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

Analysis of groundwater level trends in the Hutton Sandstone, Springbok Sandstone and Condamine Alluvium

Surat Cumulative Management Area

December 2019

Queensland Government

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Summary

The Office of Groundwater Impact Assessment (OGIA) is responsible for undertaking cumulative impact assessment and establishing management arrangements within areas declared as 'cumulative management areas' (CMA). Currently there is one CMA in Queensland, the Surat CMA, established in 2011 in response to coal seam gas (CSG) development in the Surat and southern Bowen basins.

OGIA's impact assessment and management arrangements are established in an Underground Water Impact Report (UWIR), which is revised every three years, providing for an adaptive cycle of reporting-monitoring-research-modelling. The UWIR provides an assessment of regional impacts on groundwater pressures, springs and water supply bores, and establishes integrated management arrangements, such as regional monitoring strategies. Groundwater levels and the interpretation of observed trends are key data that underpin the impact assessment.

At any given point in time, the observed trends may be influenced by a number of factors, which can be grouped into two categories: water balance (e.g. recharge, discharge, CSG groundwater extraction and non-CSG water use) and non-water balance (e.g. earth tides, barometric pressure and mechanical loading).

This report is focussed on unpacking the impacts of CSG groundwater extraction from the Walloon Coal Measures on the observed groundwater level trends in adjacent aquifers – the Springbok Sandstone, Hutton Sandstone and Condamine Alluvium.

In order to separate CSG impacts from other water balance factors (i.e. non-CSG water use), it is necessary to establish background aquifer conditions. Once background conditions and trends are established or contextualised, CSG impacts may then be inferred where there is a deviation from background trends. However, there are a number of challenges that make establishing background trends difficult, including the following:

- Many of the aquifers adjacent to the CSG reservoir have extensive current and historical non-CSG water use for which there is limited metering.
- The distribution of dedicated monitoring infrastructure prior to CSG commencement is limited to areas where aquifers are generally shallow or at outcrop, reflecting the primary areas of historical non-CSG water use.
- In the early stages of development, CSG impacts in adjacent aquifers are likely to represent a relatively minor component of the observed trends, and may be within the bounds of uncertainty associated with other more influential factors, such as climatic variations and estimated non-CSG water use.

Consequently, OGIA applied a multiple-lines-of-evidence approach, including both qualitative and quantitative methods, to establish the nature of the trends and determine the likely causes of those trends. Specifically, the approach integrates statistical methods (Mann-Kendall and Spearman correlation), sub-regional and local-scale hydrogeological conceptualisation and numerical modelling. The outcomes from these individual methods are then integrated to assess where observed trends are interpreted to be influenced by CSG groundwater extraction.

The Walloon Coal Measures is the primary reservoir for CSG development in the Surat Basin. Within the Upper Juandah and Taroom coal measures, groundwater level declines (up to 300 m) are largely restricted spatially to gas fields and the immediately surrounding areas. Drawdowns of greater than 10 m are rarely observed further than 10 km away from active CSG development areas.

In the Springbok Sandstone – overlying the Walloon Coal Measures – variable groundwater level trends are observed. Consistent with previous predictions, there is evidence of CSG impacts at some locations, particularly where connectivity is enhanced due to local geological features such as faults. Three sites – Kenya East GW4, Broadwater GW11 and Isabella 7M – are identified as likely to be affected by CSG groundwater extraction.

In the Hutton Sandstone – an aquifer underlying the Walloon Coal Measures – widespread declining groundwater level trends are observed. The observed trends in the available data correlate well with rainfall patterns – particularly in outcrop areas – and with non-CSG water use in the Hutton Sandstone, both inside and outside CSG production areas. There are no discernible changes in the rate of decline that correlate with CSG groundwater extraction.

At this stage, there is no evidence to suggest that declining trends in the Hutton Sandstone are due to CSG groundwater extraction. Non-CSG water use from 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 currently no definitive evidence at this stage. Some CSG impacts are predicted in the longer term in the Hutton Sandstone.

The Condamine Alluvium is a major water supply aquifer. In some areas, groundwater levels have been depressed by more than 25 m since the 1960s. Groundwater level trends have been analysed along the western flank of the alluvial aquifer, the area closest to existing CSG development areas. In combination with very low head differences (<20 m for most areas), it is unlikely that CSG impacts have occurred in the Condamine Alluvium at this stage.

Overall, the analysis suggests that there is definitive evidence of widespread CSG impact in the Walloon Coal Measures. In the overlying Springbok Sandstone, the groundwater level trends are mixed and there is evidence at some sites of CSG impact. 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.

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. Analysis of the influences on observed groundwater level trends in aquifers adjacent to CSG reservoirs will continue to be a major focus for OGIA during the next three-year cycle.

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1 Introduction

1.1 Background

The Office of Groundwater Impact Assessment (OGIA) is an independent entity established under Queensland legislation for the assessment and management of groundwater impacts from the extraction of associated water by petroleum and gas (P&G) and mining tenure holders (collectively referred to as resource tenure holders). OGIA is responsible for undertaking cumulative impact assessments and establishing management arrangements in areas where impacts from multiple tenure holders may overlap. Such areas are declared as ‘cumulative management areas’ (CMA). Currently there is one CMA in Queensland, established in 2011 in the Surat and southern Bowen basins in response to coal seam gas (CSG) development – the Surat CMA.

OGIA’s assessment and management arrangements are set out in an Underground Water Impact Report (UWIR), which is revised every three years to provide for an adaptive reporting-monitoring-research-modelling cycle. The UWIR provides assessment of regional impacts on groundwater pressures and establishes integrated management arrangements, such as regional monitoring strategies. It also identifies individual responsibilities for implementing various aspects of the strategies. The UWIR is a statutory instrument and provides a basis for the ongoing management of groundwater impacts in line with the strategies outlined therein. Responsible tenure holders have a statutory obligation to implement management arrangements identified in the UWIR.

The first UWIR for the Surat CMA was prepared by OGIA (then part of the Queensland Water Commission) in 2012 (Queensland Water Commission 2012), which was superseded by the UWIR 2016 (OGIA 2016a). The most recent iteration of the UWIR was completed in 2019 (OGIA 2019a).

A key component of the cumulative impact assessment that supports the UWIR is the development of a regional-scale groundwater flow model. Between 2016 and 2019, OGIA undertook a range of geological and hydrogeological assessment and investigation projects to improve the definition of the hydrogeological system geometry and improve understanding of aquifer interconnectivity, source aquifers for springs and regional conceptualisation of the flow system. This understanding, combined with the development of innovative techniques for groundwater flow modelling, was used to develop an improved impact assessment model, which underpins the UWIR 2019.

1.2 Project purpose

The purpose of this report is to:

- provide a regional overview of groundwater level trends that have been observed for the aquifers directly above (Springbok Sandstone and Condamine Alluvium) and below (Hutton Sandstone) the main CSG reservoir (Walloon Coal Measures) in the Surat CMA
- analyse potential causes of these groundwater level trends, with a primary objective of identifying CSG and non-CSG impacts.

Under current Queensland legislation, OGIA is required to identify aquifers and areas where the impacts of P&G activities exceed certain trigger thresholds: 2 m for unconsolidated aquifers and 5 m for consolidated aquifers. OGIA is also required to assess where impacts on springs exceed 0.2 m and to assess impacts on other environmental values, such as terrestrial groundwater-dependent ecosystems. However, impacts on springs are not predicted for some time and hence, during this relatively early phase of CSG development, impacts in excess of these thresholds are only predicted in close proximity to existing CSG production areas.

Accordingly, this report focusses on identifying trends in the aquifers immediately above and below the Walloon Coal Measures and develops methods appropriate to identifying trends in observed groundwater levels.

1.3 Report scope

The specific scope of this report is to document the method and outcomes of the project that involved the following:

- Describe the current level of depressurisation in the Walloon Coal Measures CSG reservoir, including analysis of individual bore-scale groundwater level trends in the upper and lower parts of the reservoir and regional-scale drawdown trends.
- Identify suitable groundwater level monitoring points in the overlying and underlying aquifers of interest (i.e. the Springbok Sandstone, Hutton Sandstone and Condamine Alluvium) for identifying groundwater level trends in these aquifers.
- Apply statistical analysis and visual interpretation to each hydrograph to describe the groundwater level trend.
- Analyse groundwater level trends from the perspective of where they are situated in the basin (i.e. outcrop versus deeper, confined locations).
- Analyse groundwater level trends during distinct hydrological periods (e.g. droughts).
- Correlate representative groundwater level records with local CSG groundwater extraction and non-CSG water use and regional rainfall trends to identify potential causes of specific trends.
- Review potential connectivity between the CSG reservoir and each adjacent aquifer to contextualise the likelihood of impacts occurring at specific monitoring locations.
- Assess the potential for CSG impacts at each representative monitoring point within each aquifer of interest.

1.4 Study area

OGIA is responsible for the assessment of cumulative groundwater impacts from P&G activities within the Surat CMA (Figure 1-1). In 2016, a regional conceptualisation and trend analysis were completed (OGIA 2016b) across the Surat CMA. Since that time, OGIA has focussed research and analysis on three primary sub-regional geographical production areas in the Surat Basin – the Northern Surat, Eastern Surat and South-eastern Surat – and on formations overlying and underlying the target CSG reservoirs. This focus reflects the increased availability of monitoring at these locations, the significant depressurisation of the Walloon Coal Measures from the gas fields in these focus areas and the higher potential for impacts in adjacent aquifers in this area.

1.5 Relationship with other studies

This trend analysis report draws on information and data from a number of previous OGIA hydrogeological investigations in the Surat Basin. Since 2011, OGIA has undertaken a number of research studies relating to various elements of groundwater conceptualisation, aquifer interconnectivity, sub-regional hydrogeological assessment and groundwater flow modelling to support development of the UWIR 2012, UWIR 2016, and UWIR 2019. Findings of these studies are published in a number of technical reports that are available on OGIA’s website. The key reports that are heavily relied upon in this current report include the following:

- ***Hydrogeological conceptualisation report for the Surat Cumulative Management Area*** (OGIA, 2016b) summarises key groundwater processes operating in the Surat, Clarence-Moreton and Bowen basins within the Surat CMA.
- ***Condamine groundwater connectivity report*** (OGIA, 2016a) provides a summary of investigations into the potential for groundwater flow between two major geological formations in the Surat Basin: the Condamine Alluvium and Walloon Coal Measures.
- ***Groundwater extraction and use in the Surat Cumulative Management Area*** (OGIA 2019b) provides a summary of OGIA’s methodology and estimates for non-CSG water use for each major hydrostratigraphic unit with the Surat CMA.
- ***Updated Geology and Geological Model for the Surat Cumulative Management Area*** (OGIA 2019c) provides a revised geological framework for and geological model of the Surat CMA, for use in the UWIR 2019.
- ***Hydrogeological assessments in the Northern Surat, Eastern Surat and South-eastern Surat*** (OGIA 2019d, 2019e, 2019f) describes the hydrogeological conditions within sub-regional areas for the Springbok Sandstone, Walloon Coal Measures, Hutton Sandstone and Condamine Alluvium. Drawing on revised groundwater level, chemistry and extraction datasets acquired since the UWIR 2016, the reports establish a contemporary understanding of groundwater flow processes in these aquifers of interest.
- ***Summary of Hydrogeological Conceptualisation – Surat Cumulative Management Area*** (OGIA 2019g) provides a comprehensive review of hydrogeological conceptualisation as part of the UWIR 2016. This new report provides details on specific aspects of conceptualisation that have been revised since that original publication and reflects the direction of OGIA’s technical investigations undertaken to support the UWIR 2019.
- ***Conceptualisation and characterisation of faults in the Surat Basin*** (OGIA 2019h) summarises OGIA's current characterisation of faulting in the Surat Basin and assesses the potential for faulting to influence aquifer connectivity and groundwater flow processes.

1.6 Report layout

This report presents an overview of the hydrogeological characteristics of the Springbok Sandstone, Hutton Sandstone and Condamine Alluvium, summarises the observed groundwater level trends in each formation and describes the plausible factors that may influence these trends. The report is structured as follows:

- Chapter 2 provides the contextual background for this report including a summary of the regional hydrogeological setting and non-CSG water use and CSG development.
- Chapter 3 presents an overview of the available monitoring infrastructure and a summary of the corrections applied to raw groundwater level data.
- Chapter 4 provides a summary of the key concepts for trend analysis and an overview of the water balance and non-water balance factors that may influence groundwater level trends.
- Chapter 5 outlines OGIA's approach to groundwater level trend analysis including statistical, hydrogeological conceptualisation and modelling methods.
- Chapter 6 provides Walloon Coal Measures trend analysis and results.
- Chapter 7 provides Springbok Sandstone trend analysis and results.
- Chapter 8 provides Hutton Sandstone trend analysis and results.
- Chapter 9 provides Condamine Alluvium trend analysis and results.
- Chapter 10 provides a summary of the key conclusions from the Springbok Sandstone, Hutton Sandstone and Condamine Alluvium groundwater level trend analysis and the relative influence of water balance and non-water balance factors on the observed groundwater levels.

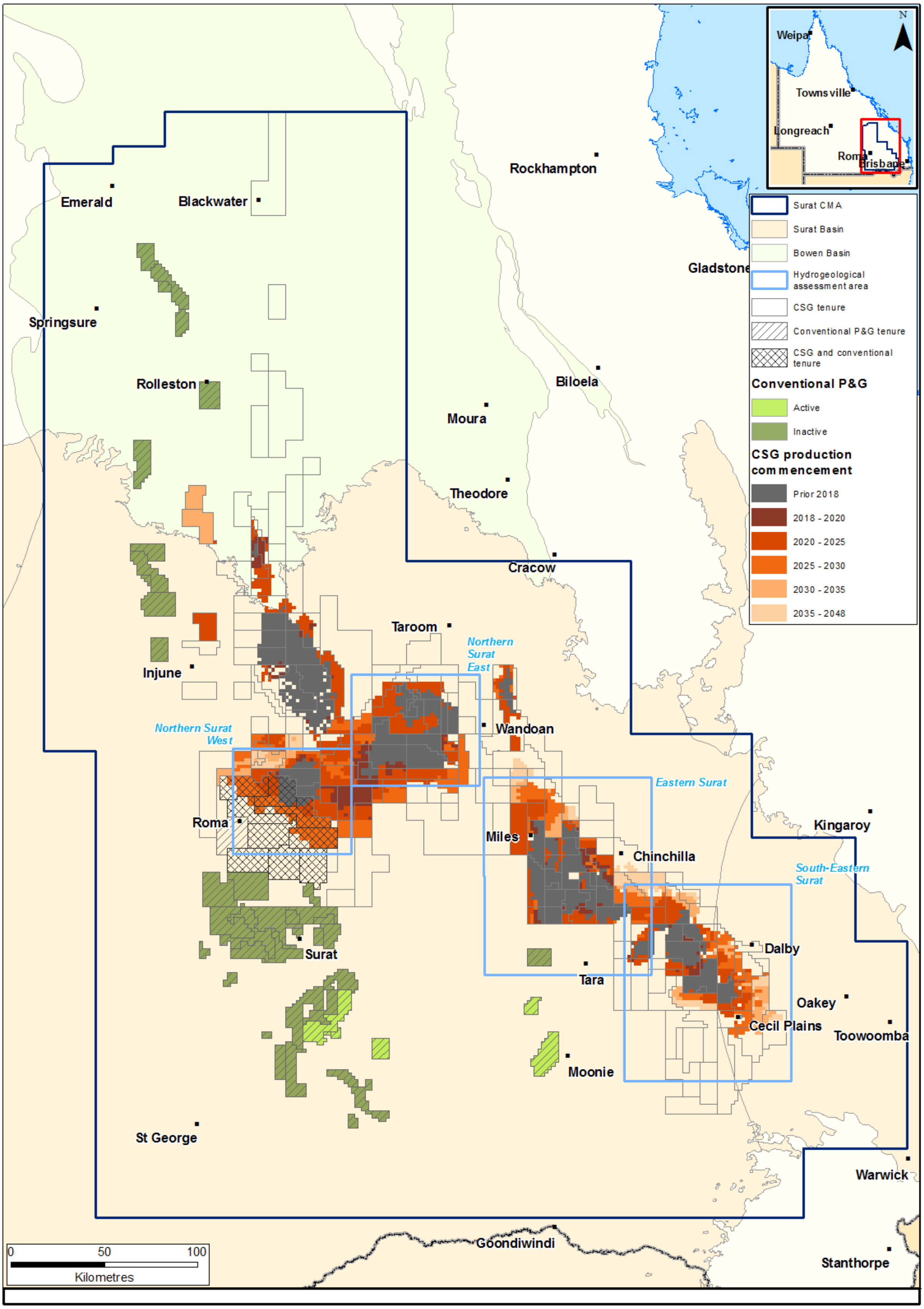

Figure 1-1 Study area – sub-regional assessment areas and P&G development

2 Regional context

This chapter provides a summary of the regional geological and hydrogeological settings for context purposes, including an overview of basin-scale non-CSG water use and CSG development.

2.1 Regional geology

2.1.1 Basin setting

The Surat CMA covers part of three geologic basins: the southern part of the Bowen Basin, the northern part of the Surat Basin and the western part of the Clarence-Moreton Basin. Geological formations within the three basins mainly comprise sedimentary deposits in the form of interbedded sandstone, siltstone, mudstone and coal.

The Bowen Basin is the deepest and oldest of the three basins and runs north to south through the centre of the region. Overlying this is the Surat Basin, which covers most of the central and southern parts of the Surat CMA. The Cecil Plains sub-basin of the Clarence-Moreton Basin interfingers with the Surat Basin across the Kumbarilla Ridge. Overlying these basins are extensive areas of unconsolidated younger alluvial sediments and volcanics.

The Surat Basin is a large intra-cratonic basin, extending from north of Taroom in southeast Queensland to the Coonamble Embayment near Dubbo in New South Wales. The northern margin of the Surat Basin has been exposed and extensively eroded due to uplift during the Cenozoic and the sediments generally dip in a southwestern direction (Exon 1976).

The Surat Basin is filled by Jurassic clastic continental sedimentary rocks and Early Cretaceous marine rock units, with a maximum thickness of 2,500 m (Babaahmadi, Sliwa & Esterle 2015; Hoffmann et al. 2009). The result is a highly heterogeneous mix of alternating layers of sandstones, siltstones, mudstones and coal lenses.

Because of the extensive surficial Cenozoic cover across much of the Surat CMA, many of the stratigraphic units present within the Surat CMA are not shown at outcrop in the available published 1:100,000 and 1:250,000 geological mapping. OGIA’s geological modelling process is therefore relied upon to best appreciate the solid geology (outcrop and subcrop of stratigraphic formations excluding Cenozoic cover) of the key aquifers and aquitards. The geology in the Surat CMA is shown in Figure 2-1. Solid geology is based on OGIA’s 2018 geological model (OGIA 2019c).

2.1.2 Structure and faulting

The shape and structure of the Surat Basin is influenced by the underlying basement structures of the Bowen Basin and older rocks (Figure 2-2). The structural features of the Bowen Basin are generally reflected, but subdued, in the Surat Basin structures. Hence, the axis of the Mimosa Syncline, the main depocentre of the basin, generally follows that of the Bowen Basin’s Taroom Trough, but the syncline is much broader and shallower than the underling trough (Ransley & Smerdon 2012).

In some areas, the reactivation of the Permo-Triassic fault systems of the Bowen Basin and basement rocks, following deposition in the Surat Basin, has also caused displacement of the overlying Jurassic-Cretaceous sequence. Renewed thrusting on these faults has led to the propagation of some of the faults up into the Surat Basin succession, but more commonly the deformation was principally by folding and uplift of the Surat succession above the reactivated fault (Copley et al. 2017; Korsch & Totterdell 2009).

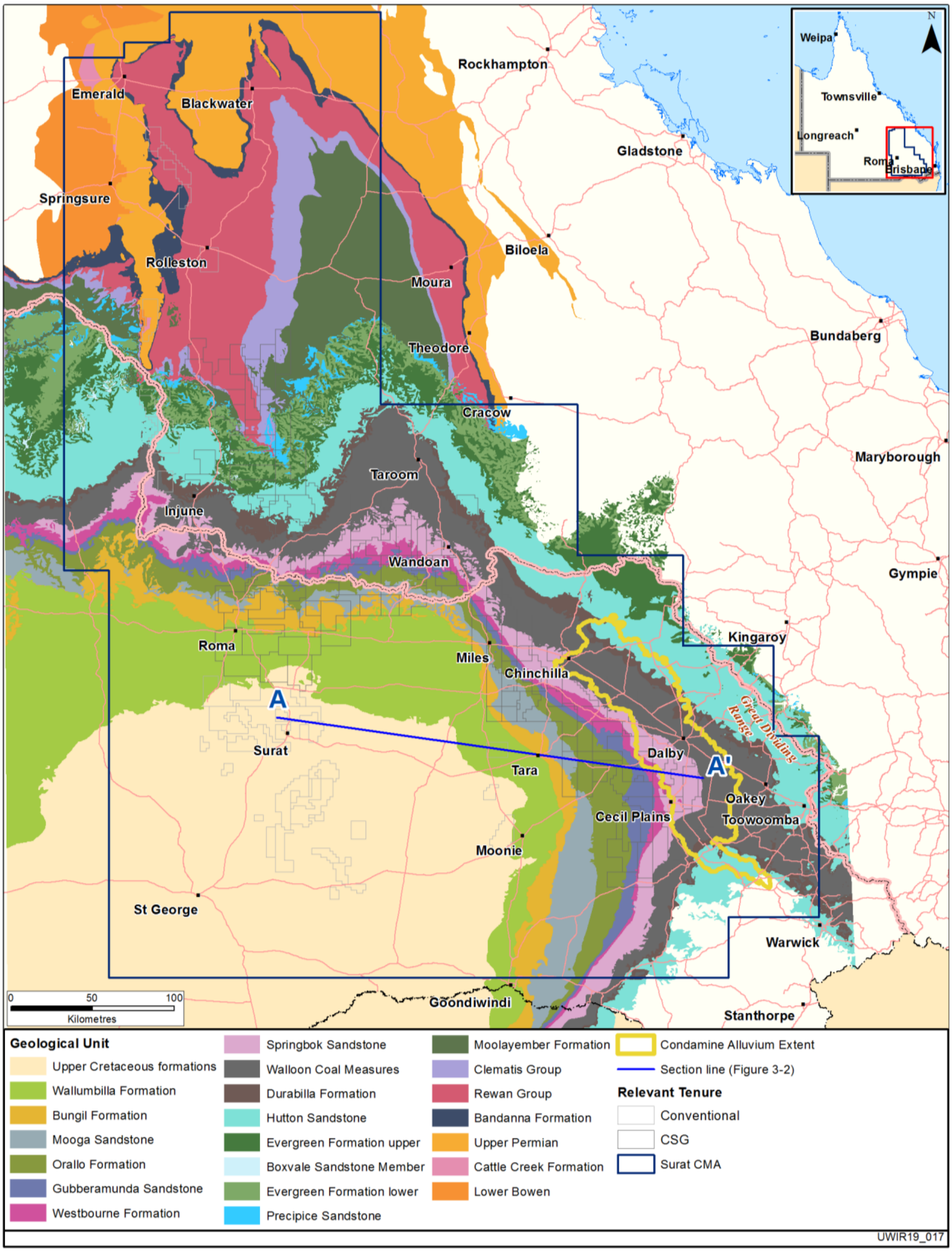

Figure 2-1 Geology of the Surat CMA (after OGIA 2019c)

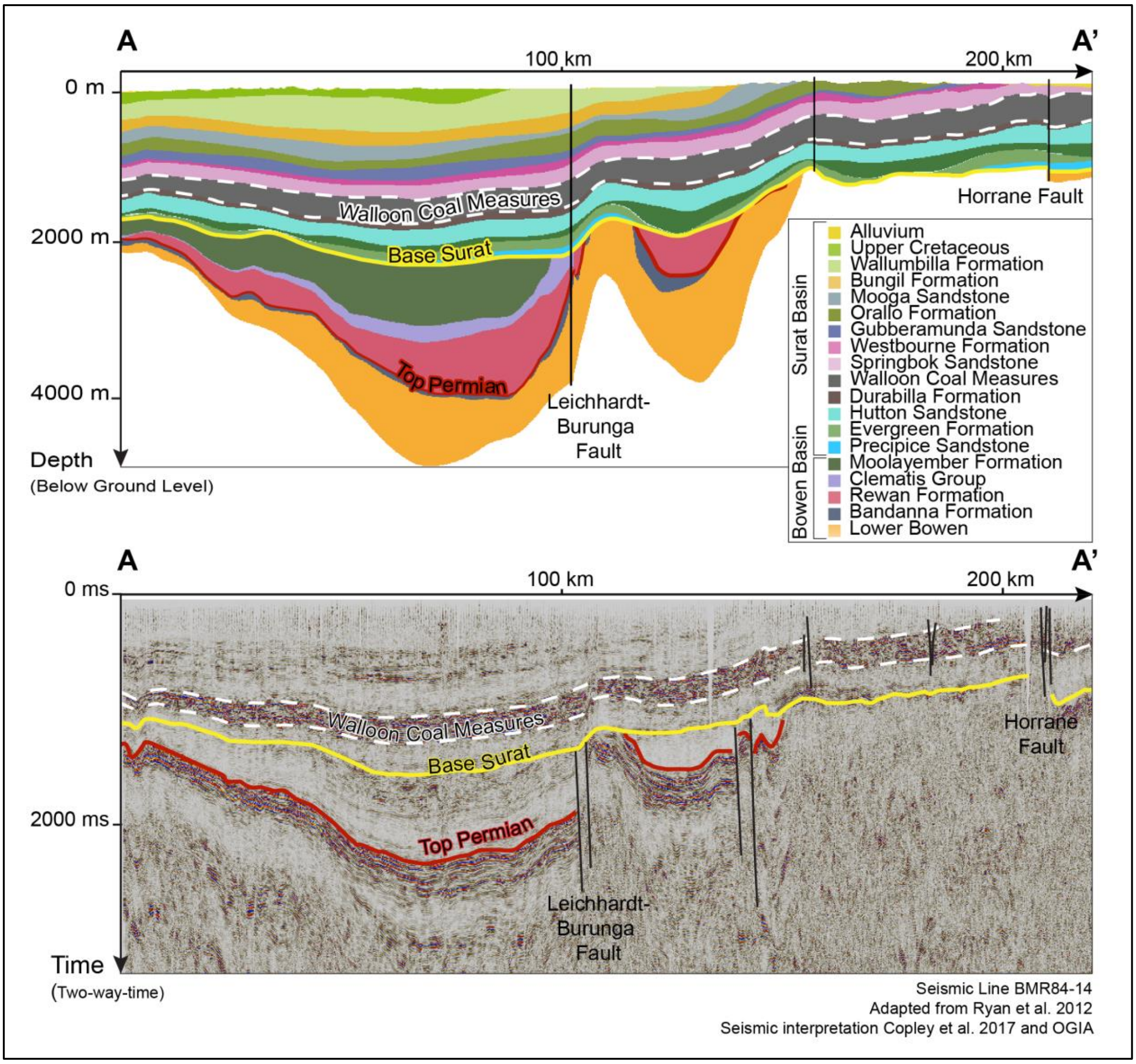

Figure 2-2 Generalised geologic cross-section of the Surat and Bowen basins with corresponding seismic section

Where present, faulting in the Surat Basin sediments is mostly evident in seismic data as flower structures, originating from deeper basement thrust faults (Copley et al. 2017). These flower structures are characterised by upwardly diverging pairs of steeply dipping faults with opposite movement, the centre of which is often a down-dropped graben block or 'keystone' block, usually tightly folded, with varying degrees of internal complexity (Copley et al. 2017). There is generally little net offset across the faulted zone, with fault displacement averaging 20 m and rarely being greater than 50 m (OGIA 2019c, 2019h).

In some cases, these features can have a lateral extent of 5–10 km following a deeper trend of weakness, but individual faults are generally discontinuous and are not typically seen on more than one seismic line (Copley et al. 2017). As such, spatial correlation is difficult and in many cases, the orientation and length cannot be assessed with a high degree of accuracy.

2.1.3 Cenozoic cover

Accumulations of Cenozoic unconsolidated and semi-consolidated alluvial sediments cover much of the surficial Surat CMA area (Figure 2-1). These typically comprise sand, silt and clay generally deposited along the old and existing streams and drainage lines. In addition, Cenozoic age volcanic rocks occur along parts of the Great Dividing Range (the Range).

The Condamine Alluvium is one of the more significant accumulations of alluvial sediments within the area. This alluvial groundwater resource is extensively developed for agriculture and lies over the western margin of proposed CSG production in a broad alluvial plain stretching between Millmerran and Chinchilla, with a width of over 20 km. The thickness of alluvium ranges from less than 10 m, in the headwaters and along the floodplain margins, to more than 120 m in the central floodplain near Dalby. The Condamine River has eroded its valley primarily along the strike of the Walloon Coal Measures, the dominant basement geology of the alluvium in the main central plain (Huxley 1982), with the Springbok Sandstone forming alluvial basement to the west (Figure 2-3). On the eastern margins, basalt of the Main Range Volcanics is geographically separated from the extents of the Condamine Alluvium.

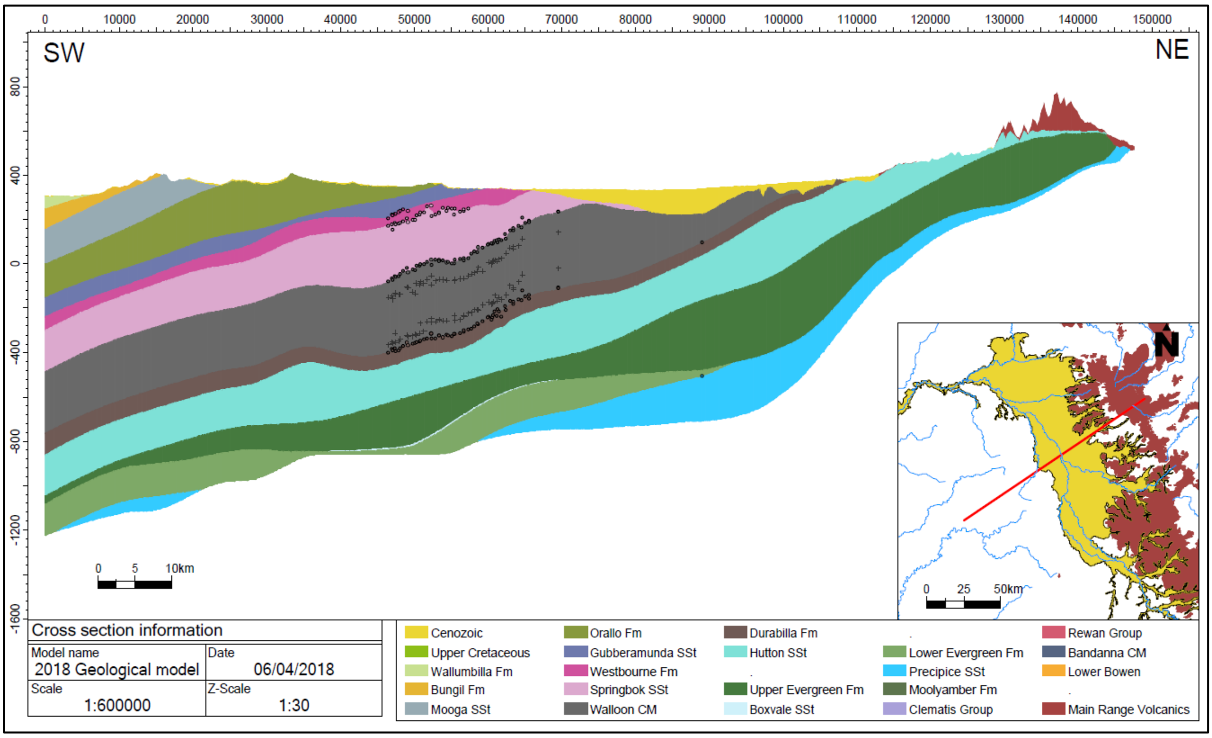

Figure 2-3 Geological cross-section of Surat Basin sediments subcropping beneath the Condamine Alluvium (OGIA 2016c)

The Main Range Volcanics occur at the eastern limit of the Surat Basin on the Range. These volcanics were formed as a part of a trail of volcanoes created in eastern and south-eastern parts of Queensland as the Australian plate moved northwards over one or more mantle hot spots during the Oligocene to Miocene epochs (Wellman 1987). The Main Range Volcanics unconformably overlie the Surat Basin sediments and Palaeozoic basement rocks (Huxley 1982). Most have been extensively eroded, producing high, steep, eastward-facing scarps (Exon 1976).

2.2 Regional hydrogeology

2.2.1 Groundwater systems

There are four primary groundwater systems in the Surat CMA:

- **Great Artesian Basin (GAB)** – Jurassic to Cretaceous hydrogeological basin comprising alternating aquifers and aquitards of various geologic formations of Surat and Bowen basin sediments and their equivalents (see Figure 2-4).
- **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.
- **Alluvium** – Quaternary unconsolidated surficial aquifers; mainly the Condamine and St. George alluviums.

