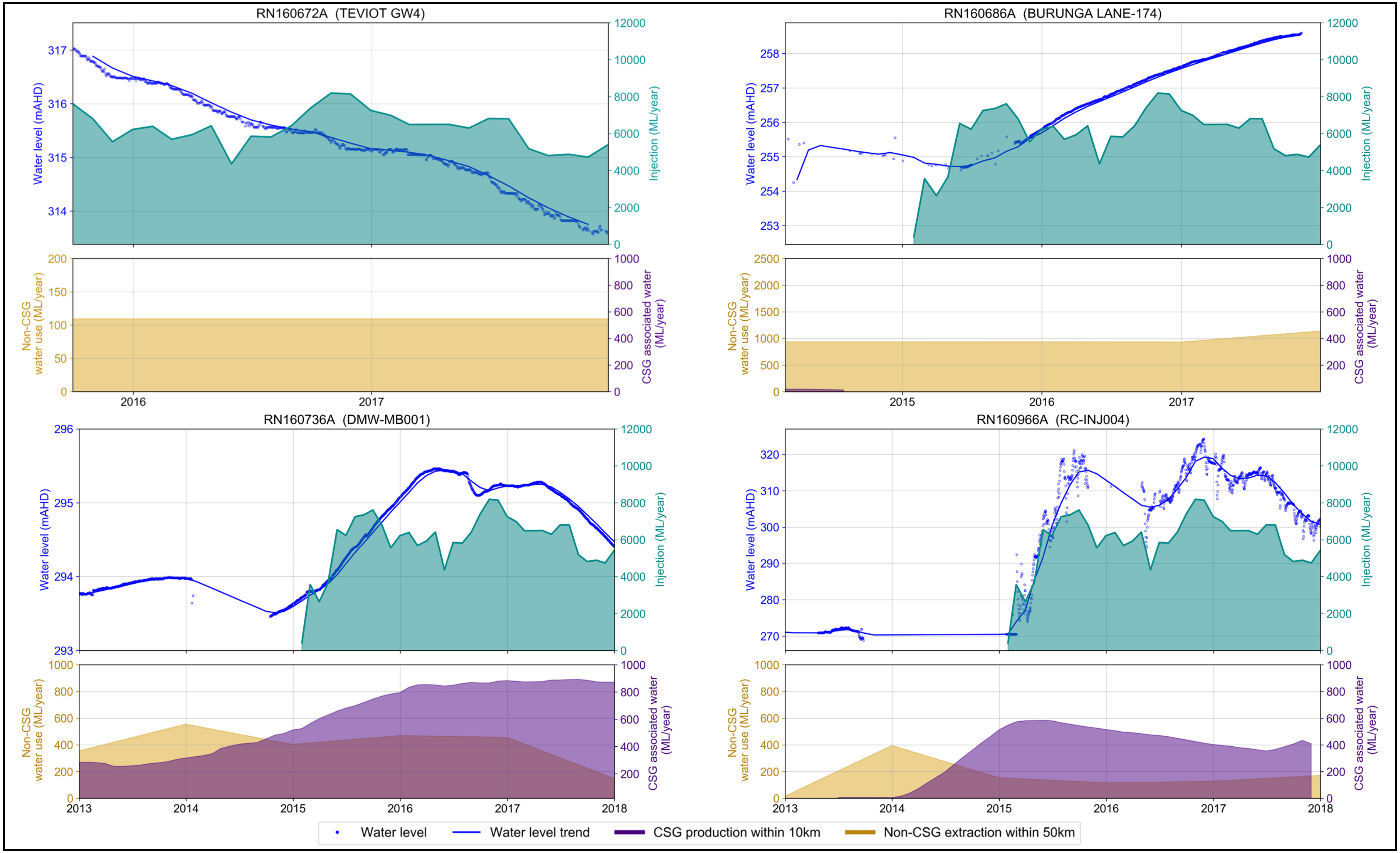

Figure 5-12 Example hydrographs showing trends in the Precipice Sandstone

Since the commencement of reinjection into the Precipice Sandstone in 2015, significant pressure responses have been observed across large parts of the Surat Basin. At the Reedy Creek reinjection facility, initial short-term water level responses of up to 50 m have been observed (RN160966, Figure 5-11). Regionally, pressure responses are observed more than 80 km from the reinjection site (RN160686, Figure 5-11), highlighting the high permeability of this unit.

With such a significant observed response to this reinjection activity, it is difficult to identify any other impacts from CSG or non-CSG development within this area. Furthermore, with such high permeability, a significant leakage to the underlying Bandanna Formation would be required to generate an observable drawdown through the contact zones. Additional monitoring in both the Precipice Sandstone and Bandanna Formation has been included in Chapter 8 to improve data availability in these areas.

At this stage, there is no evidence of CSG impacts at the two contact zones. Reinjection provides the dominant effect on water levels in these areas. Further south within the CMA, it is likely that pressures in the Precipice Sandstone have been affected by extraction from the Moonie oil field, although there is no long-term groundwater level data to confirm this.

5.5 Summary

An extensive monitoring network is in place in the Surat CMA (Chapter 8) which provides important data for ongoing analysis of groundwater level trends during the post-CSG development period.

Since CSG impacts in surrounding aquifers cannot be observed directly, OGIA has applied a multiple-lines-of-evidence approach and statistical correlation techniques to identify evidence of CSG impact. Analysis suggests that there is evidence of widespread CSG impact in the Walloon Coal Measures – up to 100 m in the upper part and up to 250 m in the lower part of the formation. In the overlying Springbok Sandstone, the trends are mixed, although there is evidence of CS impacts at some sites to suggest that CSG impacts have propagated to this formation. In the underlying Hutton Sandstone, pronounced declining trends are observed, but these are likely to be due to increasing non-CSG water use. There is no evidence of significant CSG impact in the Hutton Sandstone at this stage. In the Precipice Sandstone, reinjection has led to rising groundwater level trends in the northern part of the CMA.

Ongoing analysis of water level trends is important for understanding groundwater system dynamics, such as flow directions, and for the identification of impacts from CSG and non-CSG development. The identification of these trends and causes is also important for improving model calibration (Chapter 6).

Chapter 6 Modelling of impacts

This chapter provides an overview of the tool that is used for making predictions of impacts – the geological and regional groundwater flow models (the regional groundwater flow model). Predictions made using the model are discussed in Chapter 7. Additional details of the geological model and the groundwater flow model are available in two separate technical reports (Appendix A).

6.1 Methods and techniques for predicting groundwater impact

6.1.1 Modelling methods

A groundwater flow model is a computer-based three-dimensional mathematical representation of a groundwater system using the laws of physics. A model is generally developed for all or part of a groundwater system. The modelled area is referred to as the model domain, which exists in three dimensions. It is divided into a number of building blocks to represent key features of the groundwater flow system including the elevation of the ground surface and each geological formation present within the area.

A number of different organisations have developed guidelines that identify good practice with regard to construction and calibration of numerical models and uncertainty analysis, the most relevant of which are:

- Australian groundwater modelling guidelines (Barnett et al. 2012)
- Uncertainty analysis – Guidance for groundwater modelling within a risk management framework (Middlemis & Peeters 2018).

Broadly, there are three stages involved in constructing a groundwater flow model:

1. **Conceptualisation.** Available information is used to translate a complex three-dimensional geological system and knowledge of groundwater flow processes (derived from hydrogeological investigations) into a simple idealised representation. Numerous assumptions are involved in this process. Whilst numerical groundwater models are relatively complex compared to simple analytical techniques, they remain simplified representations of hydrogeological reality.
2. **Model construction.** The simplified conceptual representation of the system is converted into the groundwater flow model – a series of large computer files representing hydraulic parameters, boundary conditions, groundwater extraction, groundwater recharge, ground surface and geological formation elevation, the model grid, and other elements.
3. **Model calibration.** Once constructed, the model is then calibrated based on actual observed groundwater pressures, extraction rates and other available information including expert knowledge. This calibration process typically involves adjusting the hydraulic parameters of each model layer until the best possible match between predicted and observed data is achieved. Calibration of complex models is carried out using specialised computer programs.

Once constructed and calibrated, a model can be used to predict changes in water pressure or flow in response to various development scenarios.

A fourth stage – **uncertainty analysis** – is becoming a common feature of groundwater modelling and is the subject of the recent IESC explanatory note mentioned above (Middlemis & Peeters 2018). For the UWIR 2012, OGIA completed predictive uncertainty analysis and has done so again as part of the UWIR 2019. A summary of the sources of uncertainty and the methodology used to assess uncertainty in predictions reported in this UWIR are discussed in section 6.5.7.

6.1.2 Overall approach to modelling in the Surat CMA

6.1.2.1 Previous iterations

OGIA's approach to modelling and the numerical model itself have evolved since the UWIR 2012. The 2019 regional groundwater flow model represents the third iteration of conceptualisation, construction and calibration (section 6.1.1). Each iteration of the model is informed by a revised understanding of key hydrogeological processes or concepts operating within the Surat CMA at the time.

The first model iteration used to predict impacts in the UWIR 2012 was largely based on information from previous studies. Relatively little primary data interpretation was undertaken and the model was developed using a standard version of MODFLOW 2005.

A new model was constructed for the UWIR 2016 using a number of innovative modelling techniques developed by OGIA's team and a revised conceptualisation of the groundwater flow system based largely on primary data interpretation. MODFLOW-USG was the modelling platform; a number of revisions were made to the standard MODFLOW-USG modelling code. These revisions included the development of additional functionality to address unique challenges of relevance to CSG impact assessment in the Surat CMA:

- simulation of water desaturation due to gas production in coal seams around CSG wells
- more accurate representation of CSG wells using a descending MODFLOW drain methodology
- increased modelled permeability in areas where CSG wells screen multiple coal seams that would otherwise be separated by low permeability interburden
- simulation of reinjection of treated CSG water into the Precipice Sandstone.

This work was undertaken by OGIA in collaboration with one of the primary developers of the MODFLOW code. The method developed to simulate water desaturation in and around CSG wells is described in Herckenrath et al. (2015). Another journal article on the overall approach to the modelling work is currently under review.

6.1.2.2 Key improvements in the current model

This third iteration of the regional groundwater flow model used for this UWIR represents a revision of the previous model and includes a number of further refinements to the modelling approach. Key improvements incorporated into this model are:

- development of a revised regional geology model on a 250-m grid based on geophysical log data from about 7,000 P&G wells, updated geological mapping and other revised datasets (section 6.2)
- improved understanding of the groundwater flow system operating in the Surat CMA and the observed impacts of ongoing CSG and non-CSG extraction (Chapter 3 and Chapter 4)
- revised and updated initial model parameterisation drawing on expanded lithological and hydraulic parameter datasets (section 6.5.3)
- incorporation of additional major faults (section 6.5.4.3) and open cut coal mines (section 6.5.4.4)

- simulation of CSG wells partially completed into the overlying Springbok Sandstone (section 6.5.4.7)
- more detailed representation of the permeability of the upper Walloon Coal Measures based on detailed stochastic modelling of this key unit (section 6.5.4.8)
- more accurate simulation of reinjection and its impact on pressures in the Precipice Sandstone (section 6.5.4.9)
- an updated and improved model calibration workflow incorporating time series groundwater level data from about 480 groundwater level pressure monitoring points (section 6.5.5)
- completion of a predictive uncertainty analysis (section 6.5.7).

6.2 Construction of the geological model

The model is based on a revised and updated 3D representation of the geology of the area (OGIA, 2019a). The datasets used include lithostratigraphic interpretation of wireline log data from about 7,000 wells (about 2,700 more wells than the last geological model), improved surface geological mapping, stratigraphic interpretation of lithological data from nearly 24,500 water bores and quality controlled 2D and 3D seismic survey data. This information collectively provides additional control on key stratigraphic surfaces and improves understanding of the lithological variability of many of the geological units present within the area, as well as of geological structures such as faults and erosional contacts. Resolution of the current geological model is also increased by changing the cell size from 750 to 250 m, allowing more accurate representation of the geology, particularly around faults and also within CSG production areas. The Boxvale Sandstone Member within the Evergreen Formation is now explicitly represented.

The revised geological model not only provides a framework for development of the related groundwater flow model but also supports a range of other hydrogeological projects undertaken by OGIA and others, including landholder bore aquifer attribution, recharge estimation and spring assessment.

6.3 Conceptual framework for the groundwater flow model

The conceptual framework for the 2019 groundwater flow model has been derived from the current understanding of the geology and hydrogeology summarised in Chapter 3 and on the revised regional geology model described above (section 6.2).

The regional hydrostratigraphy has been represented numerically using 34 model layers (Figure 6-1). For the model, the Evergreen Formation has been split into upper and lower units to allow explicit representation of the intervening Boxvale Sandstone Member – a water supply aquifer and source aquifer for a number of springs in the north-eastern CMA. This improves the model’s ability to more accurately predict impacts on these assets.

Model layer	Formation	
1	All Alluvium and Basalt (including Main Range Volcanics)	Surat & Clarence-Moreton basins
2	Upper Cretaceous (Griman Creek Formation & Surat Siltstone) / Cenozoic Sediments *(including the Condamine-Walloon transition zone)	
3	Wallumbilla Formation	
4	Bungil Formation	
5	Mooga Sandstone	
6	Orallo Formation	
7	Gubberamunda Sandstone	
8	Westbourne Formation	
9	Upper Springbok Sandstone	
10	Lower Springbok Sandstone	
11	Walloon Coal Measures non-productive zone	
12	Upper Walloon Coal Measures	
13	Middle 1 Walloon Coal Measures	
14	Middle 2 Walloon Coal Measures	
15	Middle 3 Walloon Coal Measures	
16	Lower Walloon Coal Measures	
17	Durabilla Formation	
18	Upper Hutton Sandstone	
19	Lower Hutton Sandstone	
20	Upper Evergreen Formation	
21	Boxvale Sandstone	
22	Lower Evergreen Formation	
23	Precipice Sandstone	
24	Moolayember Formation	Bowen Basin
25	Clematis Group	
26	Rewan Group	
27	Bandanna Formation non-productive zone	
28	Upper Bandanna Formation	
29	Lower Bandanna Formation	
30	Lower Bowen 1	
31	Cattle Creek Formation non-productive zone	
32	Upper Cattle Creek Formation	
33	Lower Cattle Creek Formation	
34	Lower Bowen 2	

Regional aquifer | Partial aquifer | Tight aquifer | Interbedded aquitard | Tight aquitard

Figure 6-1 Model layers and formations represented in the regional groundwater flow model

As discussed in Chapter 3, recharge occurs predominantly by direct infiltration of rainfall in the outcrop areas, or indirectly by leakage from streams and/or overlying aquifers. Flow directions are generally towards the south-west with discharge into the remainder of the GAB to the south. However, north of the Great Dividing Range, groundwater flow in a number of aquifers is towards the north-east into the Dawson River catchment (Figure 3-5).

As described in section 3.4.3, the hydrogeology of the coal formations is complex in that they comprise highly varied sequences of sediments that contain material of high and low permeability. It is not practical to represent the individual coal seams within these coal formations as separate layers in the regional groundwater flow model. This is in part because it is often not possible to correlate individual coal seams across the area.

Detailed analysis previously undertaken by OGIA, further confirmed by observations, shows that CSG production leads to the development of pressure gradients within the target reservoirs. This demonstrates that impacts do not propagate evenly within the reservoirs. To account for this variance, a minimum of three model layers are used to represent each of the coal formations. A total of six model layers have been used for the Walloon Coal Measures, which allows for a more accurate representation of the geometry of the contact zone with the Condamine Alluvium.

The upper 'non-productive' layer represents a generally low-permeability mudstone which sits above the uppermost screens in CSG wells, while the remainder of the Walloon Coal Measures above the underlying Durabilla Formation aquitard is split into five further layers (model layers 12 to 16).

Flow to all coal measure layers is represented using 'dual porosity' functionality available through MODFLOW-USG to allow simulation of coal seams and interburden within a single layer.

Three layers have been used to represent each of the Bowen Basin coal formations (the Bandanna Formation and Cattle Creek Formation), two layers of which are simulated using dual porosity functionality. As with the Walloon Coal Measures, an upper 'non-productive' layer has been defined based on CSG well screen information, and the remaining thickness of each formation is then divided into upper and lower sections.

The Condamine Alluvium is represented using two model layers, an upper layer representing the main alluvial aquifer and a second layer representing the undifferentiated clay transition zone which marks the base of the Condamine Alluvium over most of the area (section 3.5.3).

Further detail on how key features affecting groundwater flow are represented within the model – including faults, CSG wells and coal mines – are provided in section 6.5.4.

6.4 Data availability

A range of input datasets are used to construct and calibrate the model.

Geological data for around 7,000 CSG wells, 24,500 water bores and over 5,000 seismic lines are used to construct the regional geological model which comprises the structure of the model (section 6.2).

Detailed lithology data for around 6,000 CSG wells and 13,000 permeability estimates are used to constrain numerical permeameter calculations and derive initial hydraulic parameter estimates for the model (section 6.5.3).

Initial estimates of recharge have been derived from chloride measurements in around 10,100 bores (section 3.4.1).

All available groundwater level data from a variety of sources was considered for use in model calibration, including the state groundwater database, WMS monitoring points, landholder bores that form part of the Groundwater Online and Groundwater Net initiatives, additional industry monitoring and baseline assessment data. In total, data is available for around 40,000 locations. Following a quality control process, data for almost 10,000 monitoring points was directly used for calibration of the model, excluding data for the Condamine Alluvium, Main Range Volcanics and aquitard units. The calibration dataset now includes detailed time series groundwater level data from about 480 monitoring points.

Available information on the location and depth of well screens and reported water production from thousands of CSG wells is also used for model calibration purposes.

6.5 Groundwater model construction and calibration

The model is constructed using a modified version of the MODFLOW-USG finite volume code (Panday et al. 2017), distributed by the United States Geological Survey. MODFLOW-USG supports the development of a wide variety of structured and unstructured grid types. This enables better representation of erosional features such as the contact between the Walloon Coal Measures and the overlying Condamine Alluvium. In consultation with its principal developer, OGIA has made a number of enhancements to MODFLOW-USG to improve its performance in the assessment of CSG impacts.

6.5.1 Model grid and structure

The model domain covers an area of around 460 x 650 km. The area includes parts of the southern Bowen and Surat basins and all CSG development areas within the Surat CMA. Each individual model cell covers an area of 1.5 x 1.5 km. The 2019 model comprises 34 vertical layers (section 6.3).

6.5.2 Modelling scale

The model is used to predict impacts from P&G development across the Surat CMA. OGIA has also undertaken a number of more detailed local modelling activities to inform and complement the regional model.

A detailed dual phase flow model of the Talinga CSG field, comprising several hundred layers, was constructed using PETREL – a reservoir modelling tool – to gain further understanding of the theoretical response of a coal reservoir using a highly detailed model (i.e. a model with little or no upscaling). A parallel MODFLOW-USG version of the PETREL model was then constructed to confirm that impacts on adjacent aquifers could be accurately simulated in a highly upscaled regional-scale model that also includes an approximation of dual phase flow effects.

The numerical permeameter workflow developed by OGIA and described in the following section (6.5.3) also makes use of multiple detailed lithological models of each formation present, with 21 x 21 km blocks to derive initial parameters for input to the regional model.

6.5.3 Initial model parameterisation approach

Initial parameters for use in the Surat CMA model are developed using an innovative workflow, developed by OGIA, centred around a suite of detailed numerical permeameters. This workflow was initially developed for use in the 2016 regional groundwater flow model and has been further enhanced for the current model. As illustrated in Appendix F, it involves three key steps:

1. Initial values of hydraulic conductivity for each of six lithology types (clean sand, dirty sand, siltstone, mudstone, carbonaceous shale and coal) from geophysical logs are derived from expert knowledge, literature and analysis of geophysical logs.
2. These initial values are then input to a stochastic permeability model and calibrated (or ‘conditioned’) through comparison with around 13,000 hydraulic test results at three different scales (i.e. pumping, core and drill stem tests).
3. Once calibrated, these values are then used to populate numerical permeameters – detailed 21 x 21 km numerical models of each stratigraphic unit, generated using lithological data for about 6,000 CSG wells and covering the full extent of the 12 stratigraphic units modelled. In total, more than 138,000 model runs were carried out during this part of the process.

This approach extracts full value from the large geological and hydraulic parameter dataset available for the CMA. Outputs from this process include formation scale horizontal and vertical permeabilities that are then used as input to the regional groundwater flow model for further calibration against water level and other observed data. Furthermore, through consideration of 20 alternative lithological realisations, this process also provides a range of possible alternative parameter estimates for use in both model calibration and uncertainty analysis.

Estimated permeability values for the majority of the units assessed are somewhat lower than previously estimated in 2016, predominantly since laboratory tests undertaken by CSIRO suggest a more rapid reduction in permeability with depth than previously assumed.

6.5.4 Model set-up to represent some key features

6.5.4.1 Simulation of CSG and other groundwater extractions

As mentioned in section 2.1.2, optimal conditions for the flow of CSG are typically achieved when water pressure in the production well is between 35 and 120 psi – equivalent to 25–80 metres head of water. The volume of water that needs to be pumped to achieve this pressure reduction varies from well to well and is dependent on the permeability of the coal seams.

In the initial stage of development, water is extracted from a well until the necessary pressure reduction has been attained. Extraction then continues at the rate necessary to maintain the pressure in the well. During the initial phase, the pressure in the surrounding formation is substantially higher than in the well. This pressure difference gradually dissipates until the pressure in the formation is at or close to the pressure in the well, at which point gas production declines to uneconomic levels.

As detailed earlier, the reduction in pressure tends to be smaller near the top of the formation, while greater reductions in pressure occur near its base. As far as water is concerned, each CSG extraction well acts as a kind of ‘seepage face’ towards which water flows in accordance with the reduced pressure within the well. This is simulated using the MODFLOW-USG ‘drain’ boundary condition. Multiple MODFLOW-USG drains are assigned to each well; these descend over time as pressures in the CSG extraction well are reduced.

Other non-P&G-related groundwater extractions summarised in section 4.1 have also been represented in the numerical model. Extractions from the Condamine Alluvium and Main Range Volcanics have been simulated using a MODFLOW-USG ‘drain’ boundary condition. Extractions from the remaining formations included in the model have been simulated directly using the MODFLOW-USG ‘well’ boundary condition.

6.5.4.2 Connectivity of coal seams by CSG wells

The Walloon Coal Measures typically comprises mostly thin discontinuous, but relatively permeable coal seam layers, separated by low-permeability siltstone and mudstone-dominated interburden material (section 3.4.3). The introduction of a CSG well, which typically installs slots (or screens) against each coal seam, consequently leads to an effective increase in the formation-scale horizontal permeability of the Walloon Coal Measures, since coal seams that would otherwise be isolated are connected within the well. To account for this, a number of revisions were made to the MODFLOW-USG code and a supplementary enhanced permeability parameter is input to the model.

6.5.4.3 Representation of geological faults

The current regional geological model includes representation of 32 major regional fault segments (section 6.2), 22 of which are also represented in the groundwater flow model through the inclusion of so-called ‘non-neighbour connections’. Such connections are used in MODFLOW-USG to simulate flow from one stratigraphic unit to another across the fault plane.

Parameters representing the properties of the faults have been estimated based on an approach described in Bense and Person (2006). Information on the width of the fault core and damage zone is used along with detailed lithology information (from geophysical logs where available) to calculate the likely effective horizontal and vertical resistance created by each fault.

Prior to model calibration, application of this methodology generally results in cross-fault resistances that are lower in the horizontal direction than in the vertical direction. Parameters affecting the effective resistance of each fault – in both the vertical and horizontal directions – are adjusted as necessary during model calibration.

6.5.4.4 Simulation of existing open-cut coal mines

Five existing coal mines (Cameby Downs, Commodore, Kogan Creek, New Acland and Wilkie Creek) have also been simulated in the groundwater flow model. The representation does not aim to estimate impacts from coal mining, but rather to simulate the influence that these mines could have on observed groundwater pressures and model calibration. Each mine has been simulated in the model through the use of the MODFLOW ‘drain’ boundary conditions, with drains set at the base of the surveyed open pit.

6.5.4.5 Simulation of the Condamine Alluvium

DNRME has an established model that is used to support water resource management for the Condamine Alluvium (the Condamine Model). As in previous iterations of the UWIR model, rather than seeking to duplicate the detailed Condamine Model, calibrated data from the Condamine Model was used in the regional model to define the hydraulic parameters of model layer 1 within the Condamine footprint. Time-variant water level conditions from the Condamine Model were also imported into the regional model as boundary conditions.