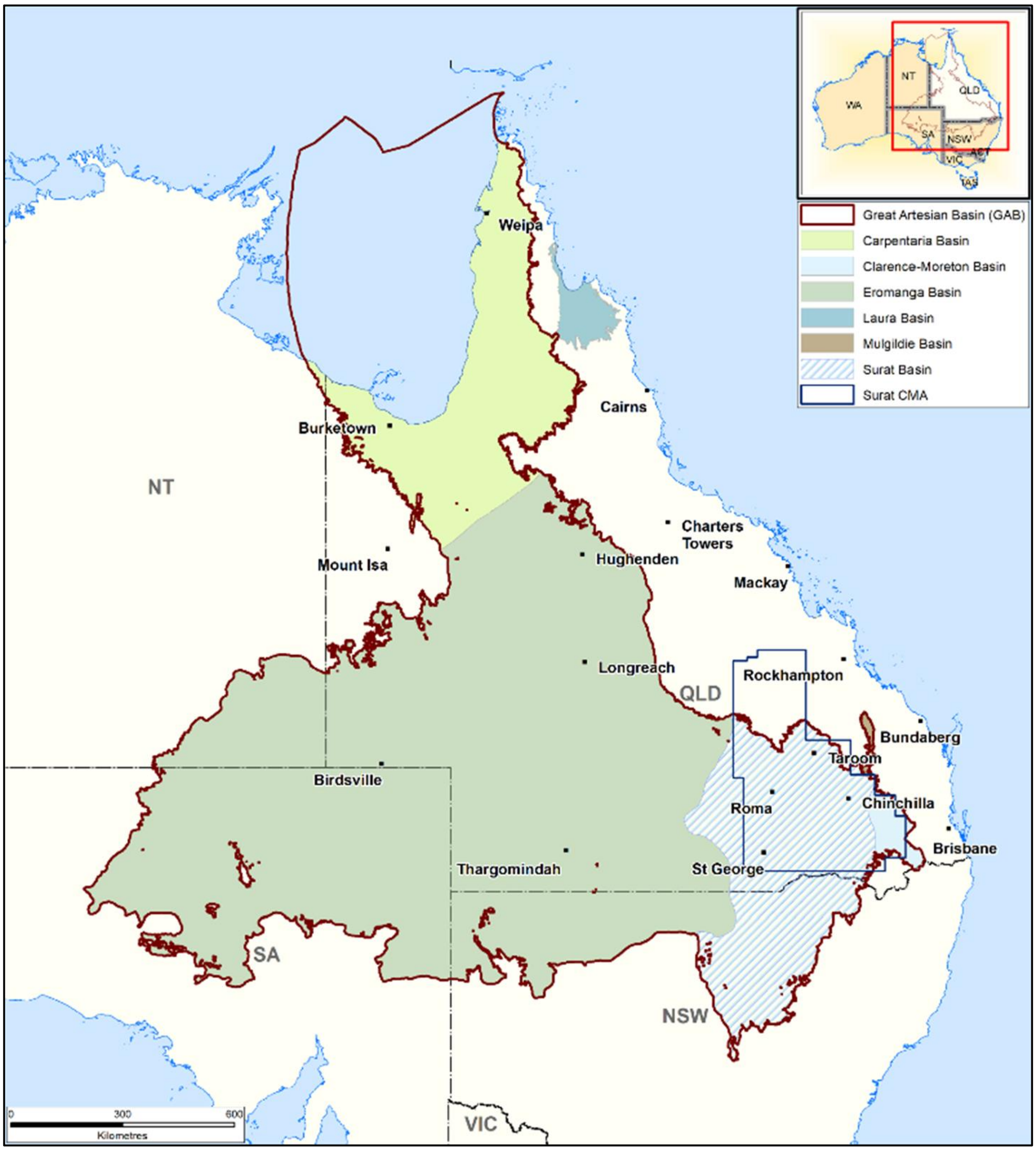

Figure 2-4 Extent of the GAB and sub-basins

The spatial and vertical relationships between these groundwater systems within the Surat CMA are illustrated schematically in Figure 2-5. In terms of productive groundwater supplies, the GAB and the Condamine Alluvium are the two most significant groundwater systems in the Surat CMA.

2.2.1.1 The Great Artesian Basin

The GAB is a hydrogeological or groundwater basin comprising various parts of other geologic basins (Figure 2-4). Collectively, the GAB extends across 1.7 million square kilometres, covering four states and nearly one-fifth of Australia (Ransley et al. 2015). In Queensland, the GAB covers about 65% of the state with a total thickness of the system ranging from less than 100 m on the basin extremities to more than 3,000 m in the deeper, central parts of the basin (DNRM 2005).

In the Surat CMA, there are two geological sub-basins of the GAB: the Surat Basin and its equivalent, the Clarence-Moreton Basin. These basins were deposited during the Mesozoic between 65 and 250 million years ago.

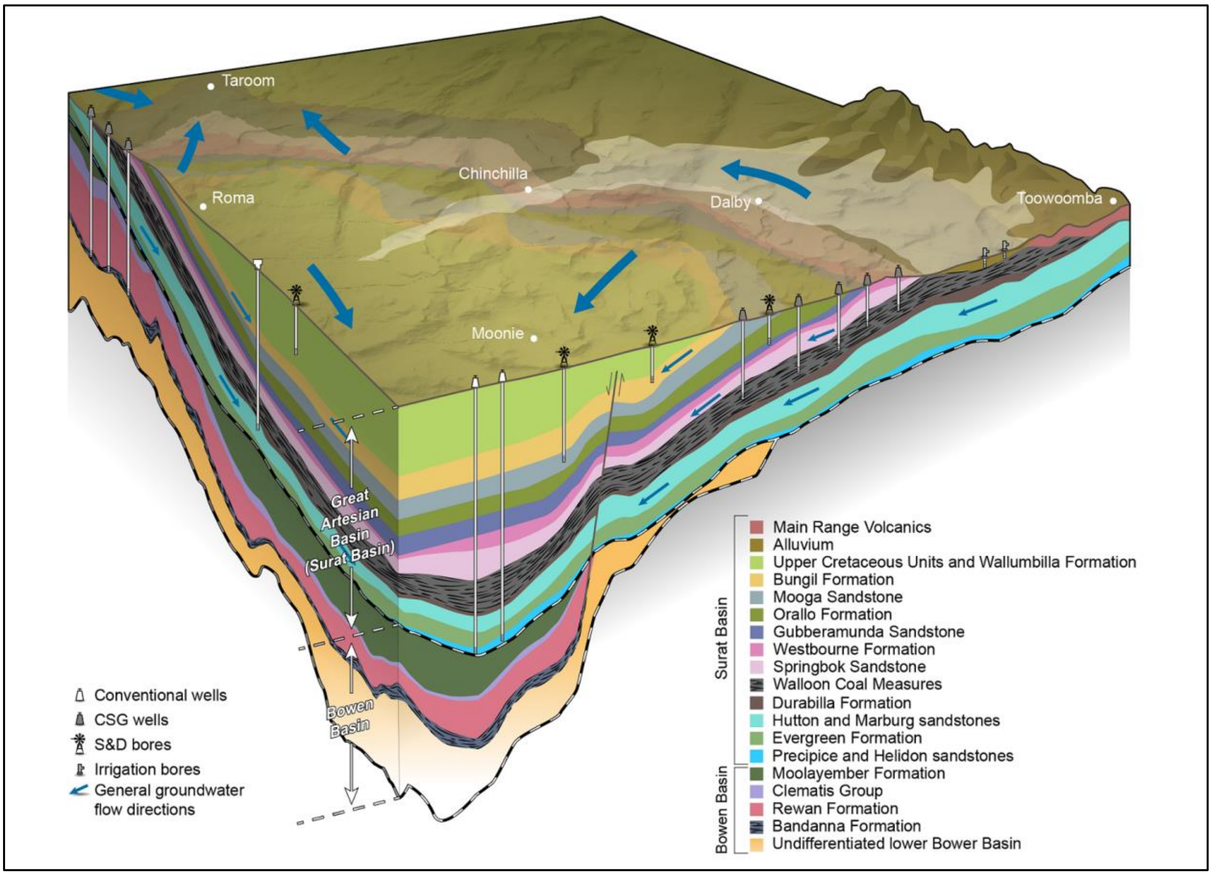

Figure 2-5 Representation of the main groundwater systems in the Surat CMA (OGIA 2019a)

The main aquifers include the Precipice, Hutton, Gubberamunda and Mooga sandstones and the Bungil Formation. The aquifers are predominately recharged by infiltration of rainfall and leakage from streams, into outcropping sandstone mainly on the eastern margins of the basin along the Great Dividing Range (the Range) (Kellett 2003). These aquifers are generally laterally continuous, have significant water storage and permeability and are extensively developed for groundwater use. Locally, aquifers that are relatively shallow and contain good-quality water are more heavily used for water supply.

Groundwater movement is very slow, estimated at less than 2.5 m per year (Ransley & Smerdon 2012). This slow rate of groundwater flow is supported by recent work completed by CSIRO using isotopic data (Suckow et al. 2018) and through use of the OGIA 2016 groundwater flow model (Siade et al. 2018), which suggest groundwater ages in excess of 1 million years over extensive areas across the Surat CMA.

The direction of groundwater flow is predominantly sub-horizontal in the aquifers and natural discharge occurs via springs and watercourses. In the classical conceptual model of the GAB, recharge water flows primarily along bedding planes and fractures from the recharge areas towards the south, southwest and west. However, over the past decade, a number of studies (Hodgkinson, Hortle & McKillop 2010; OGIA 2016b) have shown that two main regional flow systems exist, broadly separated by the Range. North of the Range, groundwater tends to flow northwards towards the Dawson River valley. South of the Range, groundwater tends to flow southwards towards New South Wales. Within these broader flow directions, there are also localised flow systems that occur as a direct result of CSG impacts in the Walloon Coal Measures, or as a result of changes in surface elevation.

2.2.1.2 The Bowen Basin

In the northern part of the Surat CMA, the Bowen Basin occurs at shallow depths. In these areas, there is limited groundwater development. Further to the south, the Surat Basin and other Cenozoic sediments overly the Bowen Basin. In these central and southern parts of the Surat CMA, productive water supplies are sourced from these overlying sediments.

As a result, there are limited data available on the groundwater conditions within the deeper Bowen Basin sediments underlying the Bandanna Formation. However, in general, these formations are fine-grained, 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 age sandstone sediments of the Clematis Group and equivalent formations of the Bowen Basin were historically recognised as aquifers of the GAB, due to their artesian pressure and potential for upward fluxes to overlying formations. However, recent studies have recognised that there is limited potential for fluxes between many underlying basins and the GAB (Ransley & Smerdon 2012; Ransley et al. 2015).

2.2.1.3 Alluvial sediments

Alluvial groundwater systems are associated with a number of significant river systems in the area. These shallow groundwater systems have been variably developed for irrigation, stock and domestic (S&D) and town water supplies. The most significant alluvial resource is associated with the Condamine River.

The Condamine Alluvium is incised into the Surat and Clarence-Moreton basins and comprises gravels and fine to coarse-grained channel sands interbedded with clays. Recharge is primarily by infiltration from the Condamine River, with some contribution directly from rainfall and laterally from the surrounding bedrock and alluvium of the tributaries of the Condamine River. The Condamine Alluvium is extensively developed for irrigation and town water supply purposes, with minor take for domestic, stock watering, industrial, stock-intensive and commercial activities.

2.2.1.4 Tertiary basalts

The basalts of the Main Range Volcanics contain significant aquifers that are accessed for irrigation, S&D and town water supply purposes. These fractured rock aquifers are typically around 45 m thick – up to 222 m in some areas. 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. The water tends to be high-quality because the aquifers respond quickly to recharge from direct infiltration of rainfall, particularly in the elevated areas, and contribute recharge to adjacent, connected aquifers. Tertiary basalts also occur in the north of the area, overlying the Bowen Basin sediments. In general, the aquifers in these northern basalts are not as high-yielding as those of the Main Range Volcanics.

2.3 P&G development

A detailed description of current and proposed petroleum and gas (P&G) development activities in the Surat CMA is provided in the UWIR 2019 (OGIA 2019a). A summary is presented in this section.

Groundwater extraction by the P&G industry is primarily for non-consumptive purposes – the incidental taking of groundwater during oil and gas production. Groundwater 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 water for consumptive purposes including construction, dust suppression and camp water supplies.

Under Queensland legislation, tenure holders are required to report volumes of groundwater extracted (associated water) on a six-monthly basis. In parallel, under the UWIR Water Monitoring Strategy (WMS), tenure holders are required to provide individual well-scale monthly water production data.

OGIA reconciles these two datasets to compile monthly water production volumes for each well. There are currently around 6,800 CSG wells and 70 conventional oil and gas production wells in the Surat CMA. The total annual water production from those wells is shown in Figure 2-6. As shown, there has been a significant increase in the volume of associated water extracted since 2014 to the current level of around 60,000 ML/year. The majority (50,000 ML/year) is from CSG production in the Surat Basin. In comparison, CSG groundwater extraction in the Bowen Basin has remained relatively stable in recent years at around 9,000 ML/year. Petroleum tenure holders also provide OGIA with their current and future production plans at a sub-block scale (Figure 2-7).

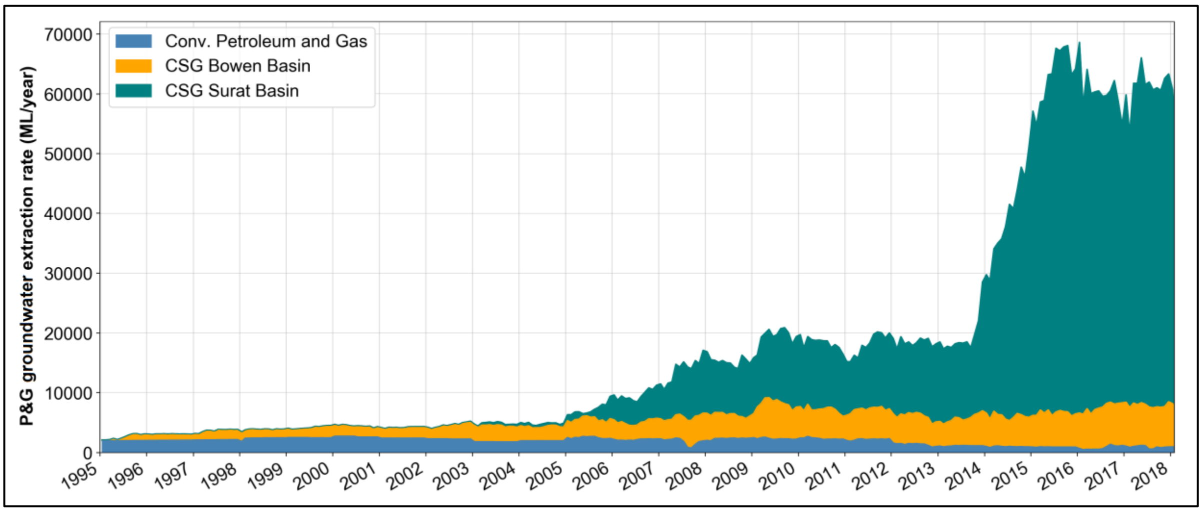

Figure 2-6 Groundwater extraction by the P&G industry in the Surat CMA (after OGIA 2019a)

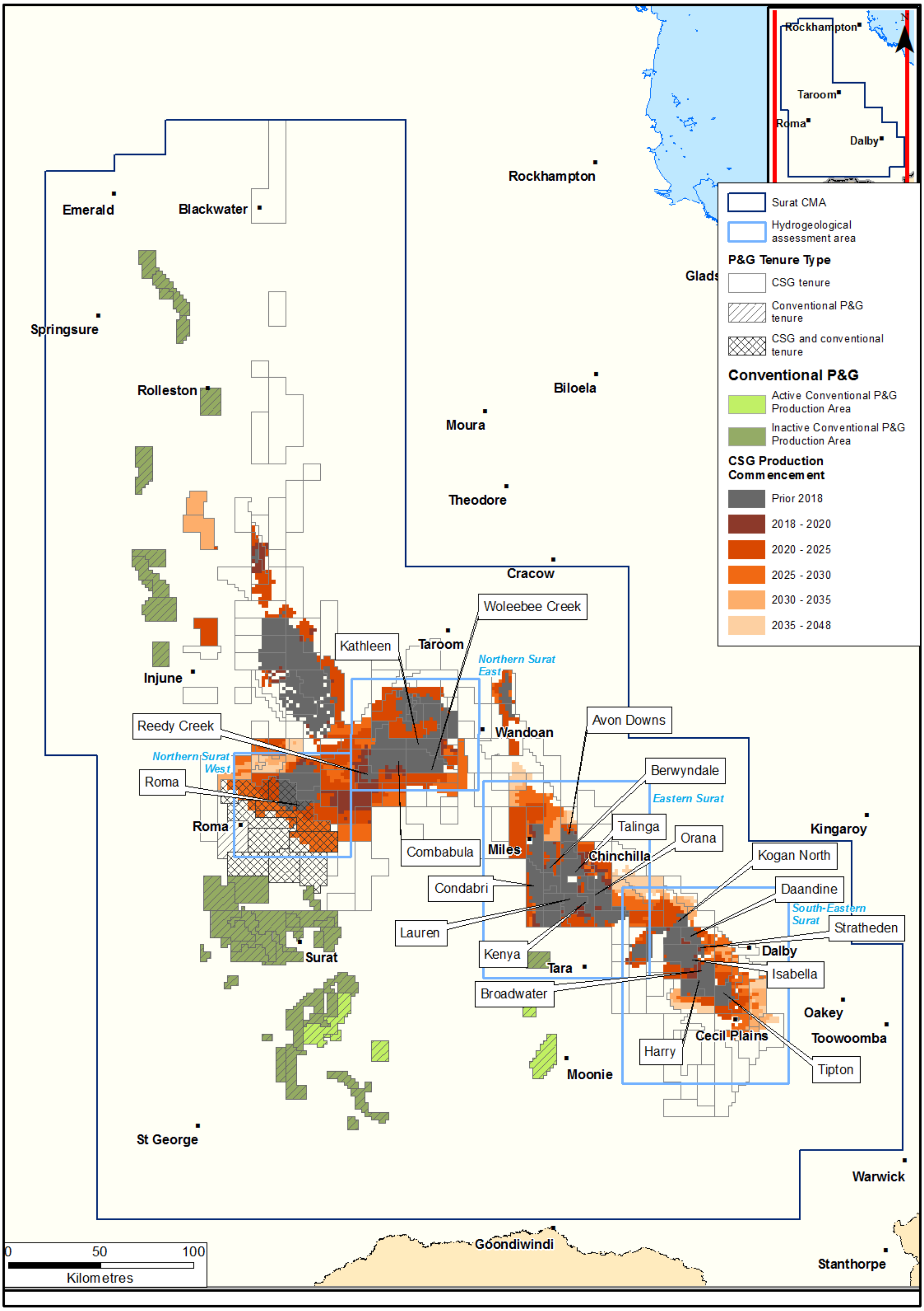

Figure 2-7 CSG production and sub-regional hydrogeological assessment areas

There are five primary CSG companies in the Surat CMA – Santos, Origin Energy, QGC, Arrow Energy and Senex Energy – within three primary production areas:

1. **South-eastern Surat** gas field area west of Cecil Plains and Dalby, primarily in and around Arrow's Kogan North (2005[1]), Tipton West (2005[1]), Daandine (2005[1]) and Stratheden (2009[1]) fields and QGC's Southern Development Area, which includes the Broadwater (2011[1]), Isabella (2011) and Harry (2014) blocks. Total CSG groundwater extraction from fields operating in this area is currently around 8,000 ML/year.
2. **Eastern Surat** gas field area southwest of Chinchilla, primarily in and around Origin's Talinga (2005[1]), Condabri (2013[1]) and Orana (2014[1]) fields and QGC's Central Development Area, which includes the Berwyndale (2005), Kenya (2006), Lauren (2009) and Avon Downs (2014) blocks. Total CSG groundwater extraction from fields operating in this area is currently around 24,000 ML/year.
3. **Northern Surat** gas field area between Roma and Wandoan, primarily in and around Santos's Roma West (2005[1]) and Roma East (2011[1]) fields, Origin's Reedy Creek (2014[1]) and Combabula (2014[1]) fields and QGC's Northern Development Area, which includes the Woleebee Creek (2014[1]) and Kathleen (2014[1]) blocks. OGIA has further subdivided the Northern Surat into west and east sub-areas. Total CSG groundwater extraction from fields operating in this area is currently around 20,000 ML/year.

2.4 Non-CSG water use

Reliable measurement of water use is necessary for hydrogeological investigations, connectivity assessments, analysis of trends in monitoring data and calibration of groundwater flow models.

The requirement to measure and report groundwater extraction in the Surat CMA varies. S&D water use does not require metering. For other purposes, metering of water use is limited (less than 1%) outside of the Condamine Alluvium and Main Range Volcanics.

In the absence of metering data, indirect methods are required to estimate groundwater use. For S&D water use, the underlying principle of the method for estimation is that the deficit between the demand for water supply and the 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, metered data are used where available. In the majority of cases, metered data are not available and the approach is based on estimating the level of use of entitlement volumes or volumetric limit. A review of the limited available metering data indicates that irrigation, agricultural and town water supply use is generally 70–90% of licensed entitlement volume, industrial use is about 50% of the entitlement volume, while groundwater use by feedlot purposes varies with the number of cattle in the feedlot.

A more complete description of OGIA's methodology for estimating non-CSG water use for each individual water supply bore is provided in a separate report (OGIA 2019b).

Estimated water use for S&D and non-S&D purposes in the Surat CMA is summarised in Table 2-1. This table focusses on the aquifers of interest for the groundwater level trend analysis report and provides aggregated numbers for the remaining formations within each groundwater flow system. Growth in estimated water use over the historical period is presented in Figure 2-8. Current estimated

[1] Petroleum Lease grant date.

water use in the Surat CMA is about 160,000 ML/year. However, in the absence of metering data, there is significant uncertainty with this estimate.

Table 2-1 Estimated water use in the Surat CMA (after OGIA 2019a)

Formation	Number of bores			Groundwater use (ML/year)[1]		
	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**
Remaining alluvium and basalt	1,533	7,574	**9,107**	43,143	7,667	**50,810**
Alluvium and basalt subtotal	2,899	10,852	**13,751**	110,466	10,103	**120,570**
Surat Basin (GAB)						
Springbok Sandstone	13	194	**207**	150	364	**515**
Walloon Coal Measures	124	1,008	**1,132**	3,398	1,215	**4,614**
Hutton Sandstone	348	2,697	**3,045**	10,159	3,596	**13,755**
Remaining GAB formations	207	3,495	**3,702**	13,266	8,633	**21,897**
Surat Basin (GAB) subtotal	692	7,394	**8,086**	26,973	13,808	**40,781**
Bowen Basin subtotal	40	594	**634**	1,414	999	**2,413**
TOTAL	**3,631**	**18,840**	**22,471**	**138,854**	**24,910**	**163,764**

Notes:

1. Sum may differ due to rounding.

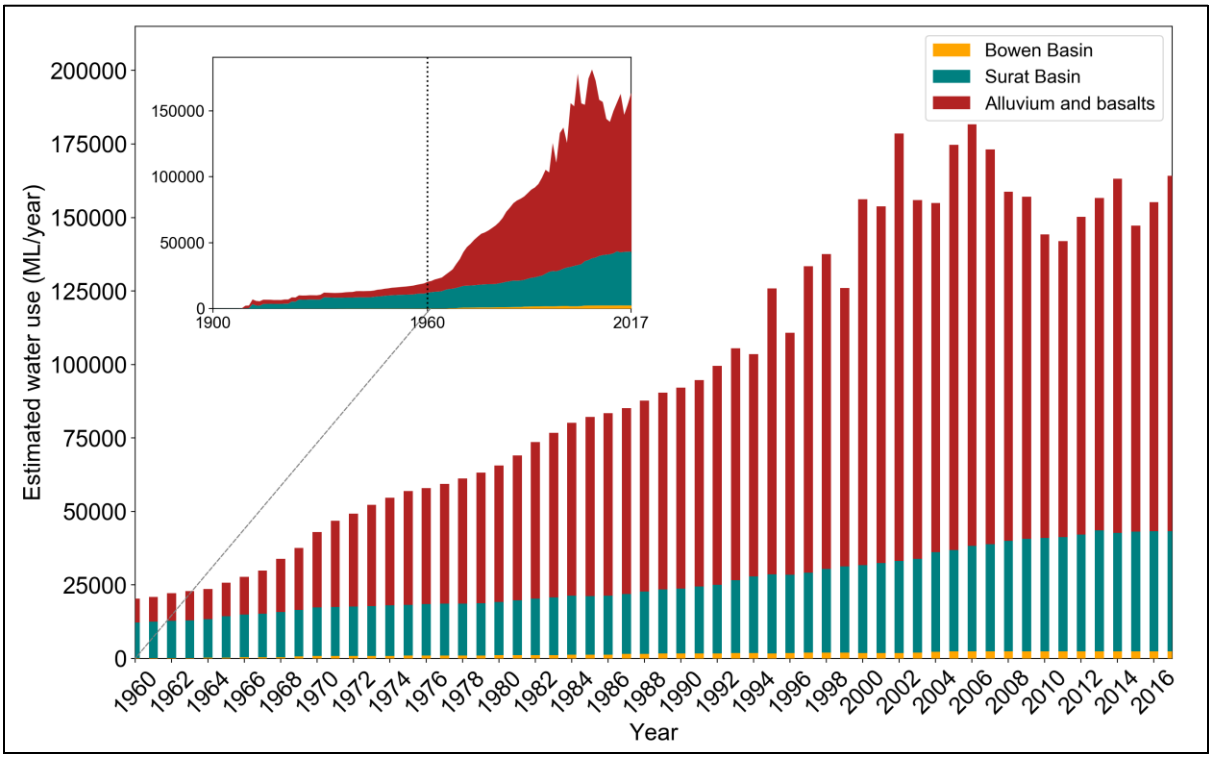

Figure 2-8 Growth in consumptive water use by major formation group (after OGIA 2019a)

3 Monitoring infrastructure and data

This chapter provides an overview of monitoring infrastructure, construction types and corrections applied to raw groundwater level data. A summary of the water quality monitoring network is also provided.

3.1 Data availability

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

Groundwater level monitoring networks for complex and multilayer aquifer systems require both spatial and vertical coverage of monitoring points to provide sufficient groundwater level measurements to inform the assessment of groundwater flow directions and trends. Within the Surat CMA, there is an extensive monitoring network established in the aquifers adjacent to the Walloon Coal Measures.

While an extensive monitoring network has existed for decades in the Condamine Alluvium (OGIA 2016c), the majority of the remaining monitoring infrastructure, particularly in and around the existing and proposed CSG development area, is more recent and was established in response to a rapid increase in CSG development in the last decade. Relatively few monitoring points existed within the gas field areas prior to the commencement of CSG development because:

- there was limited exploitation of the deeper confined parts of the GAB system for water supply and therefore limited monitoring for resource management activities
- GAB aquifers had been predominantly used for relatively small-scale, non-industrial purposes
- the cost of drilling, constructing and maintaining deeper bores (generally more than 200–300 m deep) is prohibitive, especially where only low volumes of water are required.

There are 857 locations where data are available in the Springbok Sandstone, Hutton Sandstone and Walloon Coal Measures in the Surat CMA (Figure 3-1) comprising:

- 327 monitoring points established under the UWIR 2016 WMS (UWIR)
- 279 monitoring points established by CSG operators to meet other specific purposes, including Commonwealth and Environmental Authority conditions of approval (non-UWIR)
- 224 monitoring points and water supply bores recorded on the Queensland Groundwater Database (GWDB) including dedicated monitoring bores operated by the Department of Natural Resources, Mines and Energy (DNRME) and water supply bores with lower frequency monitoring (other GWDB)
- 27 water supply bores monitored by landholders under DNRME's Groundwater Net Program (Groundwater Net).

Table 3-1 provides a summary of monitoring points in the Walloon Coal Measures and the directly overlying and underlying geological formations. Around 60% of the GAB monitoring points are constructed in the Walloon Coal Measures. The quality of monitoring data varies depending upon the construction of the monitoring point, the installation of monitoring equipment and whether the monitoring point is directly influenced by pumping in the immediate vicinity of the site.

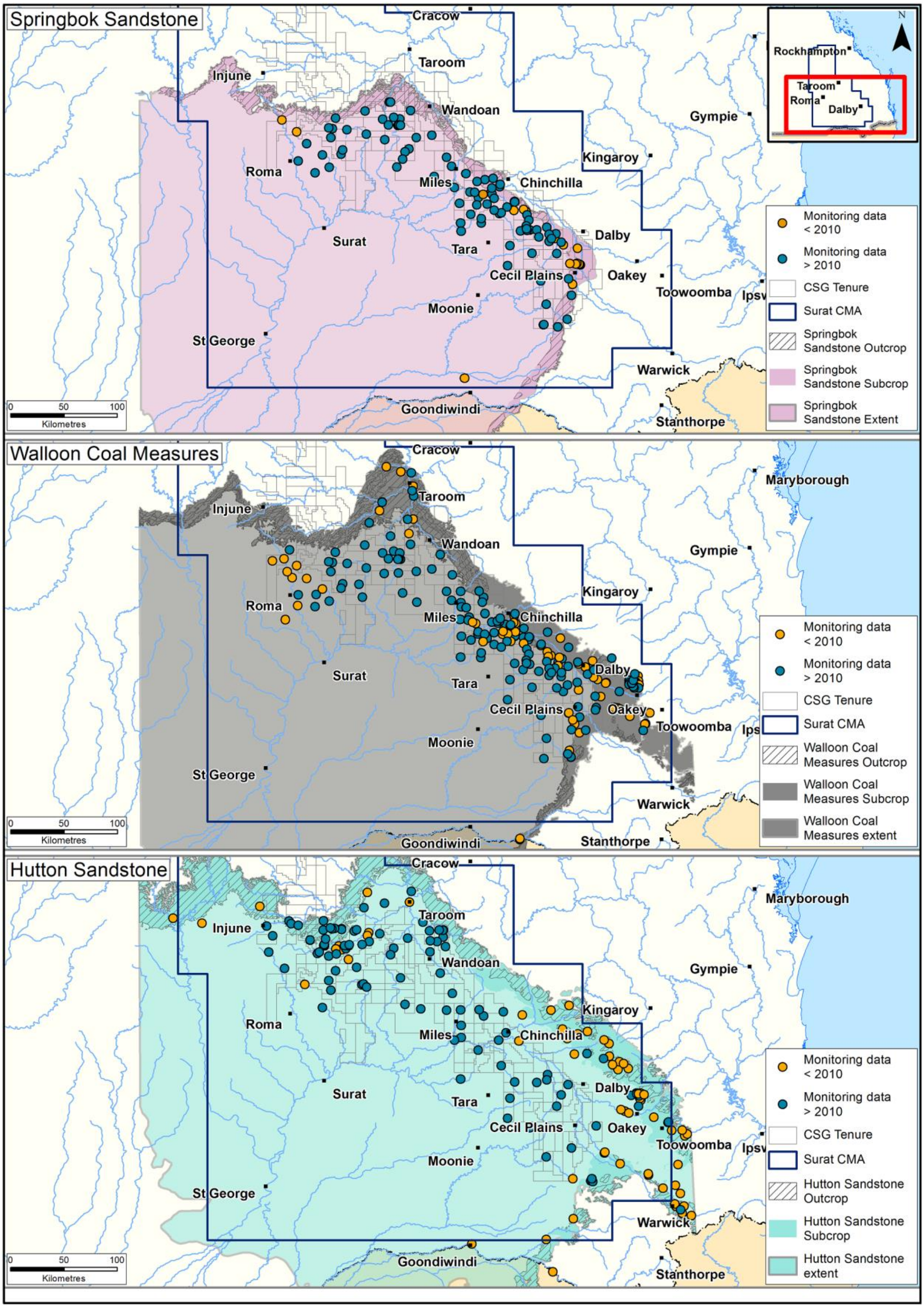

Figure 3-1 Distribution of monitoring points in the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone

Table 3-1 Summary of monitoring points in the Walloon Coal Measures and adjacent aquifers

Hydrostratigraphic unit	UWIR	Non-UWIR	Groundwater Net	Other GWDB	TOTAL
Cenozoic sediments					
Condamine Alluvium	18	12	1	181	**212**
Great Artesian Basin (GAB)					
Springbok Sandstone	54	45	1	30	**130**
Walloon Coal Measures	225	181	4	104	**514**
Hutton Sandstone	48	53	22	90	**213**
GAB Total	**327**	**279**	**27**	**224**	**857**

The distribution of groundwater level monitoring points in the Surat CMA for the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone is shown in Figure 3-1. The map symbology indicates where monitoring data prior to 2010 are available. As shown, the majority of monitoring points have been constructed in the last decade, with only a small number of points with any groundwater level records prior to 2010.

Table 3-2 provides a detailed summary of the temporal resolution of the monitoring points in the Springbok Sandstone and Hutton Sandstone. As shown, only 34 monitoring points have at least one year of data prior to 2010 (i.e. more than four records over a period exceeding one year) that can be used for trend analysis. In comparison, there are 189 monitoring points that have at least one year of continuous data post-2010.

Table 3-2 Summary of the Springbok Sandstone and Hutton Sandstone dataset

	Monitoring points		
Category	**Springbok Sandstone**	**Hutton Sandstone**	**Total**
>1 year prior to 2010	6	28	34
>1 year post 2010	91	98	189
Monitoring points with <1 year or incomplete data	33	87	120
Total	**130**	**213**	**343**

3.2 Monitoring point construction

The monitoring data included in the trend analysis have been collected from a range of monitoring infrastructure including dedicated, purpose-built monitoring points and water supply bores opportunistically monitored by landholders, tenure holders and DNRME. This section provides a brief overview of construction types in the Surat CMA.

Tenure holder monitoring installations can be broadly grouped into three categories:

- **Single aquifer piezometer** – these monitoring points have a similar construction to modern water bores and are typically used in formations above the CSG reservoir. The measurement of groundwater pressure is typically undertaken using a groundwater 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 *Petroleum and Gas (Production and Safety) Act 2004.* There are different specifications for these CSG completions compared to monitoring bores, mainly to manage risks associated with the presence of flammable gas under pressure. In most cases, multiple monitoring points are installed within a single well. The measurement of groundwater pressure is undertaken using groundwater level loggers suspended or cemented within the casing.
- **Cemented vibrating wire piezometer (VWP)** – these monitoring points are typically exploration or core holes that have been repurposed for monitoring. Multiple aquifers are often monitored at these sites with the measurement of groundwater pressure undertaken using VWP sensors cemented within the boreholes. This type of construction is gradually being phased out from the UWIR network due to reliability issues.

For the most part, the UWIR network comprises monitoring points that have been specifically constructed by tenure holders in accordance with the UWIR. These monitoring points are specified in consideration of the spatial and vertical position to provide the necessary information to monitor the propagation of CSG-induced groundwater level impacts through time. An important limitation with this network is the length of available record, with very little data available prior to the onset of large-scale CSG development. In parallel, many of the early installations utilised cemented VWPs which often take a number of years to equilibrate, and the accuracy of which is unable to be easily verified. VWPs are being gradually phased out and replaced with more appropriate monitoring installations.

The non-UWIR company monitoring network provides additional data in the immediate areas of CSG development where long-term impacts are expected. These monitoring points have been constructed by tenure holders for a range of purposes, including local hydrogeological investigations. These monitoring points are often situated within authority to prospect or petroleum lease areas and provide useful near-field groundwater level responses to CSG stresses. As with the UWIR network, these monitoring points typically only provide records in the last decade.

The DNRME monitoring network has been designed and constructed to provide long-term data on important water supply aquifers throughout Queensland. In the Surat Basin, this monitoring network is largely focussed on the Condamine Alluvium. In the other formations, including the Springbok and Hutton sandstones, monitoring has historically focussed on outcrop areas and shallower parts of the aquifers, reflecting historic patterns of groundwater extraction. Some of the records extend back over 100 years and provide valuable data on long-term groundwater level trends.

The privately owned monitoring points are those bores that are primarily also used for water supply purposes such as S&D, stock-intensive, agriculture and town water. Often, the geological formation is not known with great accuracy and the bores are used for private groundwater extraction, so they are therefore prone to pumping-induced impacts on groundwater levels. Another limitation of these data is the lack of regular temporal records, with most sites often containing only one or two records. Usually, these levels are obtained directly after drilling, with the risk being that the records are prior to equilibration between the bore and the formation. Despite these limitations, these monitoring points still provide valuable supplementary information to understand long-term groundwater level trends in the Surat Basin, particularly in areas or time periods where data from the UWIR and company networks are limited.

3.3 Density corrections

To accurately represent and interpret groundwater level trends, it is necessary to correct for variations in temperature and salinity, which are the primary influences on groundwater density (Welsh 2007). These influences can be accounted for by correcting hydraulic head measurements to a reference density (Post, Kooi & Simmons 2007).

Three types of correction have been applied (after OGIA 2016b): one for correcting the combined influence of temperature and salinity on fluid density; one to undertake a water column correction; and another to convert groundwater heads to fresh water reference heads at 20°C (TDS, 0 mg/L). Additional details on the equations and methods of correction applied are provided in 0.

3.4 Groundwater chemistry monitoring

Hydrochemical analysis is a key element of the analysis of groundwater levels. Hydrochemistry data are available from a number of different sources (Table 3-3) including:

- CSG production well data – the largest dataset, typically comprising time series data of major ion concentrations from operational CSG production wells.
- UWIR WMS monitoring points – installed and operated by tenure holders as specified in the Surat UWIR. Time series major ion data are typically available.
- Single samples taken from private water supply bores by tenure holders as part of baseline assessments. These samples typically include major ions.
- Major ion data held within the GWDB relating to state monitoring network bores and privately owned water supply bores. Data are typically limited to single sample events taken during, or soon after, completion of the bores.
- Data collected by OGIA as part of various project investigations.

There are about 1,150 CSG wells in the Walloon Coal Measures to analyse for trends in associated water quality. Additionally, there are about 170 monitoring points in the Springbok Sandstone and Hutton Sandstone to characterise the water types for the aquifers themselves. These data points are spread across the Surat Basin, with fewer points located in areas of subcrop and outcrop.

Table 3-3 Available hydrochemistry data for the Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone

Formation	Data source	Monitoring points	Samples
Springbok Sandstone	UWIR WMS	28	126
	Baseline assessment	33	36
	GWDB	31	54
	OGIA investigation	5	5
	Total	**97**	**221**
Walloon Coal Measures	CSG production well	1149	5063
	UWIR WMS	11	31
	Baseline assessment	25	25
	GWDB	101	162
	OGIA investigation	6	6
	Total	**1292**	**5287**
Hutton Sandstone	UWIR WMS	23	72
	Baseline assessment	11	12
	GWDB	38	83
	OGIA investigation	5	5
	Total	**77**	**172**

4 Key concepts for trend analysis

This chapter provides a summary of the key concepts in relation to understanding groundwater level trends in confined and unconfined groundwater systems. Specifically, the water balance and non-water balance factors that influence groundwater level behaviour are described. This is important context for the analysis of trends in the subsequent chapter.

4.1 Terminology

Hydrogeological terms commonly applied are defined in this section. This terminology has been simplified to improve accessibility for a broader audience. More technical definitions are available from text books such as Freeze and Cherry (1979) or Domenico and Schwartz (1998).

A generic term – ***groundwater level*** – is used to refer to the water table or groundwater pressure in an aquifer, unless stated otherwise.

A ***water table*** is defined as the level to which water rises in a bore screen in an unconfined aquifer, i.e. an aquifer that occurs at ground surface (Figure 4-1). Below the water table, the unconfined aquifer pore spaces and/or fractures are filled with water, i.e. the aquifer is saturated. Above the water table (and the capillary fringe), the formation is unsaturated. The water table fluctuates by physical addition or removal of water, into or out of the pore spaces.

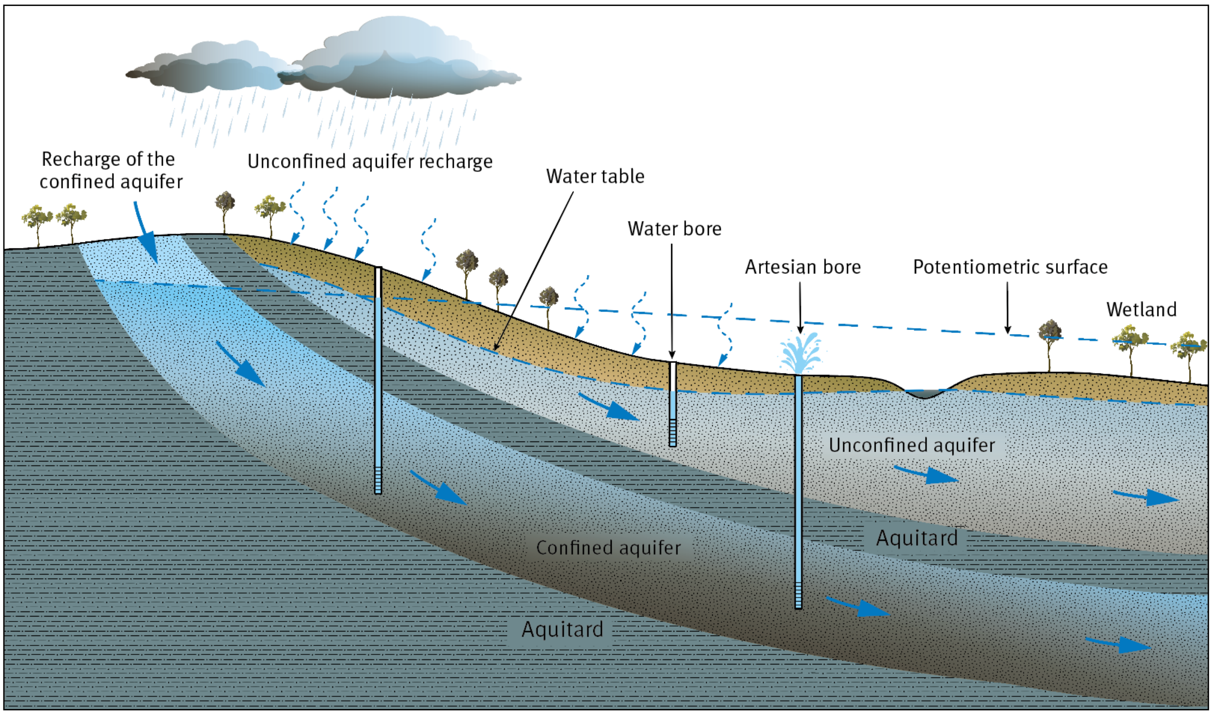

Figure 4-1 Schematic of groundwater levels in confined and unconfined aquifers (OGIA 2016a)

When a water bore is completed in a confined aquifer (Figure 4-1), the groundwater pressure in the aquifer causes the groundwater level in the bore to rise above the top of that specific formation. The level to which water rises is the ***piezometric surface*** or ***pressure level*** or ***hydraulic head*** of the aquifer. Confined aquifers are aquifers that are covered (confined) by low-permeability layers such as clay(stone), silt(stone) or mud(stone) – common lithology types encountered in most GAB formations. These confining layers are referred to as ***aquitards***. Unlike an unconfined aquifer, a confined aquifer remains fully saturated – water is held in pores and fractures under pressure because it cannot easily escape through the confining aquitard. In specific circumstances, the pressure level may be above the ground surface, allowing for artesian bore conditions, or natural discharge springs, where groundwater freely discharges at the surface.

Hydrograph is a term used for a graph of groundwater level versus time for an individual monitoring point. In Australia, a groundwater level is typically expressed as metres above Australian Height Datum (mAHD) and time will typically be a function of the length of the monitoring record – varying from days to years to decades.

Groundwater level trend is a term used to describe changes in groundwater level or pressure over a specific period. Groundwater level trends are typically compared to static conditions (or assumed static conditions) when the aquifer was in equilibrium, often referred to as ***steady-state***. An observed decline in groundwater level from static conditions is often referred to as ***drawdown***. An increase in groundwater levels from static conditions is often referred to as ***mounding***.

Monotonic trend is a mathematical and statistical term that refers to a consistent trend that occurs in one prominent direction – such as a persistent increasing or decreasing trend. Monotonic trends can be either linear or non-linear. In non-linear monotonic trends, the variable tends to move in the same relative direction, but not at the same rate through time. A monotonic trend refers to simply overall increasing or decreasing groundwater level trends.

4.2 Influences on groundwater level trends

At any given point in time, a number of factors may influence the groundwater level in a bore. These factors can be grouped into two categories:

- **water balance** – relating to a change in the volume of water stored in the aquifer
- **non-water balance** – relating to changes in pressure conditions without an associated change to the water balance.

4.2.1 Water balance factors

In an undeveloped aquifer, the groundwater level represents a balance between recharge and discharge, or input and output, established over a long period of time, i.e. steady-state conditions. When the rate of recharge to an aquifer exceeds the rate of discharge, groundwater levels will rise or 'mound'. Conversely, when the rate of groundwater discharge is greater than the rate of groundwater recharge, groundwater storage is depleted and groundwater levels decline (Taylor & Alley 2001).

4.2.1.1 Pre-development conditions

In Queensland, aquifer recharge sources typically include diffuse rainfall recharge and leakage through the bed of streams. This typically occurs in outcrop areas, where the aquifer is exposed at higher elevations. Once recharge water enters the aquifer system, it flows down-gradient, from areas of higher groundwater level to areas of lower groundwater level. Rapid flow will generally occur through higher-permeability zones, with stagnant flow conditions occurring in tighter, less permeable zones. Inter-formation flow occurs where groundwater level differences occur between formations (typically across an aquitard that physically separates two aquifers). Outflow or discharge is through base flow to rivers and streams, spring discharge, evapotranspiration losses and lateral and vertical losses to other surrounding aquifers.

All other factors being equal, if average rainfall recharge was to occur every month, there would be little or no variation in groundwater level, as the inputs and outputs would not deviate through time.

However, during extended periods of above-average or below-average rainfall recharge, groundwater levels tend to rise or fall accordingly as storage in an aquifer changes.

For a larger groundwater system such as the GAB, there may be a long lag time between the rainfall/recharge variations at surface and response in deeper parts of the groundwater system. This pressure signal or pressure wave tends to decrease in amplitude, as a function of further distance from the recharge source and closer proximity to the discharge boundary conditions. Therefore, 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 more attenuated and delayed responses.

A recharge pulse or signal is likely to become more muted in the deeper, confined parts of the basin, due in part to the time taken for the recharge pulse to propagate to these deeper areas. In connected, permeable formations, the impacts of groundwater extraction in these deeper, steady-state parts of the basin are often apparent over large distances, as they present as sudden declines in groundwater levels that reflect instantaneous removal of groundwater from confined aquifer storage.

The water table response to rainfall may be muted or diminished in low-permeability formations and/or formations with deep unsaturated zones within outcrop areas. Only minor volumes of recharge will reach these aquifers. In these circumstances, groundwater levels may not be strongly influenced by periods of drought or higher rainfall.

The magnitude of groundwater level variation or fluctuation varies between unconfined and confined aquifers. This primarily relates to the difference in storage terms for each aquifer type. Storage terms describe the volume of water released from a unit volume of aquifer, per unit decline in head. Unconfined aquifers release water owing to the ***specific yield*** term, while confined aquifers release water owing to the ***specific storage***. The specific yield varies according to aquifer type and typically varies between 0.01 and 0.3 (Freeze & Cherry 1979). The specific storage of confined aquifers depends on the mass density of water, the effective porosity, the aquifer compressibility (material-dependent) and the compressibility of water. It tends to be less than 1.3×10^{-5} (Rau et al. 2018). This means that taking water from a confined aquifer will result in much greater head declines than would taking the same volume from an unconfined aquifer, because less water removal is required to create a unit change in head.

4.2.1.2 Non-CSG water use

Groundwater extraction for non-CSG purposes (e.g. S&D, town water supply, agriculture) removes water directly from aquifer storage. Depending on other water balance components (i.e. recharge and discharge boundaries), this extraction will result in groundwater level decline. Continued extraction will further deplete storage and may impact aquifer system boundaries, by either increasing recharge or decreasing discharge. This impact on boundaries is often termed ***capture*** (Theis 1940; Konikow & Leake 2014). Eventually, continued extraction from the aquifer will result in a new water budget equilibrium condition and groundwater level decline will tend to stabilise. For very large groundwater systems, such as the GAB, the time required to reach a new equilibrium may be very long, i.e. decades to centuries. Any subsequent decrease in extraction may lead to partial or full recovery of groundwater levels, depending on the distance from the stress to the monitoring point.

4.2.1.3 CSG groundwater extraction

Direct withdrawal of water from confined CSG target formations creates immediate and large declines in reservoir groundwater levels, usually over large areas, owing to the large number of wells rather than basin-scale connectivity. In addition to lateral flow from distal parts of the coal seam and sedimentary interbeds, depressurisation also creates an appreciable vertical groundwater level difference (or head difference) between the coal reservoirs and the overlying and underlying aquifers. Depending on the vertical resistance of the beds between the reservoirs and the aquifers, this head gradient may induce vertical flow of water from the aquifers towards the CSG target formations. In instances where aquitards are present and vertical resistance is high, such vertical flow may take a long time to develop and will be restricted by the low vertical permeability; this could take decades or centuries to occur. The eventual aquifer response will be an additional discharge component that will present as a corresponding aquifer groundwater level decline.

4.2.2 Non-water balance factors

There are a number of other factors that may influence water and are unrelated to changes in the aquifer water balance. This section describes four main effect processes with relevance to the GAB: geomechanical loading and unloading, density, tidal and barometric effects. Analysis by OGIA (OGIA 2016b) indicates that these factors are minor contributors to the overall groundwater level trends observed when compared to the water balance factors (section 4.2.1). Therefore, these factors may be important for assessing very small changes in groundwater levels, but are less significant when metres of drawdown are observed in a monitoring point. Given that this project seeks to identify metre-scale drawdown trends over periods of months and years, the following non-water balance factors are not considered further in this analysis.

4.2.2.1 Mechanical loading and unloading effects

Jacob (1939) reported the first evidence of mechanical loading influencing groundwater levels when rising and falling groundwater levels in an aquifer were observed as a train passed by. The rise in groundwater level was associated with an increase in total load acting on the aquifer causing an instantaneous compaction of the aquifer matrix (Harrington & Cook 2011). Numerous researchers (van der Kamp & Maathuis 1991; Bardsley & Campbell 1994; van der Kamp & Schmidt 1997) have also shown that confined aquifers can behave as geological weighing lysimeters whereby any change in surface water loading and unloading (for example, through rainfall and subsequent evapotranspiration) leads to measurable changes in the hydrostatic pressure in underlying formations (Harrington & Cook 2011). The typical magnitude of impact on groundwater levels from loading and unloading has been shown to be minimal (mm to cm scale) and insignificant compared to the large impacts from within-aquifer pumping or inter-aquifer leakage (Brown et al. 2015).

Another phenomenon involving poroelastic effects is the Noordbergum effect, which sees sudden rising pressures in confined overlying aquifers as a result of pumping extraction in underlying reservoirs or aquifers. This effect cannot be accounted for by groundwater theory, as it relates to overburden load transfer.

4.2.2.2 Density effects

Changes in the salinity and temperature of groundwater can affect the density of water in the aquifer, which subsequently influences groundwater pressure measurements. This is the primary reason why equivalent freshwater head corrections are used when calculating horizontal or vertical flow in a variable-density groundwater system (Post, Kooi & Simmons 2007). However, for a groundwater level change to occur at a specific well, the density of water must change in the aquifer; this means that temperature or salinity must change for the groundwater level to change. This would require an influx of a less saline or more saline water body, or an influx of lower- or higher-temperature water.

4.2.2.3 Tidal effects

Tidal forces cause the crust of the Earth to distort, which can create observable groundwater level fluctuations in water bores and monitoring points (Jackson & Fenelon 2018). However, these changes tend to be up to 3 cm in wells penetrating aquifers with small storage coefficients (Jackson & Fenelon 2018). Given that the current trend analysis project seeks to identify metre-scale drawdown trends over periods of months and years, tidal effects have not been considered further in this analysis.

4.2.2.4 Barometric loading effects

Groundwater levels in water bores and monitoring points completed in confined aquifers are also influenced by changes in atmospheric pressure. An increase in atmospheric pressure results in a decrease in groundwater level in the well (and an increase in groundwater pressure in the well and aquifer), while a decrease in pressure results in an increase in groundwater level in the well (and a decrease in water pressure in the well and aquifer) (Harrington & Cook 2011).

Barometric pressure-induced groundwater level fluctuations tend to be greatest in deep, confined aquifers where the rock matrix absorbs most of the load (Jackson & Fenelon 2018). Atmospherically induced groundwater level fluctuations are typically less than 6 cm across a day, with large changes generated by regional storms resulting in up to 30 cm of change during a week (Jackson & Fenelon 2018). Given that the current trend analysis project seeks to identify metre-scale drawdown trends over periods of months and years, barometric loading effects have not been considered further in this analysis.

5 Approach to groundwater level trend analysis

This chapter provides a summary of the approach to the analysis of groundwater level trends. In this chapter, some technical content is simplified – reflecting the varied audience – and the qualitative and quantitative elements of the groundwater level trend analysis approach are described.

5.1 General

As described in section 4.2, an observed groundwater level (effect or signal) in a bore may be influenced by a range of factors that are imposed on a groundwater system. The primary focus of this assessment is to understand the extent to which the observed groundwater level trends reflect impacts due to CSG groundwater extraction.

An impact from non-CSG water use is a reference to stresses resulting from groundwater extraction for purposes such as for S&D, feedlot, irrigation or town water supply. For this assessment, non-CSG impacts are considered part of the **background trend**. This term is generally used to refer to natural variations in groundwater levels caused by natural recharge and discharge processes; however, because non-CSG water use in the GAB largely predates groundwater level monitoring records, it has become part of the 'known' background signal in most areas away from and prior to CSG development (Figure 5-1).

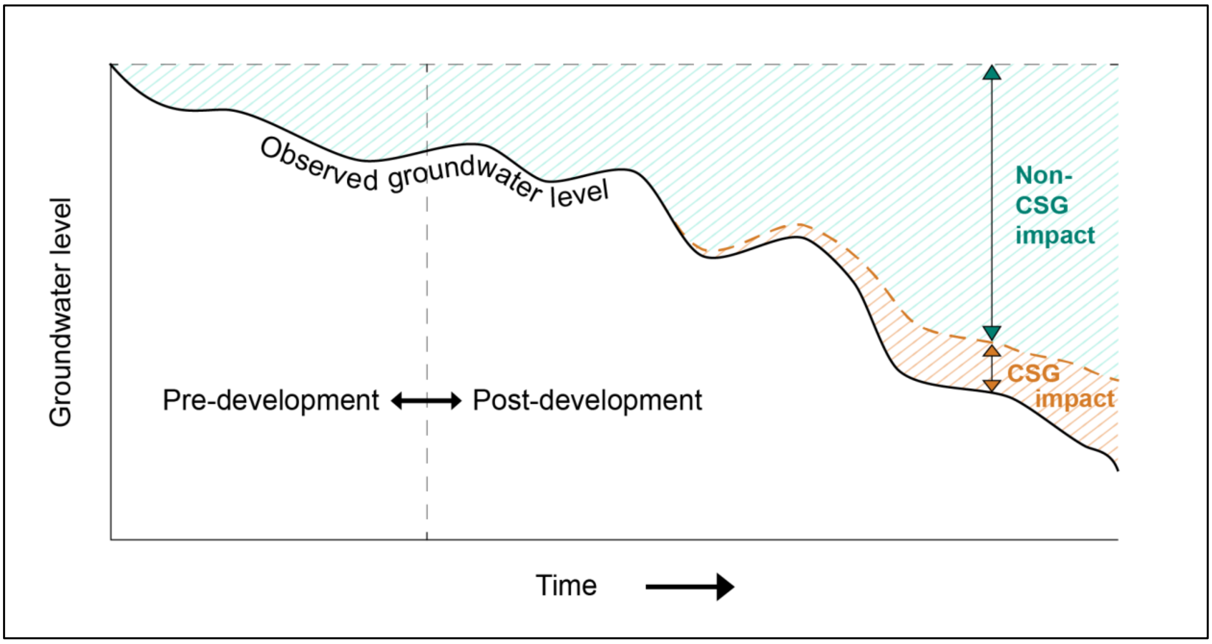

Figure 5-1 Schematic of a hydrograph showing the challenge of separating climate variability, non-CSG water use and CSG impacts from the available information

Observed groundwater levels in overlying and underlying formations may show a combined effect of CSG and non-CSG impacts. Therefore, to separate the impact of CSG groundwater extraction from non-CSG water use, an understanding of background stresses and background trends is first required.

There are two primary mechanisms by which CSG groundwater extraction can influence groundwater levels in overlying and underlying formations:

- Change in aquifer storage resulting from induced groundwater flow from those surrounding aquifers to the heavily depressurised CSG reservoir. This flow can be across the formations where they are in contact (or through localised connectivity features), or across intervening aquitards – both situations being dependent upon the degree of interconnectivity[2].
- Mechanical unloading caused by depressurisation of the CSG reservoir. As discussed in section 4.2.2.1, this effect is likely to be minimal.

For this assessment, the preferred approach to assess the influence of competing stresses was to review groundwater levels (i.e. hydrograph analysis) and temporally compare this with the timing and magnitude of known CSG and non-CSG stresses at representative locations across the basin. This type of correlation analysis does not confirm an impact, but rather frames the plausibility of an impact occurring, given the nature of the various stresses involved.

5.2 Challenges to separation of CSG from non-CSG impacts

Separating CSG impacts from non-CSG impacts is a challenging task, given that non-CSG stresses are already impacting groundwater levels in most GAB formations as a result of many decades of non-CSG water use. As will be demonstrated in later chapters, this long-term non-CSG stress has resulted in declining background levels in most aquifers. CSG impacts will therefore be an additional drawdown component on an already affected groundwater level signal. This is why understanding the nature of background trends in each formation is important.

Once a background trend is established or at least contextualised, CSG impacts can be inferred where a deviation from the background trend is noted. In simple terms, this may be a downward inflection point in an observed groundwater level trend where non-CSG stresses are stable over a reasonable period of time. This concept is illustrated schematically in Figure 5-2. There are also quantitative methods, such as spectral signal analysis and numerical modelling, which can be used for separating CSG and non-CSG impacts. The accuracy of these methods is highly dependent on the quality and comprehensiveness of the datasets used, including accurate time series records of non-CSG water use, which are often unavailable in the Surat CMA.

In practice, establishing a background groundwater level trend in the aquifers of interest in the Surat CMA is somewhat complex, since multiple time-dependent stresses are imposed on the system.

[2] The term ‘interconnectivity’ is considered here to reflect the resistance to the flow of groundwater between formations. The degree of connectivity depends upon the inherent properties of the relevant formations. If no material separates the formations, connectivity depends on the vertical hydraulic conductivity (Kv) of the two formations. If material is separating the formations, connectivity also depends on the vertical hydraulic conductivity and thickness of the separating material. This definition is similar to the one described by Renard & Allard (2013).

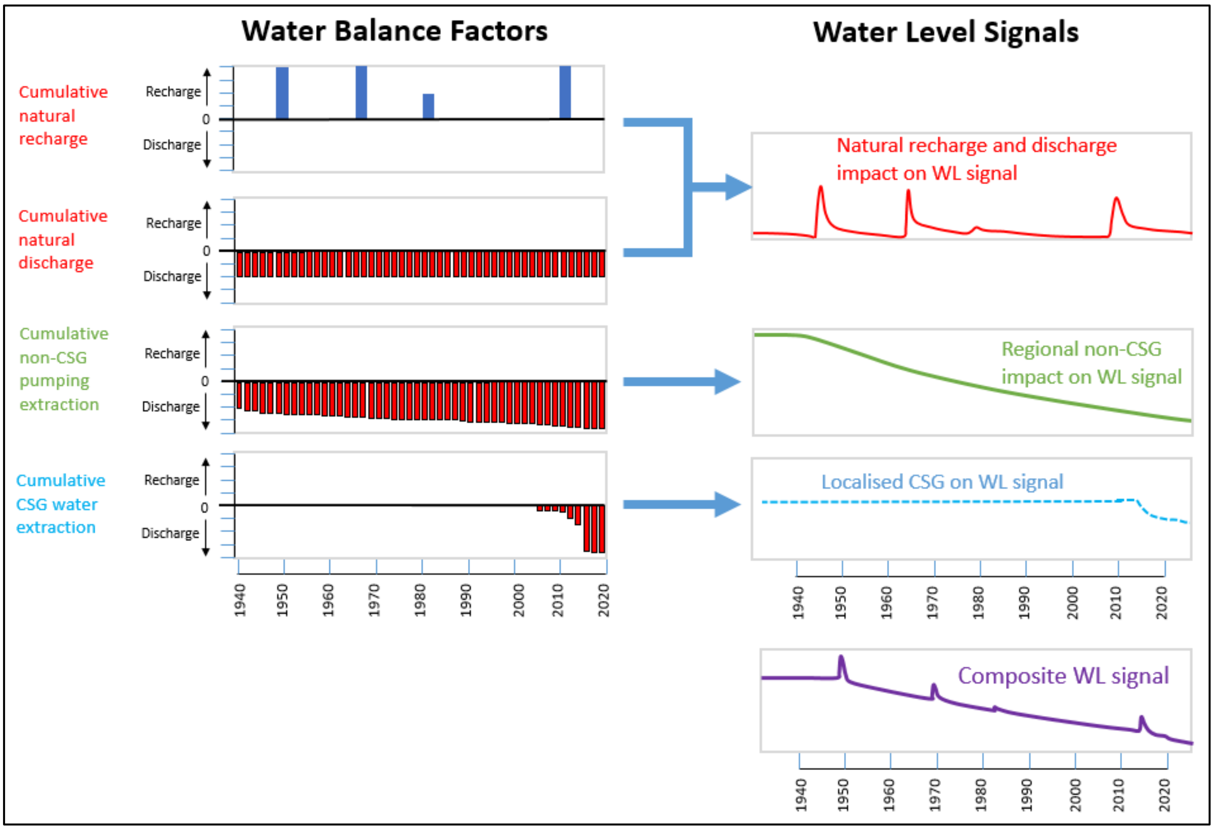

Figure 5-2 Schematic of the conceptual influence of regional water balance factors on groundwater level signals

Barriers to establishing a background trend include the following:

- Although an extensive CSG groundwater monitoring network has been implemented in the last decade, there is a general lack of reliable time series groundwater level data in overlying and underlying confined GAB formations prior to CSG development.
- Establishing background trends requires reliable temporal measurements of non-CSG water use. While the actual locations (spatially and vertically) of extractions are now reasonably well understood[3], non-CSG water use measurements are generally not available for confined GAB formations. Estimates of non-CSG water use therefore have considerable uncertainty associated with them.
- In surrounding aquifers and in early stages of development, potential CSG impacts are likely to be a relatively minor component of the overall trends in a given monitoring point and may be within the bounds of uncertainty associated with other more influential factors, such as climatic variations and non-CSG water use estimates.

5.3 Approach

To overcome the challenge of defining background trends (section 5.2), OGIA took an approach whereby multiple lines of evidence, including both qualitative and quantitative methods, are integrated to establish the nature of the trends and determine the likely causes of those trends.

[3] OGIA has invested significant time and effort in accurate aquifer attribution of all registered bores in the Surat Basin using historical drilling records supplemented with geological, hydrochemical and hydraulic lines of evidence.

Approaches developed and applied by others – such as the United States Geological Survey's (USGS) guidance on statistical methods in water resources (Helsel & Hirsch 2002) and QGC's groundwater level trend analysis framework (QGC 2013) – have also been considered.

The information gained and lessons learned from statistical analyses, sub-regional and local-scale hydrogeological conceptualisation and numerical hypothesis testing were integrated to assess the potential for CSG impact at each site. The methodology quantifies the magnitude and nature of observed trends and seeks to correlate observed trends with specific stresses, to identify plausible explanations for the observed trends. It then uses qualitative and quantitative hydrogeological analysis to incorporate knowledge of the processes occurring, in order to assess the likely degree of connectivity and evidence for causation of trends.

Key considerations in determining impact at each monitoring point included the following:

- the magnitude, timing and correlation of observed drawdown in the CSG reservoir
- the magnitude, timing and correlation of observed drawdown in the aquifers adjacent to the reservoir
- local hydrogeological characteristics of the formations between aquifers and the reservoir
- proximity to connectivity features (e.g. interpreted faults)
- proximity to non-CSG water use, including the timing and magnitude of extraction.

5.3.1 Data preparation

Prior to commencement of the trend analysis, the raw input datasets are reviewed, corrected and processed to ensure suitability for subsequent analysis. Key tasks include the following:

- Examination of the data to exclude any data errors and/or anomalies. These data errors include spurious outlier measurements, obvious datum shifts in the groundwater level time series and spurious data from some VWPs.
- Correction of density and barometric effects – see Appendix F.
- Smoothing of groundwater level record, CSG groundwater extraction volume and CDMMR using a rolling mean, resampled at a monthly frequency. The resampling and smoothing is intended to remove serial correlation and background noise (such as barometric and earth tide effects) for the purpose of long-term trend analysis. In heavily exploited unconfined aquifers, a longer rolling mean is applied to further smooth the groundwater levels and remove the natural noise and pumping variability.
- A breakpoint analysis was performed on selected monitoring points to separate the groundwater level record into discrete periods, each having a monotonic trend. In longer-duration hydrographs, this entails breaking the record into periods of sustained drawdown and periods of rapid groundwater level rises. In shorter-duration hydrographs, some monotonic segments have been further subdivided where inflection points are noted in the rate of drawdown. This further subdivision was aimed at identifying changes in drawdown that may be correlated with nearby CSG groundwater extraction.

5.3.2 Statistical analysis

Two statistical tests are completed to support the analysis. A modified Mann-Kendall analysis is used for the detection of regional trends in each aquifer for selected time periods; a Spearman correlation is then performed at selected outcrop and deeper basin monitoring sites to assess the degree of correlation between groundwater levels and water balance factors. The outputs from the application of the statistical tests are then considered as lines of evidence in the assessment of CSG impacts on groundwater levels, as follows:

- A modified Mann-Kendall analysis for all Springbok Sandstone and Hutton Sandstone monitoring points in the UWIR monitoring network, where at least 12 months of groundwater level records are available. These sites tend to be deeper in the basin, are less prone to recharge-induced seasonality and generally exhibit monotonic trends. The non-parametric Mann–Kendall test is considered appropriate for trend detection in hydrological variables because it does not require that the data be normally distributed and allows for missing values and censored observations in the time series (Bui et al. 2012).
- A Spearman correlation of groundwater level (response variable) with various water balance factors, including:
    - nearby rainfall (CDMMR) – see section 5.3.3.1
    - nearby CSG groundwater extraction – see section 5.3.3.2
    - nearby non-CSG water use – see section 5.3.3.3.

  The Spearman correlation is a statistical measure of the degree of correlation between paired data. It does not assume a linear relationship, does not need the variables to be normally distributed and is relatively insensitive to the presence of outliers.
- Visual assessment of both the Mann-Kendall and Spearman correlation analyses to ensure that the method is suitable (i.e. assumptions are met) and apply hydrogeological reasoning to the outputs. For example, a perfect positive correlation between increasing non-CSG water use and increasing groundwater levels makes no hydrogeological sense, because increased extraction should lead to decreasing groundwater levels. Therefore, in this example, the correlation does not provide a plausible explanation for the observed groundwater level trend.

5.3.3 Correlation analysis

There are three key water balance factors included in the statistical analysis – rainfall, non-CSG water use and CSG groundwater extraction. In this section, important contextual and data treatment information is provided to support the implementation of the trend analysis.

5.3.3.1 Establishing trends in rainfall

The magnitude and timing of groundwater recharge is affected by many factors including the climate, dominant recharge process (localised versus diffuse), the nature of the groundwater flow system, vegetation and soil types, land use and geomorphological factors. The most prominent of these factors is the rainfall record itself, which largely controls the amount of water available for recharge.

Rainfall records provide a means of understanding the relative timing and magnitude of groundwater level response to recharge variation, for areas both near to and more distant from outcrop recharge areas (with the assumption that higher rainfall leads to greater recharge). For these reasons, monitoring points in the outcrop areas are most likely to respond rapidly to recharge, whether from diffuse rainfall across a wider area or via leakage from discrete surface water bodies or dynamic alluvial surficial aquifers (these discrete processes are often referred to as localised recharge).

Because of the tendency for more rapid groundwater level response to recharge in outcrop areas, it is common practice to compare groundwater levels with rainfall records to evaluate recharge effectiveness. In this regard, the cumulative deviation from mean monthly rainfall (CDMMR) is a useful metric for identifying time periods of average, above-average or below-average rainfall within a long-term rainfall record. The CDMMR is therefore a powerful visual tool for identifying extended dry and wet periods and extreme rainfall events.

Analysing groundwater levels and CDMMR together helps to establish the degree to which extended dry and wet climatic periods result in changes in aquifer storage (i.e. groundwater level changes) at a given site. It also allows identification of significant changes in groundwater level as a result of individual above-average rainfall events, or a number of larger rainfall events in a short period of time, i.e. higher rainfall during a particularly wet summer leading to much more effective recharge of the aquifer than a number of smaller events over a longer period of time. It can also show the effects of extended drier periods that result from dominant and enduring El Niño–Southern Oscillation (ENSO) conditions. These El Niño periods are typically drier periods along eastern Australia, while La Niña periods tend to be associated with above-average high-rainfall periods in eastern Australia.

To determine the influence of rainfall recharge on groundwater levels, hydrographs for individual monitoring points were plotted and analysed in relation to the CDMMR from a nearby weather station. This analysis was undertaken for bores in or close to outcrop areas (where groundwater recharge is thought to occur and directly influence groundwater levels) as well as deeper in the basin (where groundwater levels are expected to respond to recharge more subtly, if at all).

For reference, Figure 5-3 provides the CDMMR over the last 20 years for four representative weather stations situated across the Surat CMA: Condamine Plains, Chinchilla WTP, Taroom and Roma. It is evident from these long-term CDMMR trends that rainfall patterns and trends are not uniform across the Surat Basin, although there are some broad similarities.

Figure 5-3 CDMMR over the last two decades for four weather stations located in outcrop

Based on Figure 5-3, the following rainfall trends are noted:

- a wet period with above-average rainfall from 1997 to 2000
- an extended drier period of below-average rainfall from 2000 to 2009 – a drought commonly referred to as the 'Millennium Drought'
- a wet period with above-average rainfall for most of 2010
- a very wet period with well above-average rainfall in late 2010
- a continued wet period with above average rainfall from 2011 to 2013
- a drier period with average to below average rainfall from 2014 to 2018.