6.5.4.6 Approximation of dual-phase flow

As discussed in section 6.5.2, in the regional groundwater flow model, MODFLOW-USG functionality that simulates water desaturation in response to a reduction in pressure is used to approximately simulate dual phase flow, i.e. flow in the water and gas phases, which occurs in CSG wells.

6.5.4.7 Representation of CSG well completions

As discussed in section 3.5.2, about 16% of CSG wells within the Walloon Coal Measures tenures are partially completed into the Springbok Sandstone. For these wells, similar to the Walloon Coal Measures, MODFLOW-USG drains have also been added into the lower Springbok Sandstone. Drain elevations applied to the Springbok are calculated in the same way as drains applied into the Walloon Coal Measures, i.e. based on the expected bottom hole pressures.

6.5.4.8 Upper Walloon Coal Measures aquitard

As discussed previously in section 3.5.4, the Walloon Coal Measures was subject to erosion prior to deposition of the overlying Springbok Sandstone. There are therefore areas where the upper coal seams of the Walloon Coal Measures are in direct contact with the Springbok Sandstone. The thickness and permeability of the material overlying the uppermost coal seam within the Walloon Coal Measures therefore represent a key control on the transmission of CSG impacts into the overlying Springbok Sandstone.

Further detailed stochastic modelling of the permeability of this material (referred to as the upper Walloon Coal Measures aquitard) has been undertaken. The modelling identified a number of areas where the upper coal seam is overlain by relatively permeable material and other areas where the coal seams are in direct contact with the overlying Springbok Sandstone (i.e. there is no upper aquitard). Relatively high connectivity between the two units is expected in both of these settings.

This work is one of the number of uses of detailed local modelling to inform construction and parameterisation of the regional model.

6.5.4.9 Precipice Sandstone reinjection scheme

As discussed in section 4.2.3, Origin has been reinjecting treated CSG water into the Precipice Sandstone via a number of bores at the Spring Gully and Reedy Creek CSG fields since January 2015. An additional package was developed to allow simulation of this reinjection in the groundwater flow model. The model has also been calibrated using additional information on actual injection volumes and observed responses in nearby monitoring bores. This has significantly improved the calibrated parameters in the Precipice Sandstone in the northern part of the Surat Basin.

6.5.5 Model calibration

6.5.5.1 Calibration set-up

Calibration of the groundwater flow model is achieved using a three-stage simulation:

1. The first simulation stage seeks to replicate conditions that existed prior to the commencement of any groundwater extraction, for CSG or other purposes, to generate ‘pre-development’ groundwater levels.
2. The second simulation stage seeks to replicate pre-CSG extraction conditions in 1995 to provide starting or initial conditions for the third and final stage.
3. A transient simulation seeks to replicate the period from January 1995 to December 2017, during which CSG extraction commenced initially from the Bandanna Formation and then from the Walloon Coal Measures.

Calibration of the model was carried out using specialist calibration software PEST. Consistent with the current Australian Groundwater Modelling Guidelines (Barnett et al. 2012), a range of quantitative and qualitative measures were used to assess each calibration iteration. The overall aim of these iterations was to gradually improve the calibration performance while at the same time avoiding calibration outcomes that were inconsistent with expert knowledge of groundwater flow processes in the area.

Calibration of the first two simulation stages was undertaken predominantly through comparison with groundwater levels observed during the period prior to 1947 and during the period 1947 to 1995. Calibration of the transient simulation stage was undertaken through comparison of model-generated outputs with monthly water production data supplied by gas companies and monthly average groundwater levels from about 480 monitoring points in the Springbok Sandstone, Walloon Coal Measures, Hutton Sandstone, Bandanna Formation and Precipice Sandstone. The scope of this transient calibration was significantly increased compared to the previous calibration, which largely focussed on data for the Walloon Coal Measures.

To assist with calibration of parameters affecting the dual phase flow approximation, some information relating to desaturation of coal seams and vertical gradients in the Walloon Coal Measures was extracted from detailed reservoir models developed by both OGIA and tenure holders.

6.5.5.2 Calibration results

Calibration performance is typically assessed through analysis of the differences between observed and modelled groundwater levels and other targets used in the calibration.

Observed groundwater levels are relatively well matched during all three calibration stages, especially in key formations including the Walloon Coal Measures, Hutton Sandstone and Precipice Sandstone. The scaled root mean square error (a commonly used measure of the overall discrepancy between observed and modelled values) for each of these formations is less than 10%. Possibly reflecting the difficulties associated with monitoring groundwater levels in the Springbok Sandstone and some uncertainty about the degree to which CSG wells penetrate into the formation, slightly larger discrepancies exist between observed and modelled levels in this formation (section 3.5.2). However, time series groundwater levels at the key Kenya East monitoring point in the Springbok Sandstone (RN160525) are well represented. The model is also able to match observed pressure reductions in the Walloon Coal Measures and observed increases (due to reinjection) in the Precipice Sandstone with a relatively high degree of accuracy.

Conversely, the model has some difficulty matching observed groundwater trends in the Hutton Sandstone occurring at Talinga (RN160634) and other locations; however, the very high pressure differences observed between the Walloon Coal Measures and the Hutton Sandstone at this location (suggesting very low connectivity) are well matched.

Total modelled CSG water production during the period 1995 to 2017 is around 355,300 ML – within 1% of the measured total during this period.

6.5.6 Model set-up for making predictions

The model was set up to run in predictive mode from 1995 onward, based on starting conditions from the second simulation stage. Two separate predictive runs were carried out to assess the cumulative impacts of approved CSG developments within the CMA:

1. a **Base Run** that included only consumptive water extraction for non P&G purposes. i.e. excluding all P&G water extraction

2. a **P&G Production Run** that included all water use and extraction from P&G and non-P&G activities, including post-2011 groundwater extraction from conventional oil and gas development, but excluding non-associated water take.

The difference in predicted water levels between the Base Run and the P&G Production Run therefore provides the water pressure impacts (or drawdown) predicted to result from associated water extraction by current and planned CSG activities and post-2011 conventional oil and gas activities.

Reflecting information provided by the tenure holders about the sequencing of development for each 1.8 x 1.8 km sub-block of the production tenures, simulated CSG wells were switched on and off in the model. This is detailed in section 2.4.3, with changes to the proposed sequencing of planned development compared to the previous UWIR.

The scenario discussed above and described in section 2.4.3 is referred to as the 'UWIR Scenario' in this report. It is used as the basis for identifying impacts on aquifers, bores, springs and other environmental values to underpin the tenure holder obligations and develop management strategies presented in subsequent chapters.

A number of further scenarios were also undertaken to provide contextual information on the impacts of other development activities within the CMA – in particular, the reinjection of treated CSG water into the Precipice Sandstone aquifer (section 6.5.4.9) and the 'high case' scenario, which includes projects where EIS processes have been completed or EAs have been granted, but development is not proposed.

6.5.7 Dealing with uncertainties in data and model predictions

As is the case with any prediction of the future, predictions made using groundwater flow modelling tools are subject to uncertainty. Potential sources of predictive uncertainty arise: from the simplification of the groundwater system; from the accuracy of field measurements of data (conceptualisation uncertainty); and because models can be calibrated to observations using quite different sets of hydraulic parameters (calibration or parameter uncertainty).

The effect of calibration uncertainty on predictions made using the numerical model can be assessed using a technique known as **predictive uncertainty analysis**. Application of this technique requires specialised skills and significant computer capacity and time. It is not practicable to use this type of technique directly to assess conceptualisation uncertainty in large models. However, alternative realisations of the geology have been considered when generating initial model parameters (sections 6.5.3 and 6.5.4.8).

Potential uncertainties in predictions made using the groundwater flow model have been assessed using a 'null space Monte Carlo' (NSMC) methodology, which is identified in the IESC guidance (Middlemis & Peeters 2018) as being the most complex of the three levels of analysis outlined. This methodology involves generating a large number (450 in this case) of alternative parameter sets, which are then partially calibrated to ensure consistency with both current hydrogeological understanding in the area and the observations. Effectively, this generates 450 different versions of the model, each of which could fit the historical data. These models are then used to generate 450 sets of alternative predictions.

6.5.8 Model complexity, assumptions and limitations

The regional groundwater flow model is designed for the specific purpose of simulating regional-scale groundwater pressure impacts caused by P&G activities where the primary mechanism for impacts in surrounding aquifers is through cross-formational flow. Although a number of local features such as geological faults and lithology variations are implicitly considered in upscaling to model grid cell scale, variations in predictions at sub-cell scale cannot be derived from the model.

Like all groundwater flow models, the model is a simplified representation of a complex groundwater flow system. Simplification is necessary to manage simulations within the computational limits of modern technology.

Development of the model represents a particularly difficult technical challenge, since it must quantify cumulative impacts in a multi-layered system over an extremely large geographic area that extends in three geological basins to depths of up to 9000 m and includes at least nine recognised aquifers and three separate coal reservoirs. Furthermore, the model must run quickly enough to allow calibration to be optimised mathematically and a predictive uncertainty analysis to be undertaken.

By necessity, the model therefore includes a relatively high degree of hydrogeological simplification (or upscaling), both horizontally and vertically. Even with this upscaling, calibration of the model has required computer time in the order of 600,000 hours and up to 600 processing nodes.

The majority of stratigraphic units present have been simulated using one or two model layers, whilst many more layers would ideally be used to represent the geological complexity present in most formations (see Figure 3-9). Detailed modelling of the Kenya East gas field area, including simulation of the Walloon Coal Measures and the overlying Springbok Sandstone using several hundred layers, suggests that impacts diminish rapidly with vertical distance from the top of the coal reservoir. Therefore, upscaling in the vertical direction is considered a more significant influence compared to model grid spacing in simulating CSG impacts on surrounding aquifer.

Similarly, the regional model by necessity also includes a relatively simple representation of surface water interaction and will consequently tend to over-estimate predicted drawdown in outcrop areas.

A number of other limitations inherent in the model are a result of data gaps. In particular, the model's ability to represent the impacts of non-CSG water use from the Hutton Sandstone and other aquifers is affected by the lack of reliable and measured groundwater extraction from these bores.

Chapter 7 Predictions of groundwater impacts

Predictions of groundwater impact are influenced by two primary factors: the construction and parameterisation of the groundwater flow model itself (Chapter 6) and the footprint and timing of P&G development (**development profile**, Chapter 2). A change to either of these two factors will result in a change in impact predictions. Predictions have been made using a redeveloped groundwater flow model and the latest available development profile (section 2.4.3).

Outputs from the model identify the spatial and temporal distribution of impacts from P&G development in terms of water level decline in each of the aquifers. This information is used in presenting a summary of impacts on key aquifers and bores in both the short and long term, predictions of CSG water extraction and anticipated timing of pressure recovery.

Predictions of groundwater impacts made using the optimal or fully calibrated parameter set are used for identifying impacts on water bores and environmental values, as it represents the best available prediction of impacts. However, the upper (95th percentile) and lower (5th percentile) bounds of predicted impacts, as derived from the uncertainty analysis, are also referred to where relevant and have been used to inform the development of the management strategies outlined in later chapters.

7.1 Terminology

The term ***bore trigger threshold*** is a reference to a decline in the water level in an aquifer, defined in the Water Act as five metres for consolidated aquifers (such as sandstone) and two metres for unconsolidated aquifers (such as alluvium). Thresholds are used to identify bores that are likely to be impacted and require further ***bore assessment*** (section 11.2.1) to establish whether bores have, or are likely to have, impaired capacity due to a decline in water level from P&G development.

Where a bore assessment determines that a bore is likely to be impaired, a ***make good*** agreement is required between the responsible tenure holder and the bore owner. Make good agreements may include decommissioning or modification of the water supply bore. Tenure holders may reach make good agreements with bore owners without necessarily completing bore assessment.

The term ***Immediately Affected Area (IAA)*** is used for identifying short-term impacts where make good obligations apply. It is defined in the Water Act as the area of an aquifer within which water levels are predicted to fall by more than the trigger threshold within three years of the UWIR release, due to water extraction by petroleum tenure holders. A water bore that is accessing water from the IAA of an aquifer is an ***IAA bore***. The predicted fall in water level is generally referred to as the ***impact*** or ***drawdown.***

A ***Long-term Affected Area (LAA)*** is defined in the Water Act as an aquifer area within which water levels are predicted to fall by more than the trigger threshold at any time in the future, due to water extraction by petroleum tenure holders. A water bore that is accessing water from the LAA of an aquifer is an ***LAA bore***. In a multi-layered aquifer system such as the GAB, LAAs may partially overlap.

LAAs and IAAs are established through an approved UWIR and remain unchanged until the next UWIR update in three years. However, IAA bores can change during that period because the ongoing review of bore information and/or bore assessments may result in corrections to GWDB records for bore location, authorisation, or changes to the attribution of the aquifers from which the bores may be accessing water.

The IAA and LAA for a particular formation are based on the maximum predicted impacts in all model layers used to represent that formation. As discussed in section 6.3, multiple model layers have been assigned to some formations, particularly the coal reservoirs, and so predicted impacts tend to be different in each layer.

7.2 Short-term impacts

7.2.1 Immediately Affected Areas

IAAs for each aquifer are shown in Figure 7-1. In these areas, impacts from P&G development are predicted to be more than five metres within three years to the end of 2021.

IAAs are predicted in the three CSG target formations – the Walloon Coal Measures, the Bandanna Formation and the Cattle Creek Formation. IAAs are also predicted in the Springbok Sandstone and to a lesser extent in the Hutton Sandstone – the formations immediately adjacent to the Walloon Coal Measures.

There is also an IAA in the Precipice Sandstone around the Moonie oil field, resulting from historical groundwater extraction from conventional oil and gas production in the area. The maximum pressure decline at the wellfield is about 120 metres. Unlike CSG production, the conventional production is nearing end of life and groundwater extraction has been steadily declining to a current level of about 1,000 ML/year. As a result, groundwater pressure will continue to recover for the IAA in the Precipice Sandstone that is affected by conventional activities in the southern part of the CMA.

An IAA related to conventional oil and gas development was not included in the previous UWIR because there was no data or information available at the time to reliably calibrate the model in that area. This is discussed further in section 7.3.8.

7.2.2 IAA bores

Table 7-1 provides a summary of newly identified water bores that are expected to experience drawdowns of more than the trigger threshold by the end of 2021 as a result of predictions presented in this report.

IAA bores are only identified in the Walloon Coal Measures and the Springbok Sandstone despite there being short-term impacts in other formations. This is because there are no bores accessing water from those other formations where IAAs are identified – e.g. the Bandanna Formation and the Precipice Sandstone.

There are 100 water bores that are identified as IAA bores for the first time in this UWIR, primarily because impacts progressively increase during each three-year rolling UWIR period. There were also 122 water bores identified as effective IAA bores through the UWIR 2012 or UWIR 2016 or due to bore record corrections since then (section 7.2.3). This leads to a total of 222 bores that have been identified as IAA bores since 2011.

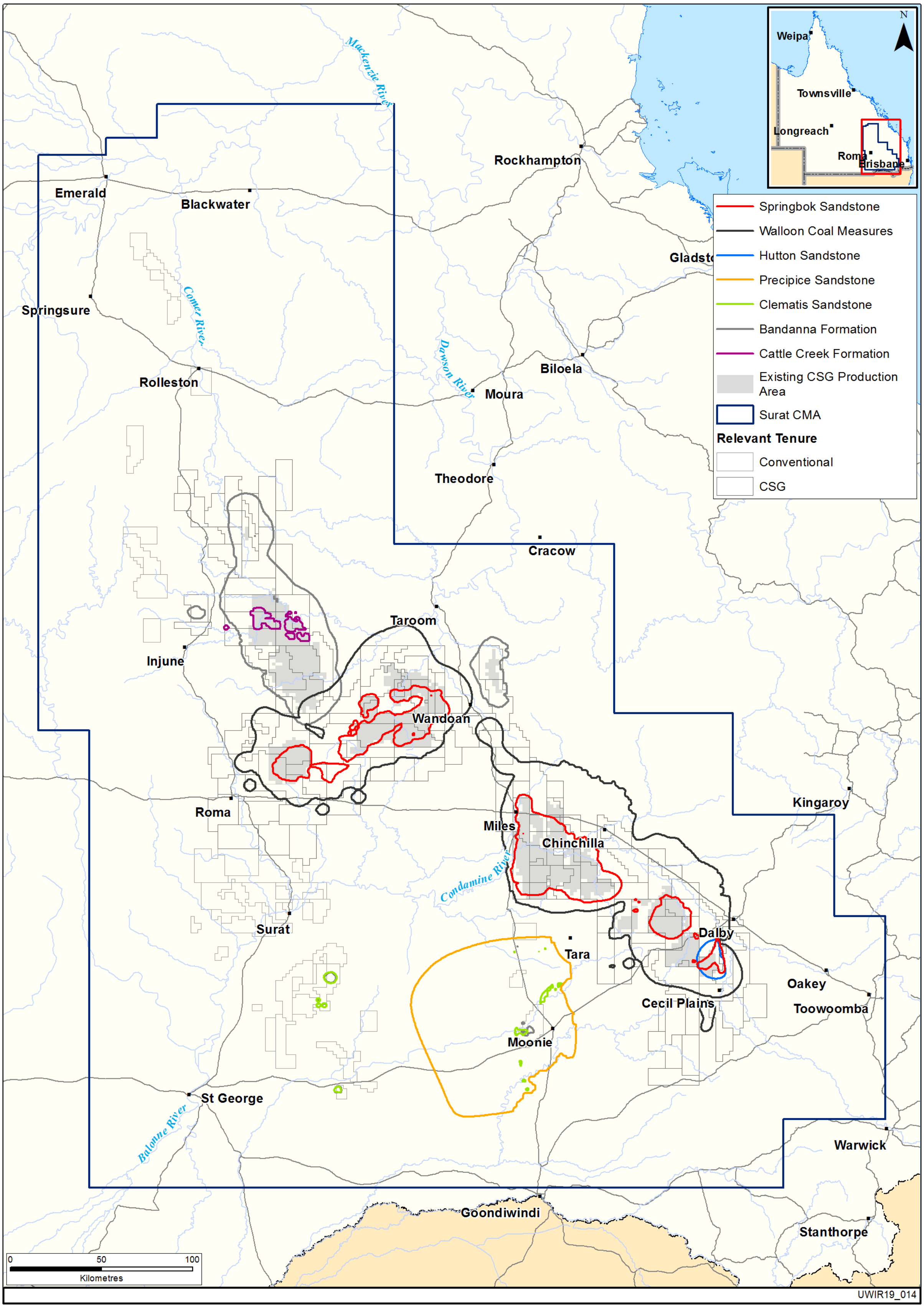

Figure 7-1 Extent of the Immediately Affected Areas

Table 7-1 Summary of newly identified IAA bores in the UWIR 2019

Aquifer / Category	Agriculture	Industrial	Town water supply	Stock and domestic	Total
Springbok Sandstone	1	1	-	7	9
Walloon Coal Measures	5	-	1	85	91
Total	**6**	**1**	**1**	**92**	**100**

A detailed list of IAA bores is presented in three tables in Appendix G:

- Table G-1 lists 100 bores that have been identified in this UWIR 2019.
- Table G-2 lists all bores identified in previous UWIRs with information on their current status.
- Table G-3 lists bores that are predicted to experience an impact of more than the trigger threshold of five metres within three years as a result of predictions in this report, but where either there is insufficient data to reliably assess whether they tap the impacted aquifers, or there are inconsistencies between the aquifers authorised under the Water Act and the aquifers predicted to be impacted. OGIA will further assess these bores during the next UWIR cycle and following the outcome, some of these bores may progressively become IAA bores.

7.2.3 Tracking changes to IAA bores

IAA bores are identified in the UWIR based on information available at the time about the water bore including location, construction and an interpretation of the aquifer(s) from which the bore may be accessing water (referred to as the bore's ***'aquifer attribution'***).

Together with the maps showing the IAAs for aquifers, the UWIR identifies and lists existing water bores understood to access water from an aquifer within the IAA for the aquifer. The predicted IAAs gradually expand with each successive update of the UWIR. This is because, as new development areas are added, the areas affected by pressure declines continue to expand, leading to identification of additional water bores as IAA bores.

Information about the bores comes initially from the GWDB and is further refined with baseline assessment, bore assessment and project specific data. In some cases, the bore data held in the GWDB may be inaccurate or incomplete. As a result, in the post-UWIR period some bores may be reassessed as accessing water from aquifers other than those predicted to be affected. Conversely, bores not previously listed may be found to be accessing water from affected aquifers. As a result, the number of IAA bores may change during a UWIR cycle without a change being made to the predicted IAAs.

A summary of all IAA bores identified in previous UWIRs and subsequent post-UWIR changes is presented in Table 7-2.

The UWIR 2012 identified 85 IAA bores. By the time the 2016 UWIR was published, 36 of those bores had been decommissioned, while 25 were reassessed as accessing non-impacted aquifers. A further 10 bores were added due to changes in aquifer attribution or recorded bore status.

Table 7-2 Tracking of changes to IAA bores

Period	IAA bore changes		Running totals	
	Added	Removed	Effective IAA bores	Decommissioned*
UWIR 2012	**85**	**-**	**85**	**-**
Post-UWIR	10	25	70	36
UWIR 2016	**57**	**-**	**127**	**36**
Post-UWIR	1	6	122	71
UWIR 2019	**100**	**-**	**222**	**71**

Notes:
* 'Decommissioned' means the bore has been decommissioned, the bore is in the process of being decommissioned, or an agreement to decommission the bore has been executed.

The UWIR 2016 added a further 57 IAA bores, resulting in a total of 127 IAA bores at that time. By the end of the UWIR 2016 cycle, six additional bores were effectively removed from the IAA bore list and one was added, resulting in 122 total effective IAA bores as of March 2019. Of these 122 bores:

- Bore assessments have been completed for 88 bores as the first step towards make good agreements.
- Make good agreements have been executed for 99 bores[4]. In some instances, make good arrangements were reached without bore assessment.
- A total of 71 bores have been decommissioned so far as a result of make good agreements.
- Six are currently under negotiation.
- The remaining 17 have been added recently due to changes in authorisation status, are awaiting clarification on their authorisation status, or have been put on hold for various reasons.

An agreement about the make good arrangement between the tenure holder and bore owner may not necessarily involve decommissioning of the water bore. The agreement may provide some form of compensation while the bore continues to supply water. The agreement may also provide for a period of ongoing monitoring and a future date for review of the agreement.

DES can issue a notice to a tenure holder to carry out a bore assessment if it has reason to believe that a bore is being affected by CSG water extraction, even though the bore has not been identified in a UWIR as an IAA bore. To date, DES has issued 16 such notices.

The above information relates to bores where an obligation exists, or did exist at one time, for tenure holders to take action, which may or may not have resulted in make good agreements and may or may not have resulted in abandonment of the bores. Tenure holders have advised that in addition to those bores, agreements for make good actions have been entered into with the owners of another 98 bores, of which 38 have been decommissioned. These are bores that are likely to have been identified as IAA bores at a later stage of development, but have been attended to at an earlier.

[4] This potentially includes some in-principle agreements.

7.3 Long-term impacts

Long-term Affected Areas (LAAs) for each aquifer are shown in Figure 7-2. LAAs associated with CSG extraction are predicted for the Walloon Coal Measures, Bandanna Formation, Cattle Creek Formation, Springbok Sandstone and Hutton Sandstone.

There is also an LAA for the Precipice Sandstone around the Moonie oil field and the Clematis Sandstone as a result of historical groundwater extraction from conventional oil and gas production in the area.

As required under legislation, the LAAs identified in Figure 7-2 show the extent of areas that are predicted to experience more than five metres of impact in the long term, based on the fully calibrated model. Further details about the distribution of long-term impacts in key formations are shown on maps in Appendix G. These maps also show the upper (95th percentile) and lower (5th percentile) bounds of predicted impacts based on the predictive uncertainty analysis described in section 6.5.7. The predictions based on the fully calibrated model sit close to the 50th percentile.

Table 7-3 provides a summary of the number of current (existing or useable) water bores predicted to be affected in the long term because they access water from the relevant aquifer within the aquifer's LAA. There may be other water bores that are located within the geographic extent of the LAA of an aquifer, but which extract water from another aquifer and hence are not predicted to be impacted by more than the trigger threshold.

Table 7-3 Water bores in Long-term Affected Areas

Aquifer or sub-aquifer	Agriculture	Industrial	Town water supply	S&D	Total
Westbourne Formation	-	-	-	5	5
Springbok Sandstone	3	1	-	77	81
Walloon Coal Measures	29	2	1	325	357
Hutton and Marburg sandstones	2	1	2	-	5
Precipice Sandstone	-	-	-	-	-
Bandanna Formation	-	-	-	1	1
Cattle Creek Formation	-	-	-	-	-
Existing bores	**34**	**4**	**3**	**408**	**449**
Previously identified bores now decommissioned					122
Total					**571**

In addition to the 449 existing and usable bores predicted to be impacted in the long term, a further 122 bores identified as long-term affected bores in previous UWIRs have been decommissioned, although not all of which will have been decommissioned because of P&G development.

The current prediction of 571 total long-term affected bores is higher than that presented in the previous UWIR (518 bores). This increase predominantly reflects an increase in the size of the predicted LAAs for the Walloon Coal Measures and Springbok Sandstone, the respective reasons for which are described in sections 7.3.1 and 7.3.3 below.

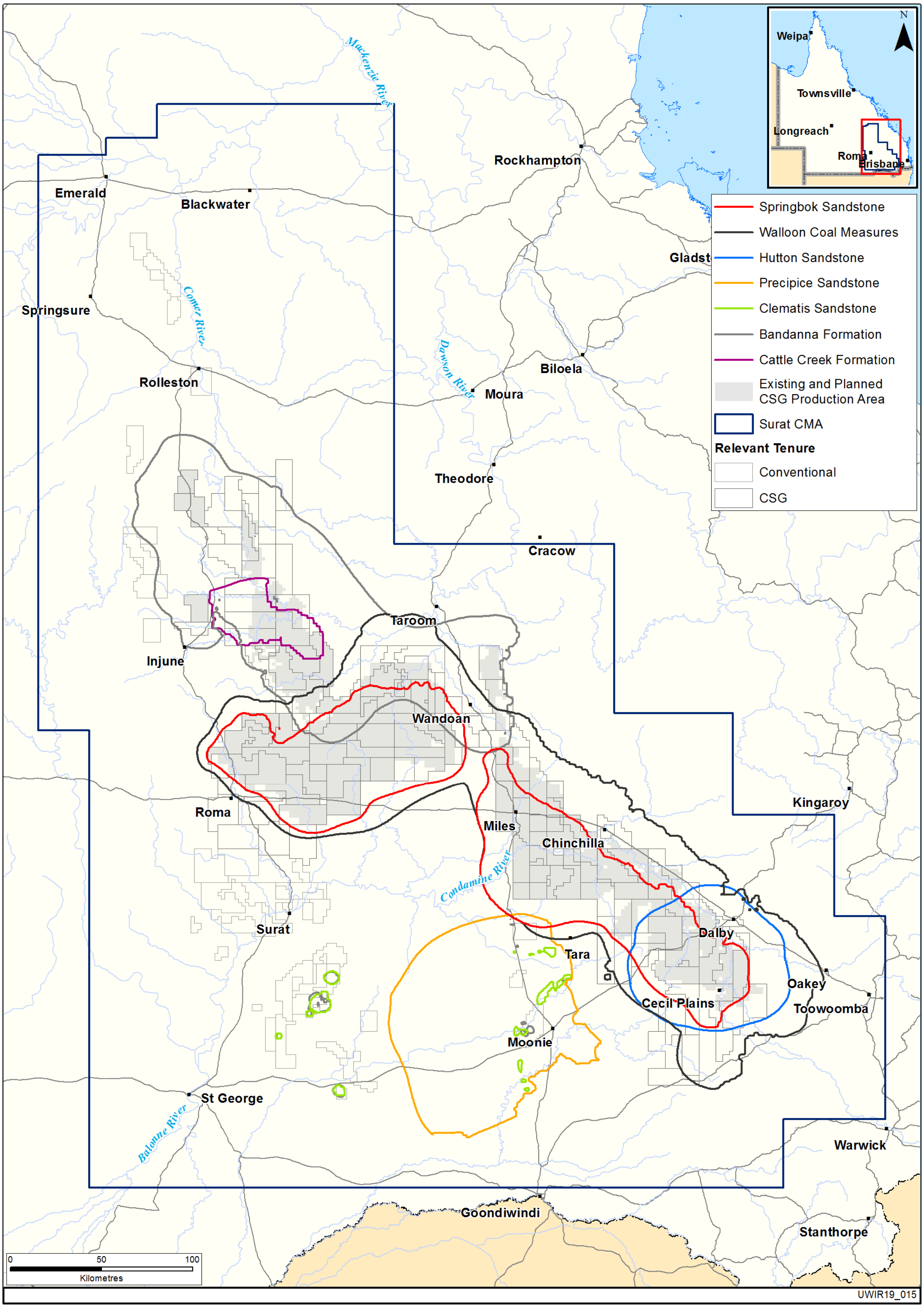

Figure 7-2 Extent of the Long-term Affected Areas

There is uncertainty in relation to the parameters used in the groundwater flow model. Uncertainty analysis results suggest that the number of water bores affected in the long term could vary from approximately 13% lower to 28% higher than the numbers in Table 7-3. There is also uncertainty in relation to the future development footprint of the industry. Two additional development scenarios were undertaken to analyse the sensitivity to increases in the footprint and found that the number of bores predicted to be affected in the long term could increase by 1–19%.

To provide information on the timing and magnitude of impacts in different aquifers, a series of plots – showing predicted impacts over time at a number of representative locations within CSG production areas in the Surat and Bowen Basin – are shown in Appendix G.

A summary of the predicted long-term impacts in key formations is provided below.

7.3.1 Walloon Coal Measures

The Walloon Coal Measures is the CSG target formation in the Surat Basin and has been subject to depressurisation since 2005 in some places. Significant drawdown has therefore already been observed and a substantial LAA is predicted, as shown in Figure 7-2 and Appendix G.

The number of bores likely to be affected in the Walloon Coal Measures has increased from 338 in the previous UWIR to 357. Most of the affected bores are located to the north and east of active CSG development areas where the formation is shallow and bore density is higher, although predicted impacts tend to be smaller in these areas.

Around half of the affected bores are likely to experience an impact of less than 32 m. Near the centre of CSG production areas, impacts of up to 350 m are typical towards the base of the Walloon Coal Measures and around 150 m towards the upper part. Impacts develop relatively quickly within the Walloon Coal Measures before recovering slowly once local CSG extraction ceases.

As would be expected, the time taken for groundwater levels to recover is related to the magnitude of the maximum drawdown. Groundwater levels in the Walloon Coal Measures in areas located close to the edge of the predicted LAA are expected to recover within five years. Conversely, groundwater levels within CSG production areas may take more than 1,000 years to fully recover. Predictions for the Walloon Coal Measures suggest that around 25% of impacted bores would recover to within 5 m levels in 250 years and around 75% of bores in 1,000 years.

The current predicted LAA for the Walloon Coal Measures is larger than previously predicted, particularly towards areas where the formation is present at the surface or overlain by the Condamine Alluvium and the Main Range Volcanics. This is due to the combined effects of revised geological mapping (suggesting the Main Range Volcanics is less extensive than previously mapped) and generally lower modelled permeabilities. In combination, these two changes reduce the volume of water drawn from adjacent formations, resulting in CSG extraction impacts within the Walloon Coal Measures spreading further east than previously predicted.

7.3.2 Condamine Alluvium

The Condamine Alluvium unconformably overlies the Walloon Coal Measures. There is no LAA in the Condamine Alluvium, based on the trigger threshold of 2 m that applies to unconsolidated aquifers. The maximum impact is expected to be around 0.2 m in the north-west of the Condamine Alluvium and less than 0.05 m across the majority of the area.

It is predicted that there will be a net loss of water from the Condamine Alluvium to the Walloon Coal Measures of about 735 ML/year over the next 100 years due to CSG development, which is about

35% less than the impact predicted in 2016. This change is largely due to recalibration of the model based on additional time series data, leading to generally lower calibrated vertical permeability values and less leakage from the Condamine Alluvium to the Walloon Coal Measures.

7.3.3 Springbok Sandstone

The Springbok Sandstone directly overlies the Walloon Coal Measures.

More impact is predicted in the Springbok Sandstone compared to 2016 primarily due to a combination of the partial completion of CSG wells into the Springbok Sandstone which has amplified the drawdown (section 6.5.4.7); and inclusion in the model of a more detailed representation of the upper part of the Walloon Coal Measures (section 6.5.4.8) which has effectively increased the vertical permeability of this zone and caused more widespread impact in the Springbok Sandstone.

Impacts of more than 5 m are expected in the long term across much of the planned CSG production area. While the number of water bores likely to be affected in the long term has also increased, around half of the LAA bores are likely to experience an impact of less than 15 m. Actual impacts have been observed at some locations within the formation (section 5.4.1).

Impacts tend to develop more slowly in the Springbok Sandstone than in the underlying upper Walloon Coal Measures. Groundwater levels will therefore recover more slowly than in the Walloon Coal Measures.

7.3.4 Hutton Sandstone

The Hutton Sandstone underlies the Walloon Coal Measures but is separated from the productive coal seams by the Durabilla Formation.

The LAA for the Hutton Sandstone is substantially smaller than was predicted in 2016. Recalibration of the model based on additional time series data and head difference measurements across the Walloon Coal Measures and the Hutton Sandstone has resulted in a lower vertical permeability of the Durabilla Formation and, hence, less interaction with the overlying Walloon Coal Measures.

The number of water bores likely to be affected in the long term has therefore reduced from 35 to seven. Most of the LAA bores are likely to experience an impact of less than 10 m and are limited to an area around Dalby where seismic data suggests that the Walloon Coal Measures and Hutton Sandstone may be in direct contact along part of the Horrane Fault.

Maximum impacts at most other locations in the Hutton Sandstone are minor and predicted to occur several hundred years after extraction from the Walloon Coal Measures has ceased. Recovery may take hundreds of years. Groundwater level monitoring data has confirmed that the Durabilla Formation is a highly effective aquitard that limits the propagation of CSG impacts into the Hutton Sandstone across most of the area (section 3.5.5).

7.3.5 Gubberamunda Sandstone

The Gubberamunda Sandstone is not well connected to any coal formations, since it is separated from the Walloon Coal Measures by the intervening Westbourne Formation aquitard and the Springbok Sandstone. There is no LAA for this aquifer.

7.3.6 Bandanna Formation

The Bandanna Formation is the main CSG target formation in the Bowen Basin and has been subject to depressurisation since 1995 in some places. Significant impact has already been observed and a substantial LAA is predicted, as shown in Figure 7-2; however, this formation is not commonly used for water supply purposes. There is only one water bore that sources water from this formation in the LAA.

7.3.7 Cattle Creek Formation

The Cattle Creek Formation is a secondary CSG target formation in the Bowen Basin, located several hundred metres below the Bandanna Formation. Development of the Cattle Creek Formation is currently only proposed within the Fairview CSG field. Only a small number of pilot CSG wells have been drilled to date and depressurisation of this formation is currently limited.

The Cattle Creek Formation is not commonly used for water supply purposes; hence, there are no water bores within this formation in the LAA.

7.3.8 Precipice Sandstone

As shown in Figure 7-2, current predictions suggest an LAA towards the south of the CMA, associated with past and ongoing extraction from the Moonie oil field. Extraction from Moonie has reduced in recent years and is expected to cease entirely by 2030. As a result, the LAA is only slightly larger than the formation's IAA shown in Figure 7-1. However, there are no known water bores accessing the Precipice Sandstone within this area.

Impacts from conventional P&G were not included in the previous UWIR because of the lack of reliable data for modelling (section 7.2.1). However, monitoring data from the reinjection scheme has significantly improved model calibration since then. Calibrated permeabilities are very high, resulting in wide propagation of a minor pressure decline. An ongoing study by UQ is currently focusing on better understanding the geology and flow dynamics in the Precipice Sandstone. Preliminary findings suggest that this formation is blocky in nature and there is stronger structural control around the Moonie field, which would tend to result in greater impacts nearer the wellfield but a less extensive impact area. Further findings from this study will improve impact assessment in future.

As shown in the detailed maps (Appendix G), minor impacts are also predicted in the Precipice Sandstone towards the north of the CMA. Impacts in these areas are associated with CSG extraction from the Bandanna Formation close to two areas where the coal reservoir is in direct contact with the Precipice Sandstone. These contact zones (section 3.5.6) have been remapped based on new borehole and seismic data. Model calibration using reinjection data has resulted in modelled permeability substantially higher than in previous assessments, leading to a different pattern of predicted drawdown in this part of the aquifer, characterised by a shallower but more extensive area of impact, predominantly associated with the western contact zone.

7.3.9 Non-aquifer formations

As shown in Table 7-3, impacts of more than 5 m are predicted in five existing water bores that are currently assessed as accessing the Westbourne Formation aquitard, which does not contain aquifer material. Although details about these bores will need to be clarified to confirm that they are in fact accessing these units, they are included as bores that are likely to be impacted.

7.4 Predictions of CSG water extraction

Predictions from OGIA's groundwater flow model of CSG water extraction from the Bowen and Surat basins in the CMA are presented in Figure 7-3. Average extraction is estimated to be around 51,000 ML/year over the life of the industry, with a peak of about 110,000 ML/year in around 2023. Current actual CSG water extraction is about 60,000 ML/year (section 4.2.1).

The model output also suggests that over a long period of time most of the CSG extracted water will be from the storage in the Walloon Coal Measures and only about 8% will be through cross-formational flow from the surrounding aquifers, including 3% from the Hutton Sandstone and 5% from the Springbok Sandstone and Condamine Alluvium.

Timing and volumes of predicted water extraction may vary in future, as they are highly dependent on the planned sequencing of new production areas and infilling of existing areas (section 2.4.3). Uncertainty analysis results suggest that the average extraction may be 13% higher than the predictions presented in Figure 7-3, based on the current development profile.

The revised predictions are about 30% lower than previous predictions and broadly consistent with tenure holders' own predictions, which are based on individual small-scale reservoir models. The change is primarily due to significant improvements to the model in this area and also because more of the less-permeable coals seams are being encountered than was expected in 2012.

There is no direct relationship between the volume of water extracted and the magnitude of groundwater level impacts. This is because CSG fields are operated to maintain a close-to-constant water level (or pressure) in the gas field. As a result, whilst reductions in modelled permeability will tend to reduce the predicted volume of CSG water extraction, this will not directly lead to a change in predicted groundwater level impacts.

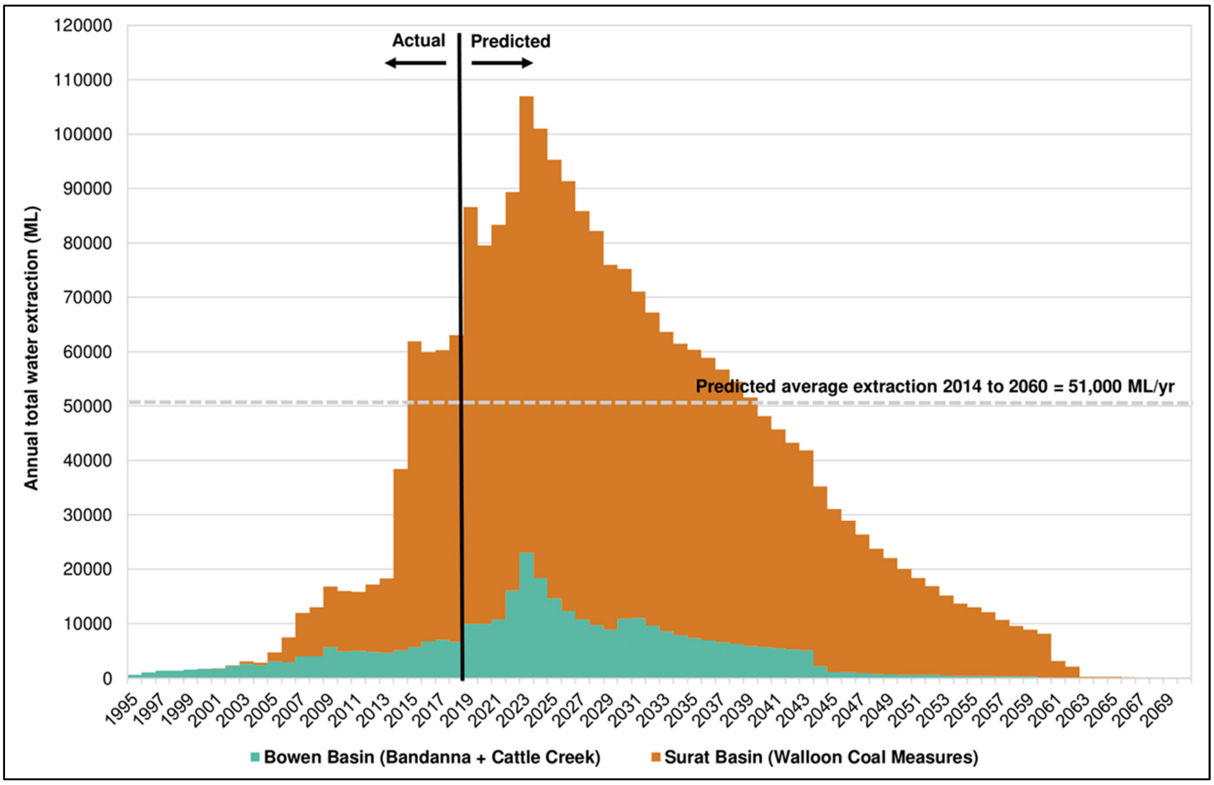

Figure 7-3 Predicted CSG water extraction

7.5 Impacts on environmental values

As detailed in Chapter 10, legislative changes have now enhanced the scope of the UWIR to include the broader suite of environmental values (EVs). Unlike the impact assessment for springs and watercourses, the assessment for additional EVs (such as the terrestrial groundwater-dependent ecosystems (GDEs)) is limited to characterisation of those values and assessment of impacts.

Impacts on EVs such as aquifers and water bores are detailed in earlier sections of this chapter. Impacts on springs and connected watercourses are described in Chapter 9, together with the spring impact management strategies. A risk-based approach is adopted for identifying impacts on other EVs such as the terrestrial GDEs and land subsidence. These are described in Chapter 10, together with characterisation of those EVs.

Chapter 8 Water Monitoring Strategy

Groundwater monitoring in the Surat CMA is required to inform three key outcomes:

- to identify groundwater impacts from P&G development that may have occurred
- to improve knowledge about the groundwater system, which improves OGIA's ability to predict groundwater impacts
- to support the evaluation of UWIR impact management strategies.

The Water Monitoring Strategy (WMS) is designed to achieve these outcomes. The WMS includes the specification of a groundwater monitoring network and tenure holder obligations for implementing that network and reporting data back to OGIA.

Since the UWIR 2012, implementation of the WMS has progressively built a substantial groundwater monitoring network across the Surat CMA. Data from the WMS has improved knowledge about the groundwater flow system and has helped to identify where further improvements are required. Data received by OGIA under the WMS is reviewed every six months and is publicly available on the Queensland Groundwater Database (GWDB) and the Queensland Globe.

8.1 Components of the strategy

The WMS includes the following components:

- installation, maintenance and collection of data from the **groundwater monitoring network** including water pressure and water chemistry
- monitoring of associated **water volumes**
- a program for **baseline assessment**
- tenure holder **reporting** of the data and activities relating to the above components.

The WMS is implemented by tenure holders as specified in this chapter. Individual tenure holders are responsible for specific obligations, which are assigned in accordance with the rules outlined in Chapter 11.

The following sections provide details of each component of the WMS.

8.2 Groundwater monitoring network

The term **monitoring network** is used in this report to describe a collection of groundwater **monitoring points** – groundwater piezometers or bores constructed into the subsurface to monitor groundwater pressure or chemistry.

8.2.1 Types of monitoring installations

A range of monitoring installation types have been constructed in the Surat CMA (Figure 8-1). Broadly, there are three categories of monitoring installations:

- **Single aquifer piezometer.** These monitoring points have similar construction to modern water bores and are typically used in formations above the CSG reservoirs. The measurement of groundwater pressure is typically undertaken using a water level logger installed within the casing.

- **CSG completion.** This type of completion is required where there is potential for interaction with gas within the CSG reservoir or in formations below the reservoir. These monitoring points are constructed in accordance with the P&G Acts to manage risks associated with the presence of flammable gas under pressure. In most cases, multiple monitoring points are installed within a single well. Groundwater pressure is typically measured using water level loggers suspended inside the casing or cemented outside the casing.
- **Cemented vibrating wire piezometer.** These monitoring points are typically CSG exploration or core holes that have been repurposed for monitoring. Multiple aquifers are often monitored at these sites with the measurement of groundwater pressure using a vibrating wire piezometer (VWP) sensor cemented within the borehole. This type of construction is gradually being phased out from the network due to reliability issues.

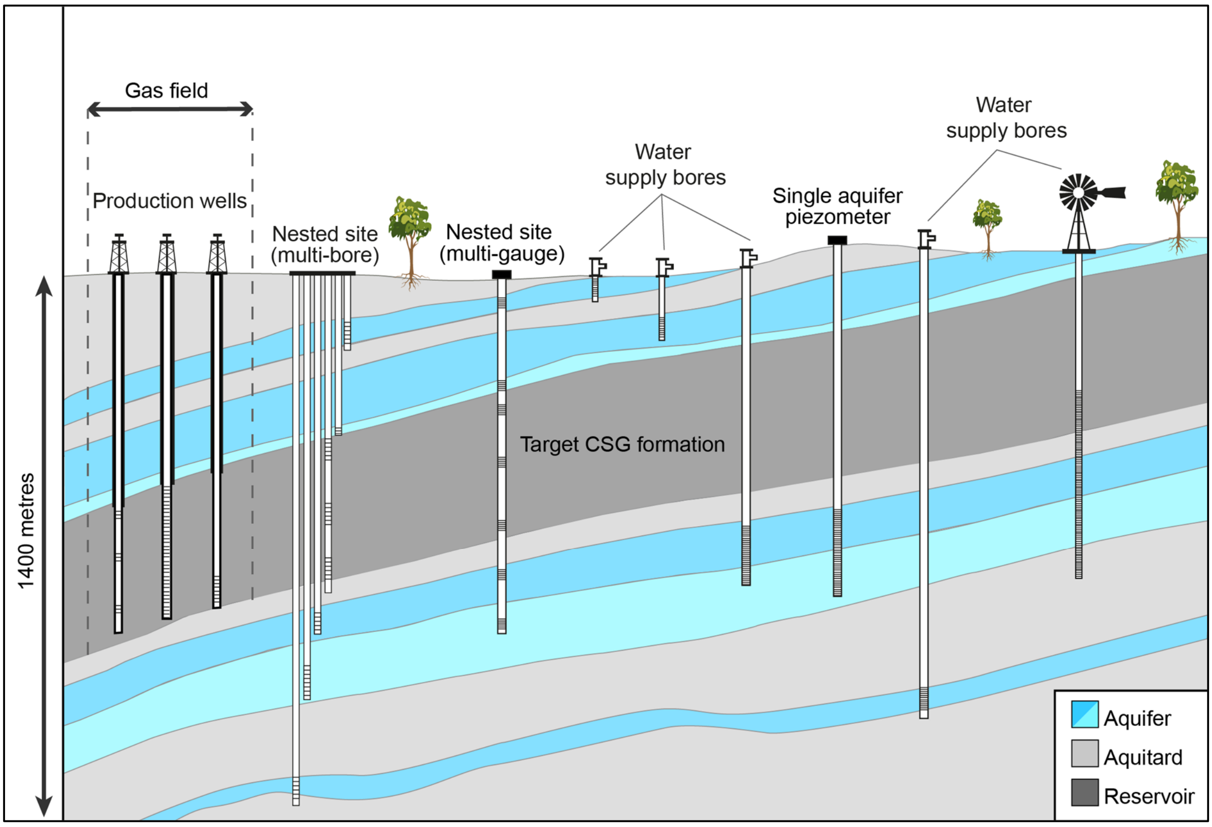

Figure 8-1 Schematic of monitoring installation types in the Surat CMA

8.2.2 Evolution of the monitoring network

The WMS groundwater monitoring network has grown progressively since its initial specification in the UWIR 2012. Changes since then reflect the availability of existing infrastructure at the time of periodic review, groundwater system conceptualisation and data needs, and the progressive deterioration of early network installations.

The initial monitoring network specified in the UWIR 2012 incorporated 106 existing monitoring points. This provided continuity of important historical monitoring data. Beyond these sites, the design of the initial network focused on understanding the regional groundwater flow system, particularly around proposed CSG production areas. By 2015, the monitoring network had grown to 440 monitoring points.