5.3.3.2 Establishing trends in CSG groundwater extraction

CSG groundwater extraction is a significant stressor in the reservoir and potentially in adjacent formations. Therefore, trends in the commencement and volume of associated water production are important contextual information for the implementation of the groundwater level trend analysis approach.

To support this analysis, a search radius of 10 km from each groundwater monitoring point is applied to calculate cumulative water extraction from all CSG wells within that radial capture zone. This distance is selected based on the distance–drawdown relationship (Figure 6-10) which indicates less than 10 m of drawdown is observed beyond 10 km from CSG gas fields. The pressure reduction in the reservoir outside of 10 km is comparatively minor, with reduced potential for impacts on other aquifers.

The growth in CSG groundwater extraction for different hydrogeological assessment areas is shown in Figure 5-4. Since 2014, CSG development has increased dramatically and has remained fairly consistent since 2015. It is inferred from this profile that CSG stresses are a relatively recent stress on the system and therefore, with the exception of the Eastern Surat and South-eastern Surat, would only potentially influence groundwater levels in adjacent aquifers post-2014. The timing of vertical impact propagation is largely dependent on the vertical resistance between the coal seams and the aquifer; while the timing could be delayed, it would not occur before the increase in stress.

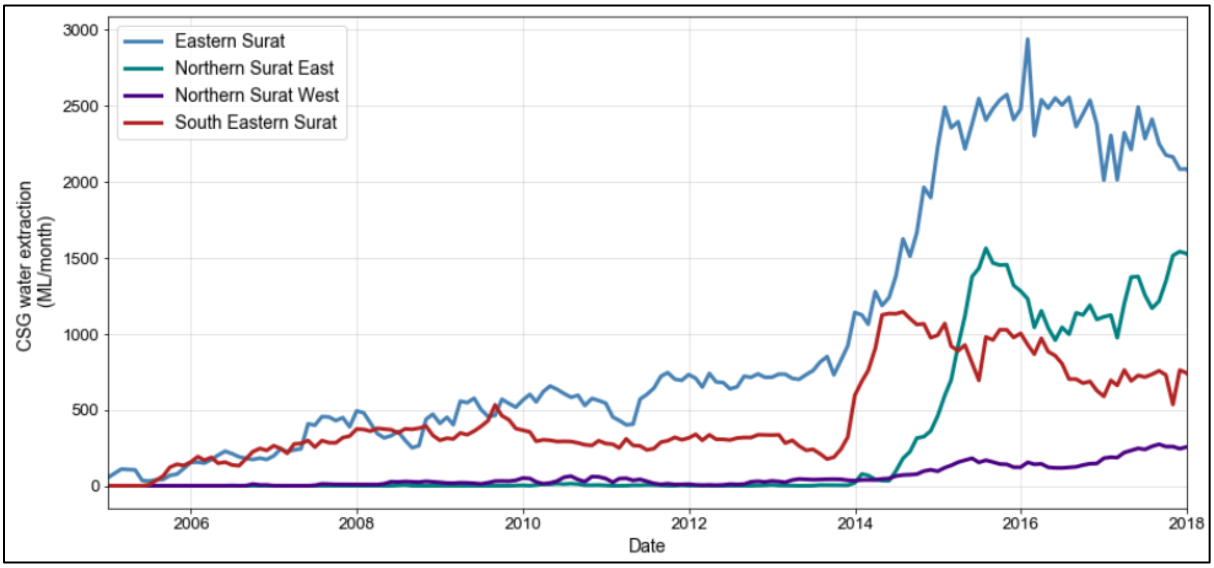

Figure 5-4 CSG groundwater extraction by hydrogeological assessment area (see Figure 1-1)

5.3.3.3 Establishing trends in non-CSG water use

Non-CSG water use is largely unmetered in the Surat CMA. OGIA has developed a method to generate a time series estimate of non-CSG water use (section 4.2.1.3). Using this estimate, a search radius of 25 km from each groundwater monitoring point is applied to calculate the cumulative non-CSG water use from the same aquifer. This is a reflection of the within-aquifer water extraction stresses.

This radius was defined using time–drawdown calculations with the Theis solution (Theis 1935) – an analytical solution for unsteady-state radial flow in a confined aquifer (Kruseman & de Ridder 1992). A simple analysis exercise was undertaken using this analytical solution, with varying aquifer parameters (transmissivity and storativity), aquifer pumping rates, duration of pumping and radial distances from that pumping. It was concluded from that analysis that a radial distance of 25 km was a reasonable approximation to cause at least 1 m of drawdown after 5 years, for an aquifer that meets one or more of the following criteria:

- has a transmissivity of 10 m^2/day or less
- has a storativity of 1×10^{-5}
- has a cumulative pumping rate of 1 L/s or more (31.5 ML/year) within that 25-km radius.

This 1 m of drawdown is considered a measurable and perceptible magnitude that is in excess of barometric and tidal noises (which are usually in the centimetre-to-decimetre scale).

5.3.4 Conceptualisation

Hydrogeological conceptualisation is an important component of the trend analysis. This involves the development of a sub-regional hydrogeological conceptual model that adequately describes the nature of the aquifers of interest and their potential connectivity to the CSG reservoir. This assessment considers the following:

- the hydraulic gradient between the reservoir and the aquifer
- the thickness and vertical permeability of any layers between the reservoir and the aquifer
- geological controls such as the lithology and cementation of the aquifer
- connectivity features, such as faults, fractures, poorly constructed bores or multi-aquifer bores
- the hydrochemistry of the reservoir and the aquifer and any hydrochemical evidence of mixing
- consideration of other influences, such as mechanical loading.

5.3.5 Sub-regional modelling

Section 5.2 outlined the challenges in separating potential CSG impacts from antecedent declining trends associated with longer-term non-CSG water use and climate variability. A numerical groundwater model is a quantitative tool that can predict the impacts of each water extraction stress on aquifer groundwater levels. These models can also assess the cross-formational fluxes from aquifers towards depressurised reservoirs as a result of large induced hydraulic gradients. Therefore, for this project, a sub-regional numerical groundwater flow model was developed to isolate CSG and non-CSG stresses to assess measured drawdowns under plausible arrays of hydraulic parameters and known aquifer/aquitard frameworks.

6 Trend analysis – Walloon Coal Measures

The Walloon Coal Measures represents the primary target formation for CSG groundwater extraction within the Surat Basin. The Walloon Coal Measures conformably overlies the Durabilla Formation and the Hutton Sandstone and is unconformably overlain by the Springbok Sandstone. In the South-eastern Surat, the Condamine Alluvium is incised into the Walloon Coal Measures by up to 120 m. This chapter is intended to provide sufficient context on the status of reservoir depressurisation to allow for meaningful aquifer trend analysis in subsequent chapters.

6.1 Formation characteristics

This section provides a summary of the characteristics of the Walloon Coal Measures. Additional detail on formation geology, derived from up-to-date CSG well data interpretation, is described in a separate OGIA report (OGIA 2019c). This section provides a contextual summary to inform the subsequent analysis of groundwater level trends.

6.1.1 Stratigraphy and lithology

The Walloon Coal Measures is the major coal-bearing formation of the Surat Basin, with interbeds of siltstone, mudstone, argillaceous sandstone and rare shale. The formation has been subdivided into five main stratigraphic groups. From shallowest to deepest, these are the Upper and Lower Juandah coal measures, the Tangalooma Sandstone, the Taroom Coal Measures and the Durabilla Formation. The Upper and Lower Juandah coal measures include the Kogan, Macalister, Nangram, Wambo, Iona and Argyle coal seams and represent a major target for CSG development. The other main target for CSG is the deeper Taroom Coal Measures, which includes the Auburn, Bulwer and Condamine coal seams.

The top of the Walloon Coal Measures is taken as the topmost coal or thick mudstone interval below the basal sandstones of the Springbok Sandstone (Green 1997). As shown on Figure 6-1, the coal seams typically comprise 8.5% of the gross thickness and include 56 individual coal seams (on average) of varying thicknesses and highly variable permeability (OGIA 2019c, 2016b, 2019g). Laterally, the thin and disconnected coal plies extend from 500 m to about 3,000 m (Ryan et al. 2012; Hamilton, Esterle & Sliwa 2014).

Figure 6-2 presents the average lithological composition of the Walloon Coal Measures (excluding the Durabilla Formation) based on processed wireline log data across the Surat CMA. Coal (9%) and carbonaceous shale (3%) make up a small percentage of the overall thickness of this formation, with the dominant lithofacies being sandstone (31%), siltstone (24%), mudstone (17%) and dirty sandstone (16%). The sandstone in the Walloon Coal Measures is typically rich in swelling clays (QGC 2014). This is noted from CSIRO (Esteban et al. 2015) laboratory testing of Walloon Coal Measures interburden core samples (where the samples underwent significant swelling when exposed to water), XRD analysis of detailed down-hole profiles (QGC, 2014) and anecdotally, from the need to inject saline water into hydraulically fractured wells to maintain well permeability (Origin Energy 2018).

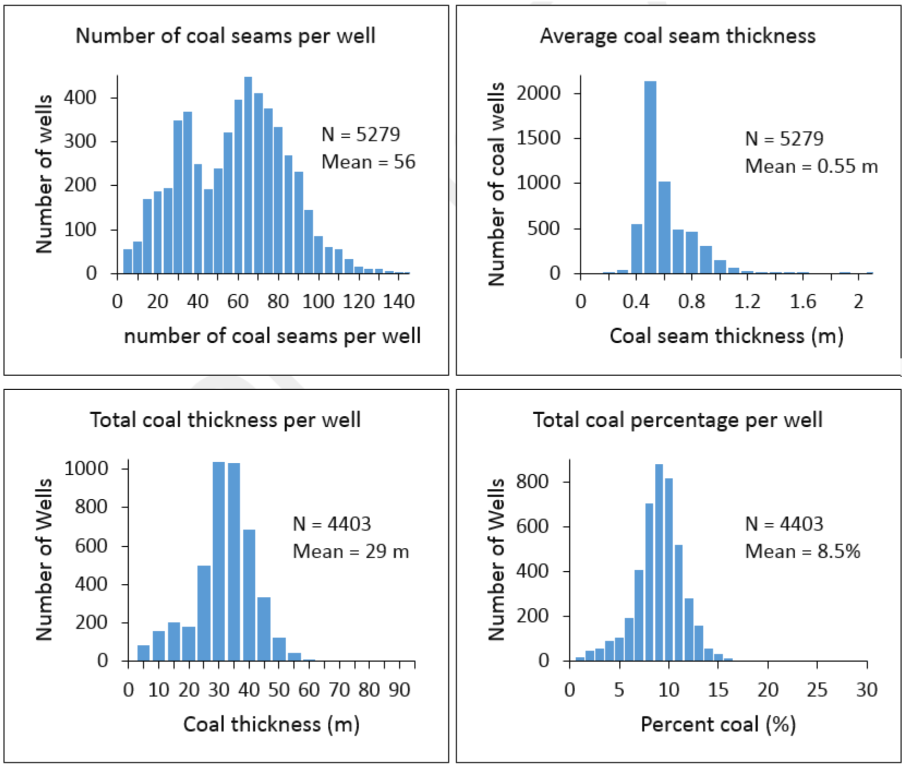

Figure 6-1 Walloon Coal Measures – coal thickness and proportions

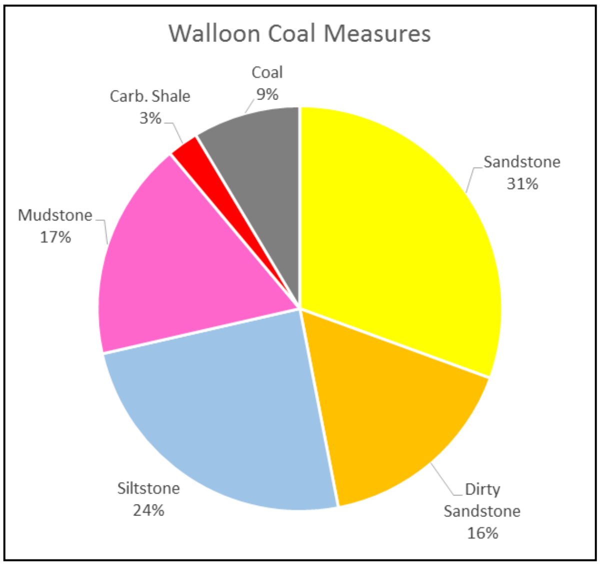

Figure 6-2 Walloon Coal Measures – lithological composition

The Durabilla Formation, which lies between the Walloon Coal Measures and the Hutton Sandstone, typically comprises a fining upward sequence of thickly cross-bedded, fine-grained, labile to sublabile sandstones and interbedded siltstones and mudstones, largely devoid of coal (Green et al. 1997, Ryan et al. 2012, QGC 2014). The unit marks a shift from the high-energy fluvial environment, which dominated during deposition of the Hutton Sandstone, to a lower-energy meandering channel and overbank deposition environment.

As shown in Figure 6-3, the thickness of the Durabilla Formation ranges from less than 10 m to more than 160 m across the Surat CMA, averaging about 46 m. However, within the CSG production areas, the average thickness of the Durabilla Formation is nearly 76 m.

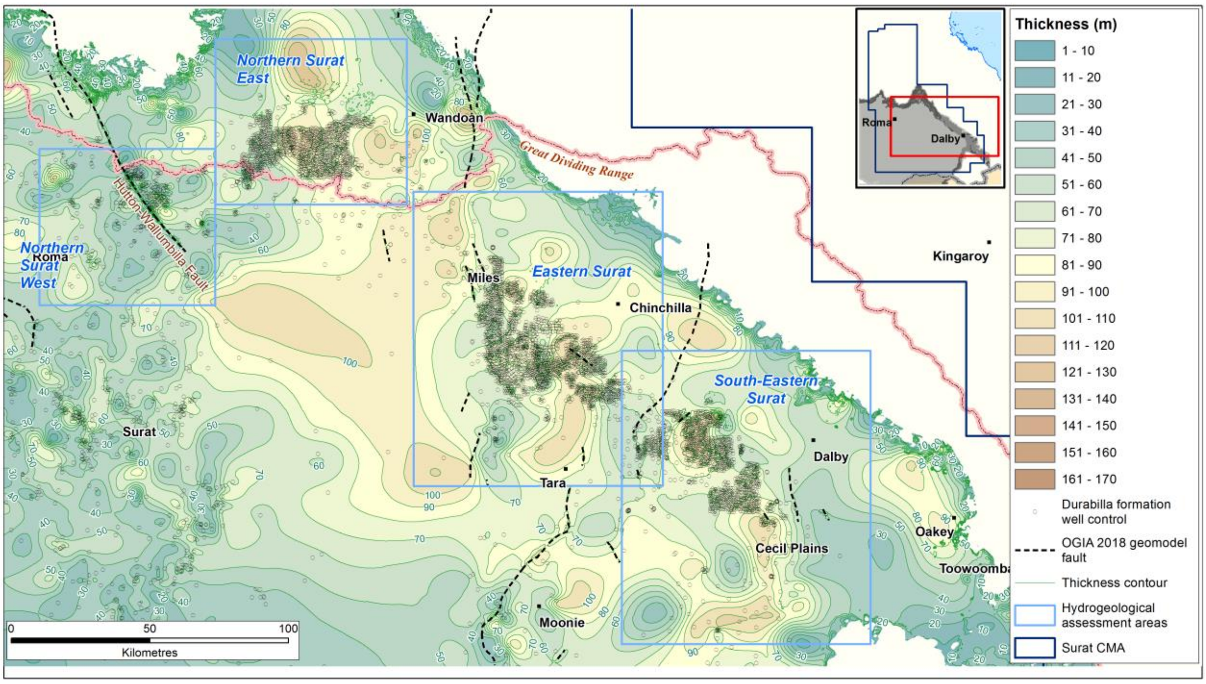

Figure 6-3 Durabilla Formation – interpreted thickness and extent (OGIA 2019c)

Summary statistics describing the lithological composition of the Durabilla Formation, based on the available wireline log data, are shown in Figure 6-4. These data confirm that there is no significant coal in the Durabilla Formation. Whilst most geophysical logs suggest the presence of sandstone, this formation typically also includes relatively high proportions, averaging 30% and ranging up to nearly 50% of illite and smectite swelling clays, similar to the Walloon Coal Measures (QGC 2014).

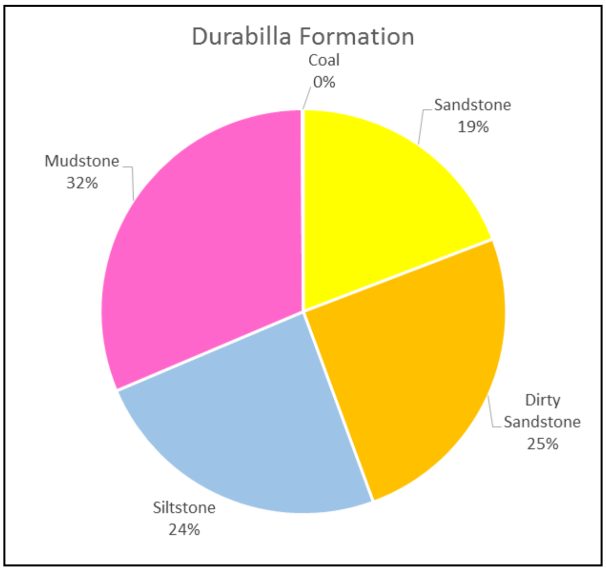

Figure 6-4 Durabilla Formation – lithological composition

6.1.2 Hydraulic properties

A detailed compilation and synthesis of hydraulic parameter data in the Surat Basin is provided in a separate conceptualisation summary report (OGIA 2019g). Hydraulic parameter data are available at three different scales in the Surat Basin – core test, drill stem test (DST) and pumping tests. Figure 6-5 presents a box plot of the Walloon Coal Measures and the Durabilla Formation horizontal hydraulic conductivity (Kh) estimates (converted from permeability). The DSTs and pumping tests show that the coal in the Walloon Coal Measures can be reasonably permeable, with median Kh for DSTs of ~0.05 m/day and for pumping tests of ~0.2 m/day. At the same time, core testing results suggest that the non-coal lithologies in the Walloon Coal Measures and Durabilla Formation are extremely tight, with Kh values typically below 1 × 10^{-4} m/day.

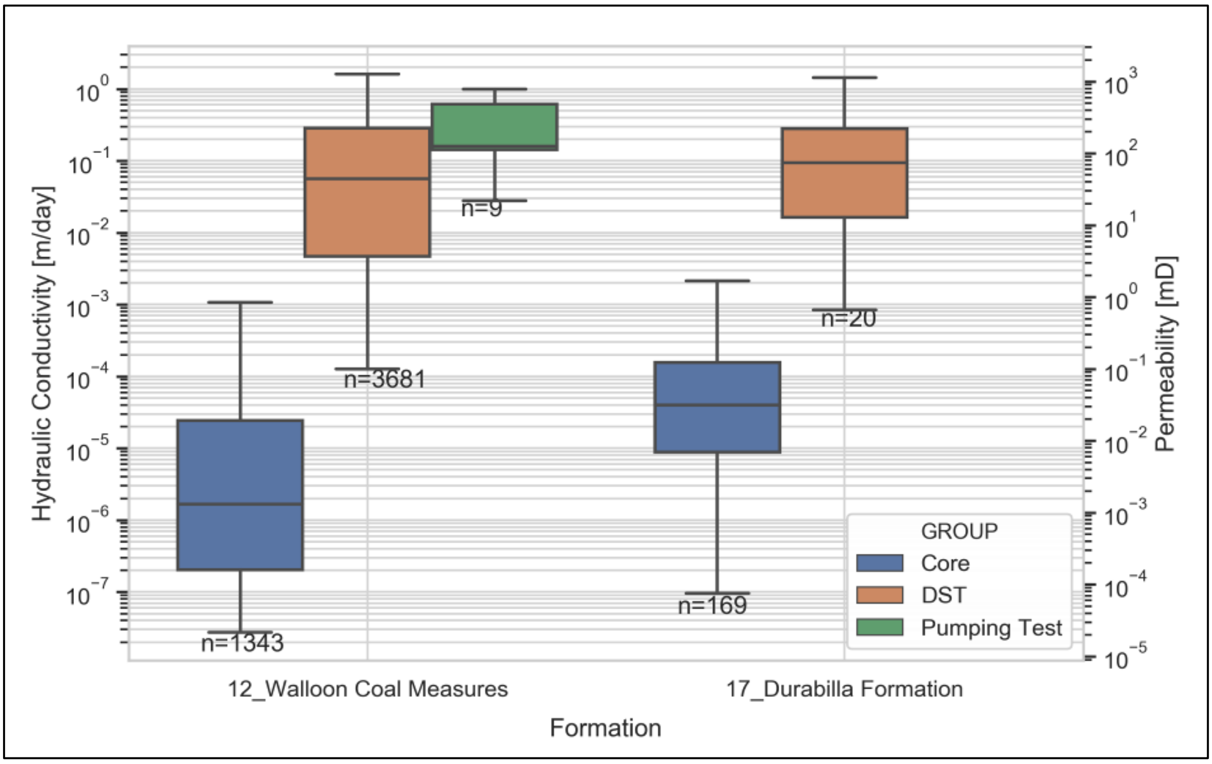

Figure 6-5 Horizontal hydraulic conductivity (K) and permeability[4] (k) for the Walloon Coal Measures and Durabilla Formation in the Surat CMA

6.1.3 Hydrochemistry

Hydrochemistry data are available from CSG production wells, UWIR monitoring points and occasional sampling from other bores. Hydrochemical analyses included multivariate K-means cluster analysis (KCA), principle component analysis (PCA) and temporal hydrochemical trend analysis using a combination of Mann-Kendall and visual techniques.

Figure 6-6 presents a diagrammatic representation of the percentage of samples within each area that were assigned to each KCA cluster class. These KCA classes evolve from fresher class 1 waters, with lower cation and anion abundancies, to more saline class 5 waters with higher concentrations of cations and anions. There is considerable variability in the Walloon Coal Measures water quality across the Surat CMA.

In the Eastern and Northern Surat (west), the majority of samples are less saline cluster class 2. This class is typically a Na-HCO_3-Cl type water with very low Ca, Mg and SO_4 and an average TDS of around 3,000 mg/L. This relatively fresher water has been largely attributed to the shallow nature of the coal seams, close proximity to recharge areas and enhanced coal permeability with its influence on the dynamic nature of the local groundwater flow systems. Conversely, in the South-eastern and Northern Surat (east), the majority of CSG well samples have been classified as more saline classes 3 and 4. These samples have higher TDS concentrations of around 5,000 to 7,000 mg/L, but also

[4] Conversion factor: 1 mD (millidarcy) = 1.27E-03 m/day

tend to be $Na\text{-}HCO_3\text{-}Cl$ type water. In the South-eastern Surat, there is a general depth trend, with better quality water in the deeper Taroom Coal Measures than the overlying Upper Juandah Coal Measures. As discussed in section 9.1.3, non-CSG water samples from beneath the Condamine Alluvium show generally good water quality (>50% of samples are class 1 with a mean TDS of 1,363 mg/L).

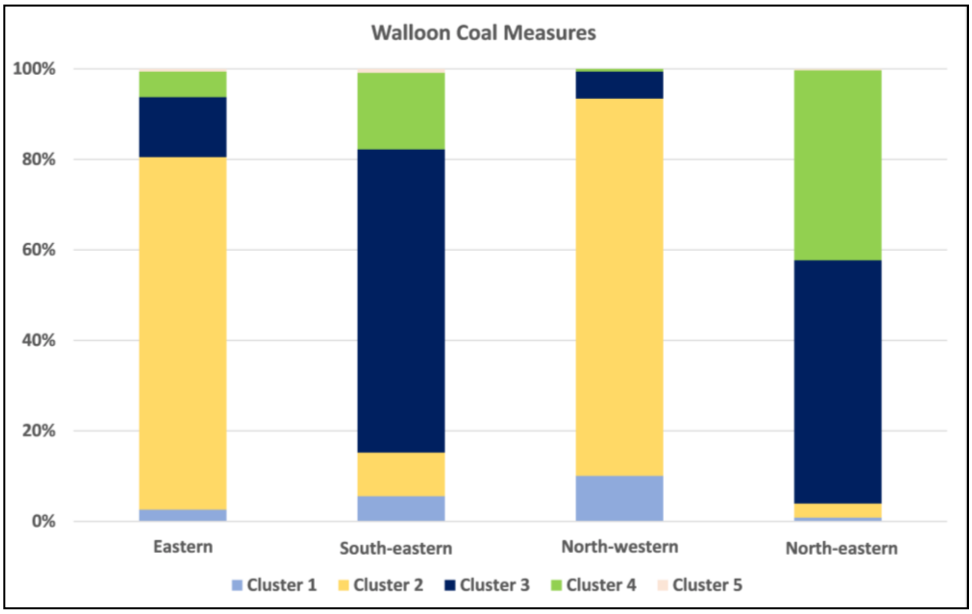

Figure 6-6 Walloon Coal Measures KCA hydrochemical cluster classes

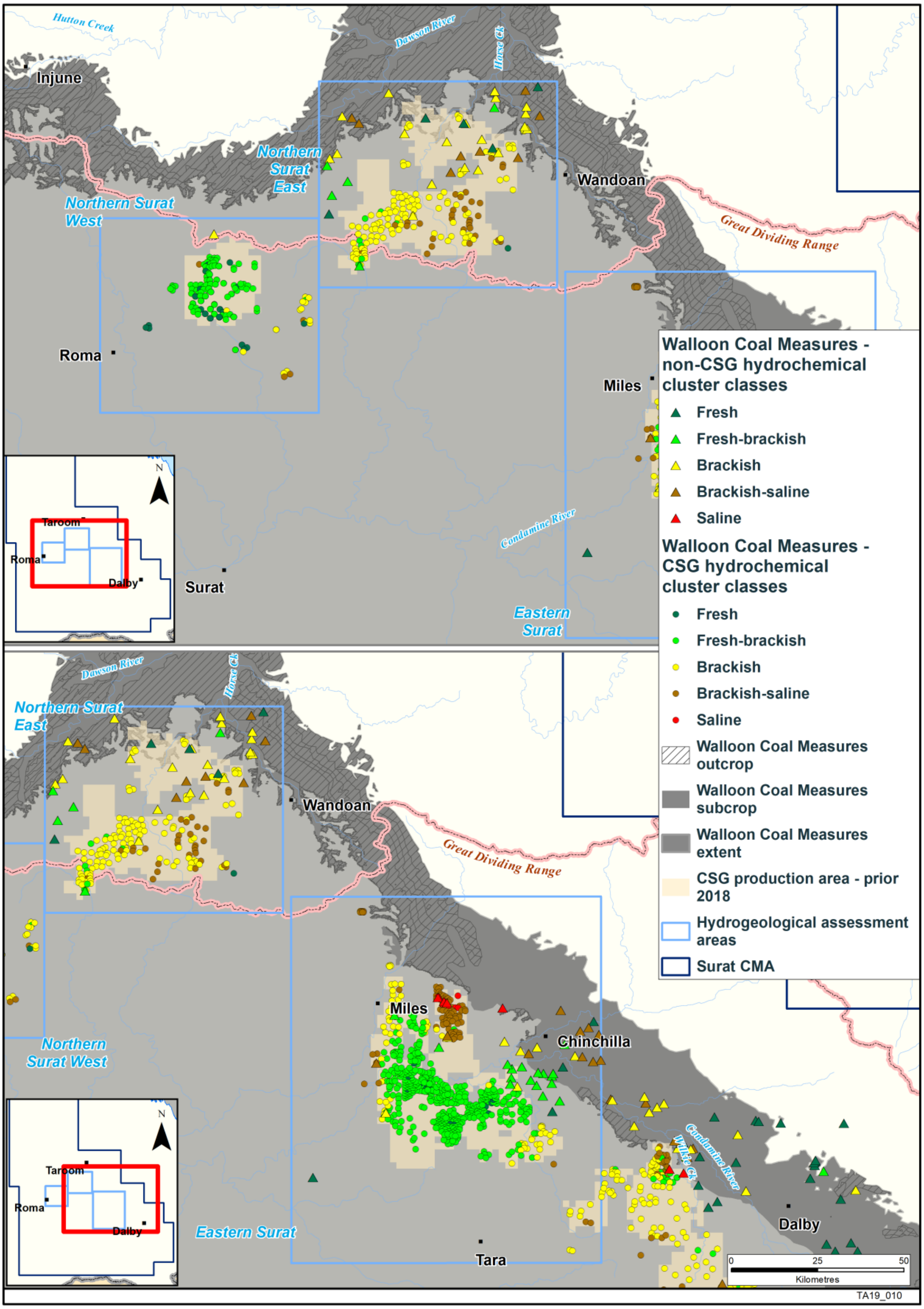

Figure 6-7 Spatial variability in hydrochemical cluster classes, Walloon Coal Measures

6.1.4 Groundwater flow directions

Two groundwater level maps are generated to support the overall conceptualisation of horizontal groundwater movement (OGIA 2019g): potentiometric surfaces for the Upper Juandah Coal Measures (Figure 6-8) and Taroom Coal Measures (Figure 6-9).

The Upper Juandah Coal Measures is present on both sides of the Range and extends from north of Taroom to south of the southern CMA boundary. The interpreted groundwater flow system is multi-directional and deviates somewhat from the traditional concept of GAB groundwater flow. This is partly natural and partly induced by CSG impacts. Groundwater recharges the Walloon Coal Measures in the northern and eastern parts of the basin. Generally, the major flow directions observed include a northwest (near Injune) to south (near St George) component, an east (near Cecil Plains) to south (near Goondiwindi) component, and a south (near Wandoan) to north (near Taroom) component on the northern side of the Range. The obvious departure from this regional flow system is the large radially convergent drawdown patterns observed in the CSG development areas. This is particularly evident in the Eastern and South-eastern Surat where groundwater levels are depressed by up to 200 m locally. At this point in time, the drawdown observed in the CSG areas is very steep, with little drawdown observed more than 10 km outside of the operating fields, reflecting the discontinuous nature of the coal and the tight nature of the non-coal interbeds in these areas.

The Taroom Coal Measures is present on both sides of the Range and has a similar spatial extent to the Upper Juandah Coal Measures described above. The regional and local flow systems in the Taroom Coal Measures are generally consistent with the Upper Juandah Coal Measures, however the magnitude and extent of drawdown in CSG areas is appreciably greater. This affirms that depressurisation has developed more rapidly in this deeper formation and has produced a general downward flow potential within the Walloon Coal Measures in these areas. As with the Upper Juandah, the drawdown cones are steep away from active CSG fields, such that little drawdown is observed some 10 km from the gas fields.

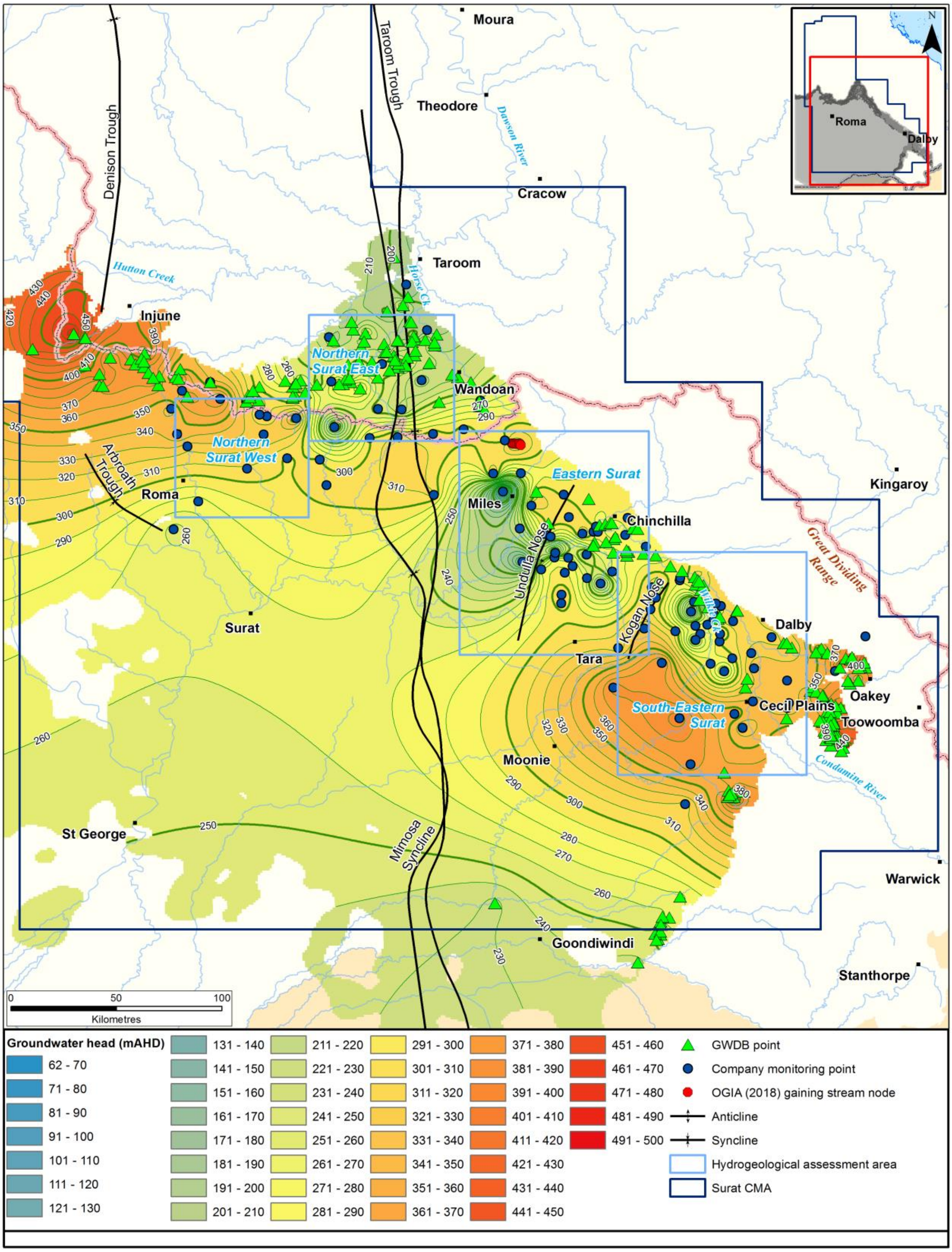

Figure 6-8 Upper Juandah Coal Measures potentiometric surface

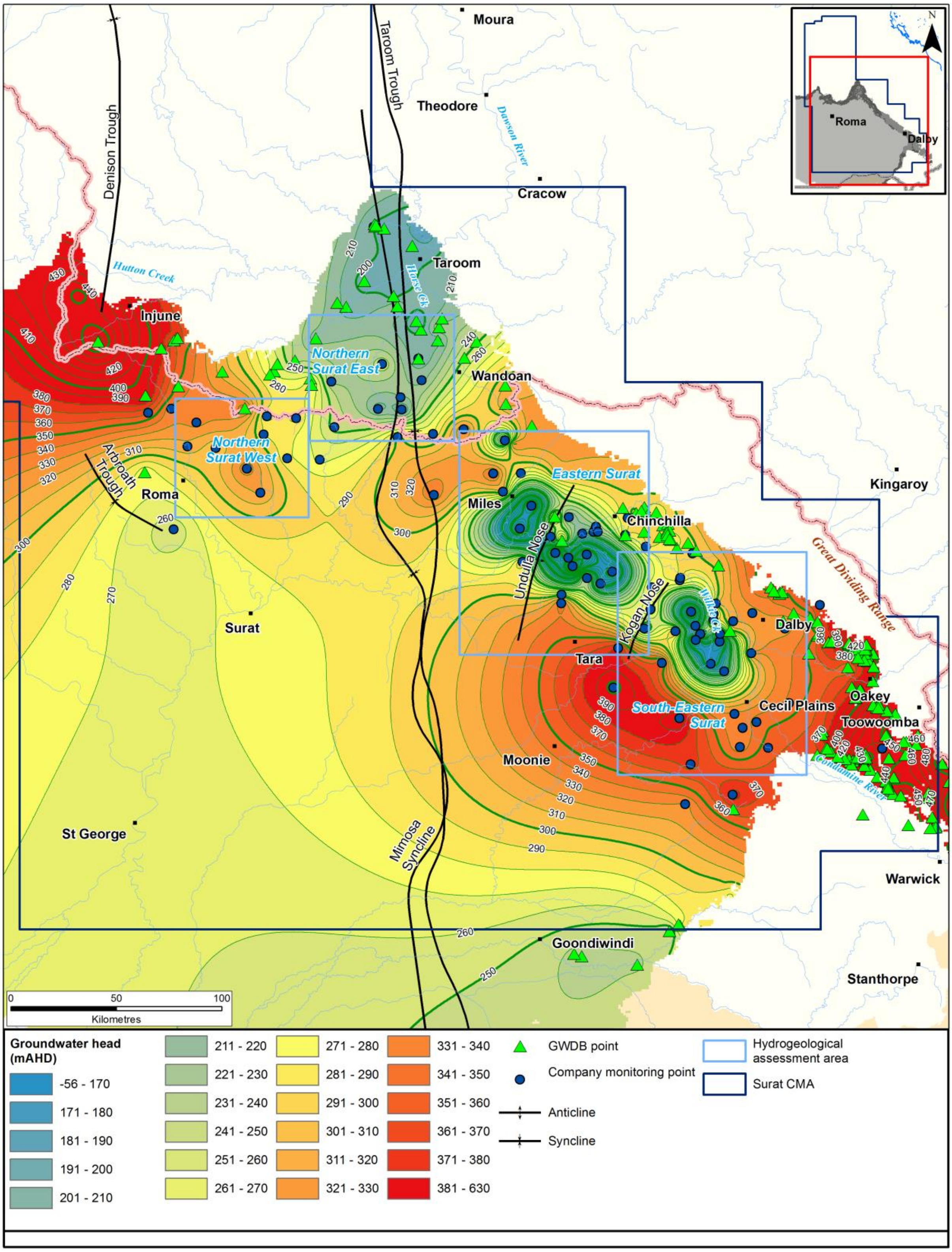

Figure 6-9 Taroom Coal Measures potentiometric surface

6.2 Observed groundwater level trends

Observed drawdown for the Upper Juandah and Taroom coal measures are shown in Figure 6-10. In many cases, the observed drawdown will tend to under-estimate total actual drawdown, as monitoring only commenced after some depressurisation had already occurred.

Across the development area, there are broadly consistent trends in groundwater level response to CSG development. Key observations include the following:

- As of 2018, there is generally less than 10 m of drawdown (blue symbols) observed outside of the CSG development footprint.
- 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 and highlights the tendency for downward flow gradient within the reservoir.

The regional potentiometric and drawdown maps for the Upper Juandah and Taroom coal measures show extensive CSG-induced drawdown in the Eastern and South-eastern Surat (Figure 6-8 and Figure 6-9). This drawdown appears as regional radial patterns of inwardly reducing, tightly spaced groundwater level contours. In the Northern Surat, impacts are less obvious, owing to a number of factors including the later timing of CSG development and fewer monitoring points in active gas fields to capture the production-induced drawdown.

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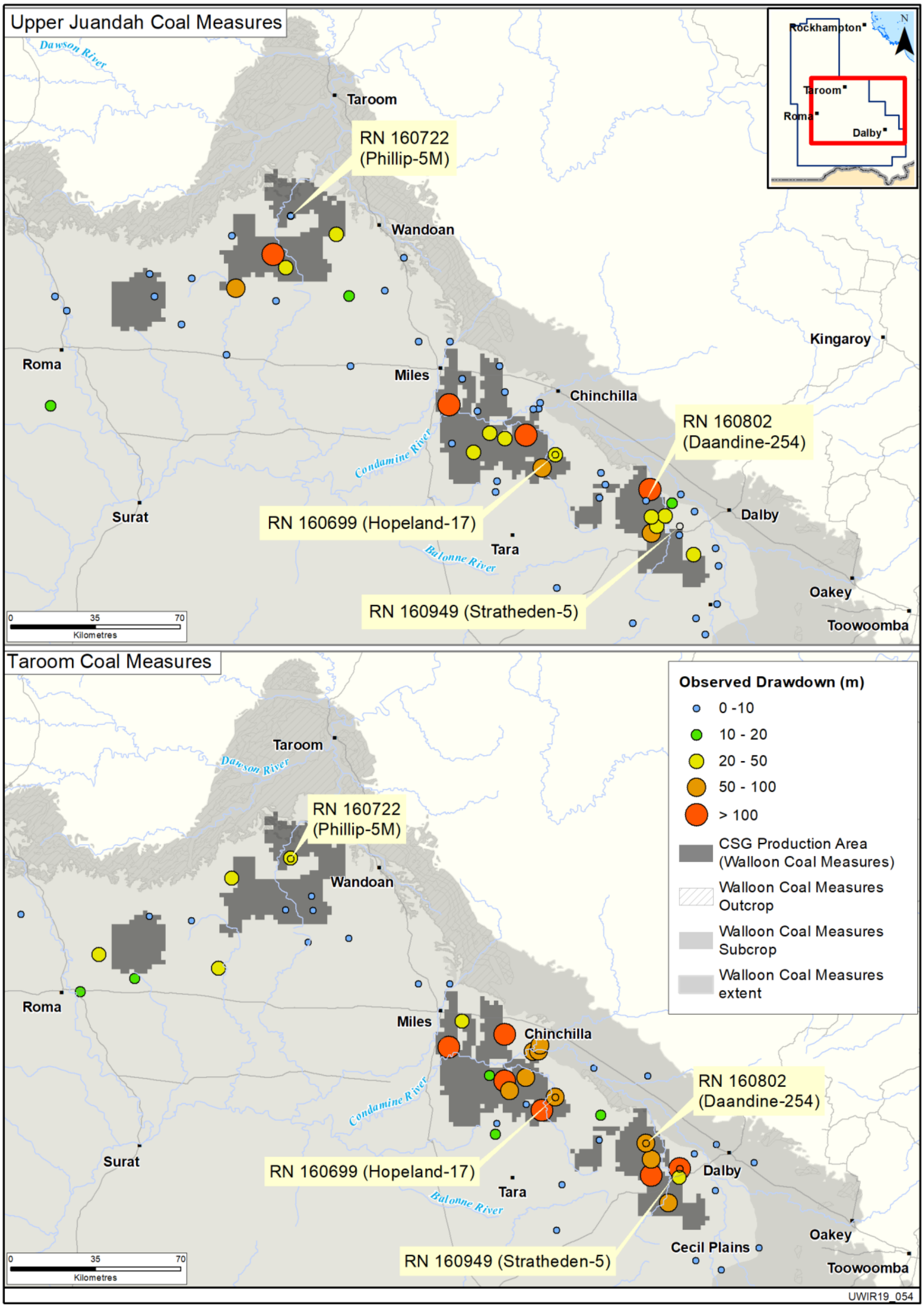

Figure 6-10 Observed drawdown in the Upper Juandah and Taroom coal measures

Examples of groundwater level response to CSG development over time within the Walloon Coal Measures are shown in Figure 6-11 for four representative locations: the Eastern Surat (Hopeland 17), South-eastern Surat (Stratheden 5 and Daandine 254) and Northern Surat (Phillip 5M).

At these locations, groundwater levels are recorded at multiple depths within the Walloon Coal Measures – the Upper Juandah, Lower Juandah and Taroom Coal Measures – providing valuable information on how changes in groundwater level occur vertically within different parts of the formation. For comparison, total CSG groundwater extraction over time (metered), for two distances from each monitoring location (0–1 km and 1–5 km), is also shown on the same figures.

The following observations (which can be extrapolated to the broader Walloon Coal Measures CSG response) are made regarding these exemplar nested hydrographs:

- Hopeland 17 (RN160699) is located approximately 30 km south of Chinchilla. This monitoring commenced prior to near-field CSG production, but following CSG appraisal. Background groundwater levels can be estimated from the post-appraisal recovery period. In this case, depressurisation from early pilot testing results in drawdown in mid-2014 and subsequent recovery in late 2014 and early 2015. Actual CSG development commenced in late 2016, with all three monitored units – Upper Juandah, Lower Juandah and Taroom coal measures – showing a rapid and prolonged response. A more pronounced drawdown is observed in the Taroom Coal Measures, creating the potential for downward flow at the site. Around two-thirds of the nested sites show downward flow potential within the Walloon Coal Measures.
- Stratheden 5 (RN160949) is located approximately 30 km west of Dalby. This site includes multiple monitoring points in a single formation, with two points in each of the Lower Juandah and Taroom coal measures. Of note, each pair of monitoring points does not respond in the same manner, highlighting the discontinuous nature of the coal seams. This observation affirms that the Walloon Coal Measures is unlikely to behave as a unified regional groundwater flow system, but rather is made up of a number of more localised coal seam flow systems hydraulically separated by bulk interbeds of lower-permeability siltstone and mudstone.
- Daandine 254 (RN160802) is located 25 km west of Dalby. This site shows downward flow potential from the Upper Juandah to the Lower Juandah coal measures. The two lowermost monitoring points show that the Lower Juandah Coal Measures is heavily depressurised to approximately 125 mAHD as a result of long-term CSG groundwater extraction within 5 km.
- Phillip 5M (RN160722) is located 30 km west of Wandoan in the northern development area. This site shows that there tends to be less drawdown observed in this area, reflecting the more recent commencement of CSG development in the area. CSG groundwater extraction within 1 km commences in 2017 and results in only 20 m of drawdown in the Taroom Coal Measures, less than 10 m in the Lower Juandah Coal Measures and no observable response in the Upper Juandah Coal Measures.

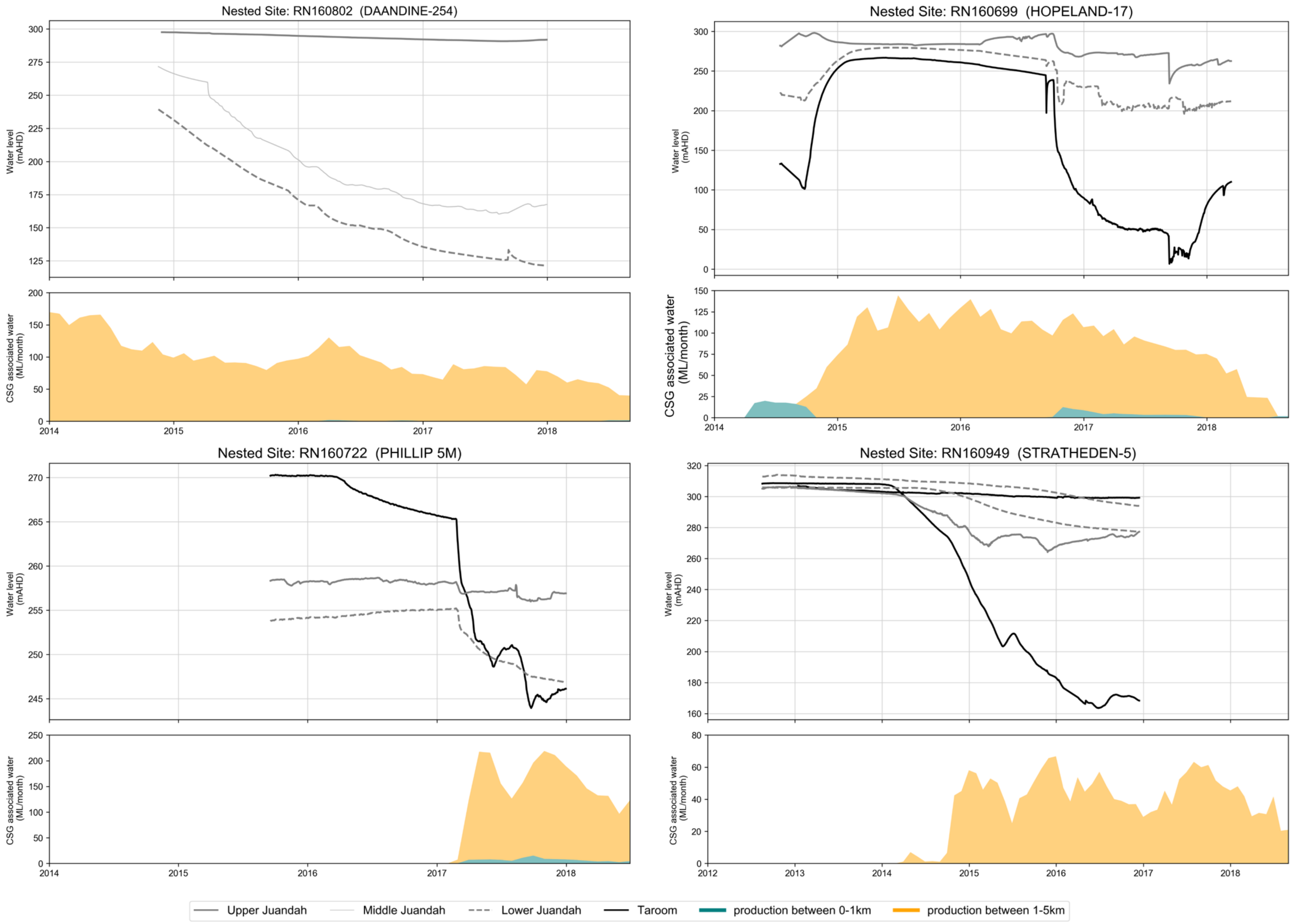

Figure 6-11 Groundwater level trends at selected sites in the Walloon Coal Measures

6.3 Analysis of groundwater level trends

6.3.1 CSG production area

Figure 6-12 shows the observed groundwater levels for the Upper Juandah and Taroom coal measures and monthly CSG groundwater extraction for the South-eastern Surat. As shown, CSG development was limited prior to 2014, at which time the volume of groundwater extraction increased as development commenced at many new gas fields. Consequently, observed drawdown in both the Upper Juandah and Taroom coal measures occurs post-2014, coinciding with the onset of CSG groundwater extraction.

Observed drawdown is greater in the Taroom Coal Measures (up to 200 m of drawdown) than in the Upper Juandah Coal Measures (less than 75 m). The cause-and-effect relationship between CSG groundwater extraction and groundwater level drawdown in the Walloon Coal Measures is clear. It is also important to note that the drawdown shown on this plot is *observed drawdown* and total drawdown will likely be greater, since observation points commenced recording in many cases after development had already commenced (as observed in Daandine 254, Figure 6-11).

Figure 6-13 shows that the same style of drawdown response is observed in the Walloon Coal Measures in the Eastern Surat, southwest of Chinchilla – i.e. more drawdown in the Taroom Coal Measures, but both units recording tens to hundreds of metres of groundwater level decline. Both Figure 6-12 and Figure 6-13 affirm that both the uppermost (Upper Juandah) and lowermost (Taroom) coal measures are both heavily impacted by CSG development in these development areas, and that significant declining trends in groundwater levels are widespread.

There are too few monitoring points and limited cumulative groundwater extraction in the Northern Surat to identify similar trends in groundwater level decline. However, data from the Northern Surat (east) are shown in Figure 6-14 and suggest that groundwater level trends in the uppermost and lowermost coal measures are somewhat different from those observed in the Eastern and South-eastern Surat. With the exception of one bore in the Upper Juandah (COMBABULA-MB3-W_DWN3_SPV), there are no observed drawdowns that exceed 50 m. At this stage, there is no obvious difference in the magnitudes of observed drawdown between the Upper Juandah and Taroom coal measures.

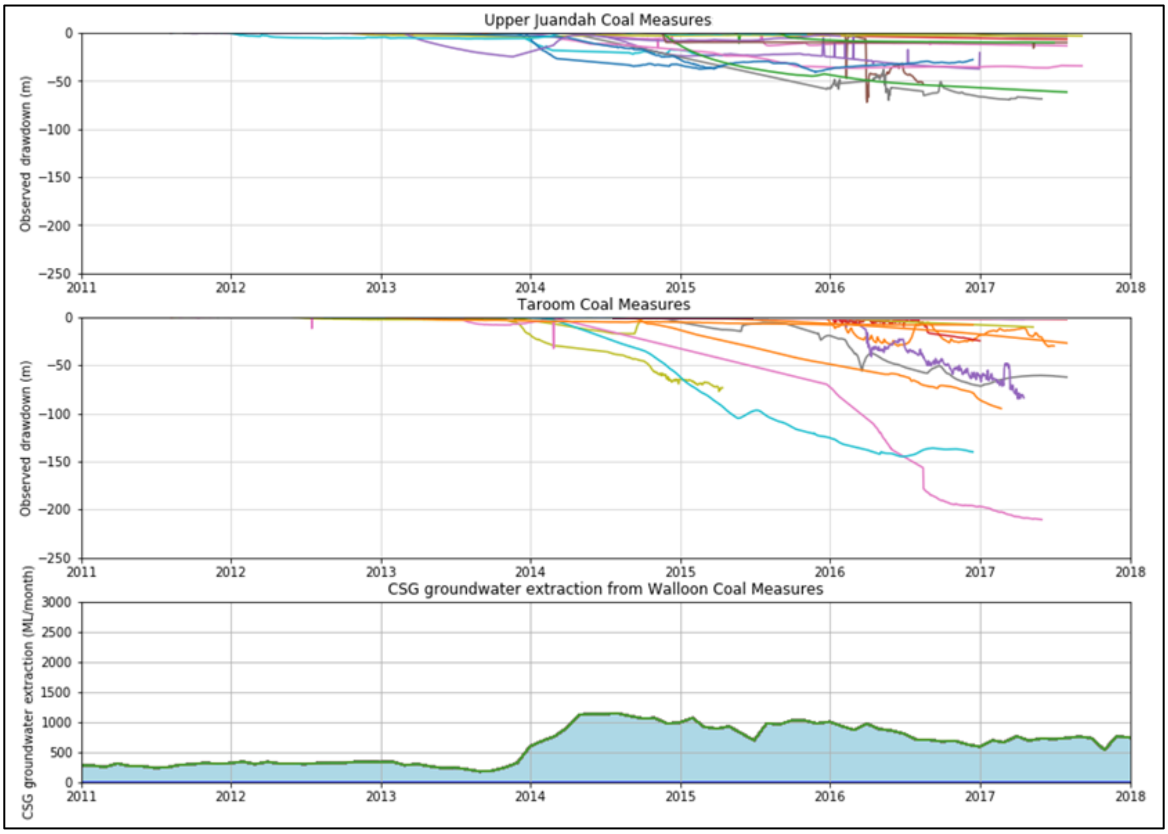

Figure 6-12 South-eastern Surat – observed drawdown in the Upper Juandah and Taroom coal measures and CSG groundwater extraction

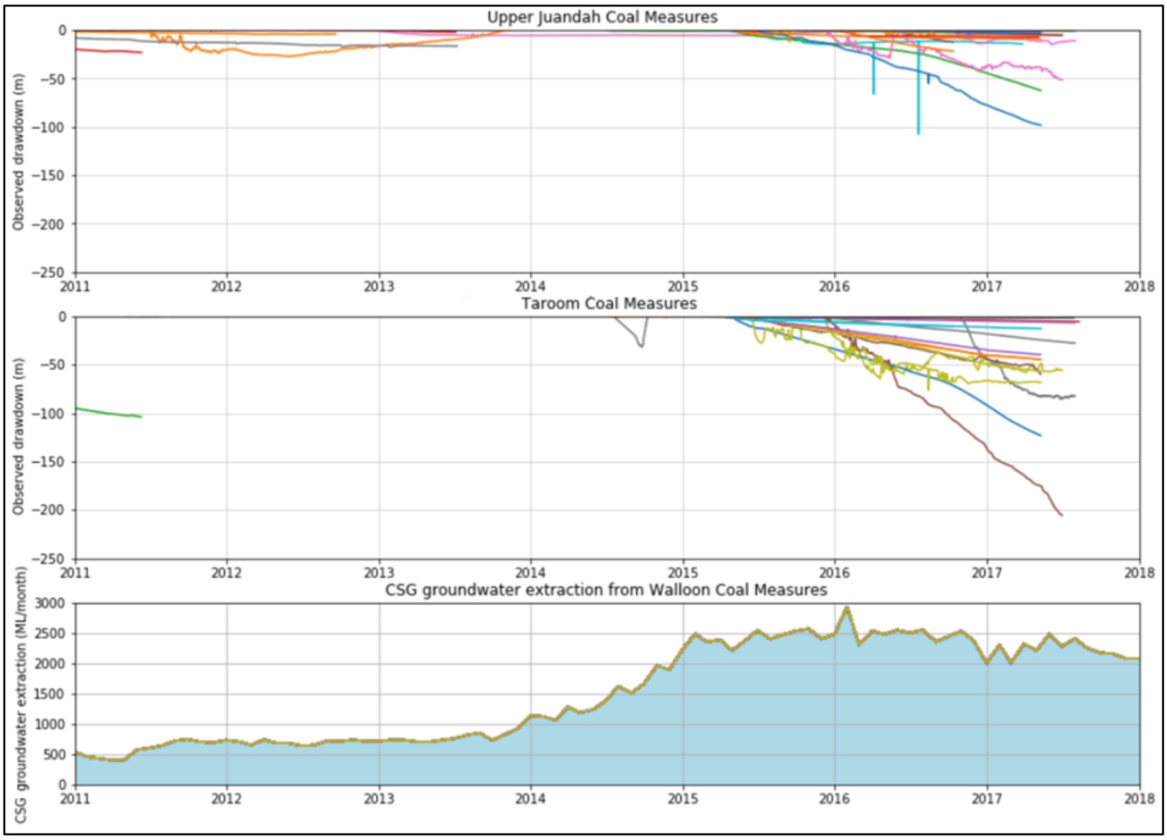

Figure 6-13 Eastern Surat – observed drawdown in the Upper Juandah and Taroom coal measures and CSG groundwater extraction

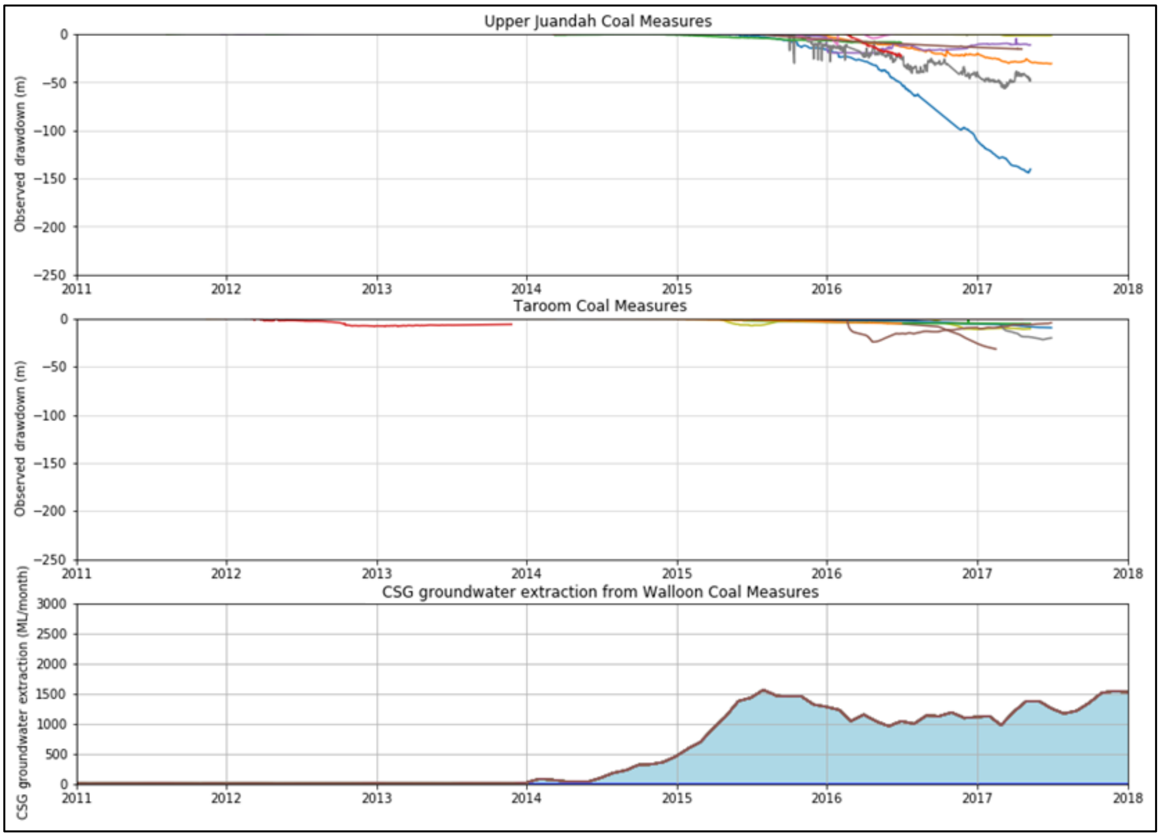

Figure 6-14 Northern Surat – observed drawdown in the Upper Juandah and Taroom coal measures and CSG groundwater extraction

6.3.2 Spatial extent of CSG-induced drawdown

The lateral extent of drawdown in the Walloon Coal Measures can be further explored via a distance–drawdown plot. Within the Surat Basin, early CSG development commenced in the Eastern Surat southwest of Chinchilla. In these areas, regional drawdown patterns are expected to be more mature, as the groundwater system has had more time to respond to sustained extraction stresses. In this section, this area is further analysed to assess the spatial expansion of the regional drawdown associated with CSG development.

Figure 6-15 shows a scatter plot of estimated drawdown at each Walloon Coal Measures monitoring point (segregated by individual coal measures) versus the measured distance to the nearest active gas field. In some cases, these estimated drawdowns are greater than those observed, as the pre-development groundwater level was estimated for each monitoring point. In these cases, the monitoring point commenced after nearby CSG development or ceased prior to full development. Estimates are based on a combination of trends in nearby monitoring points and review of sites where pre-development conditions are available.

This plot suggests that drawdowns in excess of 10 m are largely limited to areas within 10 km of CSG production areas. Consistent with the fact that CSG depressurisation is continuing, more drawdown is now estimated than what was observed at the time of the previous UWIR (OGIA 2016a). The UWIR 2016 noted only two of 37 monitoring sites around Dalby and Chinchilla with more than 5 m of drawdown beyond 5 km from CSG development. This plot also reinforces that hydraulic gradients near development areas are steep but rapidly decrease moving away from development areas, and that drawdown is typically higher in the Taroom Coal Measures when compared to the Upper Juandah Coal Measures.

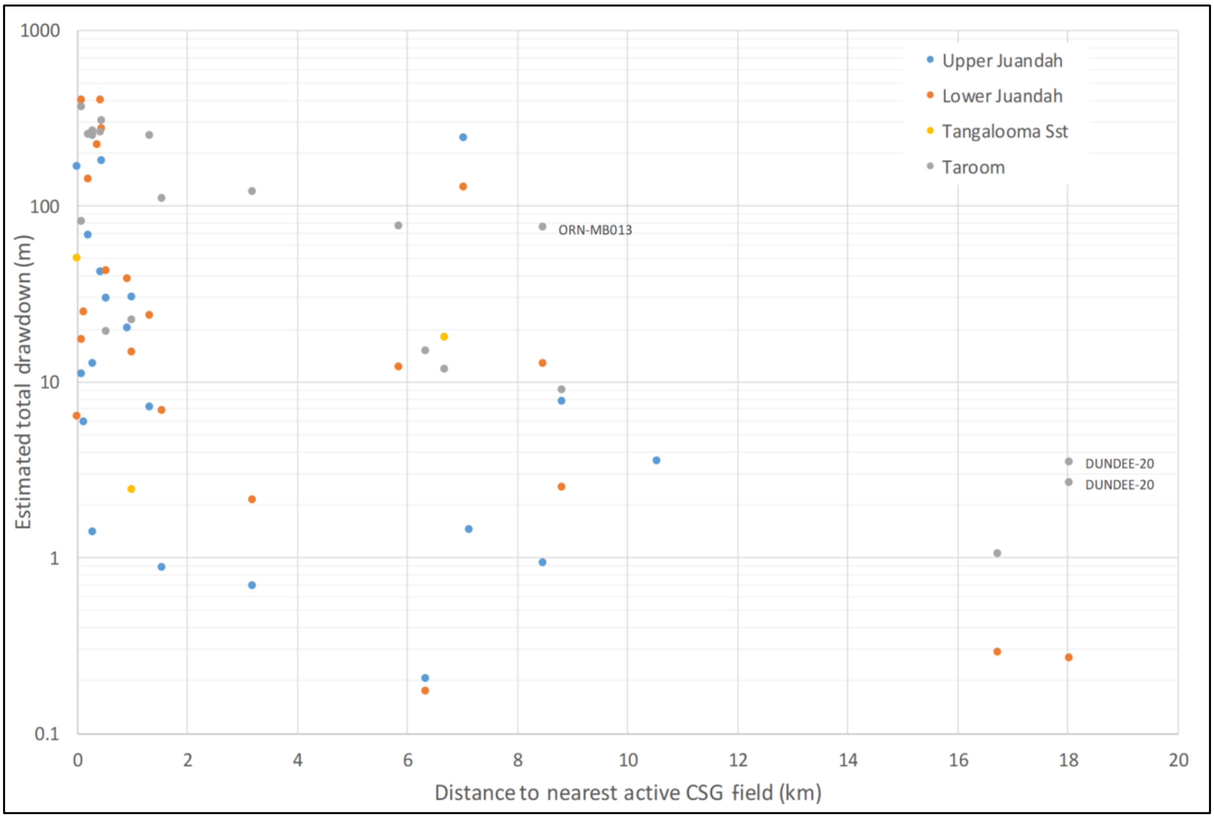

Figure 6-15 Eastern Surat – estimated maximum drawdown in the Walloon Coal Measures versus distance to nearest active CSG gas field

Figure 6-16 below presents a second distance–drawdown plot for the deeper Taroom Coal Measures only to illustrate some differences which can occur in the distance–drawdown relationship in different geographic areas. This plot highlights two groups of monitoring points, which show quite different distance–drawdown relationships as follows:

- Monitoring points to the east and northeast of Talinga and Orana gas fields (green symbols) plot on a linear trend line with a correlation co-efficient of 0.97. At 10 km distance from active CSG, the trend line predicts around 60 m of drawdown.
- Monitoring points in other areas away from active CSG fields (blue symbols) plot on a separate linear trend line with a correlation co-efficient of 0.95. At 10 km distance from active CSG, the trend line predicts 9 m of drawdown (a factor of 6 less than the northeast monitoring points).
- Monitoring points with no drawdown at distances of 6.3 km (Codie 24), 7 km (Dal-MB007) and 10.5 km (Dal-MB006).

Possible causes of the significantly higher drawdown observed at distance in the area to the east and northeast of Talinga and Orana fields include the following:

- higher lateral coal seam continuity and/or intrinsic permeability than observed elsewhere; coal plies in the Walloon Coal Measures typically only extend laterally from around 500 m to around 3,000 m
- fault, fracture or bore-induced enhanced vertical connectivity between coal seams.

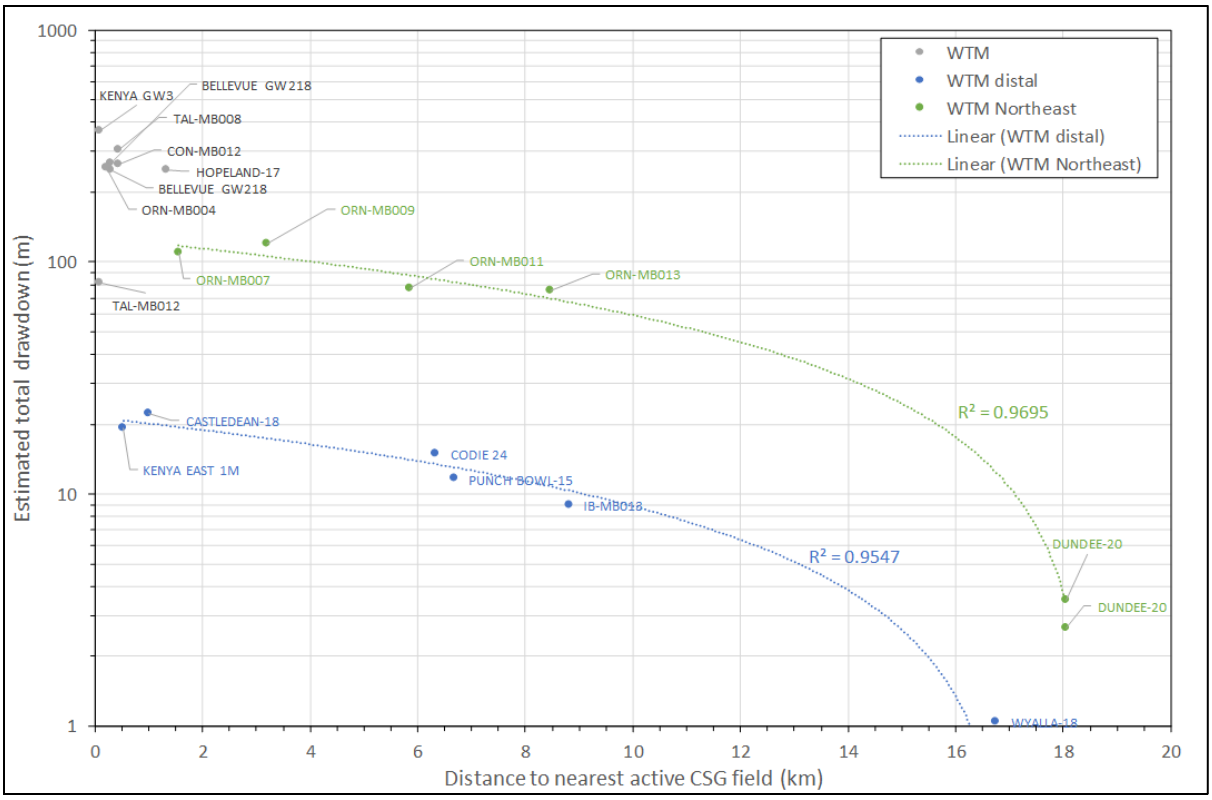

Figure 6-16 Eastern Surat – estimated maximum drawdown in the Taroom Coal Measures versus distance to nearest active CSG gas field

6.4 Conclusions

Key conclusions from the analysis of groundwater level trends in the Walloon Coal Measures are:

- Potentiometric surfaces and observed drawdown maps for the Upper Juandah and Taroom coal measures show extensive CSG-induced drawdown in the Eastern and South-eastern Surat, with less obvious drawdown in the Northern Surat. At the individual bore scale, this presents as tens to hundreds of metres of groundwater level decline in both the Taroom and the Upper Juandah coal measures. There is a tendency for more drawdown in the deeper Taroom Coal Measures in the Eastern and South-eastern Surat.
- Correlation between Upper Juandah and Taroom coal measures groundwater levels and CSG groundwater extraction has been demonstrated at the individual bore, gas field and regional scales. The observed declines are largely restricted spatially to the gas fields themselves and the immediately surrounding areas, with drawdowns greater than 10 m rarely observed beyond 10 km from active CSG groundwater extraction wells.
- Therefore, the potential for CSG depressurisation to currently affect overlying and underlying formations is largely restricted to the gas fields themselves. Impacts on adjacent aquifers should occur in those areas first and then propagate laterally as a function of each aquifer's hydraulic properties and physical characteristics.