In the UWIR 2016, the revised network significantly expanded the geographical coverage of the monitoring network, including monitoring in key aquifer units adjacent to the target reservoirs, such as the Hutton and Springbok sandstones. At the time, about 70% of monitoring points were located within the LAA, with 30% located outside the LAA in more remote areas. These distant sites were required to improve conceptual understanding around key features of interest, such as springs.

Between 2014 and 2016, there was also growth in complementary networks including Groundwater Online and Groundwater Net. This data provides bore owners with useful information about the condition of their bores as well as changes in water levels. These networks continue to provide additional data to support OGIA's assessment. As shown in Figure 8-2, as of late 2018, the monitoring network comprises about 600 monitoring points that are already in place, 90% of which are providing data. About 100 are for monitoring water chemistry.

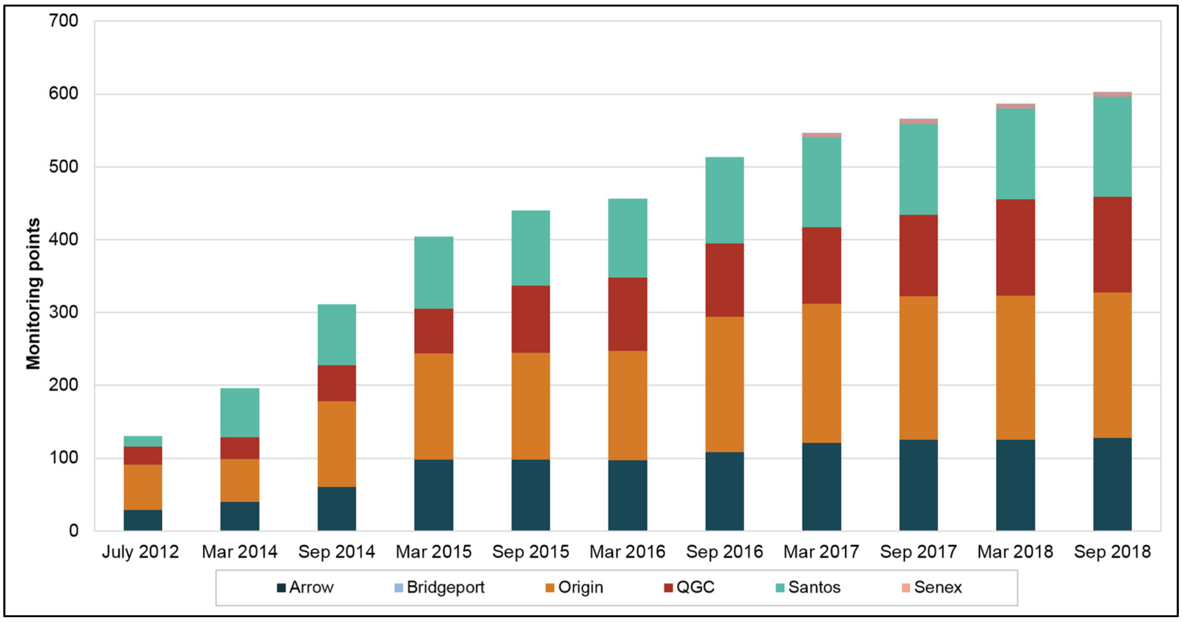

Figure 8-2 Growth of WMS monitoring points

8.2.3 Emerging knowledge and challenges

As the groundwater monitoring network has evolved, new challenges have emerged relating to new hydrogeological insights and the performance of the monitoring infrastructure. Some of the key challenges that have guided the current review of the monitoring network are listed below:

- There is significant variability in the hydraulic properties of key units such as the Hutton Sandstone (section 3.4.2), and new mapping of zones of potential connectivity between aquifers such as geological faults (section 3.5.1).
- Analyses of water level trends have identified factors that are likely to have greater influence on trends and assist in separation of CSG impacts from non-CSG impacts (Chapter 5).
- As new information has become available, more impacts are predicted in some aquifers, such as the Springbok Sandstone.
- Some of the early installations are beginning to fail or are becoming unreliable. These require replacement, particularly those installed with VWPs. In addition, a number of installations have long screen intervals, which are less effective for monitoring changes in aquifer pressure in key areas.

- The industry development profile continues to change in response to market conditions and the availability of technology to develop target reservoirs. The dynamic development scenario means that the monitoring network needs ongoing review to avoid data gaps and redundancy.

8.2.4 Review of the existing network

8.2.4.1 Objectives

Consistent with the purpose of the WMS (see introduction), the following objectives have informed the design of the groundwater monitoring network. These are broadly consistent with the objectives applied in the UWIR 2016.

- **Understand background trends.** Data is required to understand background trends in groundwater pressure due to climatic variability and the extraction of groundwater for non-CSG uses. Identifying these background trends allows separation of the impacts of CSG development from other contributing factors. This also provides insight into the functioning of groundwater systems by enabling the development of regional water level or pressure contours.
- **Identify pressure changes near areas of P&G development.** Within and adjacent to development areas, monitoring is required to understand the propagation of impacts from the CSG reservoir to overlying and underlying formations. Key formations include the upper Hutton Sandstone and the lower Springbok Sandstone.
- **Understand groundwater flow near connectivity features.** Monitoring is required in areas where there is high potential for connectivity between CSG reservoirs and other aquifers. Priority areas are those where regional faults and associated fracture zones have been identified – such as in the vicinity of the Hutton-Wallumbilla and Horrane faults – and in areas where formations separating reservoirs from other aquifers are either thin or absent. Where these features are within or near development areas, additional monitoring is necessary.
- **Understand groundwater flow near high value assets.** Data is required in areas where high-value assets such as springs and water bores are predicted to be affected at some time in the future. Understanding pressure conditions ahead of impacts occurring provides a clear picture of how and when impacts may occur at the location of environmental values and water bores.
- **Improve conceptual understanding and future groundwater flow modelling.** The regional groundwater flow model is based on a conceptualisation of the hydrogeology of the groundwater flow system. All monitoring data supports this process. In parallel, the model predictions highlight areas where additional data may be required prior to impacts occurring. This will assist in future validation of model predictions.

To an extent possible tenure holders groundwater monitoring obligations under their various project approval conditions are also considered in developing an integrated monitoring network over time. This will streamline industry reporting and provide increased transparency of monitoring at these locations.

8.2.4.2 Network design

In parallel with the above objectives, the review and design of the monitoring network has followed the following guiding principles:

- The part of the monitoring network specified in the UWIR 2016 that was not constructed by September 2018 has been reassessed as part of the current review of the WMS. The revised network specification replaces the UWIR 2016 network specification.
- In general, a higher density of monitoring points is required inside and near existing and proposed CSG development areas compared to more distant areas, where background monitoring is the primary focus.
- Where practicable, monitoring points in an area are located in close proximity for multiple target formations, providing information on pressure differences between formations.
- In some instances, separate monitoring is required for the upper and lower parts of the formations immediately overlying and underlying the CSG target formations, such as the Springbok and Hutton sandstones.
- A lead time is necessary to collect sufficient data ahead of P&G development in areas where impacts are anticipated. For this reason, implementation timeframes are earlier in areas where impacts are predicted in the shorter term.
- Roll-out of the monitoring network allows for review of the monitoring network specification in line with the ongoing changes to the development profile within the UWIR cycle.
- The use of suitable existing tenure holder monitoring points is maximised so that the drilling of new dedicated monitoring bores can be focussed in areas of greatest need.
- The network seeks to primarily comprise dedicated pressure monitoring points, i.e. monitoring points that are not also used for water extraction and not installed with pumping equipment (excluding sampling equipment).
- Monitoring points should reasonably represent water pressure and water chemistry at the formation or sub-formation scale. Monitoring points constructed as cemented VWPs or screened across multiple formations are being progressively transitioned out of the UWIR network.
- As far as practicable, an integrated single monitoring network is established over time that meets the requirements of UWIR and other State and Commonwealth approval conditions.

8.2.5 Network specification

The WMS groundwater network includes groundwater pressure and chemistry monitoring points. The following section provides additional detail on the specification of these networks as detailed in Appendix H.

At each monitoring point, a status ('WMS status') is assigned based on the outcome of the network review. Where a UWIR 2016 WMS monitoring point continues to be required, 'Maintain' is assigned. If maintenance or replacement of a WMS monitoring point is required, 'Repair' or 'Replace' is assigned. Where an existing tenure holder monitoring point is being included in the network for the first time, 'Integrate' is assigned. Where a new monitoring point is required, 'Proposed' is assigned. Where a monitoring point is no longer required, 'Remove' is assigned.

A comprehensive list of existing and new groundwater monitoring points in the 2019 WMS network is available at OGIA's website and a summary is provided in Appendix H.1, Tables H-1 to H-3. The status of each monitoring point is included in these tables. Where a new monitoring point is required, the due date for completion is also specified at some locations. The proposed timing for completion at some locations will be reviewed each year through the Annual Report, in consideration of the development profile at the time and nearby monitoring data. In addition to the sites included in these tables, OGIA may identify additional monitoring sites within the UWIR cycle where new information becomes available that identifies a critical information gap.

The locations of the 2019 WMS monitoring points and other complementary monitoring networks are shown in Appendix H.3, Figures H-1 to H-3. Monitoring locations in key formations – the Walloon Coal Measures and Springbok, Hutton and Precipice sandstones – are shown in Figure 8-3 and Figure 8-4.

8.2.5.1 Groundwater pressure

The WMS groundwater pressure network includes 622 pressure monitoring points – 83 are proposed new monitoring points (Table 8-1). As a minimum, daily groundwater pressure measurements are required at these locations.

Table 8-1 Summary of the WMS groundwater pressure network

Formation	Status					Total
	Maintain	Integrate	Replace	Repair	Proposed	
Alluvium and basalt						
Condamine Alluvium	24	3	-	-	3	30
Other	2	-	-	-	6	8
Surat Basin (GAB)						
Springbok Sandstone	53	11	2	3	12	81
Walloon Coal Measures	180	20	18	27	22	267
Hutton Sandstone	52	9	4	1	20	86
Other formations	81	13	3	6	13	116
Bowen Basin						
Bandanna Formation	14	-	2	3	6	25
Other formations	8	-	-	-	1	9
Total	**414**	**56**	**29**	**40**	**83**	**622**

The main features of the network are as follows:

- Of the operational monitoring points, about 13% require repair or replacement.
- About 47% are within the CSG reservoirs.
- There are 19 new monitoring points (proposed and integrate) in the lower Springbok Sandstone and 23 in the upper Hutton Sandstone. These are key formations for assessing impact propagation from CSG development within the Walloon Coal Measures.
- There are 97 nested monitoring locations. At these locations, monitoring is specified in the CSG target formation and in one or more adjacent aquifers at the same location.
- About 95% of the monitoring points are in formations and locations where CSG impacts on groundwater pressure of more than five metres are predicted in the long term. The other 5% are located outside areas of significant impact.

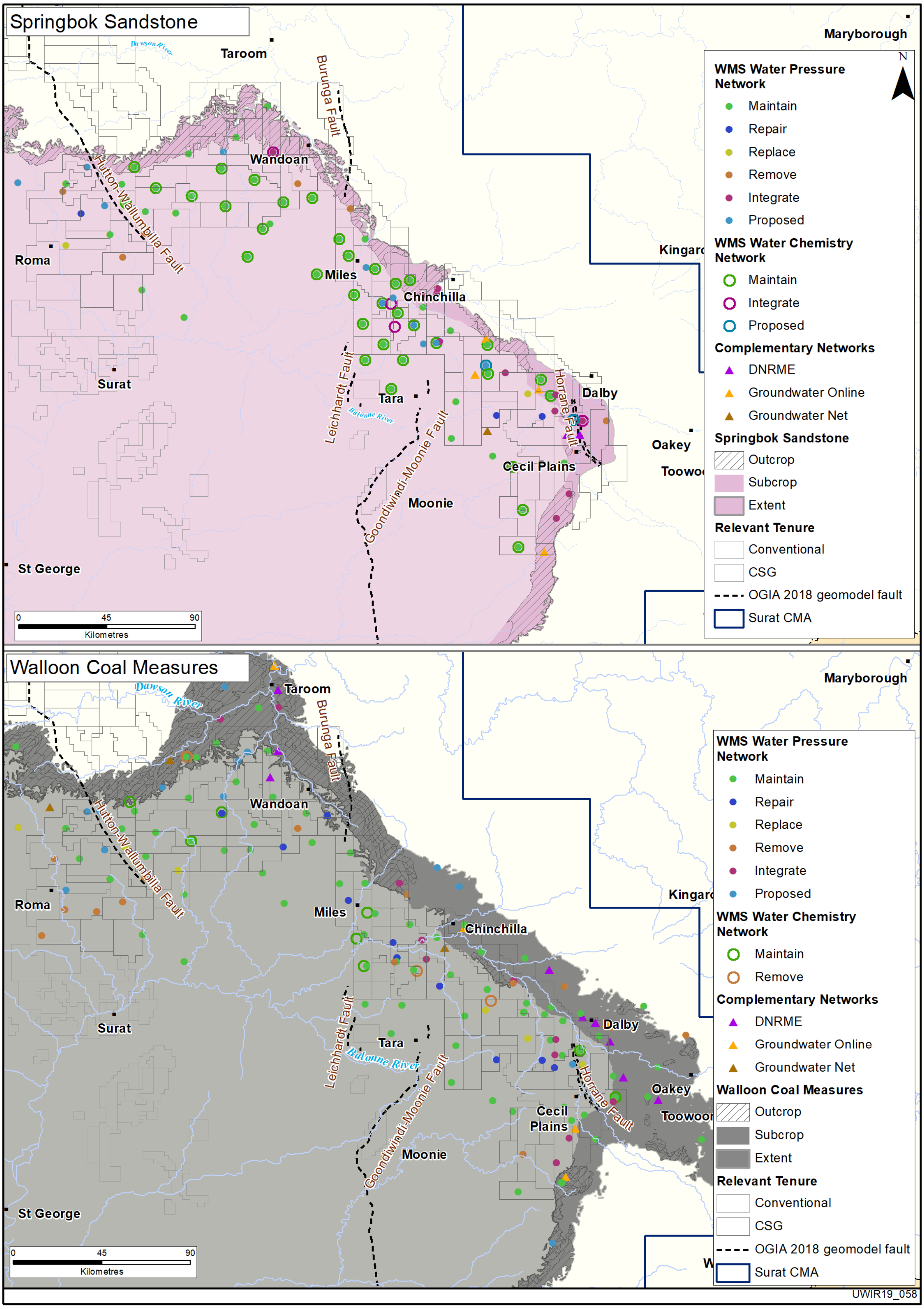

Figure 8-3 Groundwater monitoring networks in the Walloon Coal Measures and the Springbok Sandstone

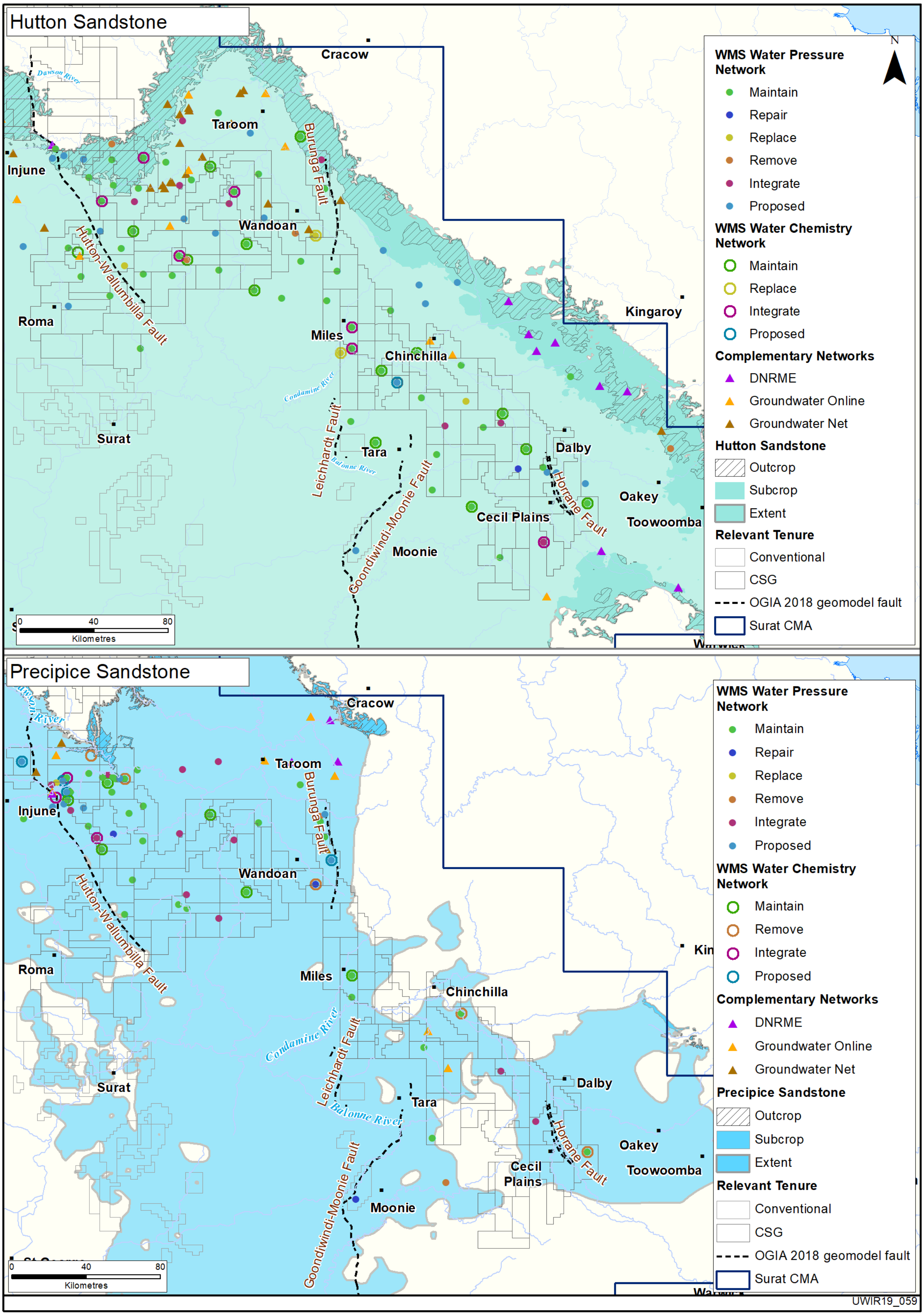

Figure 8-4 Groundwater monitoring networks in the Hutton and Precipice sandstones

8.2.5.2 Groundwater chemistry

The water chemistry network has evolved since its initial prescription in the UWIR 2012. There has been an evolution of the primary aim of the network from groundwater system characterisation to the assessment of CSG-related impacts. Similar to the groundwater pressure network, a status has been assigned to each monitoring point.

The suites for water chemistry have also changed to include both major ions and isotopes (Appendix H.1, Table H-4). This change enhances OGIA's ability to detect impacts from development. Major ions, dissolved metals and field parameters (suite A) are required every six months from all existing and new monitoring points until at least five complete samples have been received by OGIA. In terms of isotopes (suite B), a strontium sample is required once only for all existing and new monitoring points in the Hutton, Springbok and Precipice sandstones. A strontium sample is required annually for monitoring points in the CSG reservoir and production wells (section 8.3).

A summary of WMS water chemistry monitoring points is provided in Table 8-2. The WMS groundwater chemistry monitoring network includes 103 monitoring points, of which 92 are operational monitoring points and 11 are new proposed monitoring points. About 17% monitor the CSG target formations. In additional, water chemistry monitoring is also specified for selected production wells (section 8.3).

Table 8-2 Summary of the WMS groundwater chemistry network

Formation	OGIA status					Total
	Maintain	Integrate	Replace	Repair	Proposed	
Alluvium and basalt						
Condamine Alluvium	5	-	-	-	-	5
Surat Basin (GAB)						
Springbok Sandstone	34	4	-	-	2	40
Walloon Coal Measures	8	-	-	-	-	8
Hutton Sandstone	14	7	2	-	1	24
Other formations	9	3	-	-	3	15
Bowen Basin						
Bandanna Formation	5	1	-	-	4	10
Other formations	-	-	-	-	1	1
Total	**75**	**15**	**2**	-	**11**	**103**

8.2.5.3 Summary of rationale for changes to the monitoring network

At some locations, tenure holders have recently constructed, or plan to construct, monitoring points for specific purposes relating to ongoing investigation or to meet project approval conditions. Where these locations align with the WMS network objectives (see section 8.2.4.1), the locations have been integrated into the network. Examples include monitoring points 858 and 875 (Santos), 862 and 879 (QGC) and 732 to 734 (Arrow).

New monitoring points are added to specific locations where gaps in coverage are identified (e.g. 795) or where improvement is required in knowledge about groundwater flow or impact propagation in and around connectivity features. For example, since the UWIR 2016, there is substantially more information about the location and displacement of faults (see section 3.5.1.3). Where faults occur, there is potential for increased connection between the reservoir and adjacent aquifers. Therefore, four new monitoring nests are added along the Hutton-Wallumbilla Fault and one adjacent to the Horrane Fault.

Recognising the heterogeneity of the Hutton and Springbok sandstone (see section 3.4.2), new sub-formation-scale monitoring is specified within production areas, targeting the part of the formation closest to the reservoir. This data will improve early detection of impacts and provide better model calibration, e.g. monitoring points 795 (QGC), 823 (Origin) and 825 (Santos). Similarly, in shallower parts of the groundwater system, new monitoring is specified to provide better control on groundwater flow boundaries and the ability to assess impacts on environmental values (see section 10.2) such as terrestrial GDEs, i.e. 877 and 878 (Arrow).

At some of the older monitoring locations, the target formation is screened over a long interval or the equipment is beginning to fail, particularly those monitoring points that are installed with VWPs. In locations where data continues to be required, monitoring points are to be replaced or repaired (e.g. monitoring points 264 (Origin), 155 (QGC) and 383 (Santos)). Where appropriate, the location is also rationalised in consideration of the other available data around that area, such as around Roma, where seven VWP nests are merged into four.

Some monitoring points are also removed from the network due to infrastructure or equipment failure, or because of lack of saturation of the aquifer to measure the water level (e.g. 429 and 526). Some points are also removed if there is sufficient data coverage from other points in the area.

The network is designed as a dedicated monitoring network. Water supply bores are generally not accepted as monitoring points unless the bore construction is sound, a continuous logger is installed, corresponding water extraction data is available and there is historical data available to demonstrate that reliable trends can be established from the data.

In the previous UWIR, some monitoring points further from production areas were conditional upon CSG development occurring within 10 km. However, information gathered since then suggests the industry development profile is dynamic and changes materially within a UWIR cycle. Therefore, to ensure that sufficient background monitoring is available ahead of development, proposed timing of those points is based on current development profile. The proposed timing for some specific points will be reviewed each year through the Annual Report on the UWIR, in consideration of the development profile at the time and nearby monitoring data. These points are explicitly identified in the monitoring point details table, which is available online.

8.2.5.4 Complementary monitoring

In addition to data sourced from the UWIR monitoring network, OGIA also receives monitoring data made available through the Queensland Government's ambient groundwater monitoring network, community-based monitoring and from other monitoring undertaken by petroleum tenure holders.

- **Other state government monitoring.** Within the Surat CMA, there are around 440 dedicated monitoring points. These sites are generally located in shallower parts of the formations, where consumptive water use is more concentrated (see Chapter 4). These are a combination of manual measurement and data logger installations.

- **Groundwater Online and Groundwater Net.** Since 2014, DNRME has progressively grown two monitoring programs that focus on increasing community understanding of groundwater system responses within resource development areas. 'Groundwater Online' represents a subset of the Queensland Government's monitoring network and includes a combination of landholder and dedicated monitoring infrastructure. In the Surat CMA, there are about 70 landholder bores monitored through this program. 'Groundwater Net' is a community based initiative that encourages landholders to monitor their own water bores and submit their information to the GWDB. This currently includes around 100 monitoring points within the Surat CMA.
- **Other tenure holder monitoring.** In the Surat CMA, tenure holders provide data for an additional 200 monitoring points beyond those required by the WMS. These monitoring sites are typically on tenure and have been established for operational reasons or to meet other State or Commonwealth approval conditions.

8.2.6 Installation and maintenance

The responsible tenure holder identified for each monitoring point is responsible for construction, completion and maintenance of the monitoring points, including the collection of monitoring data. Tenure holders are required to submit monitoring data to OGIA every six months.

For new monitoring points, it may not be practicable in some instances to complete works at the specified locations, and to meet specific timeframes. Details of proposed changes to specified locations and dates must be submitted to OGIA for approval prior to construction.