7 Trend analysis – Springbok Sandstone

The Springbok Sandstone immediately overlies the Walloon Coal Measures in the Surat Basin. It is not a major water supply aquifer in the GAB, with 515 ML/year estimated for non-CSG water use (see section 2.4) – OGIA characterises this formation as a tight aquifer (OGIA 2019g). Importantly, however, there is no intervening aquitard separating the Springbok Sandstone and the Walloon Coal Measures. Therefore, there is some potential for CSG impacts to occur in the Springbok Sandstone in places where coal seams are in hydraulic connection with the basal sandstones in the Springbok Sandstone.

This chapter provides a summary of the main formation characteristics for context (section 7.1). The types of groundwater level trend that are observed in outcrop and deeper in the basin are then described (section 7.1.5). An analysis of groundwater level trends is then presented which features correlation analyses with water balance factors (sections 7.3.1 to 7.3.4) and consideration of inter-aquifer connectivity to the CSG reservoir (section 7.1.5). Conclusions related to groundwater level trends in the Springbok Sandstone are presented in section 7.4.

7.1 Formation characteristics

7.1.1 Stratigraphy and lithology

The Springbok Sandstone typically comprises medium to fine-grained, feldspathic to lithic sandstone with minor pebbly layers, siltstone, mudstone and occasional thin bentonite and coal lenses (OGIA 2016b). The matrix of the sandstones is often very clayey or contains calcareous cement (OGIA 2016b). The unconformity between the Springbok Sandstone and the Walloon Coal Measures is erosional, as scouring is observed at the contact (Green et al. 1997).

OGIA (2016b) has previously subdivided the Springbok Sandstone into two hydrostratigraphic units based primarily on lithological composition: an upper unit containing sandstone interbedded with siltstone and mudstone; and a lower unit that is predominantly stacked sandstone channels. Processed wireline logs show that, on average, the clean sandstone percentage is much lower in the upper Springbok (32%), compared with 71% in the lower Springbok Sandstone (Figure 7-1).

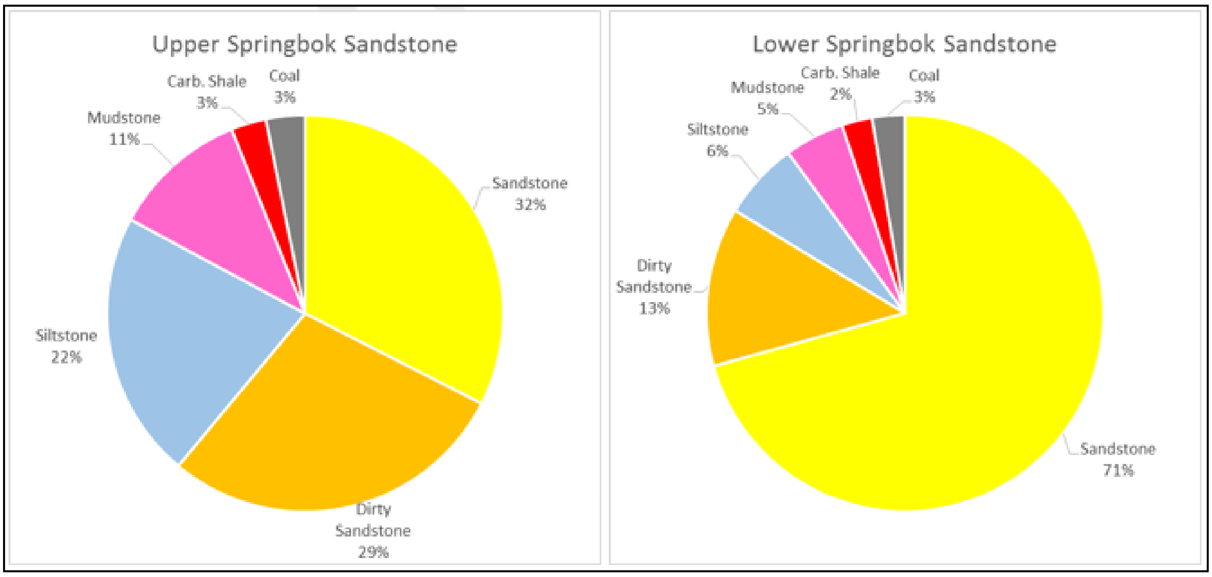

Figure 7-1 Springbok Sandstone – lithological composition

Figure 7-2 shows a cross-section of lithological logs for the Springbok Sandstone across the basin, flattened to the top of the Walloon Coal Measures. Consistent with Figure 7-1, this section also shows that the lower Springbok Sandstone is more abundant in clean sandstone compared with the commonly thicker but more heterogeneous upper Springbok Sandstone. The thickness of the lower Springbok Sandstone ranges up to 140 m, but averages less than 40 m. The more variable upper part of the Springbok Sandstone is typically much thicker, reaching up to 216 m and averaging over 70 m (OGIA 2019c).

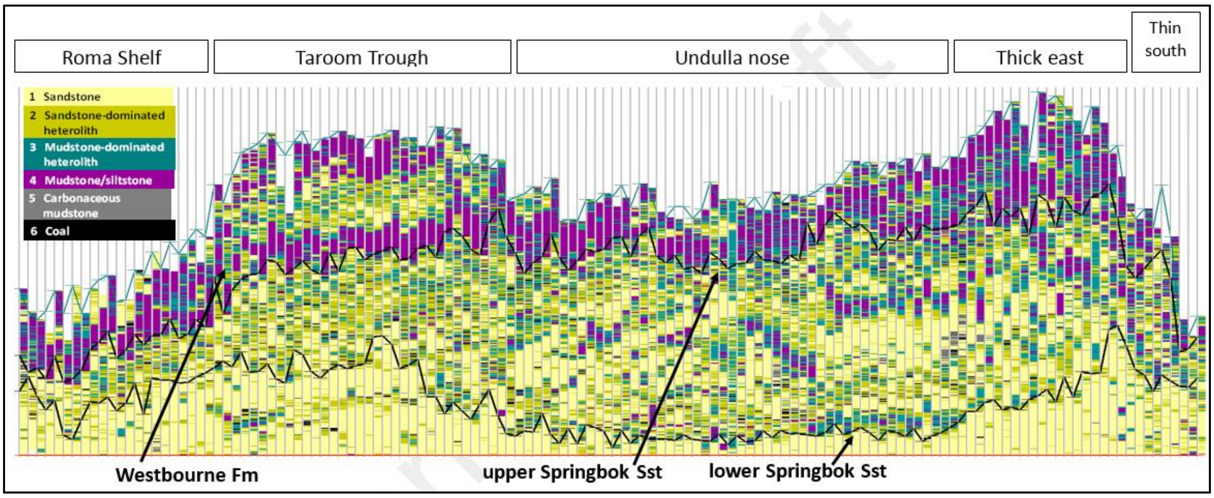

Figure 7-2 Lithology of the Springbok Sandstone to Westbourne Formation, flattened to the top of the Walloon Coal Measures

7.1.2 Hydraulic properties

Figure 7-3 presents a box plot of the available horizontal hydraulic conductivity (Kh) estimates (converted from permeability) for the main test types. The scale of measurement is an important factor affecting these estimates, with DSTs typically yielding appreciably higher permeability than the point-scale core tests. The DST interquartile ranges for both the upper (0.0015 to 0.67 m/day) and the lower (0.0011 to 0.15 m/day) Springbok Sandstone are up to three orders of magnitude higher than the core interquartile ranges, which are typically <0.001 m/day.

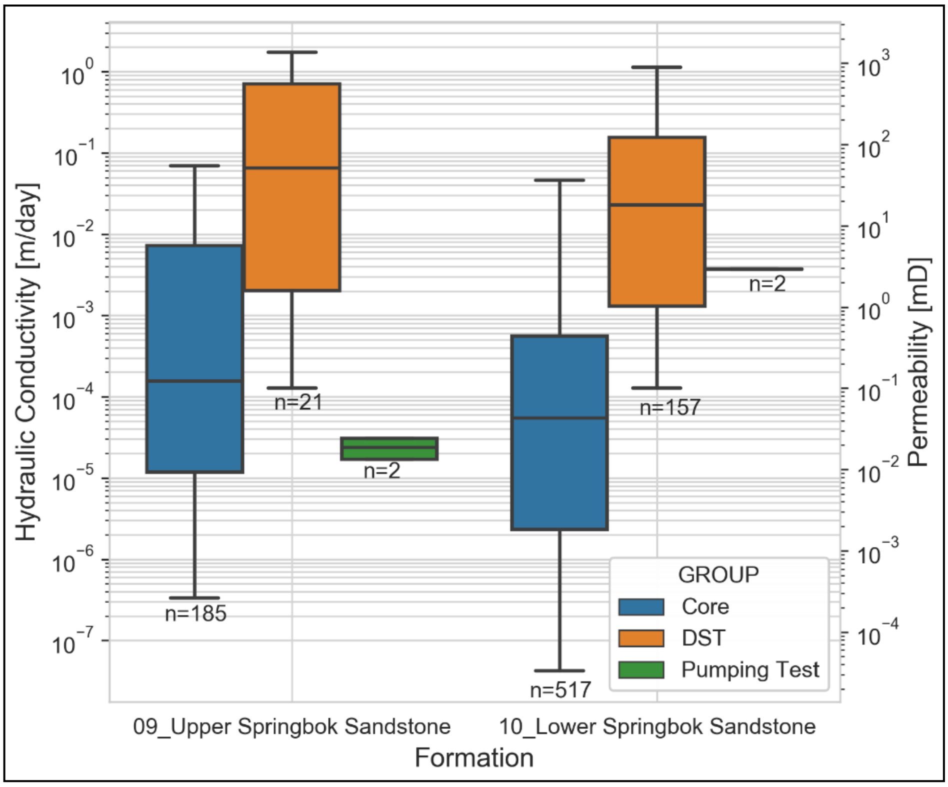

Figure 7-3 Horizontal hydraulic conductivity (Kh) and permeability[5] (k) for the Springbok Sandstone in the Surat CMA

7.1.3 Hydrochemistry

Figure 7-4 shows the spatial distribution of Springbok Sandstone hydrochemical KCA cluster classes across the Surat CMA. The hydrochemistry of the Springbok Sandstone varies considerably on a sub-regional basis, although in general, the water quality of the formation tends to be fresher than the underlying coal measures. Accordingly, Figure 7-5 shows that cluster class 1 (the freshest type in the Surat CMA) is the dominant water type for the Springbok throughout the Surat CMA. The water in this formation is typically Na-HCO_3-Cl or Na-Cl-HCO_3 type and has a mean TDS of <2,000 mg/L. However, zones of poorer-quality Springbok Sandstone water are also observed throughout the region.

[5] Conversion factor: 1 mD (millidarcy) = 1.27E-03 m/day

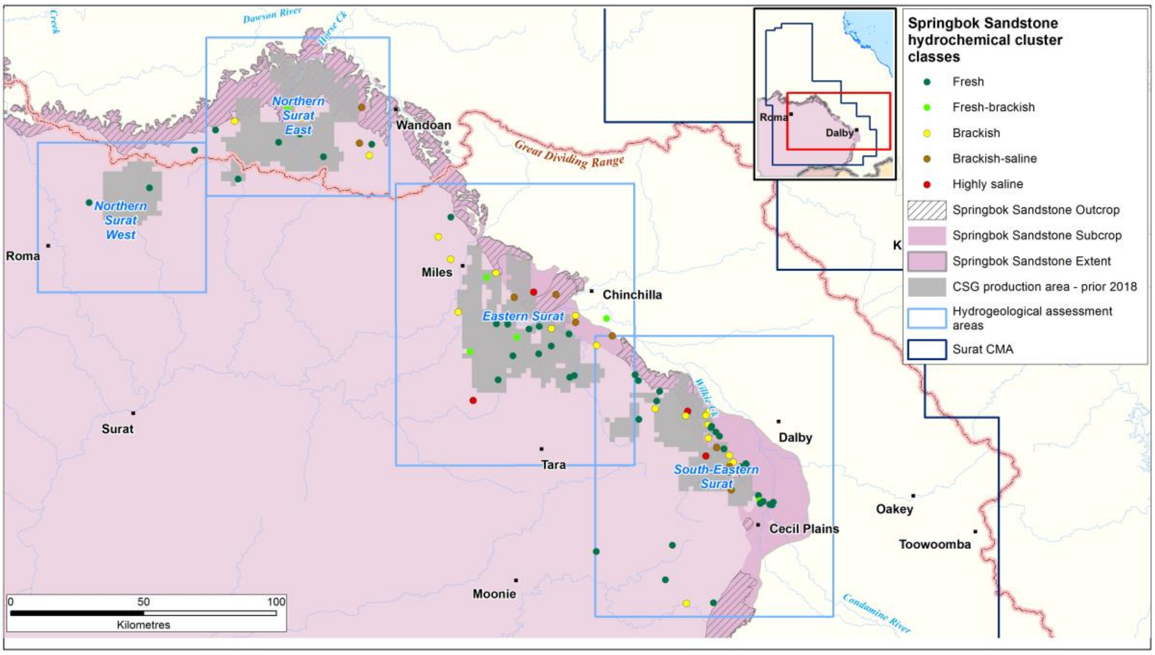

Figure 7-4 Springbok Sandstone – spatial variability in hydrochemical cluster classes

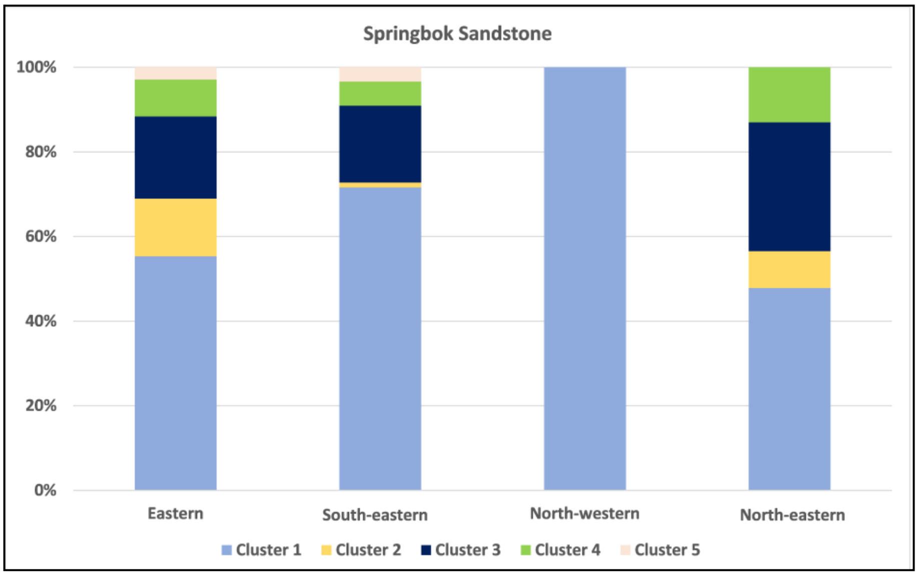

Figure 7-5 Springbok Sandstone KCA cluster class data for hydrogeological assessment areas

7.1.4 Groundwater flow directions

Figure 7-6 presents a map of current groundwater levels in the Springbok Sandstone. Overall, the interpreted regional groundwater flow system has two main regional flow systems, with each system having localised flow patterns. Based on overall flow patterns, groundwater recharges the Springbok Sandstone in the northwest (near Injune) and eastern (near Cecil Plains) parts of the basin. Generally, the two major flow systems include the following:

- a regional north-to-south flow system with a northwest (near Injune) to south (near St George) pattern and an east (near Cecil Plains) to southwest (near Goondiwindi) pattern
- a south-to-north flow pattern on the northern side of the Range, with apparent localised convergence of flow along reaches of Horse Creek.

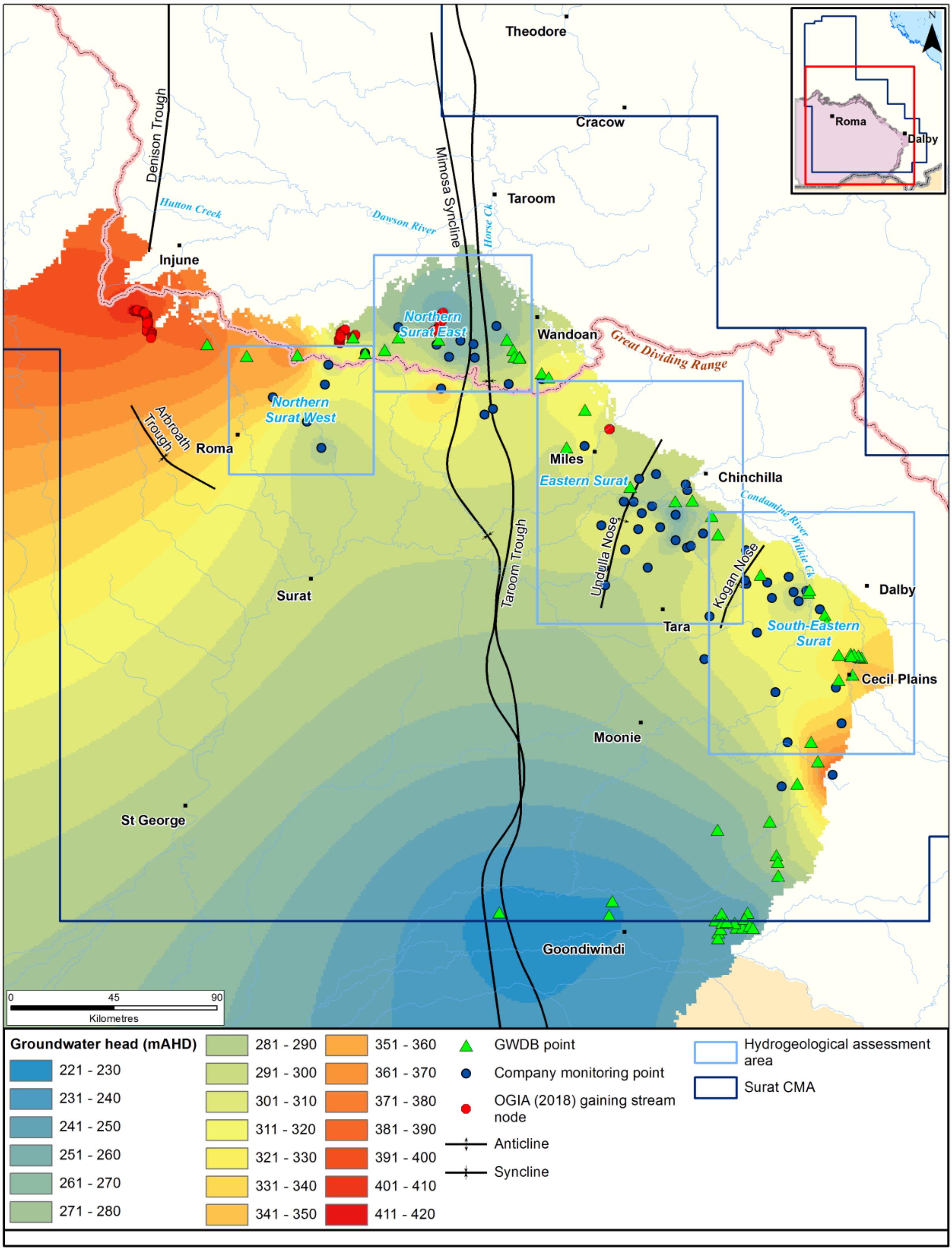

Figure 7-6 Springbok Sandstone potentiometric surface

7.1.5 Connectivity with the CSG reservoir

There may be opportunities for direct hydraulic connectivity between the Walloon Coal Measures and Springbok Sandstone in places, owing to both geological and bore connectivity factors. To provide context for the following sub-section on the assessment of potential CSG impacts at Springbok Sandstone monitoring sites, below is a brief overview of these connectivity features:

- The Springbok Sandstone and Walloon Coal Measures are characterised by very low vertical permeability as they include significant proportions of siltstone and mudstone (section 7.1.1). Interconnectivity between these two units is therefore considered likely to be low despite the direct erosional contact (i.e. the absence of an intervening aquitard). However, since the contact is erosional, there are areas where the Springbok Sandstone is understood to be in contact with the productive coal seams and a higher degree of interconnectivity is expected in these areas. Furthermore, connectivity may potentially be enhanced in other areas by a number of other features including coal exploration holes and multi-formation water bores.
- A large proportion of faults affecting the upper boundary of the Walloon Coal Measures have sufficient throw to juxtapose coal seams against basal sandstones in the Springbok Sandstone (OGIA 2019h). However, of the hundreds of these fault locations, only 16 have been characterised to have sufficient juxtaposed sandstone-on-coal connections and little enough clay smearing on the fault planes to allow potential for direct hydraulic connection between the two formations. These 16 localised sites therefore present a higher risk for CSG impact propagation. One of these sites is in the near vicinity of Kenya East GW4, where CSG impacts are likely to be already occurring. As described in section 7.3.3, this site shows a strong correlation between the commencement of CSG groundwater extraction in 2014 and subsequent onset of marked lower Springbok Sandstone drawdown in late 2014, indicating there is little hydraulic resistance between the coal seams in the reservoir and the sandstone aquifer.
- Despite a large number of potential connectivity features identified, the majority of the Springbok Sandstone pressure and chemistry data suggest a low degree of connectivity at the regional scale. The available hydrochemistry data (section 7.1.3) suggest that the Springbok Sandstone is distinctly fresher and less chemically evolved than the Walloon Coal Measures and few trends are observed in chloride time series data for CSG production wells.
- A large proportion of sites within and close to currently operating CSG fields show lower heads in the Upper Juandah Coal Measures than in the overlying Springbok Sandstone, resulting in a dominant positive head difference with a strong potential for downward flow from the Springbok Sandstone to the CSG reservoir.
- Comparison of well construction data with geological modelling results suggests about 16% of CSG wells in the Surat Basin may be completed partially into the Springbok Sandstone (OGIA 2019g). Analysis of associated water extraction rates and water chemistry indicates that there may be localised enhanced connectivity from only 3% of wells partially completed into the Springbok Sandstone.

In summary, there is evidence of localised connectivity between the Springbok Sandstone and the CSG reservoir, owing to a variety of features including geological features, water bores and CSG wells. Overall, however, the degree of connectivity between the two formations is expected to be low.

7.2 Observed groundwater level trends

The following sub-sections describe the groundwater level trends observed in the Springbok Sandstone in different hydrogeological settings across the Surat CMA. Figure 7-7 shows a selection of example hydrographs from outcrop/subcrop areas and locations deeper in the basin where CSG development is present. This figure provides a regional overview of the different types of trends that are observed and highlights some of the limitations associated with the short duration of monitoring at many locations. Appendix B provides group plots of groundwater levels and groundwater level trends for all Springbok Sandstone UWIR and non-UWIR company monitoring points in the Surat CMA.

For the Springbok Sandstone, there are 129 bores (99 UWIR WMS and CSG company bores and 30 additional bores from the GWDB) that provide groundwater level monitoring data within the Surat CMA. Of these 129 bores, 17 have groundwater level readings prior to 2010, with the remaining 112 sites only containing more recent groundwater level records (i.e. post-2010). Of the 17 sites with earlier records, only six have more than one year of regular readings (i.e. at least four records per year) to allow for meaningful trend analysis.

7.2.1 Shallow and subcrop

Figure 7-8 presents the groundwater level trends for all Springbok Sandstone bores that have a minimum of five temporal groundwater level records across the Surat CMA from 1940 to 2018. Excluding all UWIR WMS and company monitoring points that have been recently installed, Figure 7-8 is focussed on long-term, decade-scale records from across the basin.

Figure 7-8 shows that decreasing groundwater level trends (decline varying between 0.04 and 0.7 m/year) were commonplace throughout the basin over this period leading up to 2010, despite the considerable variability in the long-term rainfall patterns. In some bores, the infrequent records prevent any sort of meaningful trend analysis; however, the consistency in responses across the basin identifies some important long-term declining trends in groundwater level. Post-2010, seven of the hydrographs show increasing groundwater level trends that coincide with basin-wide above-average rainfall. The causes of these increasing and declining trends are discussed further in sections 7.3.1 to 7.3.3.

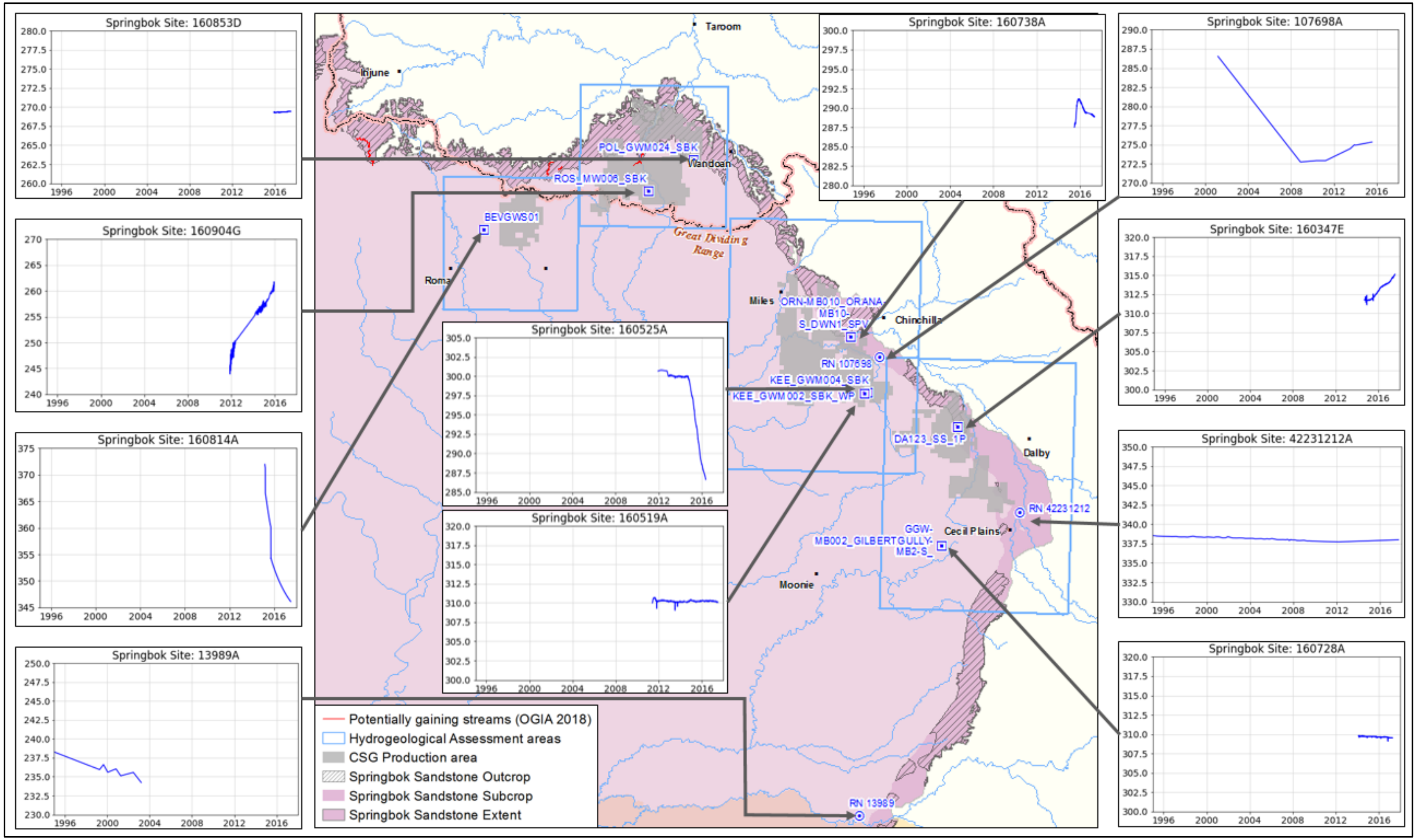

Figure 7-7 Selection of Springbok Sandstone hydrographs from different parts of the Surat CMA

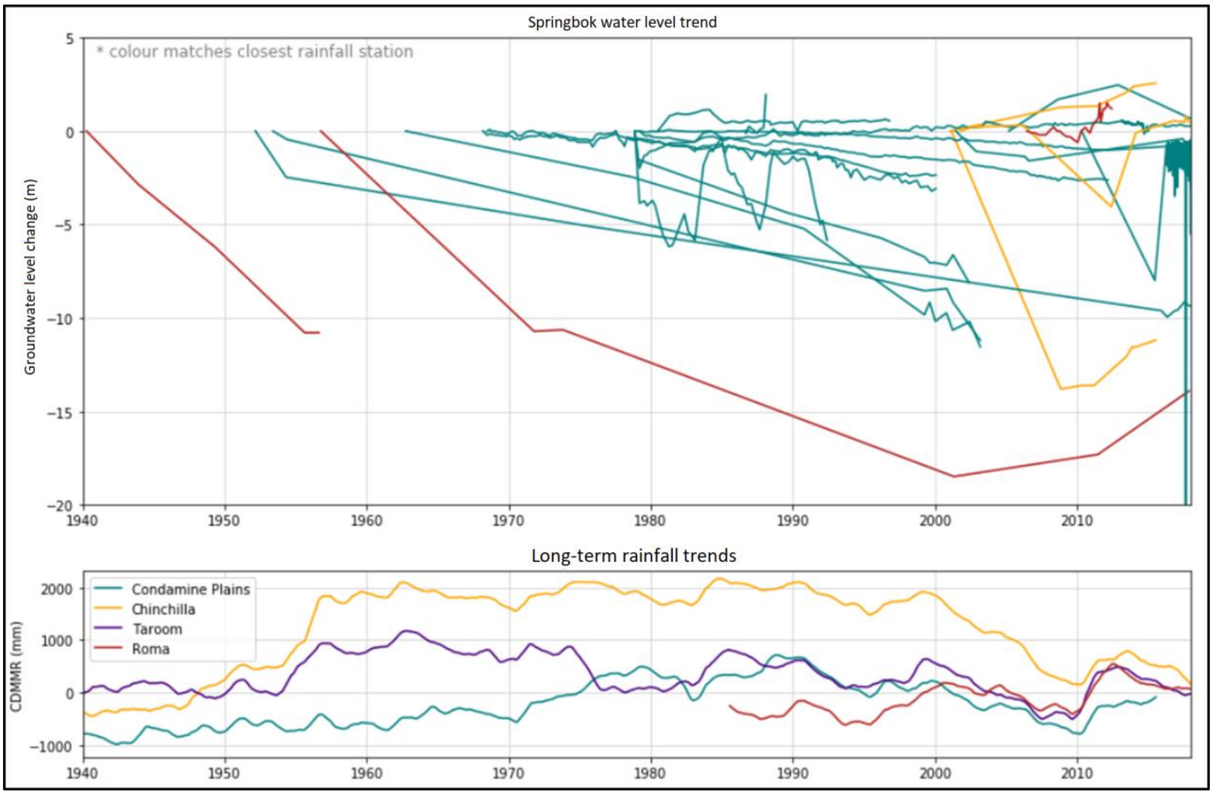

Figure 7-8 Springbok Sandstone groundwater level trends and long-term rainfall patterns (1940–2017)[6]

7.2.1.1 Monitoring types and trends

Of the six sites with one or more year of continuous records (see section 7.1.5), three are situated in the outcrop area (or shallow subcrop) and have semi-continuous records prior to 2010 that can be analysed to broadly assess longer-term trends. There are also a further 13 dedicated Springbok Sandstone outcrop/subcrop monitoring points within the UWIR and non-UWIR company monitoring networks which have sufficient temporal groundwater level data after 2010 to undertake a trend analysis assessment (i.e. greater than 12 months of regular groundwater level data). Most of these monitoring points have only two to four years of monitoring records. The distribution of the 16 Springbok Sandstone monitoring points (three GWDB and 13 dedicated UWIR or non-UWIR) is shown in Figure 7-9.

A statistical trend analysis was undertaken for these monitoring points. The purpose of the trend analysis is to identify statistically significant increases or decreases in groundwater levels, using a modified Mann-Kendall trend test (Mann 1945; Kendall 1975). The resulting trend rates across two time periods are shown on Figure 7-9. These time periods were rationalised as being representative of:

- the Millennium Drought (2000 to 2009) when CSG production in the basin was limited to only a few fields, such as Talinga and Daandine

[6] Only water bores and monitoring points with pre-CSG data and five or more groundwater level records are considered.

- a more recent period (2010 to 2018) when CSG production became much more widespread throughout the basin (especially during and after 2014) and cumulative CSG groundwater extraction increased exponentially
- the 2010 recharge event, which separated these two time periods, having influenced groundwater levels in both the Springbok Sandstone and Hutton Sandstone (as described in sections below).

Table 7-1 provides a summary of the outcomes of the analysis. It is evident from Figure 7-9 and Table 7-1 that decreasing trends are the only observed trend (from a very limited dataset) in the outcrop area during the Millennium Drought (2000 to 2009) and that an equal mix of no trend and increasing trend is dominant during the period after the 2010 regional recharge event.