Consistent with the previous UWIR, a guideline for constructing new monitoring points is provided in Appendix H.2. Monitoring points must be constructed in a way that is consistent with this guideline.

For all new constructions, the responsible tenure holders are required to provide a summary of the planned design of monitoring points to OGIA for endorsement. Following completion, a monitoring bore completion diagram must be provided to OGIA within six months. Details of these requirements are specified in Appendix H.2.

The responsible tenure holder must maintain each monitoring point. If a monitoring point fails and it is not practicable to repair, the tenure holder must notify OGIA. The need for continued monitoring at the location will then be considered by OGIA. Where this occurs, a new monitoring point may be required by OGIA ahead of any future UWIR.

8.3 Monitoring of groundwater extraction

Groundwater is extracted in association with the production of P&G products (Chapter 2). In accordance with their legislative requirements, tenure holders are required to monitor and report the volume of water extracted from P&G wells. The WMS also requires tenure holders to provide, every six months, monthly associated water extraction volumes for each well.

In addition to monitoring volume, the WMS now also requires annual monitoring of water chemistry from 157 production wells (Figure 8-5 and Appendix H.1). For the proposed points monitoring will commence when production wells are completed around that location. The density of these sites is generally one per production block with higher density specified in areas where there is higher potential for connectivity. The required water chemistry analysis is specified as suites A and B in Appendix H.1, Table H-4. Where there are operational issues that limit the effectiveness of the specified well for ongoing monitoring, OGIA will work with the responsible tenure holders to select a new location. The data collected through this additional monitoring will assist OGIA to identify cross-formational flow induced by development of the reservoir.

In addition to the production of associated water, Origin Energy has established a reinjection scheme to inject treated associated water into the Precipice Sandstone (section 4.2.3). Since 2015, more than 20,000 ML have been injected. Daily injection volumes must be reported to OGIA every six months.

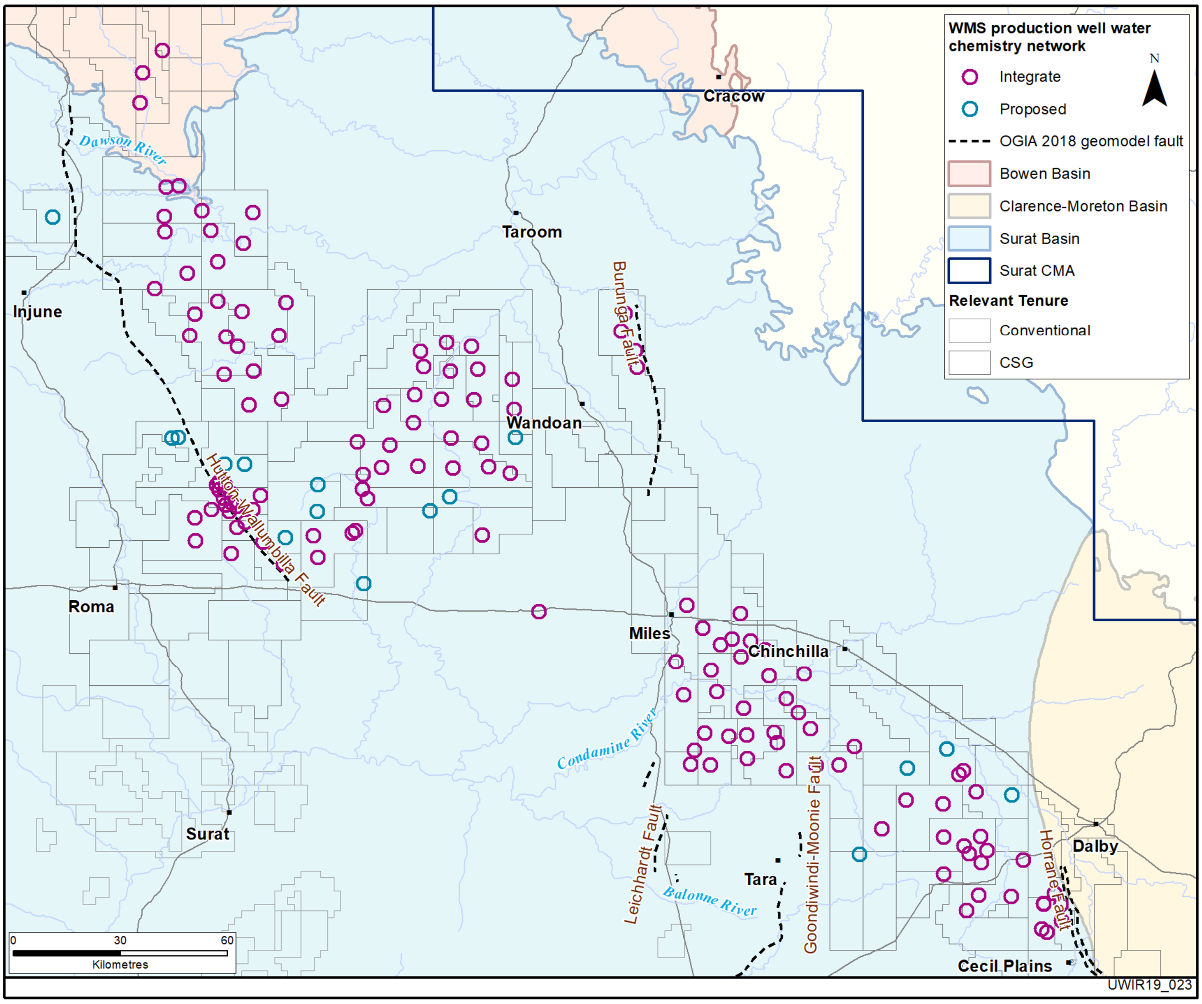

Figure 8-5 Water chemistry monitoring points for CSG production wells

8.4 Monitoring of consumptive water use

There is significant non-P&G use in aquifers adjacent to the target reservoirs. OGIA has developed a method for estimating non-P&G water use (Chapter 4). However, limited metering data means that there is substantial uncertainty in the estimated use. This data gap significantly affects OGIA's ability to separate P&G from non-P&G impacts (Chapter 7).

To support water resource planning activities, DNRME has identified the Hutton Sandstone as a priority for metering of volumetric entitlements. DNRME will be incorporating the metering of these entitlements into its forward implementation program for improved metering under the Rural Water Management Program.

8.5 Reporting of monitoring data

The WMS requires responsible tenure holders to submit data to OGIA every six months. This includes information about bore construction, monitoring data and water production from more than 7,000 locations including production wells and monitoring bores.

Upon receipt of this information, OGIA completes a quality assurance process to ensure completeness of the received datasets, consistency with previous submissions and to identify potential erroneous measurements. Corrections and resubmission is requested from tenure holders where necessary before the data is uploaded to the GWDB and made available through QLD Globe.

While the quality of data submission from tenure holders has gradually improved as the processes are maturing, there are some ongoing issues in relation to the submission of accurate bore construction information and the submission of data related in the quality and format required by OGIA.

OGIA submits an implementation report to DES every six months and continues to engage with DES in relation to implementation issues. Compliance actions are undertaken where appropriate.

8.6 Tenure holder obligations

This section summarises the responsible tenure holder (RTH) obligations in relation to the WMS. Rules for assigning RTH are specified in Chapter 11.

On 1 April and 1 October of each year, the RTH is required to submit the following to OGIA.

A **WMS network implementation report** that must include:

- current status of the groundwater monitoring points
- planned installation of monitoring points
- emerging implementation issues
- proposed changes to the location or timing of any installations for OGIA endorsement.

A **WMS water monitoring report** that must include:

- details about the monitoring point or production well construction
- the data collected for each monitoring location including groundwater pressure, water chemistry, associated water volumes and reinjection volumes where applicable
- an explanation of any gaps or changes in the monitoring record associated with maintenance issues or failure of a monitoring point.

The reports and data must be submitted in the format specified by OGIA. If, as a result of tenure holder quality assurance processes, a tenure holder needs to amend monitoring data previously submitted in a water monitoring report, the tenure holder must submit to OGIA a **data correction report** providing an explanation of the corrections.

Where a new monitoring point is required under the WMS, the RTH must provide:

- the planned design of monitoring points prior to construction for endorsement by OGIA
- upon completion, a monitoring bore completion diagram for endorsement by OGIA.

OGIA acknowledges the difficulties for tenure holders to install and maintain monitoring points off tenure, away from production areas, particularly those that are some distance from tenure. Therefore, OGIA intends to engage with industry in near future to explore alternative approaches to gather monitoring data in those areas.

8.7 Baseline assessment

8.7.1 General requirements

A baseline assessment is a field survey of a water bore by a tenure holder to obtain information about bore construction, water levels and water quality. The information provides a baseline of a bore’s condition and performance, ahead of any predicted impacts occurring at the bore.

This information supports the development of agreements between bore owners and petroleum tenure holders about ‘making good’ any impairment of bore supply caused by the extraction of groundwater by petroleum tenure holders. The water level and water quality information collected also assists OGIA in its ongoing assessment of the groundwater system.

There are three broad criteria for identification of bores for baseline assessment:

- water bores on tenures prior to production commencement
- water bores for which the tenure holder is directed by DES to undertake a baseline assessment
- any other water bores within LAAs for which the WMS in a UWIR contains a program for baseline assessments.

The program for baseline assessment in this section relates to the final bullet point above. Baseline assessments are carried out in accordance with baseline assessment plans approved by DES and in accordance with guidelines prepared by DES.

8.7.2 Program of assessment

This program includes areas where no CSG production is currently occurring. In many parts of the LAAs, impacts on water level or water pressure will not occur for some time. Baseline assessments are most effective when they are undertaken immediately before the impacts are expected to occur. If the assessment is completed too early, the information collected would be less useful for assessing changes.

For this reason, the program for carrying out baseline assessments for the LAAs supports the progressive expansion of the area assessed, so that assessments are completed close to the time that the impact is predicted to occur. Similar to the previous UWIR, a predicted impact of one metre within three years has been adopted as the trigger for carrying out a baseline assessment. Each time a new UWIR is prepared, a new one-metre impact area is established.

The baseline assessment program is as follows:

- The baseline assessment area for an aquifer is the area where a water pressure fall of more than one metre is expected within three years, as shown in Figure 8-6. A baseline assessment area for the Precipice Sandstone around the Moonie oil field is not identified, as there are no water bores accessing that aquifer and production from the field is approaching end of life.
- Responsible tenure holders must carry out baseline assessments for bores that tap an aquifer within the baseline assessment area for that aquifer.

- If a baseline assessment has already been carried out in accordance with other obligations arising under the Water Act, no further assessment is required.
- Assessments are to be carried out in accordance with the current guidelines for baseline assessments from DES.
- Assessments must be completed and the results reported to OGIA within 12 months of the UWIR being approved.
- Each time the UWIR is reviewed, new baseline assessment areas will be established until the baseline assessment areas for an aquifer coincide with the entire LAA for the aquifer.

8.7.3 Data gathering and validation

OGIA has a statutory obligation to maintain a database of the baseline assessment information collected by tenure holders. The database currently holds more than 3,500 assessments completed in the Surat CMA.

The quality of the information and data collected during baseline assessment varies. The information collected by the tenure holder at the time of visiting the bore is often heavily reliant on existing information available on the GWDB. For example, bores recorded in the GWDB may be unable to be located, and bores not previously recorded on the GWDB are identified (referred to as 'unregistered bores'). In some instances, baseline assessments have been completed for a bore by more than one tenure holder. Also bores often have pumps installed, limiting the assessment of water levels and bore depth.

For these reasons, the baseline assessment dataset includes duplication and potential misassignment of bore registered numbers. The baseline assessment dataset often therefore cannot be used with confidence or uploaded to the GWDB without an extensive verification process.

Since 2017, OGIA, in collaboration with DNRME, has undertaken a project to verify the registered number assigned during 2,800 baseline assessments completed by tenure holders. This subset of the more than 3,500 of baseline assessments were reviewed as a priority, as they are located within the IAA and LAA footprints and may have a material influence on the identification of affected water bores.

The project includes a desktop check to validate the registered number assigned at the time of the baseline assessment. The process includes a cross check of data, photos and other information provided by tenure holders with data held in various DNRME databases (GWDB, Water Management System, QDEX, MERLIN, MYMinesOnline). Where available, field reports and photos are matched with aerial imagery.

Thus far, the verification process has identified that 3% of baseline assessments have incorrectly assigned RNs and 14% were not assigned RNs as part of the baseline assessment. Approximately half of these bores have subsequently been attached to existing RNs. The bores that remain without RNs are processed by DNRME and allocated new RNs. Once bores are verified, the associated non-confidential information from the baseline assessment is progressively uploaded to the GWDB.

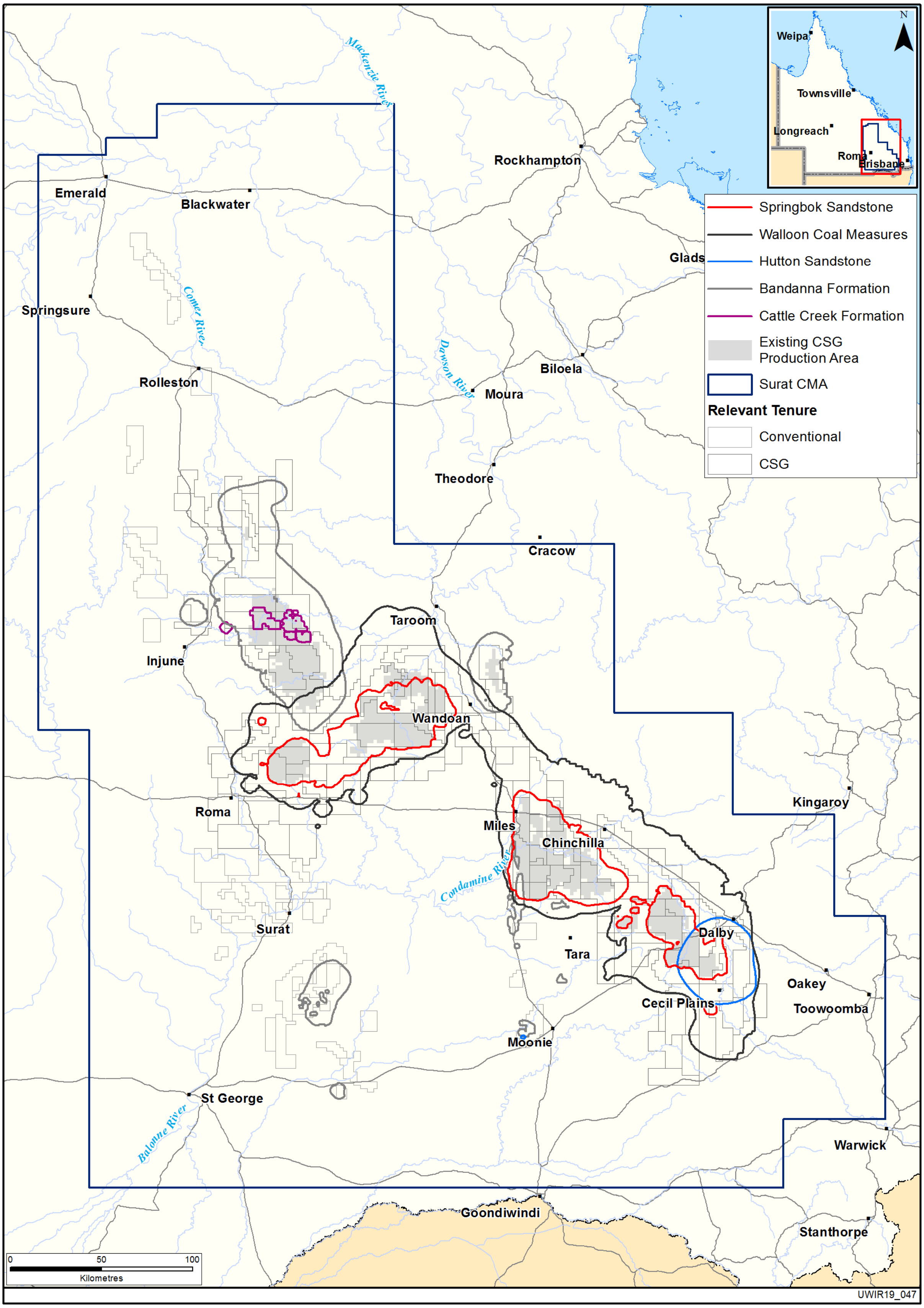

Figure 8-6 Baseline assessment areas

Chapter 9 Spring Impact Management Strategy

The Spring Impact Management Strategy (SIMS) is developed for managing impacts on springs and sections of streams that are fed by groundwater ('watercourse springs') within the Surat CMA. The SIMS is specified to achieve the following key outcomes:

- enhance hydrogeological knowledge about springs, including an assessment of the connectivity to underlying aquifers
- improve the prediction and assessment of potential impacts on springs
- prescribe actions for the management of predicted impacts where necessary.

Since 2012, there has been a significant investment by OGIA and industry to improve understanding about the aquifers that support springs in the Surat CMA. Research has also focused on the way springs respond to seasonal climatic conditions, non-groundwater related stresses, and groundwater extraction by tenure holders and other water users.

This chapter updates the SIMS in response to the revised predictions of groundwater impact as well as new knowledge acquired since the UWIR 2016.

9.1 Components of the strategy

The SIMS includes the following components:

- Characterisation of springs and an assessment of **connectivity to underlying aquifers**: for springs of interest, identification of aquifer(s) that provide flow to the spring.
- Identification of the **springs of interest**: springs that overlie an aquifer with a predicted impact of more than 0.2 metres drawdown at any time.
- An **assessment of risks** to springs: the risk of current and planned P&G development impacting on the source aquifers of the springs of interest.
- A spring **impact mitigation strategy**: a strategy for preventing or mitigating impacts on springs where predicted impacts are more than 0.2 metres.
- A spring **monitoring program**: the program identifies monitoring sites, appropriate techniques and frequency.

The monitoring and mitigation strategies identified in the SIMS are implemented by tenure holders in accordance with their individual responsibilities as assigned in Chapter 11.

9.2 Evolution of knowledge

Since the CMA was established in 2011, there has been significant investment in research to improve knowledge about the location, values and seasonal dynamics of springs in the Surat CMA. This new knowledge, together with output from the redeveloped regional groundwater flow model, has enabled an improved assessment of risk and management actions.

Prior to 2011, some spring complexes had previously been surveyed by the Queensland Herbarium. The focus of these early surveys was primarily to record location and botanical information. Building upon that dataset, an extensive hydrogeological and botanical survey was led by OGIA (formerly the Queensland Water Commission) in 2011. The updated dataset provided the basis for the initial source aquifer assessments, and was also used to characterise ecological values at spring complexes for the UWIR 2012.

The UWIR 2012 provided the first assessment of cumulative impacts on springs in the Surat CMA. Five spring complexes were predicted to be impacted by more than 0.2 metres in the long term. As a result, detailed desktop and field investigations were undertaken by OGIA and the industry at these locations. In parallel, quarterly seasonal monitoring was completed by industry in accordance with the UWIR 2012 and their EPBC approval conditions across 17 spring complexes.

In early 2015, OGIA collated and analysed these datasets to build local scale conceptualisations at each of the monitored spring complexes (OGIA 2015). These local conceptualisations improved the collective understanding of the springs' source aquifers and likely responses to changes in groundwater level.

These detailed assessments informed the establishment of a spring typology (see section 9.3.3). The typology groups spring wetlands by type, using characteristics relating to how a wetland has formed and how it is likely to respond to a change in the groundwater regime (OGIA 2015). This typology continues to support the design of the spring monitoring requirements specified in the monitoring program and has been incorporated into the system for assessing risks to springs.

In 2017, OGIA remapped and field-verified a number of gaining streams (OGIA 2017a). This information identified areas where impacts may occur. Industry has also undertaken investigations to identify areas of potential surface water-groundwater connectivity.

In parallel, the significant time series monitoring dataset that had been accumulated was available to assess dynamics at spring complexes. The monitoring data highlighted that a range of seasonal climatic and land use factors influence spring discharge and condition. Importantly, to understand if changes in spring discharge are related to changes in the groundwater regime, all spring water balance components need to be identified and monitored, where possible.

Between 2017 and 2018, OGIA led a pilot project on new methods to evaluate which spring attributes and monitoring tools are most appropriate for ongoing monitoring (OGIA 2019d). The outcomes from that project have guided the specification of monitoring in this chapter.

9.3 Springs in the Surat CMA

Springs are commonly described as either 'spring vents' or 'watercourse springs'. The terminology used to describe springs in this report is set out in Table 9-1. In addition to the terms in Table 9-1, springs may also be further classified by other characteristics such as their size, location in the landscape and regional hydrogeological setting (for example, whether they are in recharge or discharge areas).

Table 9-1 Terminology

Term	Description
Spring vent	A single location in the landscape where groundwater discharged at the surface. A spring vent can be mounded or flat and can also present as wetland vegetation, with no visible water at the location of the spring.
Spring complex	A group of spring vents located close to each other. The spring vents are located in the same surface geology and share the same source aquifer and landscape position. No adjacent pair of spring vents in the complex is more than 10 km apart.
Watercourse spring	A section of a watercourse where groundwater from an aquifer enters the stream through the streambed. This includes waterholes and flowing sections of streams dependent on groundwater. This type of spring is also referred to as a baseflow-fed section of a watercourse.
Spring group	A collection of spring complexes and/or watercourse springs, which share the same source aquifer and are located within the same geographic area.

9.3.1 Occurrence and distribution

In this section, the term 'spring' includes spring complexes and watercourse springs.

The occurrence and distribution of springs in the Surat CMA is primarily driven by regional and local geology, topography and groundwater flow regimes. There are three fundamental hydrogeological mechanisms by which springs occur (Figure 9-1) (OGIA 2016d, 2016e). These include (a) where *changes in formation permeability* result in flow laterally to the surface; (b) where a *geological structure* provides a path to the surface along which water can flow; and (c) where erosion of the landscape by surface water flows can provide opportunities for groundwater to reach the surface.

In the Surat CMA, the majority of springs are located along the northern and central outcrop areas of the Surat and Bowen basins (Figure 9-2 and Table 9-2).

9.3.2 Source aquifers for springs

Understanding the connection between a spring and underlying aquifers is necessary to assess the risk to the spring from groundwater impacts. The source aquifer to a spring depends upon the local hydrogeological setting and the mechanism through which groundwater flows to the surface (Figure 9-1). The source aquifer could be the same geological formation in which the spring occurs, or it could be a deeper formation from which groundwater flows along a fault to the spring.

The source aquifer for each spring complex was assessed as part of detailed conceptualisation work in 2015 (OGIA 2015). This assessment incorporated secondary information about the springs, local and regional scale geology, hydrogeology, hydrochemistry and monitoring data.

As summarised in Appendix I.1, the key aquifers which feed springs in the Surat CMA are the Clematis, Precipice, Hutton and Gubberamunda sandstones. An important outcome from the detailed assessments completed is that some springs are supported by local flow systems, in addition to the regional aquifer systems.

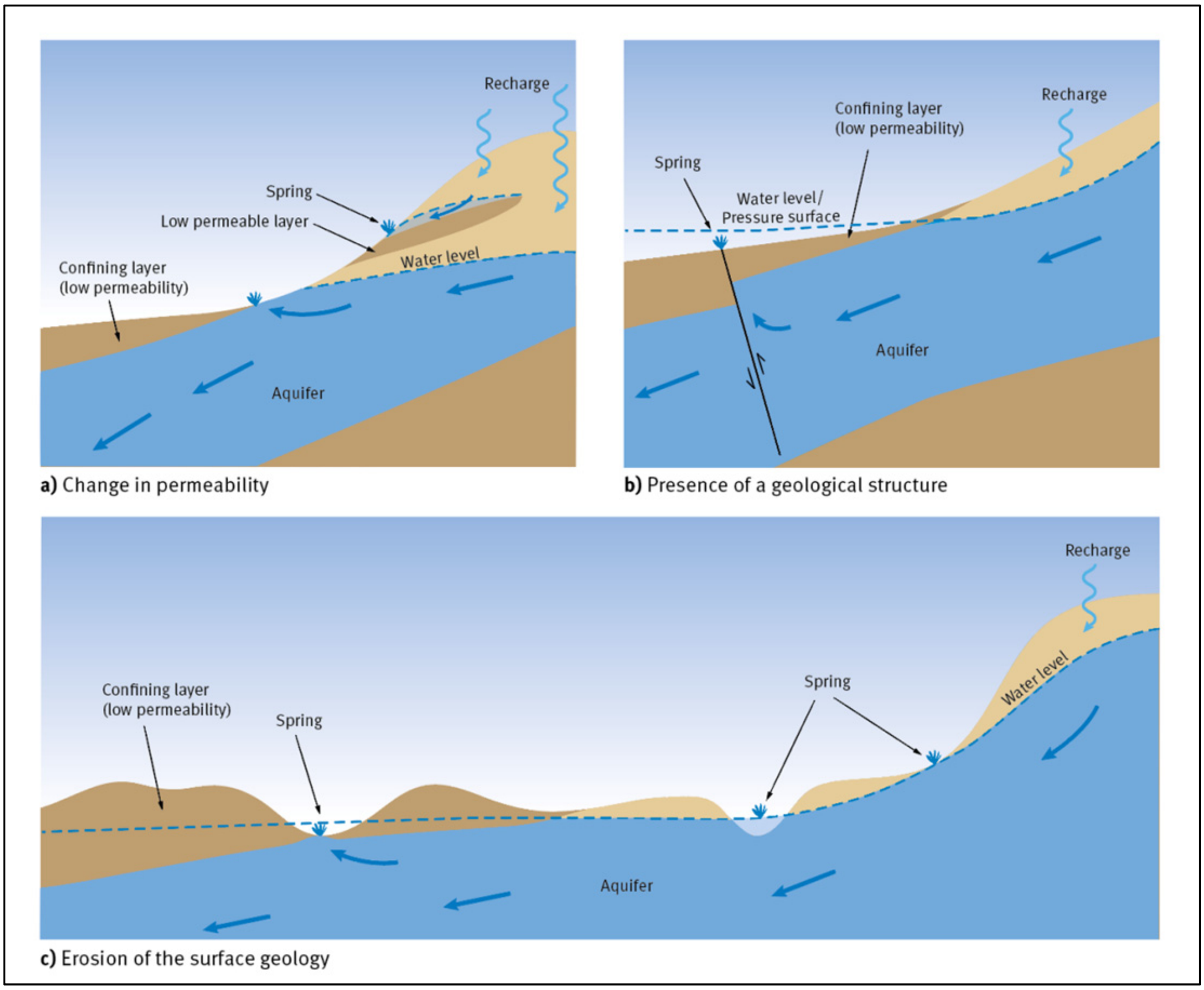

Figure 9-1 Hydrogeological mechanisms for groundwater discharge to the surface

In addition to spring complexes, the source aquifer for each watercourse stream is summarised in Appendix I.1. In contrast to spring complexes, there has been less research into watercourse springs. In 2017, OGIA completed a research project to identify potential watercourse springs (OGIA 2017a). The assessment included revision of a desktop methodology and field verification at priority locations. Where field verification has been completed, the confidence level in determining the watercourse springs is higher, as listed in Appendix I.2.

9.3.3 Spring wetland typology

Following the identification of a spring's source aquifer, OGIA has shifted towards classification of springs based on wetland features. This provides a better understand about the dependency of a wetland ecosystem on groundwater, and its likely response to change in the groundwater regime.

The term 'spring' relates to hydrogeological pathways by which groundwater discharges to the surface. The term 'wetland' relates to the resulting water body and associated ecosystems.

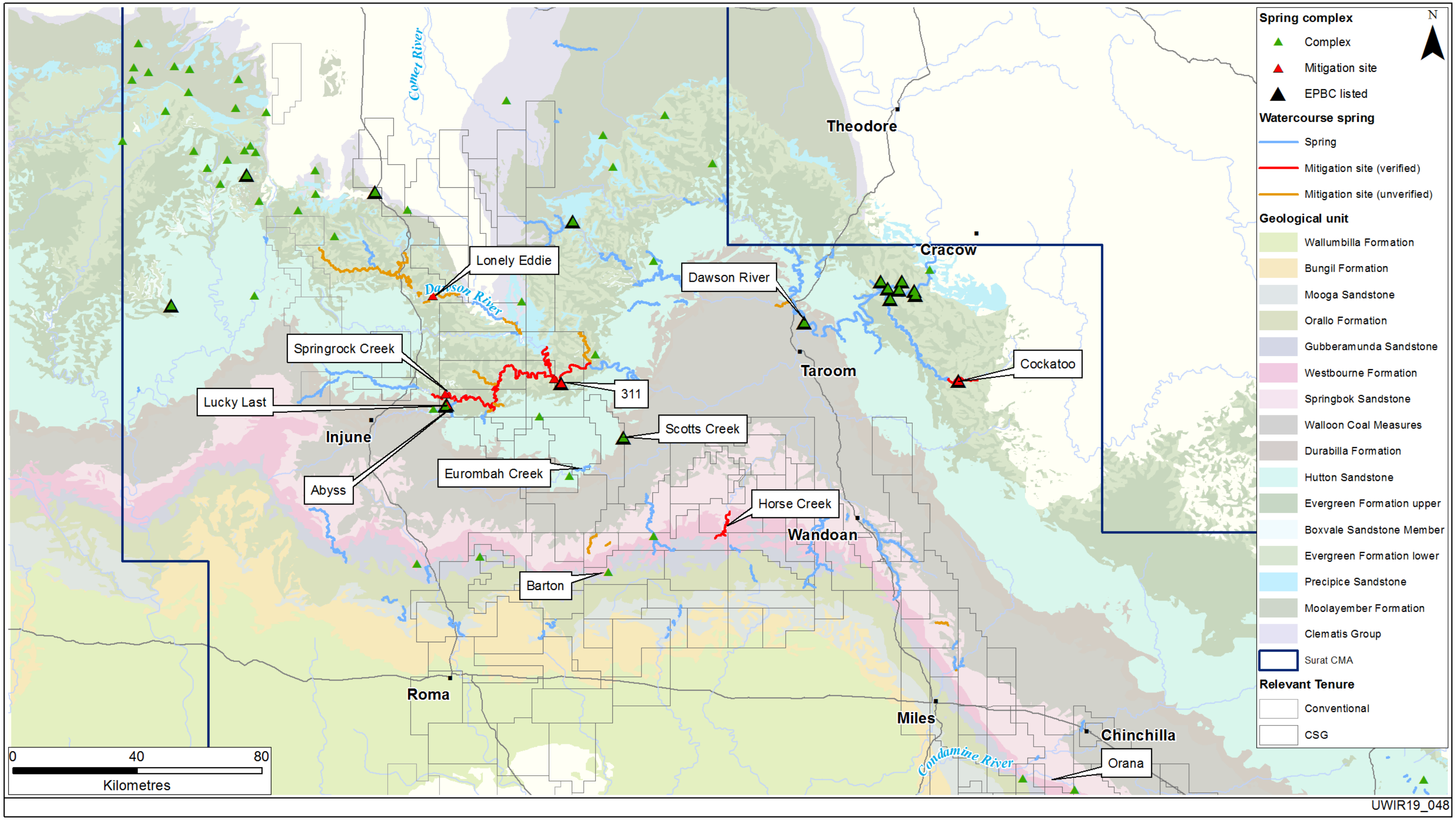

Figure 9-2 The location of springs in the Surat CMA

Using the new knowledge, a wetland typology was developed to support the assessment of risks and specification of monitoring under the UWIR (2016b, 2016c). The wetland types are based on how and where the wetlands occur within the landscape, as they will have a similar hydrogeological response to a change in the groundwater regime. The landscape setting and the main hydrological processes for each wetland type are shown in Figure 9-3. A summary of the wetland types for all springs in the Surat CMA is available in Appendix I.1. A full list of springs is available on OGIA's website. Additional information on the wetland types is provided in supporting technical reports (Appendix A).

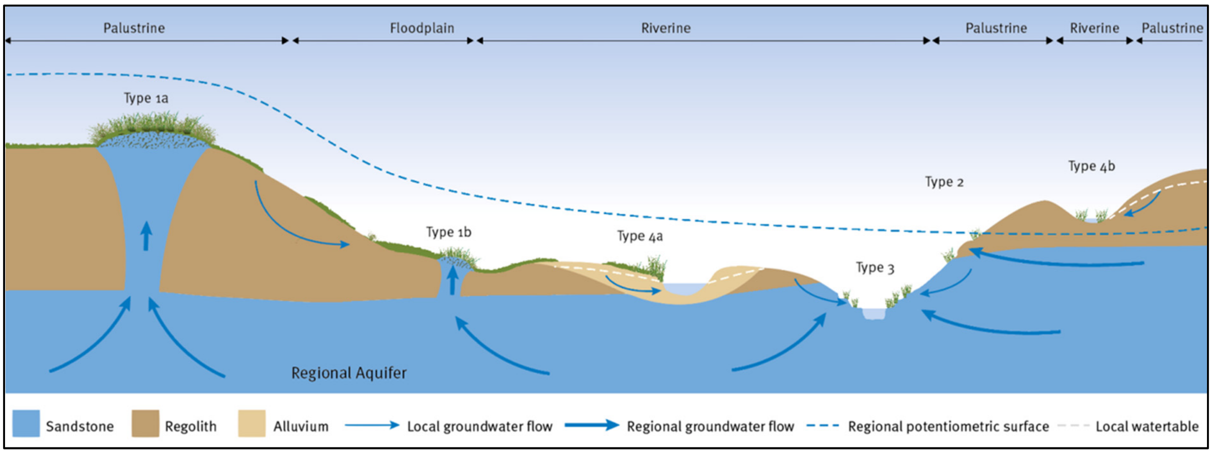

Figure 9-3 Wetland types in the Surat CMA

9.3.4 Ecological values of springs

A number of spring complexes support species and ecosystems recognised under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the Queensland *Nature Conservation Act 1992* (NC Act). Watercourse springs may also play an important role in maintaining stream ecosystem functions and processes, particularly during dry periods.

Information on the conservation significance of springs has been used in assessing the risks to springs (section 9.4.2). Table 9-2 shows the numbers of springs in the Surat CMA recognised for their conservation significance under the EPBC Act.

Table 9-2 Springs in the Surat CMA

Spring type	Total	Springs associated with an EPBC Act listing	Springs of interest*
Spring complexes (spring vents)	88 (389)	19 (138)	52 (212)
Watercourse springs (reaches)	98 (142)	-	78 (119)

Notes:
* Springs of interest are those that overlie an aquifer where the long-term predicted reduction in water pressure exceeds 0.2 metres (see section 9.4.1).

To sustain ecological assemblages and functions, springs and watercourses have an ecological water requirement. Essentially, this is the water regime necessary to sustain the values of water-dependent ecosystems at a low level of risk (Richardson et al. 2011). Springs and watercourses require discharge above ground level to sustain wetlands. Available pressure at each spring varies and depends on a range of factors including the source aquifer and the elevation of the spring within the landscape. In the Surat CMA, available pressure at springs varies from more than 20 to less than one metre above ground surface.

As mentioned in section 9.3.2, in addition to regional groundwater flow, the water requirements of some spring wetlands are also met from local inflows, such as groundwater in shallow alluvium, surface water flows, rainfall and overland flow. At some locations, springs expand and contract in response to the presence of these additional inflows and changes in evapotranspiration, resulting in distinct seasonality in wetland extent and floristic composition.

9.3.5 Conceptual response to a change in water level

Hydrological responses at springs and ecological impacts in wetlands are likely to be complex. The magnitude of predicted impacts and the availability and timing of additional inflows will influence the degree of response. Changes in groundwater level are likely to be a more significant influence on impact than changes in groundwater chemistry.

Depending upon the available pressure, the wetland type (Figure 9-3) and the magnitude of the predicted impact, there is potential for significant change in the spring wetland. A change in pressure is likely to result in a reduction in the volume of groundwater discharged to the surface. Depending on the degree of change, the extent of free water and the wetland area will contract. In response, the composition of the ecological community would be expected to transition from aquatic to more terrestrial-dominated assemblages. A change in pressure is likely to induce a shift to the terrestrial phase, and loss of the species associated with the wetland phase. Additional information on conceptual response to changes in groundwater level is provided in supporting technical reports (Appendix A).

9.3.6 Cultural values of springs

The Queensland Government has recently undertaken engagement with Aboriginal people in the Murray-Darling Basin to further understand cultural values and uses of water (Department of Natural Resources Mines and Energy 2019). The project incorporated both surface water and groundwater resources.

In terms of cultural values, the project highlighted the holistic and interconnected relationship between Aboriginal people and water – one connected system with spiritual, cultural, social, economic and environmental values. Water is vital for many aspects of Aboriginal life, such as fishing, hunting, swimming, storytelling, family gatherings, ceremonies and other sacred activities (Department of Natural Resources Mines and Energy 2019). Springs in many cases are permanent sources of water in semi-arid environments and are often associated with cultural values.

In addition to this recent project, a number of previous studies highlight the connection between cultural values and springs in the Surat CMA. Although studies vary in their purpose and spatial extent, values generally align with the following categories (CQCHM 2005):

- **Mythological association:** the linkage between a spring and its water, and mythological events and/or creator beings or other beings.
- **Ritual and ceremonial association:** the role that a spring and its water play in the conduct of ceremonies. This may also be linked to the mythological associations.

- **Economic and subsistence association:** the role that a spring, or group of springs, and the water available from them, play in the patterns of seasonal, economic and subsistence activities of particular Aboriginal groups.
- **Major or personal historical event:** events such as births, massacres, and long-term camping and habitation.

9.4 Predicted impacts on springs

9.4.1 Springs of interest

Under the Water Act, the UWIR is required to assess the potential for groundwater impacts on ***springs of interest*** – a spring overlying an aquifer where the long-term predicted reduction in water pressure exceeds 0.2 metres. Predictions from the regional groundwater flow model (Chapter 7) have been used to identify springs of interest (Figure 9-2 and Table 9-2). The location, source aquifer and discharge mechanism (section 9.3) are summarised in Appendix I.1. A full list of springs in the Surat CMA is available on OGIA's website.

In the UWIR 2016, springs of interest were referred to as 'potentially affected springs'. Compared to the UWIR 2016, the number of springs of interest has increased. This is primarily the result of more extensive predictions of impact in the Precipice Sandstone. There are eight spring groups where impacts of more than 0.2 metres are predicted in the springs' source aquifers. At the majority of these springs, predicted impacts are less than one metre.

9.4.2 Risk assessment

As for the UWIR 2016, an assessment of risk has been carried out for all springs of interest to ensure management strategies are commensurate with risk. The assessment identifies springs for which responsible tenure holders are required to develop and implement **mitigation actions** and the selection of locations where **monitoring** is required.

The risk assessment criteria relate to:

- the likelihood and timing of a drop in pressure in a source aquifer due to P&G water extraction
- the uncertainty associated with the predicted drop in pressure at the spring
- the consequence for the spring should the pressure drop.

The likelihood is assessed using the regional groundwater flow model. The consequence is evaluated using a combination of factors, including the estimated magnitude of pressure in the spring's source aquifer and the conservation significance of the spring.

The methodology is similar to the approach applied in previous UWIRs. A summary of the method and the updated risk assessment based on current data is provided in Appendix I.2. Table 9-3 provides a summary of current and previous risk assessments at springs where more than 0.2 metres of drawdown has been predicted in either 2012, 2016 or 2019. These locations are also shown in Figure 9-2.

Table 9-3 Summary of outcomes from risk assessments for springs

Spring group	Spring complex / watercourse spring	Source aquifer	Max impact *		Time until 0.2 m (years)	Overall risk score		
			Metres	Timing		2012	2016	2019
Springrock	Springrock Creek (561)	Precipice Sandstone	0.4–1.8	25–50	<5	5	5	5
	Hutton Creek (W216)					NA	NA	5
	Hutton Creek (W217)					NA	NA	5
Lonely Eddie	Lonely Eddie (339)		0.6–0.8	27–30	< 5	NA	3	4
311	Dawson River (W40)		0.4–0.7	25–27	<10	NA	3	4
	Hutton Creek (W81)					NA	3	5
	311 (311), Yebna 2 (591)					4	5	5
Cockatoo	Cockatoo Creek (W28)		0.3–0.5	29	8–12	NA	2	4
	Cockatoo (362)					NA	3	4
Lucky Last	Lucky Last (230)	Boxvale Sandstone	0.2–0.4	26	< 5	5	3	5
Barton	Barton (283)	Gubberamunda Sandstone	0.0–0.5	> 100	> 100	4	5	2
Horse Creek	Horse Creek (W215)	Alluvium, Springbok Sandstone	38–58	36–51	< 5	NA	NA	5
Orana	Or (765)	Cenozoic	0.2–0.5	> 100	> 100	NA	2	3
Scotts Creek	Scotts Creek (260)	Hutton Sandstone	< 0.2	-	-	5	5	3
Abyss	Abyss (592)					3	3	3
Eurombah	Eurombah Creek (W59)					NA	3	3
Dawson River	Dawson River 8 (8)					3	3	2

Notes:
* = The magnitude and timing of impact is for the impact of P&G activities only – the Water Act requirement. The impacts presented exclude the influence of reinjection on water levels, which will materially change the magnitude and timing of impacts presented in the Precipice Sandstone and the Boxvale Sandstone.
NA = Spring not previously identified as a 'spring of interest'.

9.5 Spring impact mitigation strategy

The UWIR is required to include a strategy to prevent, minimise or mitigate the impact of P&G water extraction on springs. This section provides an overview of locations where mitigation actions are required.

9.5.1 Mitigation groups

A mitigation group is a location where, on the basis of current knowledge, actions are likely to be required at some stage to avoid, mitigate or offset future impacts at the springs. The outcomes from the risk assessment, which incorporates predictions of impact in the spring's source aquifer, spring condition and ecological value, are used to determine locations for which a plan for mitigation actions is required.

Six groups of springs are identified for mitigation actions (Table 9-4 and Figure 9-2). Two spring groups predicted to be impacted by more than 0.2 metres – Orana and Barton – have been excluded from mitigation actions at this stage, based on the outcomes from the risk assessment. At these locations, impacts are small and predicted to occur more than 100 years into the future. This will be reviewed with the UWIR in three years' time.

As discussed in section 9.3.1, some watercourse springs have been identified on the basis of a desktop assessment. Only watercourse springs where field verification has been completed are included in the mitigation groups. However, it is acknowledged that there remains some uncertainty at Horse Creek and additional site-specific field assessments are currently being undertaken by the responsible tenure holder. Therefore, the requirement for a mitigation plan at this location will be reviewed following the outcomes of these investigations.

Where an unverified watercourse spring is identified as a high risk, field verification by tenure holders is necessary (see section 9.7). This should include a dry season longitudinal survey of the reaches to assess where groundwater is discharging to stream and to identify the source aquifer. The field methods must include surface water chemistry (recommended chemistry suites are provided in Appendix I, Table I-8), stream gauging, and the measurement of water levels and chemistry in nearby shallow water bores. These sites are shown in Figure 9-2 and listed in Appendix I.2, Table I-4. Where a watercourse spring is verified through these activities, OGIA will specify monitoring and mitigation actions where appropriate. The annual report will provide an update on the progress and outcomes from these activities.

Since the initial UWIR 2012, predictions of impact and the number of mitigation sites have varied. The changes reflect the evolution of knowledge about springs, such as in the spring's source aquifer, and changes in the industry development scenario, which directly influences the predictions of impact. Impacts identified in previous UWIRs indicated that impacts were unlikely to manifest for some time in the future and that there were uncertainties in springs' source aquifers. As a result, the initial action has been further investigations to establish source aquifers, monitoring and understanding of flow mechanisms. An example is the Lucky Last Spring group, where investigations have revealed that the source aquifer of the spring is likely to be the Boxvale Sandstone rather than the Hutton Sandstone as previously assessed.

Table 9-4 Spring impact mitigation groups

Group	Complex / Watercourse	Overall risk	Actions	Residual risk	RTH
Springrock	Springrock Creek (561)	5	*Ongoing*: Baseline survey, monitoring and local scale conceptualisation completed by the RTH. Nearby monitoring bores have been commissioned in the source aquifer. At this stage, no mitigation actions have been implemented.	High	Santos
	Hutton Creek (W216)	5			
	Hutton Creek (W217)	5			
311	Dawson River (W40)	4	*Ongoing*: Baseline survey, monitoring and local scale conceptualisation completed by the RTH. Monitoring bores have been commissioned in the source aquifer. At this stage, no mitigation actions have been implemented. Pressure responses from reinjection activities are predicted to delay impacts at this location.	Medium	
	Hutton Creek (W81)	5			
	311 (311), Yebna 2 (591)	5			
Lonely Eddie	Lonely Eddie (339)	4	Site not previously identified. Actions to be specified by RTH in the SIMS mitigation plan.	High	
Lucky Last	Lucky Last (230)	5	Site not identified in the UWIR 2016. Actions to be specified by the RTH in the SIMS mitigation plan. No mitigation actions currently implemented. Pressure responses from reinjection activities are predicted to delay impacts at this location.	Medium	
Horse Creek	Horse Creek (W215)	5	Site not previously identified. At this location, there is some uncertainty to the degree of connectivity between groundwater and surface water. The RTH is currently undertaking investigations. The need for ongoing monitoring or a mitigation plan will be reviewed following the outcomes of the RTH investigations.	Moderate	QGC
Cockatoo	Cockatoo Creek (W28)	4	Site not previously identified. Pressure responses from reinjection activities will delay predicted impacts at this location. *Actions and the assignment of a RTH will be determined following initial assessments to be conducted by OGIA at this location.	Medium	*
	Cockatoo (362)	4			

Compared to the UWIR 2016, at one location – Scotts Creek (Hutton Sandstone) – predictions of impact are now less than 0.2 metres and mitigation actions are no longer required. In contrast, there are now two additional mitigation groups – Lonely Eddie and Cockatoo Creek (Precipice Sandstone).

Predictions of impacts on some spring locations have changed due to the revised calibration of the regional groundwater flow model (section 6.5). In particular, there has been significant increase in calibrated permeability value from reinjection data in the Precipice Sandstone, which is the source aquifer for many springs. The high permeability results in reduction in the magnitude of groundwater level impacts in areas close to production, but much more lateral propagation of impacts.

At the Cockatoo Creek spring group site the predicted impact for the first time is greater than 0.2 m in the source aquifer (Precipice Sandstone) despite the site being much further away from the production area. At this location, predicted impacts are small and potentially influenced by aquifer properties in the southern part of the CMA and also the impacts are not predicted to occur for another 25 years or so. Therefore, OGIA intend to undertake further assessments to improve understanding of impact propagation at this spring site before assigning a responsible tenure holder.

In the short term, for springs fed by the Precipice Sandstone (Table 9-3), because of the lateral extent of the observed reinjection pressure responses (see section 5.4.4), predicted impacts in this unit are expected to be significantly delayed. This should be considered as part of any mitigation plan.

9.5.2 Mitigation actions

In accordance with the mitigation actions in the UWIR 2012 and 2016, detailed investigations have been undertaken at several previously identified mitigation groups – Barton, Scotts Creek, Springrock Creek and 311 (Table 9-4). Barton and Scotts Creek are no longer predicted to be impacted. Thus far, at Springrock Creek and 311, Santos has established that it is not technically possible to balance out impacts by relocating existing water bores that currently impact the source aquifer pressures at these locations. Options for mitigation are not yet identified for these locations.

Where mitigation actions are not yet in place, a **mitigation plan** is required that details the actions to prevent, minimise, mitigate or offset the predicted impacts at the locations identified in Table 9-4. Considering the evolution of knowledge and gradually increasingly confidence about spring source aquifer, a firmer plan of action is expected from tenure holder for mitigating actions where appropriate.

The mitigation plan must be submitted to DES for approval within six months of the finalisation of the UWIR 2019. The plan must be updated within six months of the approval of subsequent UWIRs.

At one location - Cockatoo Creek – reinjection by Origin Energy into the Precipice Sandstone is currently predicted to reduce impacts to less than the 0.2 metre trigger threshold. As the operation of the reinjection facility may change through time, the responsible tenure holder must consider alternative mitigation actions as part of a mitigation plan.

During the UWIR cycle, additional mitigation groups may be identified as knowledge about the local hydrological setting of springs is improved or through confirmation of the existence of watercourse springs at locations where long-term pressure impacts are predicted.

9.6 Spring monitoring program

Spring monitoring is necessary to understand the natural variability in spring discharge. Chapter 8 specifies monitoring of groundwater pressure to assess changes in groundwater levels in the aquifers which feed springs. Collectively, monitoring at springs and in the spring's source aquifer ensures any future impacts from P&G water extraction are correctly identified.

9.6.1 Monitoring locations

Nine spring complexes and six watercourse springs are identified for ongoing monitoring (Appendix I.3, Table I-5 and Table I-6). Springs vary considerably in terms of their ecological values, physical condition and suitability for monitoring. Site suitability in conjunction with the outcomes from the risk assessment have been used to guide site selection.