Table 7-1 Trend analysis results for monitoring points located in outcrop / subcrop areas

Hydrostratigraphic unit	Time period	Position in basin	Monitoring points	Groundwater level trend		
				Increasing	Decreasing	No trend
Springbok Sandstone	2000-2009	Outcrop/ subcrop	3	0	3	0
	2010-2018		16	7	2	7

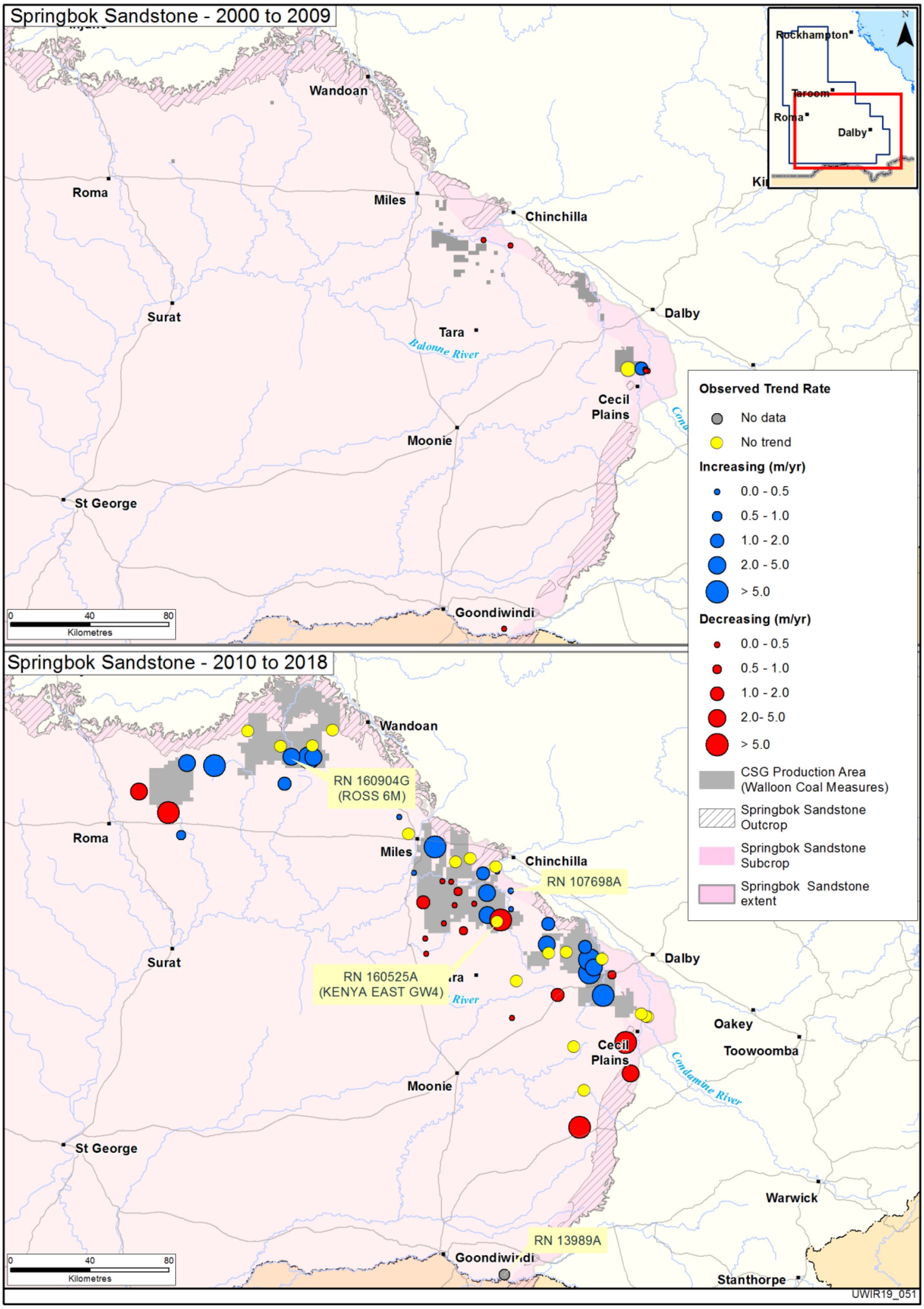

Figure 7-9 Springbok Sandstone groundwater level trends

7.2.1.2 Example hydrographs

One DNRME monitoring bore, two private bores and three company monitoring points have been selected at different locations throughout the Surat CMA, to undertake a more thorough hydrograph review and also to complete statistical correlation analysis with various water balance factors (sections 7.3.1 to 7.3.3).

The individual hydrographs for these six sites are provided in Figure 7-10 and their locations are shown on Figure 7-7. Ideally, only dedicated monitoring points would be used in this review. However, in the absence of data from dedicated points, two non-dedicated points (RN13989 and RN107698), which are also used for water supply purposes, were added to provide information on groundwater level trends prior to CSG development. The reliability of the data from these non-dedicated points is lower.

RN13989 is an existing water supply bore tapping the upper Springbok Sandstone near the southern boundary of the Surat CMA. This bore is situated within 2.5 km of the mapped outcrop area and shows a steady decline in head over 40 years, totalling approximately 12 m from 1962 through to 2003. There are large gaps in the data record for this site, although its long record provides valuable insight. The long-term groundwater level decline predates CSG development by over 40 years and this site is more than 100 km from CSG development areas, making it a useful control site.

RN42231212 is an existing state monitoring bore tapping the upper Springbok Sandstone near Cecil Plains. The bore is situated in the subcrop area and shows a steady decline over 23 years, totalling approximately 1 m from 1987 through to 2010. There are subtle fluctuations over this period that are likely related to short periods of increased rainfall. Each one of these rises is typically less than 10 cm in magnitude. After December 2010, there is almost 30 cm of groundwater level recovery.

RN107698 is an existing water supply bore situated in Springbok Sandstone outcrop, in the Eastern Surat hydrogeological assessment area near Chinchilla. This upper Springbok Sandstone bore shows approximately 11 m of decline between readings in 2001 and in late 2008, albeit with few temporal records. Similar to RN42231212, the groundwater levels after 2011 commence a two-metre recovery.

Figure 7-10 also includes shorter-term monitoring from three non-UWIR company monitoring points:

- ORN-MB010 (RN160738A) shows a short-term rising and then falling groundwater level trends in outcrop area southwest of Chinchilla.
- Daandine 123 (RN160347E) is an example of a short-term increasing groundwater level trend in the south-eastern outcrop area.
- Polaris GW24 (RN160853D) is an example of a short-term slight increasing trend in shallow subcrop in the northern parts of the basin.

Overall conclusions from the six hydrographs (Figure 7-10) located in the outcrop area include the following:

- The three hydrographs with long-term records indicate declines prior to any CSG groundwater extraction.
- The two hydrographs with data before and after 2010 show increases in groundwater levels around this time, suggesting significant widespread recharge during the period of above-average rainfall from late 2010 to 2013.
- Data for RN42231212 show minor groundwater level fluctuations associated with smaller rainfall events.

- The three selected company monitoring points highlight the difficulties associated with trying to interpret groundwater processes with such limited monitoring duration. At these sites, parts of the records show increasing groundwater level trends that may not be related to the 2010-to-2013 wet period, as they occur a number of years after 2010. Further monitoring of these sites will be required before longer-term trends at these locations can be confidently established.

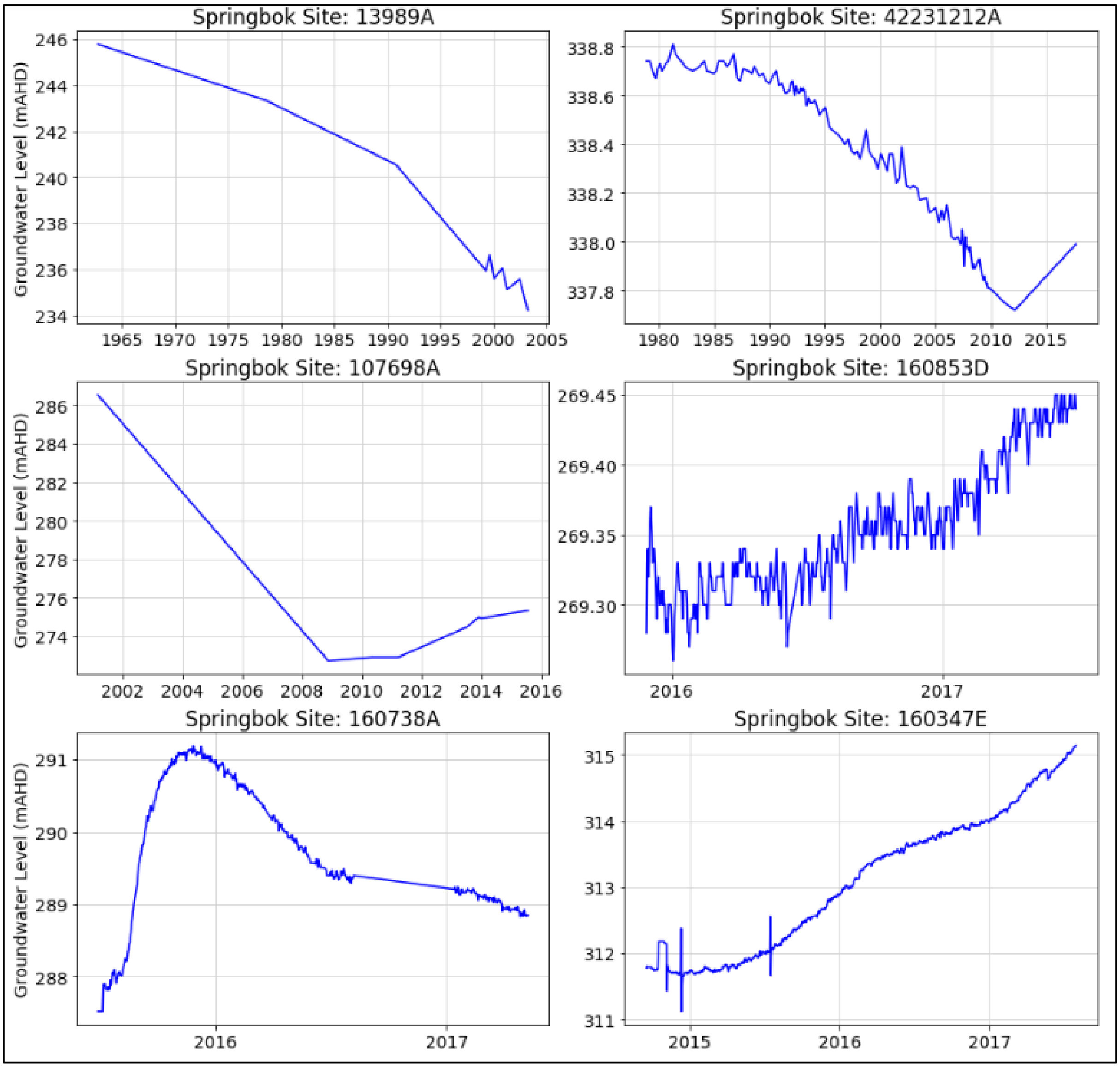

Figure 7-10 Selected Springbok Sandstone outcrop hydrographs

7.2.2 Confined basin interior

7.2.2.1 Monitoring types and trends

The UWIR and non-UWIR company monitoring network has a more extensive spatial coverage of the Springbok Sandstone in the interior of the basin, as compared to the state and private monitoring bores, which are more abundant in shallow outcrop areas. In these interior basin areas, the Springbok Sandstone underlies a number of other GAB aquifers and aquitards. As a result, this formation is predominantly a confined, sub-artesian aquifer system. A limitation of this network is that data typically only relate to the post-2010 period. Therefore, any detected trends are more recent and occur while both CSG and non-CSG stresses are active in the basin (as described further in section 7.3).

There are 49 dedicated Springbok Sandstone monitoring points within the UWIR and non-UWIR company monitoring network that are located within confined parts of the system and have sufficient temporal groundwater level data to undertake a trend analysis assessment (Figure 7-9). Most of these monitoring points have only two to four years of monitoring record. Only six monitoring points have pre-2010 data to inform deeper basin trends prior to CSG development.

The trend rates for these bores are shown in Figure 7-9. Table 7-2 provides a summary of the outcomes of the Springbok Sandstone groundwater level trend analysis in the deeper, confined parts of the basin. It is evident from Figure 7-9 and Table 7-2 that there is no dominant trend in these deeper confined areas in the period after 2010, with an equal mix of increasing and decreasing trends and 13 monitoring points showing no trend. Figure 7-9 also shows that the monitoring points with decreasing trends tend to be situated furthest from outcrop. Decreasing groundwater levels are dominant during the Millennium Drought – 2000 to 2009.

Table 7-2 Trend analysis results for monitoring points located in confined areas

Hydrostratigraphic unit	Time period	Position in basin	Monitoring points	Groundwater level trend		
				Increasing	Decreasing	No trend
Springbok Sandstone	2000-2009	Deeper confined basin	6	1	4	1
	2010-2018		49	18	18	13

7.2.2.2 Example hydrographs

For this assessment, five non-UWIR company monitoring points have been selected at different basin interior locations to gain an appreciation of basin-scale groundwater level trends in deeper, confined parts of the Springbok Sandstone. The hydrographs for these five sites are provided in Figure 7-11 and their locations are shown on Figure 7-7. These five sites were selected as they are from different geographic parts of the basin and represent the different types of groundwater level trends that are observed, including rising trends, falling trends and no trend. Additionally, the groundwater level trends for these five sites are plotted together in Figure 7-12, using consistent time and groundwater level axes. Further correlation analysis of three of these sites is summarised in section 7.3.

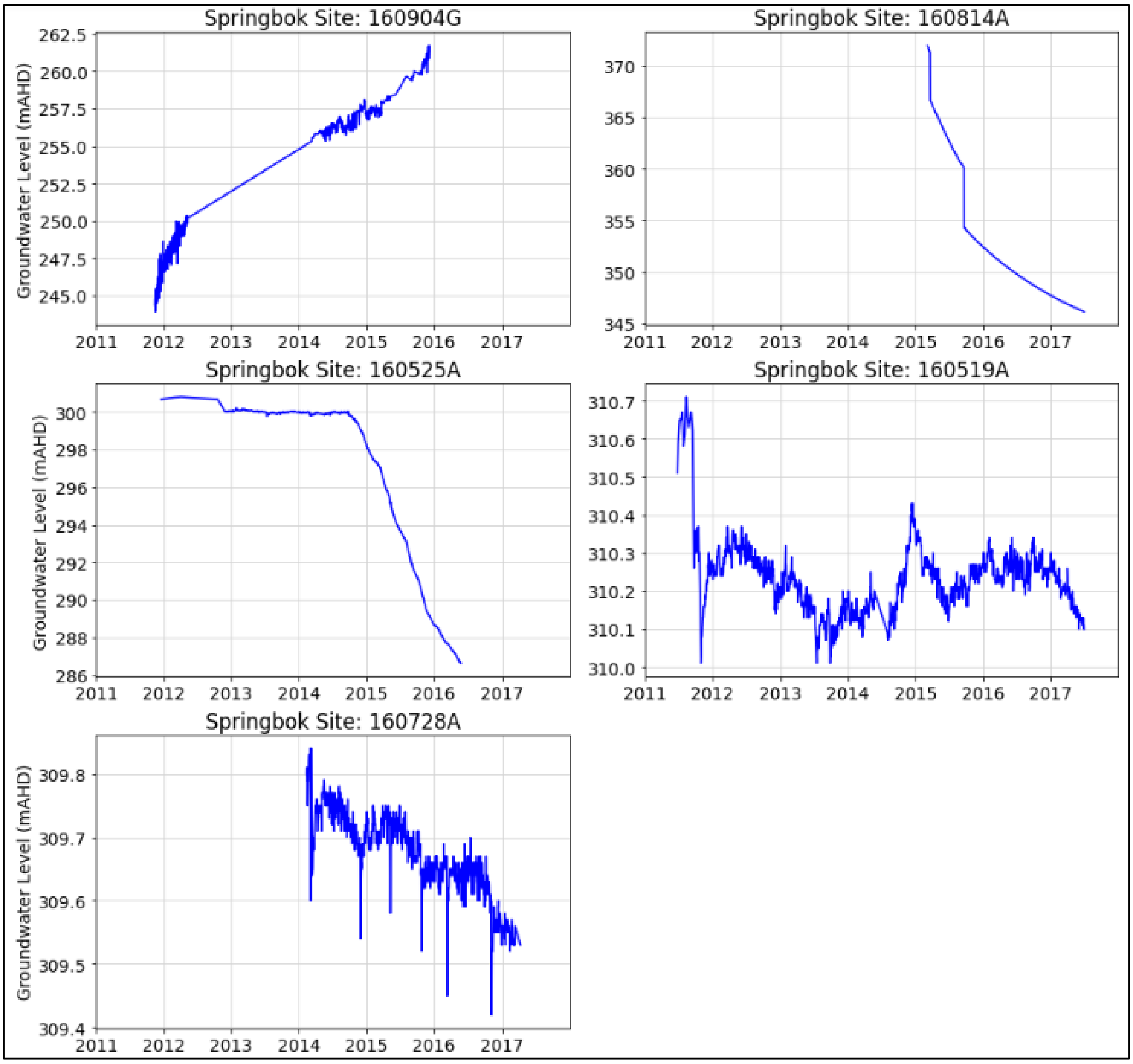

Figure 7-11 Selected confined Springbok Sandstone hydrographs

A lower Springbok Sandstone monitoring point, Kenya East GW4 (RN160525A) is one of the few sites in the network where a clear inflection point in groundwater levels is observed shortly after near-field CSG groundwater extraction. After nearly three years of stable groundwater levels, a sudden declining groundwater level trend occurs from late 2014 onwards. Kenya East GW2 (RN160519A) is located within 2 km of Kenya East GW4 and monitors the upper Springbok Sandstone. As shown in Figure 7-12, despite the considerable drawdown observed at Kenya East GW4, there is a continuing stable trend (with minor fluctuations) in Kenya East GW2, without any obvious sustained drawdown.

Ross 6M (RN160904G) is a lower Springbok Sandstone monitoring point in the Northern Surat that shows rising trends in groundwater level (the dominant trend in the Northern Surat). BEVGWS01 (RN160814A) taps both the upper and lower Springbok Sandstone in the Northern Surat and shows more than 25 m of drawdown over a two-year period.

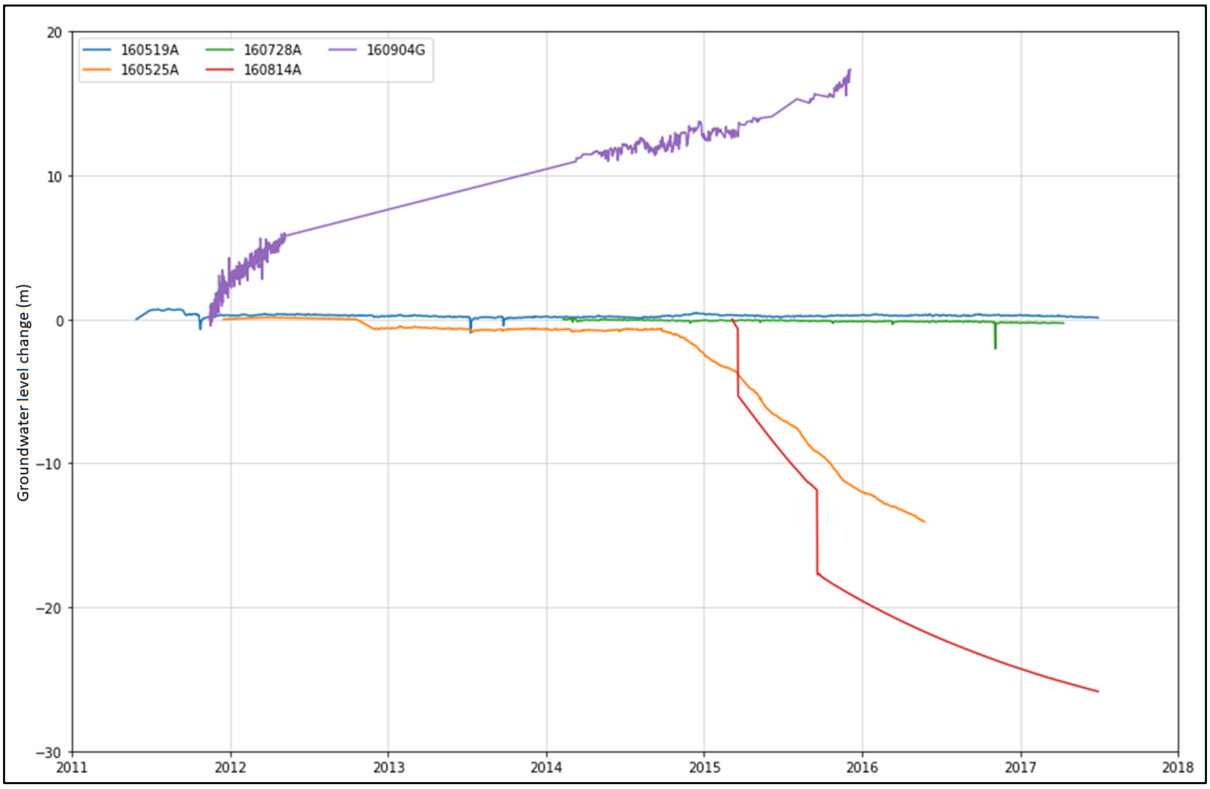

Figure 7-12 Selected confined Springbok Sandstone hydrographs

7.3 Analysis of groundwater level trends

This section provides a summary of the detailed analysis of Springbok Sandstone groundwater level trends and the potential influence of three water balance factors (section 4.2.1) – rainfall, non-CSG water use and CSG groundwater extraction. Only a number of selected example sites are shown in this section, in order to highlight important findings. Further details and examples are provided in Appendix C.

The intention of the detailed correlation analysis is to consider the influence of each water balance factor in isolation and draw conclusions on which factors are most likely to affect overall groundwater level trends, both in outcrop areas and deeper in the basin. This provides the basis for assessing the potential for CSG impact, using both statistical tools and hydrogeological judgement.

7.3.1 Correlation with rainfall

The two hydrographs presented in the sub-sections below have been correlated with CDMMR from a nearby weather station, using the Spearman rank correlation method (see Appendix G).

7.3.1.1 Shallow outcrop and subcrop areas

As described in section 4.2.1.1, groundwater levels in outcrop areas are expected to respond relatively rapidly to periods of above-average and below-average rainfall.

Figure 7-13 presents the Condamine Plains weather station CDMMR and hydrograph for RN42231212A, which is an existing state monitoring bore tapping the Springbok Sandstone near Cecil Plains in the South-eastern Surat. The bore is situated in the shallow subcrop and shows a steady decline of approximately 1 m in head over 23 years, from 1987 through to 2010. There are subtle groundwater level fluctuations over this period, with each being typically less than 10 cm in magnitude. As shown, the CDMMR and hydrograph broadly correlate post-2000:

- There is an extended period of below-average rainfall conditions from 2000 to 2010 (the 'Millennium Drought') which coincides with ~0.5 m decline in groundwater levels, resulting in a positive linear correlation between the two variables.
- Above-average rainfall after December 2010 presents as almost 30 cm of groundwater level recovery, although the groundwater level response has a lag, indicating that the recharge signal takes some time to reach this site.

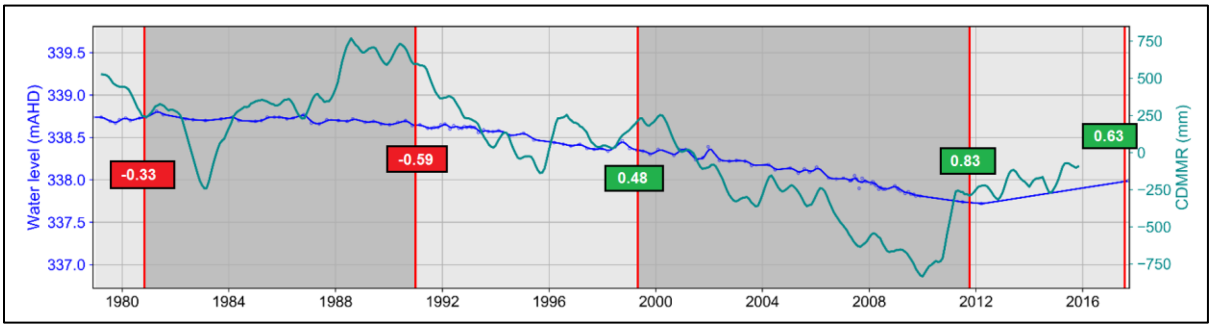

Figure 7-13 Spearman correlation, RN42231212A groundwater level and Condamine Plains weather station CDMMR

Further examples are provided in Appendix C.1.1.

7.3.1.2 Deeper basin interior

As described in section 4.2.1.1, it is expected that groundwater levels in deeper confined areas will show either a muted or no response to periods of above-average and below-average rainfall. As further described in section 7.2.2 there is an even mix of rising, falling and no trends for the post-2010 period. Of the falling trends, only three have pronounced inflection points in drawdown that identify the onset of an impact. One of these three sites, Kenya East GW4, is used as the example site below.

Figure 7-14 presents the Chinchilla weather station CDMMR and a hydrograph for Kenya East GW4 (RN160525A), which is a lower Springbok monitoring point situated in the Kenya East gas field southwest of Chinchilla. As expected, the correlation coefficient of 0.05 in the period before the onset of observed drawdown suggests little or no correlation with rainfall. During the period of drawdown, the correlation coefficient erratically shifts between positive and negative numbers, which is considered likely to be purely coincidental, especially given the magnitude of the observed drawdown. It is evident from this analysis that rainfall is having little or no significant impact on groundwater levels at this site, although it could be a minor component of the drawdown observed during the latter part of the record, coinciding with a dry period.

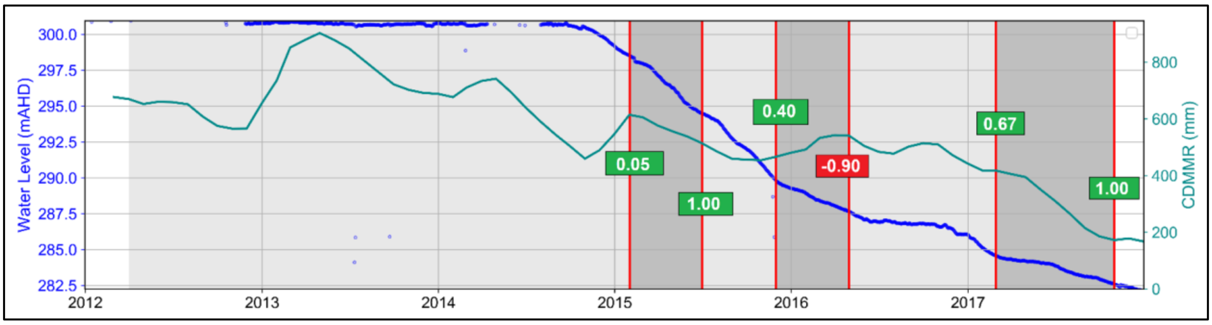

Figure 7-14 Spearman correlation, RN160525A (Kenya East GW4) groundwater level and Chinchilla weather station CDMMR

Further examples are provided in Appendix C.1.2.

7.3.2 Correlation with non-CSG water use

As described in section 2.4, there is limited metering outside of the Condamine Alluvium, and therefore an estimate of non-CSG water use has been prepared by OGIA (2019b). As previously shown in Table 2-1, the Springbok Sandstone is not a major water supply aquifer within the Surat CMA. The total estimated groundwater extraction of 515 ML/year makes up ~1% of the cumulative estimated water (40,781 ML/year) extracted from all GAB formations in the Surat CMA. However, revised temporal estimates of long-term water use in the Springbok Sandstone by OGIA (OGIA 2019b) show that non-CSG water use is present prior to the 1970s, highlighting the long-term influence of this stress on the aquifer system.

Figure 7-15 shows the Springbok Sandstone groundwater level trends compared with both non-CSG water use per 8×9-km grid cell and the current CSG development footprint. This figure shows that Springbok Sandstone non-CSG water use is typically limited to stock and domestic purposes close to shallow outcrop and subcrop areas, with sporadic use in the internal, confined parts of the basin, such as in the Eastern Surat.

The two representative outcrop/subcrop monitoring sites described in section 7.3.1 are again subjected to Spearman correlation analysis, however this time, each groundwater level time series is correlated with OGIA's estimates of non-CSG Springbok Sandstone water use within 25 km of each monitoring point.

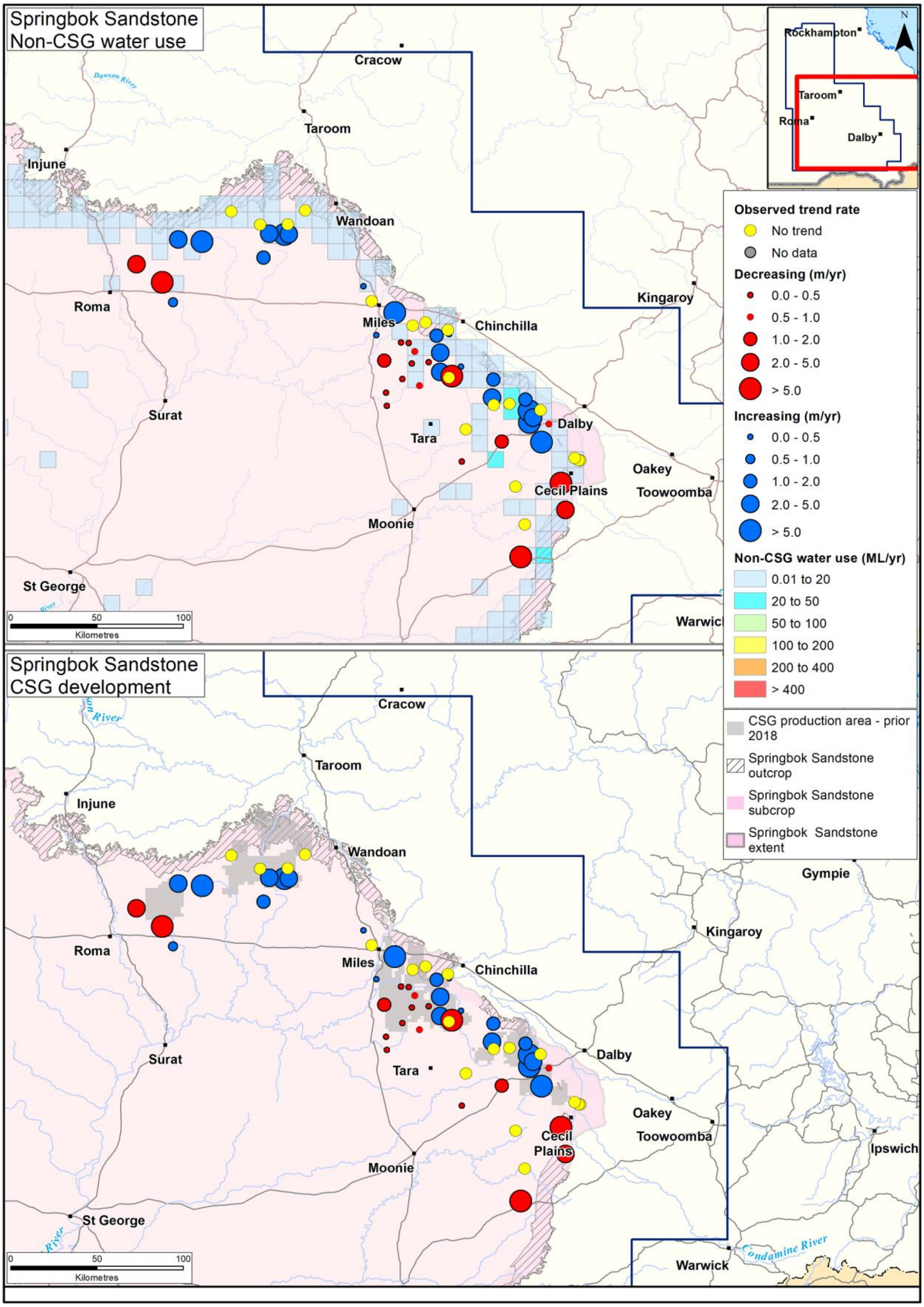

Figure 7-15 Springbok Sandstone groundwater level trends for the 2010 to 2018 period, current non-CSG water use (upper frame) and CSG production areas as at 2018 (lower frame)

7.3.2.1 Shallow outcrop and subcrop areas

In all instances, the non-CSG water use predates the monitoring record (prior to the 1960s), which emphasises the long-term water budget influence of non-CSG water use on this aquifer. As shown in Figure 7-15, the non-CSG water use occurs predominantly in and around the outcrop areas, so it would be expected that this long-term stress is impacting groundwater level trends in these shallow outcrop areas and inverse correlation (i.e. declining groundwater level response to increasing extraction) would be expected.

Figure 7-16 presents annual non-CSG water use within 25 km of RN42231212A compared with the hydrograph for that site. There are 60 water supply bores within a 25-km radius of this site. The estimated cumulative non-CSG water use progressively increased from less than 10 ML/year in the 1980s to more than 40 ML/year in 2017.

Overall, the inverse correlations are very strong over 20-year period (1992 to 2012), with increases in non-CSG water use coinciding with sustained decreases in groundwater levels. The major rainfall event in late 2010 (more than 300 mm rainfall over a 30-day period) instigated much more effective recharge to the aquifer, which has led to strong groundwater level recovery that has diminished the influence of non-CSG water use over this more recent period.

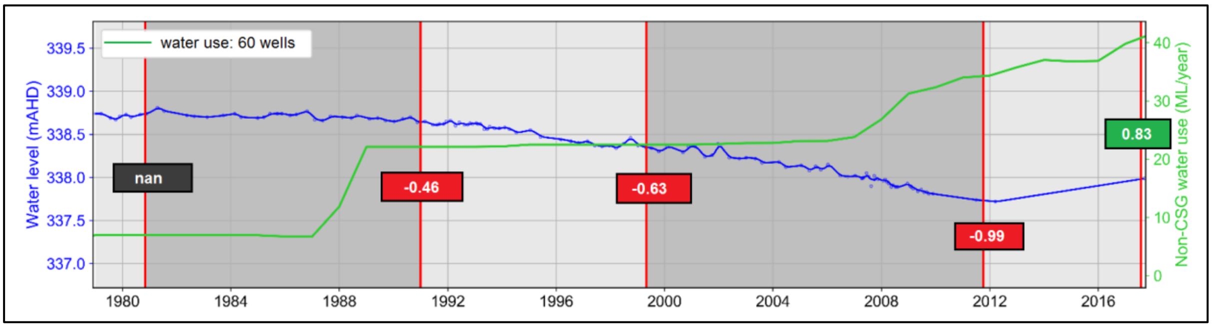

Figure 7-16 Spearman correlation, RN42231212A groundwater level and non-CSG water use from the Springbok Sandstone within 25 km

Further examples are provided in Appendix C.2.1.