Additional watercourse springs may be included following field validation. Appendix I.3 specifies monitoring methods for each location, monitoring attributes and the responsible tenure holders.

As described in Chapter 8, the WMS specifies pressure monitoring at locations near some springs. For some spring locations, there are new groundwater pressure monitoring requirements prescribed to understand available groundwater pressure above ground. Data from those pressure monitoring sites will be used in conjunction with spring monitoring data for future assessments.

9.6.2 Monitoring methods

In 2017, a pilot spring monitoring project was undertaken by OGIA to evaluate new approaches to monitoring springs at four spring complexes. The project applied multidisciplinary monitoring methods incorporating expertise and tools from hydrogeology, botany, ecology, ground geophysics and remote sensing. Additional information is available in the supporting technical report (Appendix A).

Overall, the existing approach of measurement of the aquatic wetland extent and discharge extent was found to be most appropriate for assessing spring dynamics in the short and long term. In terms of tools, remote sensing was unable to delineate the aquatic wetland extent or the discharge extent but was able to assess change in the condition of vegetation within a predefined boundary.

Groundwater pressure, field observations and climate data continue to be critical contextual information for interpretation of any monitoring data collected in the field. However, water chemistry was less effective in assessing change, as it was significantly influenced by sampling location from the wetland, which resulted in reduced repeatability.

These outcomes have informed the specification of the monitoring obligations under the SIMS.

9.6.3 Monitoring attributes and parameters

9.6.3.1 Spring discharge

At the majority of springs in the Surat CMA, the volume of flow of groundwater to the springs is relatively small. At many springs, discharge can be almost completely consumed by evaporation and by transpiration by plants, leaving no flow away from the springs. For these drier springs, conventional monitoring methods may not be capable of assessing change in the volume of discharge. As a result, a range of approaches to monitoring is required, as detailed below.

At springs where flow is concentrated into a single channel (type 3, section 9.3.3), flow is to be measured by a standard technique. At springs where no flow is visible, wetland attributes are to be monitored as indicators of change in the spring water balance. The area of aquatic wetland vegetation is the area of permanent saturation sufficient for colonisation by wetland species. Beyond that boundary, there is often a seasonally moist zone of increased discharge from the spring in response to seasonal rainfall, evaporation and transpiration by the vegetation.

For these locations, the boundary of the aquatic vegetation extent and the extent of the seasonally moist zone are to be monitored. A list of terrestrial and aquatic species is provided in Appendix I.3 to assist in delineating the boundaries.

Monitoring will be undertaken using two approaches:

- Responsible tenure holders will use a differential global positioning system to measure wetland and discharge extents in April and November at the specified monitoring locations.
- In parallel, OGIA will undertake remote sensing analysis at key locations to assess change in vegetation condition within the aquatic vegetation extent. This will provide an additional line of evidence for the condition and trend of the spring wetland.

Measuring these attributes provides a basis for estimating groundwater flux and related changes observed in the wetland, along with other monitored attributes such as groundwater pressure, physical condition, climate, rainfall and evapotranspiration.

Appendix I.3 specifies the monitoring methods required at each monitoring site.

If monitoring identifies significant changes in condition from historical observations, OGIA may request tenure holders to undertake additional monitoring activities such as vegetation transects, ground geophysics or other activities considered appropriate.

9.6.3.2 Water chemistry

During the previous UWIR cycles and during the monitoring pilot, water chemistry was found to be less effective as it was significantly influenced by sampling location from the wetland, which varies depending on the discharge environment. This results in reduced repeatability of this tool to detect a change in the groundwater regime.

9.6.3.3 Field observations

Field observations about groundwater discharge and a spring's physical condition provide important contextual information about changes in the groundwater regime which may not be apparent from other monitoring data. For example, the extent of salt scalding and iron staining around the periphery of a spring indicates recent changes in the groundwater regime.

Also, springs can be influenced by a range of non-groundwater-related stressors such as animal disturbance. Depending on the extent of disturbance, these factors may alter the accuracy of the monitoring data on the wetland vegetation boundary, the moist zone and the water chemistry.

A guide to observing the physical condition of springs is specified in Appendix I.3, Table I-7.

9.6.4 Outcomes from previous monitoring

At the majority of higher risk locations, more than 10 monitoring rounds have now been completed since monitoring commenced in 2013. This provides an important baseline dataset and provides useful insights into spring dynamics and functioning as highlighted in previous reports (OGIA 2016e; Lyons et al. 2015) and has been enhanced through the monitoring pilot (OGIA 2019d).

Overall, monitoring indicates that spring form and discharge are significantly influenced by climate and land use activities within the immediate vicinity of the springs. Seasonal variation in discharge and wetland area has been observed through the mapping of the extent of wetland vegetation and discharge. Seasonal changes in evapotranspiration and local groundwater inflows at some locations are plausible underlying causes of observed short-term variation.

Long-term variation was identified through the analyses of historical imagery and the initial industry baseline survey in 2014. A range of landscape features that indicated wetting or drying phases of the wetland area were noted, such as dead trees, salt-scalded soil, collapsed spring vents, and spring vents that have stopped flowing. These highlight longer-term changes at many locations.

9.7 Tenure holder obligations

This section summarises the responsible tenure holder obligations in relation to SIMS.

A **SIMS monitoring report** must be submitted to OGIA by 1 April and 1 October each year. This must include all monitoring sites identified in Appendix I.3. OGIA will use this information for ongoing assessment, and to provide a summary to DES through the annual review process.

The report must include:

- current status of spring monitoring activities
- spring monitoring data collected by the responsible tenure holder
- key conclusions from the monitoring data and any emerging implementation issues.

A **watercourse spring investigation report** is also required to be submitted to OGIA within 12 months of the approval of the UWIR for sites identified in Appendix I.2. The investigation must include the chemistry suite specified in Appendix I.3.

The report must include:

- details of the desktop investigations of the identified watercourse spring
- details of any field investigations of the identified watercourse spring
- findings on the groundwater-surface water connectivity of the identified reach
- identification of an ongoing monitoring program where the reach is identified as connected.

For each mitigation site identified in Appendix I.2, a **SIMS mitigation plan** is required. A plan must be submitted to DES for approval within six months of the approval of the UWIR.

The plan must include:

- a summary of the hydrogeological conceptualisation for the mitigation site
- an evaluation of the options for prevention, minimisation, mitigation or offset of the predicted impacts, with specification of the preferred mitigation option
- a plan, including ongoing monitoring, mitigation actions, triggers and timeframes, for the implementation of activities.

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Chapter 10 Other environmental values

A change to the Water Act in late 2016 extended the scope of the UWIR to include a description of impacts on environmental values (EVs) or assets arising from the exercise of underground water rights. EVs are defined in the *Environmental Protection Act 1994* (EP Act). The intent of the change is to provide consistency between the Water Act and the EP Act and ensure that there is ongoing review of EAs in response to potential impacts on EVs which may occur during the operational phase of resource projects.

Unlike springs and connected watercourses, which are addressed in the SIMS (Chapter 9), the assessment of additional EVs (such as the terrestrial GDEs) is limited to the characterisation of those values and an assessment of risk and does not include the development of strategies for managing those impacts.

10.1 Environmental values

The EP Act defines an EV as a quality or physical characteristic of the environment that is conducive to ecological health, public amenity or safety, or another quality of the environment identified or declared to be an environmental value under an environmental protection policy or regulation.

In the context of the UWIR, the relevant policy is the Environmental Protection (Water) Policy 2009 (Water EPP). The Water EPP identifies specific EVs that are to be protected with corresponding water quality objectives (WQOs). Under the Water EPP, all Queensland waters, including groundwater, have identified EVs and WQOs.

In relation to groundwater, EVs in the Surat CMA include:

- **aquatic ecosystem:** groundwater aquifers, GDEs such as groundwater inflows to rivers (baseflow) and springs, and terrestrial GDEs
- **human use:** consumption or use of groundwater for a range of purposes including aquaculture, recreation (e.g. waterholes), industrial, cultural and spiritual values.

The characterisation and assessment of the majority of these environmental assets – aquifers, springs and water supply bores – was within the scope of previous UWIRs. The additional EVs related to terrestrial GDEs and groundwater quality are included for the first time.

Within the Surat CMA, groundwater in aquifers supports a range of EVs. There are four primary groundwater systems in the Surat CMA: the GAB, Bowen Basin, Basalts and Alluvium. These are described in Chapter 3 with an assessment of predicted impacts presented in Chapter 7.

Human-use EVs primarily relate to groundwater use through water supply bores as described in Chapter 4. An assessment of the predicted impacts on water supply bores is presented in Chapter 7. Where waterholes are fed by groundwater, they are assessed as part of the SIMS in Chapter 9.

GDEs require access to groundwater permanently or intermittently to maintain ecological assemblages, processes and ecosystem services (Eamus et al. 2006). Three types of GDEs are broadly recognised:

- **ecosystems dependent on the surface expression of groundwater:** associated with wetlands, lakes, seeps, springs and river baseflow
- **ecosystems dependent on the sub-surface presence of groundwater:** associated with terrestrial vegetation accessing the water table below ground

- **cave and aquifer ecosystems:** located within the pore or void spaces of caves and aquifers.

Description, characterisation and assessment of impacts on springs are provided in the SIMS (Chapter 9). The following sections provide an overview of the knowledge and an assessment of the risk to terrestrial GDEs within the Surat CMA.

10.2 Groundwater-dependent vegetation

Terrestrial GDEs occur where vegetation requires access to groundwater either intermittently or permanently to maintain ecological composition and function. In contrast to springs, which are usually relatively localised features, terrestrial GDEs may be extensive and may intergrade with non-GDE vegetation communities, depending on variations in surface geology, landform and soil. A vegetation community may access groundwater in one location, or many locations. This makes understanding dependency and impact more difficult.

In the Surat CMA, areas of likely groundwater-dependent vegetation have been mapped by the Queensland Herbarium. This results in polygons or areas of vegetation that may access groundwater. Each of the mapped areas is attributed with regional ecosystem (RE) information. REs are groupings of vegetation communities that are associated with a particular combination of geology, landform and soil type. Each individual RE has a biodiversity status, highlighting its importance in relation to remaining extent and condition.

By their relatively extensive nature and varying degrees of groundwater dependency, terrestrial GDEs can be difficult to identify. The Queensland GDE mapping attributes each identified terrestrial GDE with a level of confidence, which reflects whether the dependency was determined based on field data or expert opinion. Field-verified areas are attributed higher confidence.

For the purpose of the UWIR 2019, OGIA has completed a desktop assessment (OGIA 2019e) to: integrate existing mapping of potential terrestrial GDEs with areas of predicted drawdown in the regional groundwater model (Chapter 7); develop conceptual understanding of groundwater dependency and response to drawdown; and identify areas for improvement of knowledge. In most cases, additional field verification will be required to confirm groundwater dependence.

10.2.1 Ecological water requirements

Terrestrial GDEs occur in areas where aquifers outcrop at the surface and where the water table is shallow enough for vegetation to access it. Groundwater use by flora can vary spatially and temporally, within and between species. The water requirements of terrestrial vegetation may also be met by infiltrating rainwater, flooding from watercourses and overland flows.

Water levels in unconfined aquifers fluctuate at a variety of time scales, including daily, and in response to rainfall events. The ability of vegetation to switch water sources is a key adaptation in areas of highly variable rainfall and soil moisture conditions. As a result, vegetation may only use groundwater for short periods or opportunistically during dry periods. The ecological water requirement of terrestrial vegetation may not only be volumetric, but importantly may have a timing component. Access to groundwater during dry periods may have a crucial role in the maintenance of aspects of plant life cycles, such as sapling establishment and growth.

The ability to access groundwater is conferred by the root architecture and rooting depth. Processes affecting root architecture are complex and depend on a range of site-specific variables. A widely adopted rule of thumb is that vegetation use of groundwater is likely where the depth-to-water is less than 10 metres below ground level (mbgl), possible at 10 to 20 mbgl, and unlikely at 20 mbgl (Eamus et al. 2006).

10.2.2 Response to a change in the groundwater regime

In the short term, decreased availability of groundwater is more likely to be evident in changes in the productivity of vegetation. Drawdown is associated in the short term with reduced leaf production and in the longer term with an absence of saplings, loss of biodiversity and changes in community structure and composition.

Where terrestrial GDEs are confirmed through field investigation, impacts are conceptualised into three categories of response: productivity and growth; biodiversity; and reproduction and recruitment (Figure 10-1). Where predicted impacts are minor and the rate of change in the groundwater level is slow, some vegetation communities may have the ability to adapt to the new water level.

Within the outcropping aquifers, terrestrial GDEs may be sustained by infiltrating rainfall when groundwater levels are impacted. Given the seasonality of the rainfall, however, this may only provide a short-term buffer and may not compensate for a reduction in water level during dry periods. Further research into responses is required to clarify the resilience of these terrestrial GDEs.

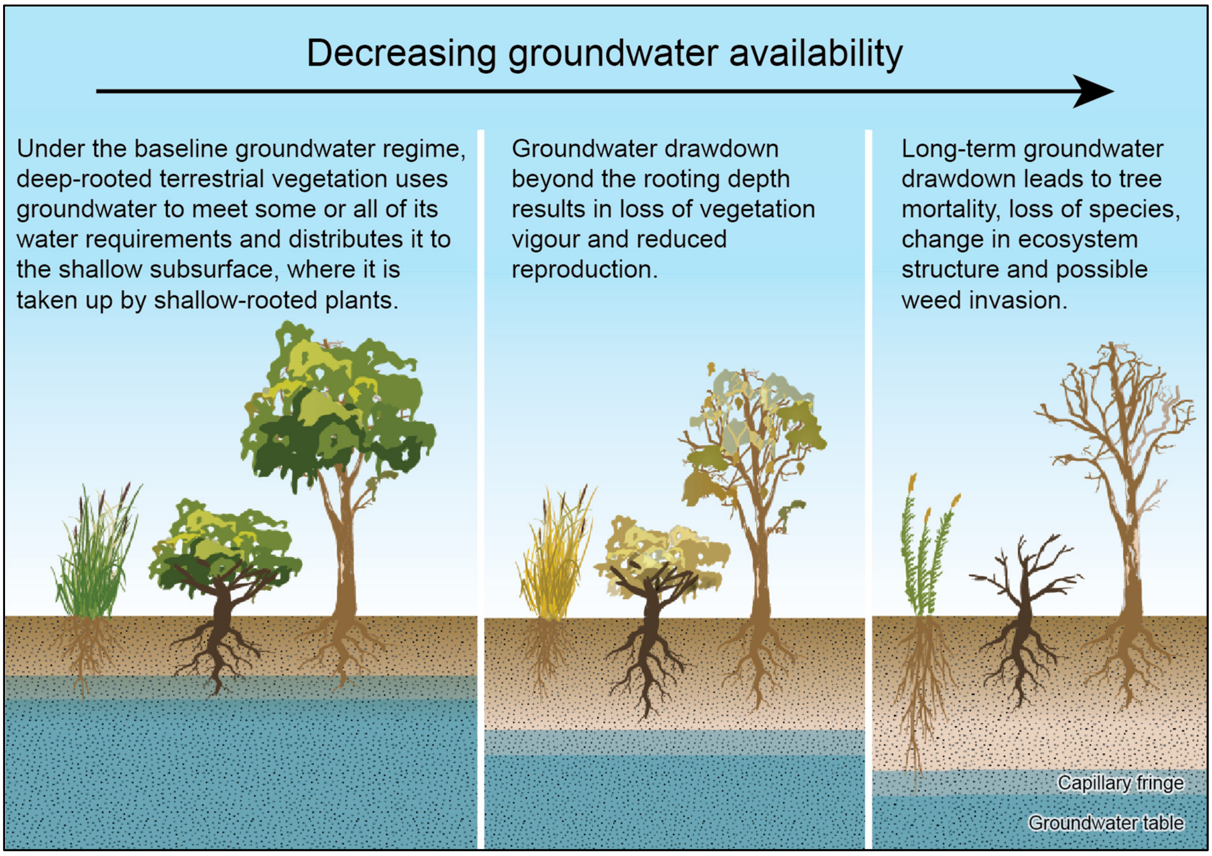

Figure 10-1 Conceptual model of terrestrial GDE response to a reduction in water level, after Eamus et al. (2006) and Rohde et al. (2017)

10.2.3 Assessment of potential impacts

For the UWIR 2019, an assessment of the risk to terrestrial GDEs from predicted impacts is undertaken. Consistent with OGIA (2019d), the approach integrates outcomes from the regional groundwater flow model, the geological model and mapped potential terrestrial GDEs.

A conservative area of interest is generated using the long-term predicted drawdown of 0.2 metres (Figure 10-2). Since GDEs occur in outcrop areas, the areas of mapped potential GDEs are identified where impacts are predicted within the outcropping aquifers.

Areas where an impact of more than 0.2 m but less than one metre is predicted are identified as low risk. Areas where an impact of more than one metre is predicted are assigned a moderate risk. Areas of potential terrestrial GDEs associated with REs with an 'Endangered' or 'Of concern' biodiversity status are assigned a high risk.

The risk mapping identifies areas of drawdown associated with potential terrestrial GDEs. It should not be used to infer likely ecological responses to predicted impact. The risk mapping should be used, in combination with the RE biodiversity status, to prioritise further investigation of potential GDEs to verify groundwater use and to inform future monitoring locations to test hypotheses about ecological responses.

As shown in Figure 10-2, areas of high risk are primarily associated with the outcrop of the Walloon Coal Measures south-east of Wandoan.

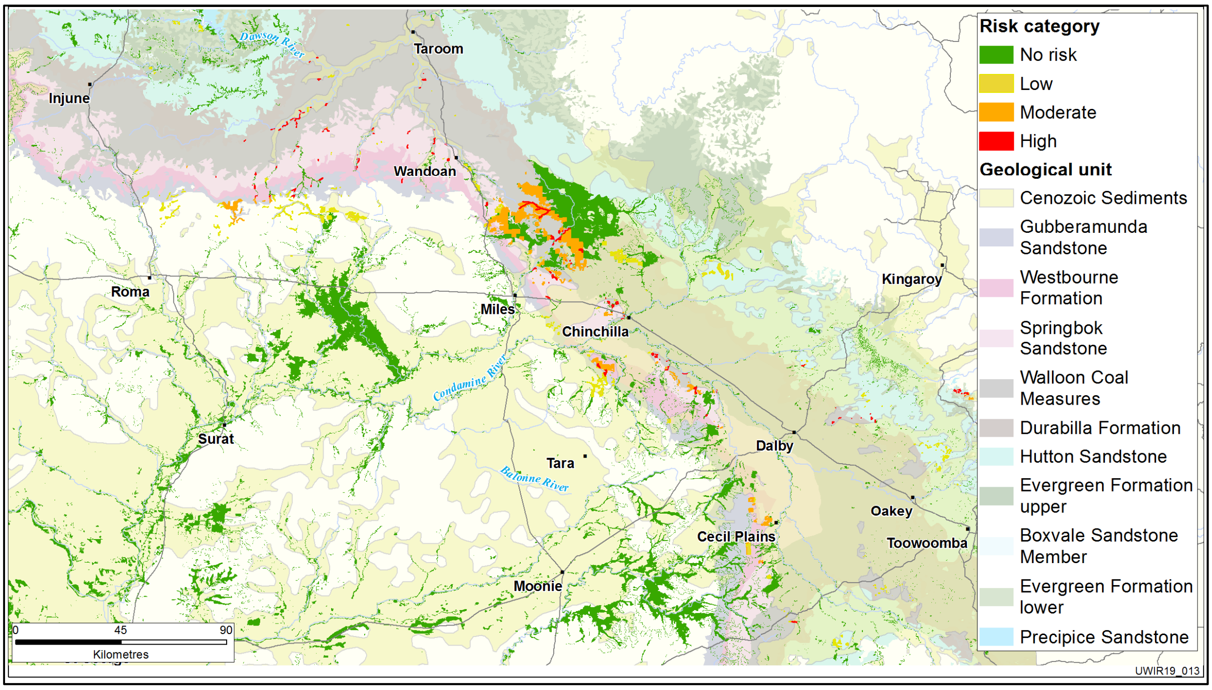

Figure 10-2 Mapped potential terrestrial GDEs and areas at risk of predicted impacts in the Surat CMA

10.3 Surface subsidence

Depressurisation associated with CSG water extraction may result in reservoir compaction. This has the potential to cause subsidence at the land surface. Depending on the amount of subsidence, this may have implications for human-use EVs (e.g. agricultural land and water bores) and aquatic ecosystem EVs, such as watercourse springs and terrestrial GDEs.

The potential for subsidence to occur is influenced by two primary factors: the magnitude of change in groundwater level; and the thickness and type of formations overlying the reservoir. Where consolidated sandstone formations are located above the reservoir, these are likely to attenuate impacts, as the strength of these consolidated formations is likely to result in a 'bridging effect' and reduce the degree to which compaction at depth in the coal measures manifests as subsidence at the ground surface.

The Australian Government commissioned reports on subsidence related to coal mining (Commonwealth of Australia 2014a) and the CSG industry (Commonwealth of Australia 2014b). It reported that that the maximum estimates of subsidence in the Surat Basin, related to CSG development, are likely to be less than 0.5 metres (Commonwealth of Australia 2014b).

For the UWIR 2019, an assessment of the risk of subsidence to EVs has been undertaken. The approach incorporates an assessment of the likelihood of subsidence occurring and a description of the EVs located within those areas.

The likelihood of subsidence occurring was assessed using two risk factors: an estimate of compaction within the Walloon Coal Measures, using the predictions of water level change; and the presence or absence of overlying consolidated sandstone formations to attenuate any potential impacts to the surface (Chapter 7).

Three risk classes are assigned: areas of low risk, where compaction is predicted to be less than 0.1 metres; moderate risk between 0.1 to 0.2 metres, and high risk for greater than 0.2 metres of compaction. In areas where there are consolidated formations overlying the reservoirs, the assigned level of risk is reduced to a lower level.

Figure 10-3 identifies EVs where a moderate to high risk is identified. With the exception of Woleebee Creek near Wandoan, all remaining EVs are subject to moderate risk of subsidence. This includes an area of irrigated cropping land, near the Condamine Alluvium and between Chinchilla and Miles, and potentially gaining streams in this area including Bottle Tree Creek, the Condamine River, Horse Creek (East Branch), Kangaroo Creek, L Tree Creek, Punch Bowl Creek, Wilkie Creek and Yuleba Creek.

At this stage, there is insufficient data and understanding to assess the resilience or susceptibility of these features to subsidence, i.e. to assess the consequence of the predicted subsidence impacts. Future monitoring and evaluation of subsidence and EVs will provide data to inform this understanding.

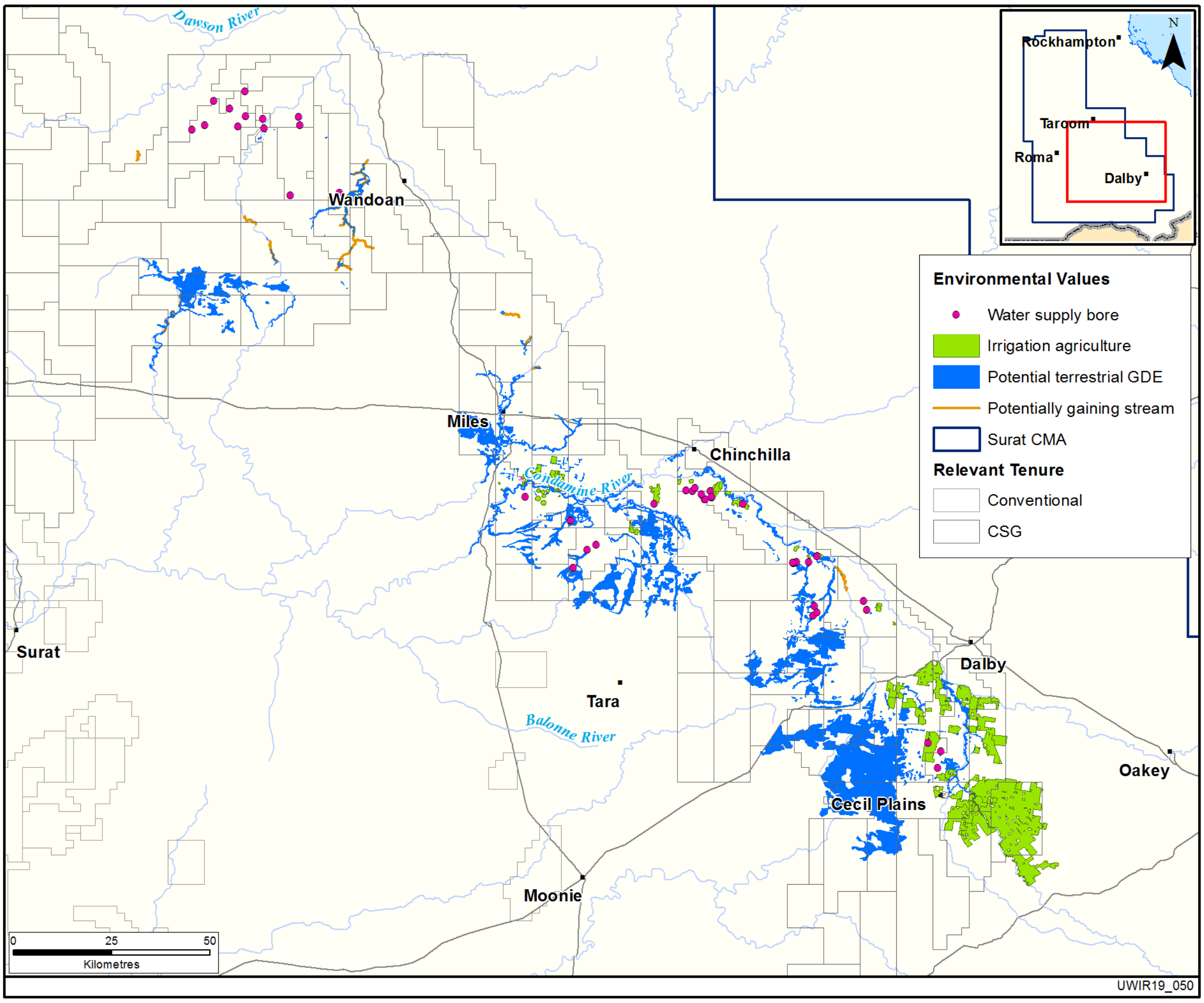

Figure 10-3 Environmental values at moderate to high risk from subsidence

Chapter 11 Responsible tenure holder obligations

11.1 Meaning of responsible tenure holder

As outlined in section 1.1, under Queensland's regulatory framework, petroleum tenure holders have the right to take associated groundwater in the process of producing petroleum and gas. A number of obligations are associated with this right, comprising 'make good' obligations and reporting obligations, in particular:

- baseline assessment of water bores to obtain information about bore construction, water levels and water quality prior to commencement of production
- 'make good' of water bores that are impaired or likely to be impaired, including an assessment of water bores to establish impairment
- monitoring obligations as per the WMS outlined in the UWIR
- implementation of the SIMS outlined in the UWIR
- any other obligations that are identified in the UWIR.

'Make good' applies to all IAA bores as well as other bores where DES directs tenure holders to undertake bore assessment. Similarly, baseline assessment applies to all water bores within the tenure as well as other LAA bores to which the baseline assessment program – outlined in the UWIR – applies (section 8.7).

In a CMA, where a number of petroleum tenure holders operate, there may be overlapping impacts on water pressure in an aquifer from the separate operations. In such areas, supply from a water bore may be impaired because of the cumulative impacts from water extraction by multiple tenure holders. Therefore, within a CMA, individual petroleum tenure holders are identified as the tenure holders responsible for specific activities. These arrangements ensure that in areas where integrated approaches are needed to manage cumulative impacts, there is clear legal responsibility for actions.

This chapter assigns responsibilities for specific obligations in the Surat CMA to individual petroleum tenure holders.

11.2 Underground water obligations for responsible tenure holders

11.2.1 'Make good' obligations

Obligations are specified in section 409 of the Water Act that ensure that a bore owner is not disadvantaged by resource operations, and that proactive measures are put in place if there is a likelihood that a bore's capacity to supply water for its intended purpose may be impaired from resource activities. These obligations are referred to as ***make good obligations***. A guideline (Department of Environment and Science 2012) provides further clarity on make good obligations.

Make good obligations require a bore assessment under section 411 of the Water Act to establish whether a bore has, or is likely to have, impaired capacity due to a decline in water level from the exercise of the resource activity and whether, because of the decline, the bore can no longer provide a reasonable quantity and quality of water for its authorised purpose. If the outcome suggests that the bore is or likely to be impaired, then a make good agreement with the bore owner is required to ensure that the bore owner either continues to have access to a water supply or is appropriately compensated.

There are effectively two pathways for bore assessment, which may lead to make good:

1. Water bores within the IAA for a formation require bore assessment because there is significant risk that the supply of water from the bore tapping the formation will be impaired within three years.
2. DES may also issue the petroleum tenure holder a direction notice, for example, because a bore supply may be affected by reductions in water pressure that are smaller than the trigger threshold, or because local conditions could cause water pressure impacts to be greater than predicted in the UWIR.

Water bores within the IAA that are expected to experience pressure reductions of more than the trigger threshold within three years are listed in Appendix G.

11.2.2 Reporting obligations

The Water Act requires that a responsible tenure holder must comply with reporting obligations as specified in an approved UWIR. For a CMA, there are two types of reporting obligations:

- Water monitoring obligations: these involve constructing monitoring installations, carrying out baseline assessments and reporting data on an ongoing basis. The activities are specified as part of the WMS in Chapter 8.
- Spring impact management obligations: these involve implementing a program for monitoring springs and a mitigation plan where impacts of water extraction on springs are considered high risk. The activities are set out as part of the SIMS in Chapter 9.

11.3 Assigning underground water obligations

The locations of current and planned petroleum and gas production tenures are shown in Figure 2-6 as relevant tenures. These include petroleum leases that have been applied for or granted. Since the ownership of tenures can change over time, in assigning the responsible tenure holder, a reference to an **authorised holder** is the authorised tenure holder at a given point in time. This implies that if there is a change of tenure ownership, obligations of the responsible tenure holder will fall to the new owner.

Details about the current authorised holders as of February 2019 for the tenures identified in Figure 2-6 are listed on the OGIA website.

11.3.1 Assignment rules for 'make good' obligations

In the UWIR 2016, the rules for make good obligations were referenced to production tenures. A tenure was identified as a production tenure if production wells existed or were proposed in that tenure. Since the planned production changes over time, the status of the production tenure may also change without a change in tenure ownership or its authorised purpose. Therefore, to add further certainty, the rules are now referenced to relevant tenures (refer to section 2.3) which includes PLs both approved and under application.

The following rule assigns responsibility for make good obligations for the IAA bores.

> <u>Rule 1:</u> The authorised tenure holder over land identified as a relevant tenure in Figure 2-6 is the responsible tenure holder for make good obligations in relation to a bore on the land.

Because water pressure impacts can extend outside a tenure boundary, there may be IAA bores outside the lands covered by Rule 1. The following rule assigns responsibility for make good obligations in relation to those bores.

> Rule 2: For a bore to which Rule 1 does not apply, the authorised tenure holder over land identified as a relevant tenure in Figure 2-6 that is closest to the bore is the responsible tenure holder for make good obligations in relation to the bore.

Under these rules, the responsible tenure holder may change if the ownership of a tenure changes. The responsible tenure holder for a bore can be identified at any time by referring to the DNRME tenure database.

11.3.2 Assignment rules for reporting obligations

The individual activities identified within the WMS and SIMS, specified in Chapter 8 and Chapter 9 respectively, are reporting obligations. The following rules assign responsibility for these activities.

11.3.2.1 Baseline assessment

A baseline assessment is an assessment of a water bore by a petroleum tenure holder to obtain information about bore construction, water levels and water quality. As detailed in Chapter 8, under the Water Act, tenure holders are required to carry out baseline assessment of water bores on tenures before production or production testing begins on the tenures, and also in accordance with a program outlined in a UWIR for the baseline assessment of the LAAs. The program is detailed in section 8.7 and the rules for assignment are prescribed in this section.

There is a change in assignment rules for baseline assessment compared to UWIR 2016. To better align with the broader baseline assessment requirement under the Water Act, the rules are now referenced to petroleum leases as well as ATPs instead of production tenure alone.

> Rule 3: The authorised tenure holder over land identified as P&G tenure in Figure 2-5 is the responsible tenure holder for carrying out the baseline assessment program identified in section 8.7.2 in relation to a bore on the land.

> Rule 4: For a bore to which the baseline assessment program in section 8.7.2 applies, but the bore is outside the land identified as P&G tenure in Figure 2-5, the responsible tenure holder is the authorised tenure holder over land identified as P&G tenure in Figure 2-5 that is closest to the bore.

11.3.2.2 Other report obligations

All other obligations specified in Chapter 8 and Chapter 9 relating to the WMS and SIMS are to be carried out by the authorised holders of the tenures on which the activities are to be carried out.

> Rule 5: The authorised tenure holder over land identified as a relevant tenure in Figure 2-6 is the responsible tenure holder for obligations identified in Chapter 8 and Chapter 9.

Some of the obligations identified in Chapter 8 and Chapter 9 are to be carried out outside the relevant tenure areas shown in Figure 2-6. The obligations arise because of CSG water extraction from nearby tenures. Therefore, the following rule assigns responsibility in relation to those obligations other than the requirement for carrying out baseline assessment.

> Rule 6: For WMS and SIMS obligations, other than baseline assessment, to be carried out outside the area to which Rule 5 applies, the responsible tenure holder is the authorised

tenure holder over the land identified as relevant tenure in Figure 2-6 that is closest to the bore.

There have been some instances where a tenure holder other than the one identified as the responsible tenure holder in the UWIR has taken responsibility for activities relating to monitoring or baseline assessment through a mutual agreement. This has generally occurred where obligations for such activities are assigned to a tenure holder over land where another tenure holder holds an ATP. Compared to the previous UWIR, the changes outlined in this chapter will minimise such instances. However, in circumstances where this occurs, the following rule will apply:

> Rule 7: A tenure holder with an obligation under application of Rules 1 to 6 may transfer to another tenure holder the obligation to carry out future activities required under the obligation, if the transfer is approved by OGIA.

Assignment rules have evolved through the UWIR cycles in consultation with affected tenure holders. The applicable rules have been used in identifying the responsible tenure holder's obligations in a UWIR effective at the time. Therefore, to provide certainty, tenure holders obligations from previous UWIRs will continue to be maintained based on the following rule:

> Rule 8: Regardless of the Rules 1 to 6 above, a tenure holder's obligation from the previous UWIR arising from applicable assignment rules from those UWIRs will continue unless the tenure holder transfers the obligation to another tenure holder and the transfer is approved by OGIA.

Chapter 12 Periodic reporting and review

This chapter describes the arrangements for ongoing reporting on matters relating to this UWIR and the subsequent revisions of the UWIR.

Once approved, the UWIR becomes a statutory instrument and provides a basis for ongoing management of groundwater impacts in line with the strategies outlined in the report.

12.1 Annual reporting

An annual report is prepared to provide an update on changes to circumstances that would impact on the predictions reported in the UWIR, and to provide updates on the implementation of management strategies specified in the UWIR. For example, two annual reports were prepared for the UWIR 2016 reporting cycle: Annual Report 2017 (OGIA 2017b) and Annual Report 2018 (OGIA 2018).

OGIA will continue to provide annual reports to DES for the current UWIR. These reports will be published on the OGIA website. In addition to changes, the future annual reports will also include a revised list of IAA bores resulting from ongoing verification of bore status, authorisation and aquifer attribution for bores referred to in Appendix G.

12.2 Access to information and data management

OGIA is the custodian of the following datasets that are reported by tenure holders in relation to implementation of the UWIR in the Surat CMA:

- monitoring data under the WMS (Chapter 8) including groundwater pressure, water chemistry and CSG water extraction data
- bore baseline assessment data reported under section 405 of the Water Act and under Chapter 11 of the UWIR
- outcomes of bore assessments
- any other information collected and acquired under section 460 of the Water Act.

The primary purpose of the data is to enable OGIA to undertake impact assessment activities and develop management strategies for the UWIR.

Following a quality control process, the majority of data received by OGIA is made available through the DNRME GWDB and QDEX, which is accessible through the Queensland Globe. Tenure holder reports, including data about the construction of CSG bores and water extraction, are also available from QDEX.

Information about predicted impacts on individual water bores, and bore status at the time of preparing the UWIR, is available through a 'Bore Search Tool' on OGIA's website.

12.3 Revising the UWIR and future research directions

Queensland's regulatory framework requires revision of the UWIR every three years, unless the Chief Executive of DES requires an earlier amendment. The revision would incorporate new data and knowledge generated from research work in the preceding three years.

Knowledge about the groundwater flow system continues to improve as data accumulates and is used to build knowledge through targeted research. OGIA's work program in the lead up to the next update of the UWIR will include research in the following key areas:

- **Groundwater flow modelling:** continued refinement of the current regional groundwater flow model and exploring options to address challenges associated with modelling scale.
- **Trend analysis:** ongoing analysis of additional groundwater monitoring data to identify impacts associated with CSG development.
- **Hydrogeological conceptualisation:** further targeted assessment of the hydrogeological characteristics of geological faults (in particular, the Horrane Fault), aquifer interconnectivity, regional groundwater flow patterns and groundwater flow in the Precipice Sandstone.
- **Data management:** verification of bore aquifer attribution, the location and status of water bores, and better public access to data and information.

OGIA will also continue to collaborate with research organisations and other government agencies to explore synergies in research and data/information management.

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Glossary

Alluvium: deposits of clay, silt, sand, gravel, or other particulate material that have been deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain.

Analytical technique: mathematical relationships that can be used to forecast water pressure changes in a simple homogenous formation in response to relatively uniform and localised extraction.

Aquifer: a saturated underground geological formation or group of formations, that can store water and yield it to a bore or spring. A saturated formation that will not yield water in usable quantities is not considered an aquifer.

Aquifer attribution: an interpretation of the aquifer (or aquifers) from which a bore may be accessing water.

Aquitard: a geological formation that prevents significant flow of water due to its low permeability (e.g., clay layers or tight deposits of shale).

Artesian water: water that occurs naturally in, or is introduced artificially into, an aquifer, and which if tapped by a bore, would flow naturally to the surface.

Associated water: groundwater that is taken, or interfered with, as a result of carrying out an authorised activity for a tenure, such as groundwater extraction to depressurise the reservoir for gas production or drilling of a petroleum well. Tenure holders have a statutory right to take this water subject to a range of obligations relating to impact assessment and management arrangements.

Baseline assessment: a field survey of a water bore by a petroleum tenure holder to obtain information about bore construction, water levels and water quality.

Basement (geological): generally low permeability hard rock strata of igneous or metamorphic origin which lie below sedimentary rocks or sedimentary basins. In the same way the sediments or sedimentary rocks on top of the basement can be called a "cover" or "sedimentary cover".

Basin (geological): an area in which the rock strata dip from the margins toward a common centre; the site of accumulation of a large thickness of sediments.

Basin (groundwater or hydrogeological): a groundwater system made up of multiple aquifers; may be equivalent to a geological basin.

Bore assessment: an intensive field evaluation of a private water bore by a petroleum tenure holder to assess if a bore has, or is likely to experience, an impaired capacity as a result of CSG development

Bore trigger thresholds: thresholds used to identify bores that are likely to be impacted and require further bore assessment*.* The Water Act defines bore trigger thresholds as a decline in the water level in the aquifers of five metres for consolidated aquifers (such as sandstone) and two metres for unconsolidated aquifers (such as alluvium).

Confined aquifer: a saturated aquifer bounded between low permeability materials such as clay or dense rock.

Consolidated aquifer: a water-bearing aquifer made of consolidated rock such as sandstone, coal, limestone or granite.

Conventional petroleum and gas: petroleum and gas that is generally found in permeable formations such as sandstone and trapped in reservoirs by an overlying low permeability rock formation, or within geological structures that allow the petroleum and gas to concentrate or pool.

Deposition: the laying down/settling of material (clay, sand, rock) carried by wind, water, or ice.

Depressurisation: the extraction of groundwater by pumping to decrease pressure in the groundwater system or reduce groundwater head.

Development profile: a tenure holder’s production footprint with associated planned commencement, development sequencing and cessation.

Drawdown: the difference between the groundwater pressure before and after pumping or depressurisation.

Drill stem test: a procedure used to test the surrounding geological formation through the drill stem when a petroleum well is drilled. It is used to estimate the productive capacity, pressure, porosity or permeability of a petroleum producing formation.

Dual phase flow: the simultaneous flow of two substances through porous material; for example when gas and water are flowing through a geological formation to a well.

Fault (geological): a break in a geological formation along which some measurable movement, or displacement, has occurred typically due to tectonic movement and uplift of the earth's crust (see also ‘Fracture’).

Fold (geological): when a stack of originally flat sedimentary strata are bent or curved typically due to tectonic movement and uplift of the earth’s crust.

Formation (geological): a sediment or rock, or group of sediments or rocks. Geologists often group rocks of similar types and ages into named formations, for example the Hooray Sandstone of the Great Artesian Basin.

Fracture (geological): a minor break in a geological formation with no measurable movement, or displacement (see also ‘Fault’).

Geological formation: see ‘Formation’.

Groundwater: also known as underground water. Water found in the cracks, voids, pores or other spaces between particles of clay, silt, sand, gravel or rock within the saturated zone of a geological formation.

Groundwater database: a database maintained by DNRME that stores information relating to registered groundwater bores drilled within the state of Queensland.

Groundwater flow model: a set of equations, which, subject to certain assumptions, quantify the physical processes active in a groundwater system. While a model cannot simulate the detailed reality of the groundwater system, its behaviour approximates that of the actual system and is used to simulate that behaviour.

Groundwater level: a level to which groundwater rises in a monitoring bore. This reflects the water pressure in the aquifer tapped by the bore.

Groundwater level trend: changes in water level or water pressure over a specific period of time. A trend can be rising or falling.

Head (groundwater): groundwater level or pressure.

Homogenous formation: a geological formation that has identical material properties throughout its entire extent.

Hydraulic gradient: the difference in water pressure or water level across one or more formations over a unit distance. The hydraulic gradient indicates which direction groundwater will flow, and how rapidly.

Hydraulic parameters: the parameters that describe the material properties that control the flow and storage of water within an aquifer, such as permeability and storavitity.

Hydrogeology: the study of how groundwater moves, how it is distributed and how it interacts with rock.

Hydrostratigraphy: the identification of units on the basis of hydraulic properties.

IAA bore: a water bore that is accessing water from the IAA of an aquifer.

Immediately Affected Area: the area of an aquifer within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger threshold within three years. The trigger thresholds are specified in the Water Act as five metres for consolidated aquifers (such as sandstone) and two metres for unconsolidated aquifers (such as sand). Within the Immediately Affected Area, there is significant risk that the supply of water from a bore tapping the formation will be impaired within three years.

Interbedded: where beds, or layers, of geological material of different lithology or properties are layered together.

Interfinger: in relation to sedimentary rocks, to change laterally or vertically from one type to another, where the two types gradually merge, or overlap, to form interpenetrating wedges.

LAA bore: a water bore that is accessing water from the LAA of an aquifer.

Licensed entitlement: a water allocation or authority granted under the *Water Act 2000* to access and use groundwater.

Lithic: geological deposits or sedimentary rocks that contain abundant fragments of previously formed rocks.

Lithology: the physical characteristics of rock, with reference to qualities such as colour, composition and texture.

Long-term Affected Area: the area of an aquifer within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger thresholds at any time in the future. The trigger thresholds are specified in the Water Act as five metres for consolidated aquifers (such as sandstone) and two metres for unconsolidated aquifers (such as sand).

'Make good': the Water Act specifies the circumstances under which petroleum tenure holders need to investigate impairment of water bores and develop 'make good' agreements with bore owners about the impairment.

Measures (geological): a series of coal-bearing rocks, such as the Walloon Coal Measures.

Member (geological): a named lithologic subdivision of a formation; for example, the Boxvale Sandstone Member.

Model domain: the areal extent of the regional groundwater flow or associated geological model.

Monitoring installation: an individual borehole equipped to monitor water quality and/or water pressure, potentially at multiple vertical levels.

Mudstone: an extremely fine-grained sedimentary rock consisting of a mixture of clay and silt-sized particles.

Non-associated water: any extracted groundwater that is not associated water. This typically includes groundwater extraction by tenure holders for consumptive purposes such as construction activities or camp supplies.

Numerical permeameter: local-scale block models of the subsurface developed to derive effective formation-scale hydraulic properties from detailed lithological data.

Outcrop (noun): a geological formation or rock strata exposed at the ground surface.

Outcrop (verb): to be exposed at the ground surface.

Permeable: capable of transmitting water through porous rock, sediment or soil.

Permeability: a property of a soil, sediment or rock indicating how easily water will be transmitted through it under a hydraulic gradient.

Permeameter: see 'Numerical permeameter'.

Petroleum: naturally occurring hydrocarbons such as oil, gas and CSG.

Petroleum tenure holder: an entity that holds an authority to prospect and/or a petroleum lease under the *Petroleum and Gas (Production and Safety) Act 2004*.

Potential relevant tenures: ATPs where EAs are applied for, or where EISs are completed or submitted.

Potentially affected spring: a spring where the water level in the underlying aquifer is predicted to fall by more than 0.2 metres at any time in the future.

Production area: the area from which petroleum and gas production is planned.

Queensland Globe: an online tool which provides access to information on petroleum and gas development activities, water bores and groundwater monitoring.

Recharge: the process of water flowing into an aquifer.

Relevant tenures: all tenures which are petroleum leases and petroleum lease areas.

Responsible tenure holder: the petroleum tenure holder identified as being responsible for specific activities such as monitoring and mitigating the impact of water extraction on springs.

Sediment: material suspended in water or deposited from suspension. The plural form, sediments, is applied to all kinds of deposits from the waters of streams, lakes and seas.

Sedimentary basin: a geological basin containing a sequence of mainly sedimentary rocks.

Sequence (geological): a sequence of geological events, processes, or rocks, arranged in chronological order.

Sheetwash: fluvial material, mainly fine-grained, deposited by extensive overland flow, typically fan-shaped.

Siltstone: fine-grained sedimentary rock consisting of consolidated silt.

Spring complex: a group of spring vents located close to each other. The vents are located in a similar geology and are fed by the same aquifer. No adjacent pair of spring vents in the complex is more than 10 km apart.

Spring of interest: under the Water Act, a spring of interest is a spring (including watercourse springs) overlying an aquifer where the long-term predicted reduction in water pressure exceeds 0.2 metres.

Spring vent: a single point in the landscape where groundwater is discharged at the surface. A spring vent can be mounded or flat and can also present as wetland vegetation, with no visible water at the location of the spring.

Storativity: also known as storage coefficient. The capacity of the material through which groundwater flows to store or release water in response to a pressure change. Measured as the volume of water that a column of aquifer releases from storage or takes into storage per unit surface area of the aquifer per unit change in head.

Strata: a series of layers of rock in the ground (singular: stratum).

Stratigraphic unit: a volume of rock of identifiable origin and relative age range that is defined by the distinctive and dominant, easily mapped and recognizable petrographic, lithologic or paleontologic features (facies) that characterise it.

Sub-basin (geology): a smaller depression or accumulation of sediments within a larger basin; for example, the Surat Basin is a sub-basin of the Great Artesian Basin.

Trough (geological): an elongated, linear structural depression or narrow basin that is not steep-walled.

Uncertainty analysis: a technique for assessing the effect of uncertainty on prediction, using multiple realistic parameter sets to generate a large number of predictions which can then be statistically analysed to provide a measure of uncertainty in model prediction.

Unconfined aquifer: an aquifer with no overlying low permeability layers that restrict water movement into the aquifer. The water level in an unconfined aquifer is known as the water table.

Unconsolidated aquifer: an aquifer comprised of material such as sand that has not been turned into rock.

Unconventional gas: gas that is extracted from formations including coal seams (CSG) and low-porosity rock formations such as shale (shale gas) or low-permeability sandstone/siltstone (tight gas).

Underground water management framework: under the Water Act, petroleum tenure holders are subject to responsibilities including the requirement to assess, monitor and manage impacts on water bores caused by the exercise of underground water rights, and to enter into 'make good' agreements with the owners of the water bores.

Underground water right: under the P&G Acts, petroleum tenure holders have a limited statutory right to take or interfere with underground water (or groundwater).

Unit (geological): see 'Stratigraphic unit'.

Vertical permeability: the property of a formation indicating how easily or rapidly water is transmitted vertically.

Water monitoring authority: an authority under the P&G Acts that allows a petroleum tenure holder to carry out water monitoring activities in the area to which the water monitoring authority relates, which could be outside the actual tenure.

Watercourse spring: a section of a watercourse where groundwater enters the stream from an aquifer. Also referred to as a baseflow-fed watercourse.

Wellfield: an area within a petroleum lease with multiple wells used for P&G extraction.