7.3.2.2 Confined basin interior

As shown in Figure 7-15, non-CSG water use is irregularly distributed in the confined basin interior of the Springbok Sandstone. There are wide areas with little or no extraction and other areas with localised concentrations of water supply wells. Overall, non-CSG water use is not expected to have a widespread impact on groundwater levels in the deeper parts of the basin.

Figure 7-17 presents annual non-CSG water use within 25 km of Kenya East GW4 (RN160525A) compared with the hydrograph for this site. There is a sustained period of non-CSG water use that predates groundwater level monitoring at this site, with 73 bores within the radius of influence. However, prior to 2015, the non-CSG water use at Kenya East GW4 appears to have had only a very minor influence on a very slightly reducing groundwater level and there is no sudden increase in extraction in the period leading up to the sudden drawdown. Despite the perfect inverse correlation for a number of time periods after 2015, it is interpreted to be unlikely that the pre-existing non-CSG water use stress from 73 bores has suddenly had a major influence on the groundwater level record.

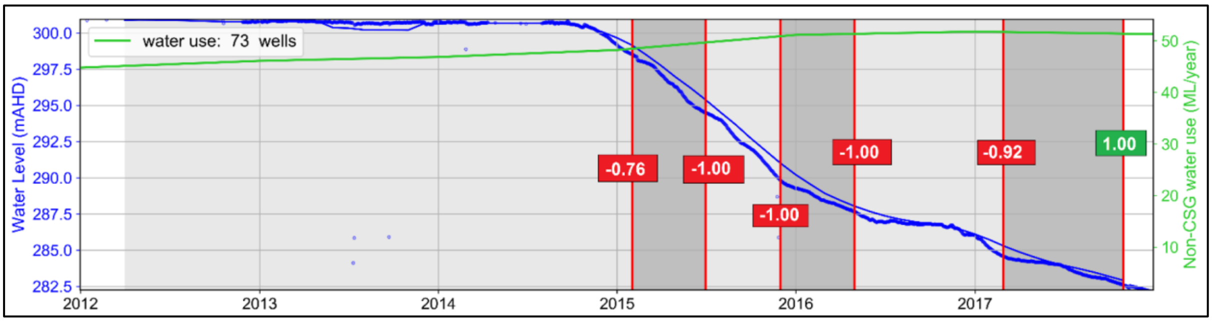

Figure 7-17 Spearman correlation, Kenya East GW4 (RN160525A) groundwater level and non-CSG water use from the Springbok Sandstone within 25 km

Further examples are provided in Appendix C.2.2.

7.3.3 Correlation with CSG groundwater extraction

This section seeks to identify correlation between local CSG groundwater extraction from the Walloon Coal Measures with groundwater level trends for the outcrop/subcrop and basin-interior monitoring points described in the sub-sections above.

7.3.3.1 Shallow outcrop and subcrop areas

Based on the Walloon Coal Measures distance–drawdown plots presented in section 6.3.2, it is expected that drawdown in the reservoir is currently restricted to gas field areas. CSG-induced groundwater level impacts are therefore not expected in the distal Springbok Sandstone outcrop areas.

Figure 7-18 presents the cumulative monthly CSG groundwater extraction within 10 km of RN42231212A compared with the hydrograph for that site. There are 35 CSG wells within 10 km of this site and cumulative groundwater extraction varies between 15 and 50 ML/month. The Spearman correlation over the period of extraction is quite low, both before and after the 2012 breakpoint in groundwater levels, and switches between positive and negative, suggesting no overall correlation. In addition, there is no obvious change in the rate of groundwater level decline as CSG groundwater extraction commences in 2008.

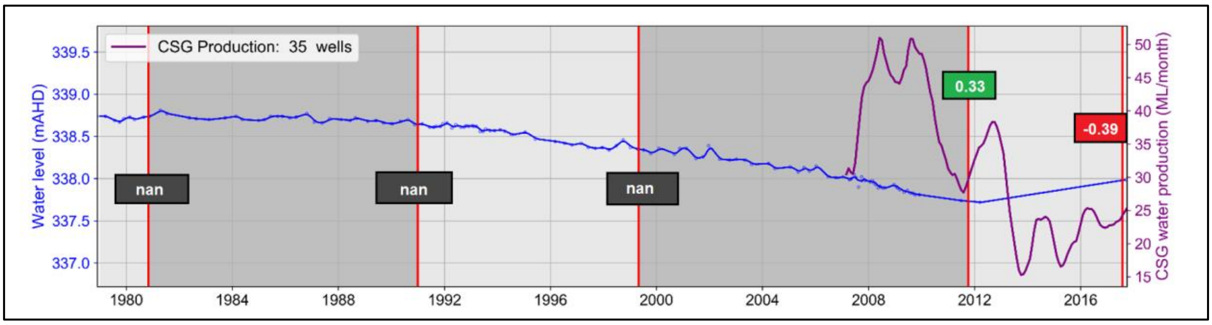

Figure 7-18 Spearman correlation, RN42231212A groundwater level and CSG groundwater extraction from the Walloon Coal Measures within 10 km

Further examples are provided in Appendix C.3.1.

7.3.3.2 Confined basin interior

Figure 7-19 presents the cumulative monthly CSG groundwater extraction within 2 km of Kenya East GW4 (RN58605A) compared with the hydrograph for that site. The smaller (2-km) radius was applied at this site because there is a distinct inflection point in drawdown and localised impacts from CSG are suspected. There are 21 CSG wells within 2 km of this site, with CSG groundwater extraction rapidly increasing during mid-2014. By late 2014, there is a sudden commencement of drawdown in Kenya East GW4.

The data show a perfect inverse correlation between the start of 2015 and mid-2015, when CSG cumulative extraction was climbing towards a peak extraction rate and the monitoring point was rapidly drawing down. After this period, the coal seams are effectively depressurised and the rate of groundwater extraction steadily reduces to maintain a static pressure in the coal reservoir as the wells operate. This results in a strong positive correlation during this period of declining groundwater extraction, since groundwater levels in the Springbok Sandstone appear to continue to decline due to lag effects.

This shows that actual CSG groundwater extraction volume may not always be the best variable with which to correlate over the entire life cycle of the CSG well. In future, a different variable, such as change in vertical hydraulic gradient (between reservoir and aquifer), may be preferable in these situations.

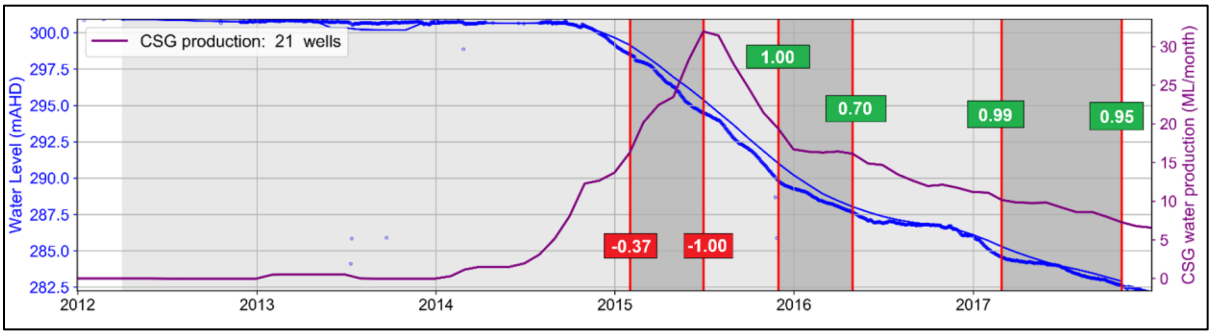

Figure 7-19 Spearman correlation, Kenya East GW4 (RN160525A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 2 km

Further examples are provided in Appendix C.3.2.

7.3.4 Summary of correlation analyses

Sections 7.3.1 to 7.3.3 provide a summary of the degree of correlation between Springbok Sandstone groundwater levels at selected sites and three water balance factors – rainfall, non-CSG water use and CSG groundwater extraction. Further examples are provided in Appendix C.

Table 7-3 below provides a summary of the outcomes of the correlation analyses for the Springbok Sandstone. Importantly, a persistent strong positive correlation for groundwater levels with rainfall would make it an influential factor for groundwater level trends, while negative correlation with non-CSG and/or CSG use would make them influential factors. This is because rainfall is an input to the water budget (so groundwater levels tend to rise when rainfall increases and vice versa) while CSG groundwater extraction and non-CSG water use are outputs from the water balance (so groundwater levels tend to fall when extraction rises).

Table 7-3 Summary of Springbok Sandstone correlation analyses

Location	Representative monitoring site	Length of record (years)	Correlation with rainfall[1]	Correlation with non-CSG water use	Correlation with CSG groundwater extraction	Factors influencing groundwater levels
Shallow outcrop/ subcrop	RN42231212A	38	Yes (+)	Yes (-)	No	Rainfall and non-CSG water use.
	RN107698A	15	Yes (+)	Yes (-)[2]	No	Rainfall and non-CSG water use.
	RN160347E (Daandine 123 SS)	3.5	No	Yes (+)	No	Uncertain. Short-term rising groundwater levels are difficult to interpret. Rising levels may relate to bore equilibration or the influences of gas, however, further monitoring is required.
Confined basin interior	RN160525A (Kenya East GW4)	6	Variable	Yes (-)	Yes (-)[3]	Local CSG groundwater extraction is the major influence. Long-term non-CSG water use appears to have very subtle influence on groundwater levels prior to 2015 and may also be a minor overall influence on groundwater levels.
	RN160519A (Kenya East GW2)	6	No	No	No	Uncertain. Short duration of monitoring and fluctuating trends make correlation with stresses difficult at this point in time.
	RN160728A (Gilbert Gully MB2-S)	4	No	No	No	Uncertain. Noisy and subtle trend makes correlation difficult at this point in time.

Table notes:

1. Sign shown in brackets indicates whether a persistent correlation is positive (+) or negative (-).
2. Negative correlation during period of drought, positive correlation after 2010 when groundwater levels recover.
3. Negative correlation during depressurisation phase of CSG, positive correlation thereafter.

Key observations from the correlation analysis include the following:

- When the monitoring length is greater than one decade (e.g. RN42231212A and RN107698A), the correlation with long-term rainfall trends is more apparent. These sites with longer records are also situated in outcrop areas, where groundwater levels are expected to be heavily influenced by rainfall-induced recharge.
- As expected, there is no correlation with rainfall for any of the deeper confined basin sites.
- Three of the six sites show a correlation with non-CSG water use, with two of those sites occurring in outcrop areas where the majority of non-CSG water use is located (see Figure 7-15).
- Only site (Kenya East GW4) shows a strong inverse correlation with CSG groundwater extraction (as would be expected if a CSG impact were to occur), and the correlation only occurs during the first year of depressurisation. This period is when groundwater extraction from the Walloon Coal Measures was building to a peak rate of almost 30 ML/month in mid-2015.

7.4 Conclusions

Key conclusions from the Springbok Sandstone groundwater level trend analysis are:

- Three locations in the Springbok Sandstone have been identified as showing likely impacts from CSG development – Kenya East GW4, Broadwater GW11 and Isabella 7M.
- In total, there are 129 dedicated monitoring points completed in the Springbok Sandstone. Only 50 sites have hydrographs that have been deemed suitable for statistical trend analysis.
- Decreasing groundwater level trends are dominant in outcrop areas during the Millennium Drought (2000 to 2009). An equal mix of no trend and increasing trends is common during the post-2010 period, after the major 2010 regional recharge event.
- Deeper in the basin, decreasing groundwater levels are the most common trend in the Millennium Drought period from 2000 to 2009. In the period after 2010, there is an equal mix of increasing and decreasing trends and slightly lesser occurrence of no trend.
- Connectivity features are likely to influence groundwater level trends in areas where the Springbok Sandstone is in contact with the productive coal seams (i.e. the upper non-coal zone is thin or absent). Other local features which may influence trends are CSG wells partially completed into the Springbok Sandstone, coal holes or water bores open to both formations and local-scale faults.
- Correlation analysis indicates the following:
    - There is a tendency for groundwater level decline since the 1960s towards 2010. This declining trend tends to be highly correlated with long-term, within-aquifer, non-CSG water use and longer-duration periods of below-average rainfall (such as the Millennium Drought).
    - During periods when rainfall is significantly above average, such as the late 2010 flooding event in southeast Queensland, recharge is highly effective and becomes the dominant water budget component for several years afterwards.

- Correlation with CSG is difficult in many deeper basin sites, owing to the short duration of monitoring records (typically less than 4 years) and the monotonic nature of the groundwater level records themselves. Only three sites show a large (>1 m) and sudden drawdown impact that can be correlated with local CSG groundwater extraction from the Walloon Coal Measures.
- The interpretation of CSG impact is based on analysis of groundwater level trends, correlation analysis with various water balance factors, nested site hydrodynamic profiles and consideration of inter-aquifer connectivity between the CSG reservoir and Springbok Sandstone at each location.

8 Trend analysis – Hutton Sandstone

The Hutton Sandstone underlies the Walloon Coal Measures in the Surat Basin, separated from the CSG reservoir by the intervening Durabilla Formation aquitard. The Hutton Sandstone is a heavily utilised water supply aquifer in the GAB, owing to moderate transmissivity and reasonably high proportions of sandstone, particularly in the upper parts.

This chapter provides a high-level summary of the main formation characteristics for context (section 8.1). The types of groundwater level trends observed in outcrop and deeper in the basin are then described (section 8.1.5). An analysis of groundwater level trends is then presented, featuring correlation analyses with water balance factors and consideration of inter-aquifer connectivity with the CSG reservoir. Conclusions related to groundwater level trends in the Hutton Sandstone are then presented in section 8.4.

8.1 Formation characteristics

8.1.1 Stratigraphy and lithology

The Hutton Sandstone consists mainly of sublabile to quartzose sandstone with interbedded siltstone and shale and minor mudstone and coal (Green 1997). The siltstone and shale are micaceous, carbonaceous and commonly interlaminated with very fine-grained sandstone. In outcrop areas, the sandstone is often partly silicified and ferruginised or with kaolinite clay infilling pores (Kellett et al. 2003); in the subsurface, chlorite infilling is common (Exon 1976). The Hutton Sandstone is highly heterogeneous, especially towards the eastern margin of the Surat CMA (OGIA 2016b).

Based on processed wireline log data across the Surat CMA, Figure 8-1 presents the average lithological composition of the upper and lower Hutton Sandstone and reflects the heterogeneous nature of this formation. The upper Hutton Sandstone is dominated by clean sandstone (~60%), with minor dirty sandstone, siltstone and mudstone components. In contrast, the lower Hutton has approximately half the clean sandstone percentage (~30%) and more prominent dirty sandstone, mudstone and siltstone. This difference in lithological composition between the two units is further emphasised in Figure 8-2, which shows a cross-section of processed wireline logs across the basin. The composite formation is a relatively thick sedimentary package, with thicknesses typically in excess of 200 m. The upper Hutton Sandstone is present at thicknesses ranging up to around 370 m, averaging over 100 m, whereas the maximum thicknesses of the lower Hutton Sandstone is nearly 400 m, but averages around 80 m (OGIA 2019c).

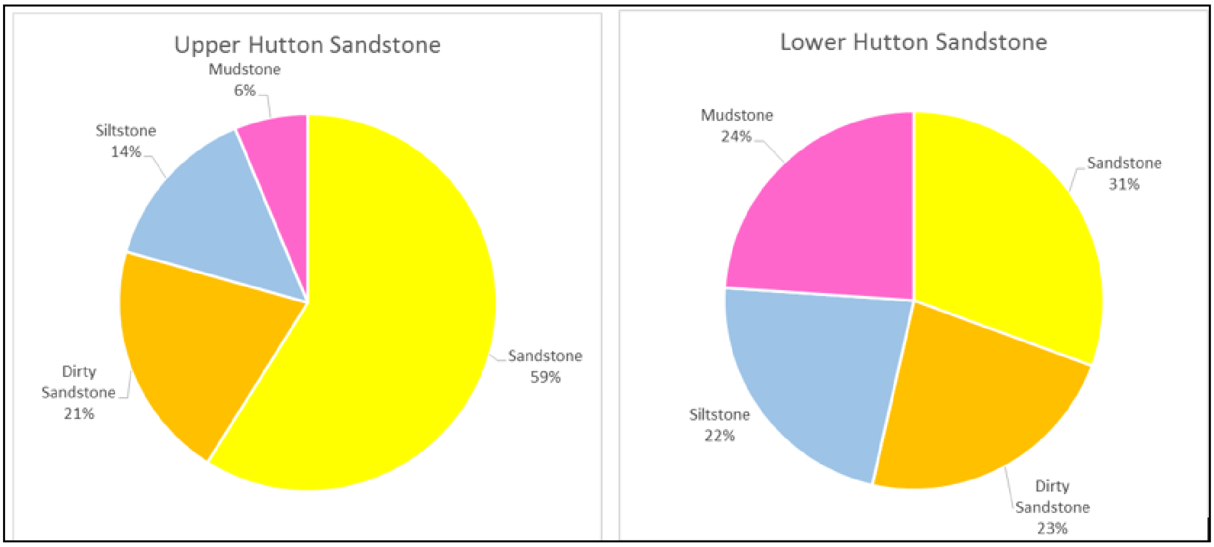

Figure 8-1 Hutton Sandstone – lithological composition

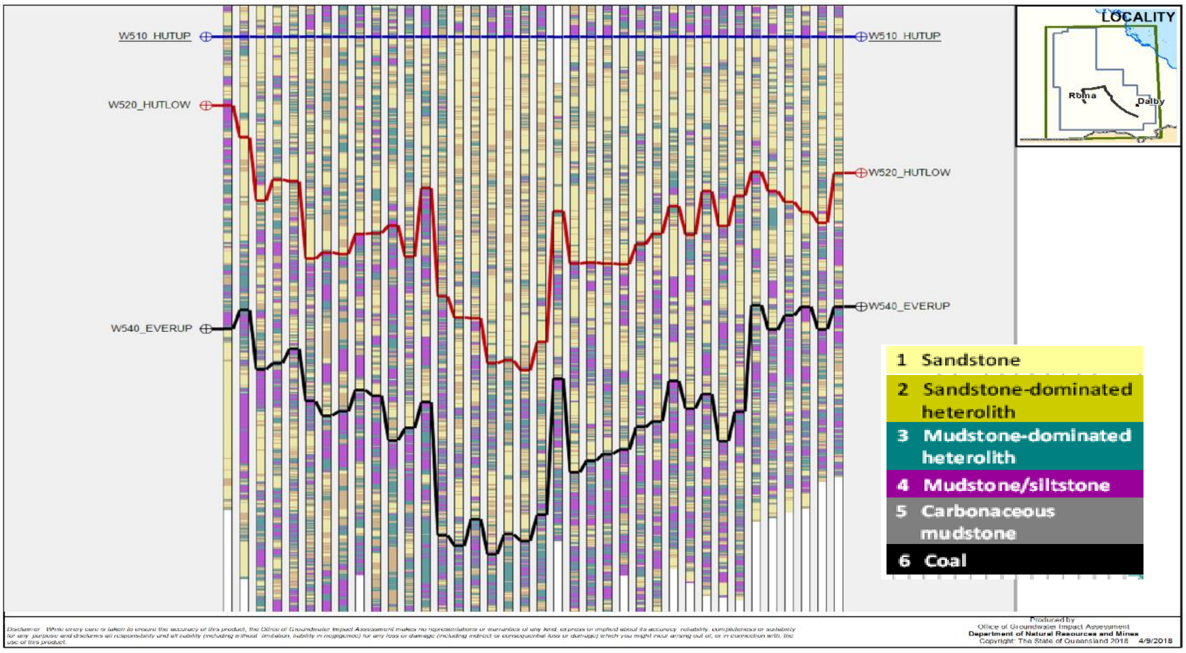

Figure 8-2 Lithology of the upper (between blue and red lines) and lower (between red and black lines) Hutton Sandstone to Evergreen Formation, flattened to the base of the Durabilla Formation

8.1.2 Hydraulic properties

Figure 8-3 presents a box plot of the upper and lower horizontal hydraulic conductivity (Kh) estimates (converted from permeability) for the main test types. The issue of measurement scale is apparent, with larger-volume tests (i.e. pumping tests and, to a lesser extent, DSTs) yielding appreciably higher permeability estimates than the point-scale core tests. The pumping test interquartile ranges for the upper (0.1 to 5.8 m/day) and lower (0.4 to 4.9 m/day) Hutton Sandstone indicate that there are higher yielding parts of both units, with potential for high aquifer yields where interconnected clean sandstone channels are encountered. Conversely, the core interquartile range is three to six orders of magnitude lower than for the pumping tests, reflecting the variable aquifer nature of the Hutton

Sandstone, i.e. outside of discrete stacked channel belts, both the permeability and aquifer potential can be limited.

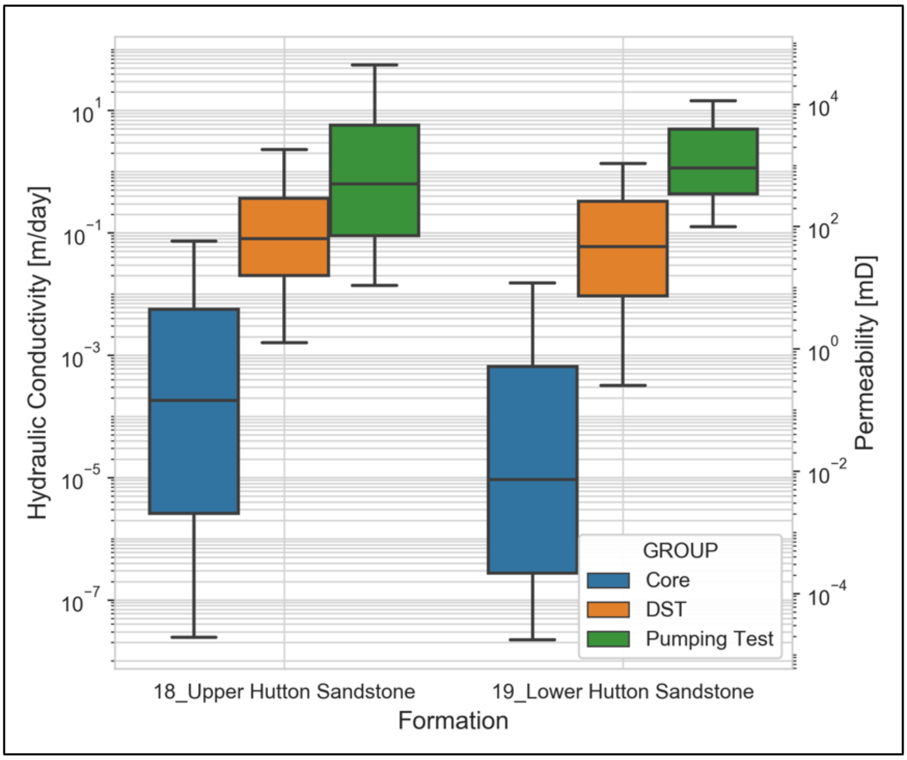

Figure 8-3 Horizontal hydraulic conductivity (Kh) and permeability[7] (k) for the Springbok Sandstone in the Surat CMA

8.1.3 Hydrochemistry

Figure 8-4 shows the spatial distribution of Hutton Sandstone hydrochemical KCA cluster classes across the Surat CMA. Generally, the water quality tends to be fresher (Class 1) in outcrop areas along the east and north of the basin, and transitions to more saline class 2 deeper in the basin (Figure 8-5). Both dominant classes tend to be classified as Na-HCO_3-Cl type water, with low concentrations of Ca, Mg and SO_4.

[7] Conversion factor: 1 mD (millidarcy) = 1.27E-03 m/day

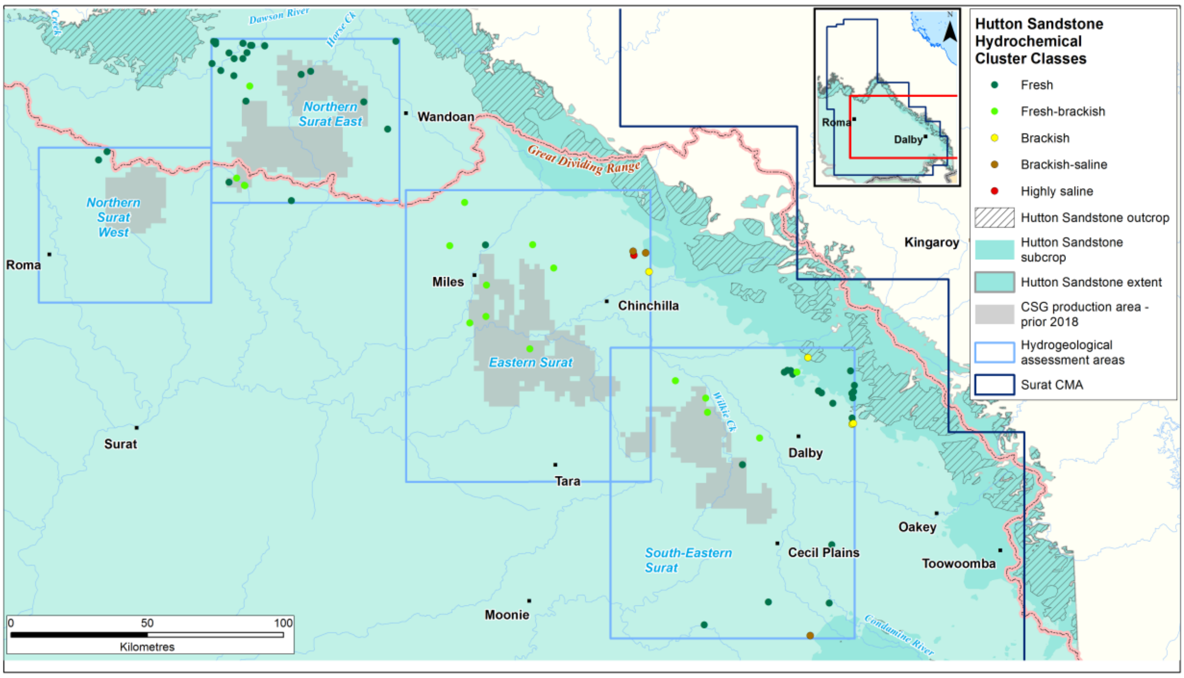

Figure 8-4 Hutton Sandstone – spatial variability in hydrochemical cluster classes

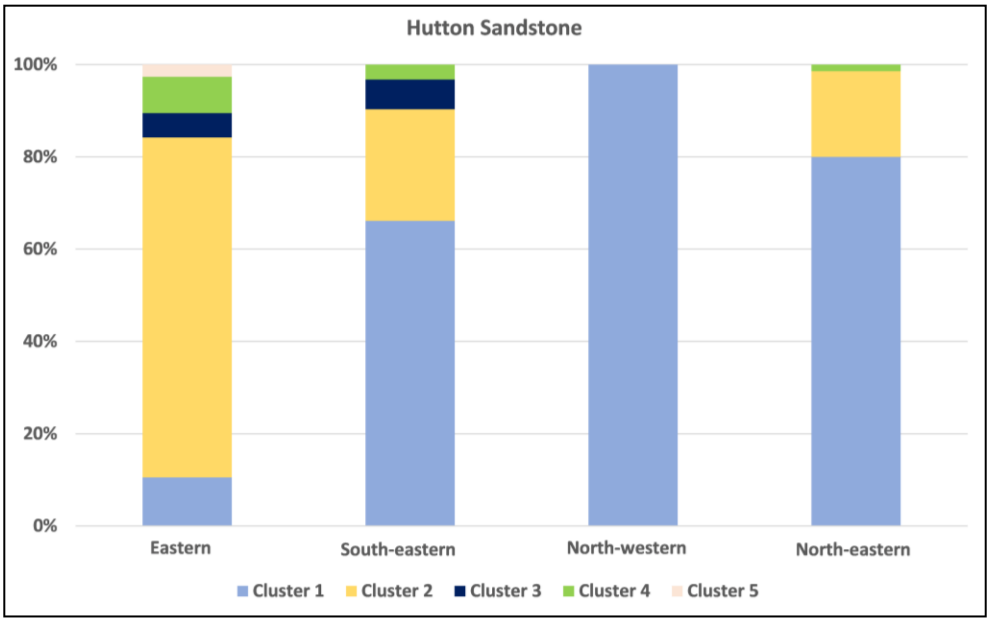

Figure 8-5 Hutton Sandstone KCA cluster class data for each hydrogeological assessment area

8.1.4 Groundwater flow directions

Figure 8-6 presents an interpretation of regional groundwater levels in the Hutton Sandstone and shows the influence of two main regional flow systems. The Hutton Sandstone is predominantly recharged in the north-western (northwest of Injune) and eastern (east of Dalby) parts of the basin. An east–west groundwater divide is also present, broadly situated between the towns of Roma and Miles. North of this divide, groundwater flows northward towards the Dawson River valley, where a number of Hutton Sandstone-fed springs and watercourses have been identified. South of the divide, flow appears to be south, beyond the Surat CMA southern boundary.

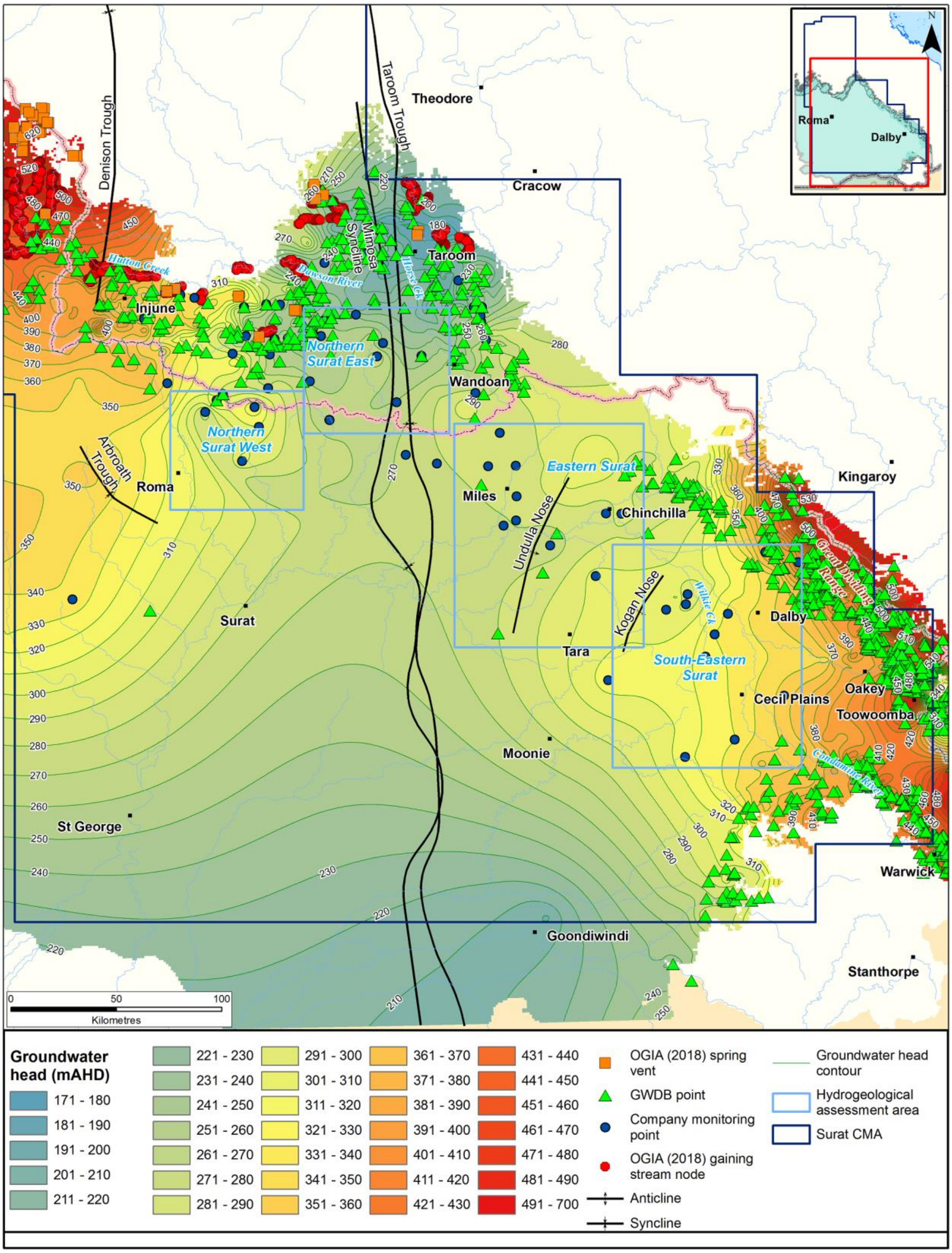

Figure 8-6 Hutton Sandstone potentiometric surface

8.1.5 Connectivity with CSG reservoir

Interconnectivity between the Walloon Coal Measures and the underlying Hutton Sandstone is largely controlled by the properties of the intervening Durabilla Formation aquitard. The Durabilla Formation is continuous across the current and proposed CSG footprints at thicknesses of around 55 m across the major gas field areas. The Durabilla Formation predominantly comprises siltstone, mudstone and fine to medium-grained poorly sorted sandstones with almost no coal and consequently little permeability.

The results from OGIA's numerical permeameter workflow (OGIA 2019i) suggest a median vertical permeability of less than 1×10^{-07} m/day. Interconnectivity between the Walloon Coal Measures and the underlying Hutton Sandstone in current and proposed CSG production areas is therefore considered to be limited. Unlike the Springbok Sandstone, there are relatively few features which could potentially increase connectivity between the Hutton Sandstone and Walloon Coal Measures across the Durabilla Formation, for the following reasons:

- Coal exploration bores terminate in the upper parts of the Walloon Coal Measures and therefore do not extend into the Hutton Sandstone.
- An evaluation of CSG well intake and down-hole wireline logs 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 mapped 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.

Analysis of the available groundwater level and hydrochemistry data also suggests the following:

- Significant head differences (up to 271 m) exist between monitoring points in the Walloon Coal Measures and the Hutton Sandstone. This tends to confirm that the Durabilla Formation is an effective aquitard, consistent with the very low vertical permeability estimated for this unit.
- Background pressure declines in the Hutton Sandstone in areas where there has been little or no drawdown in the Walloon Coal Measures (e.g. Teviot GW4).
- Pressures in the Hutton Sandstone steadily decline at the Kenya East GW32, Phillip 5M and Condabri MB12 sites, where local CSG groundwater extraction started after commencement of monitoring.
- The hydrochemistry of the Walloon Coal Measures and Hutton Sandstone is quite different. Water in the coal seams is typically more saline; however, there are some areas where the Walloon Coal Measures water quality is relatively fresh (classes 1 and 2), such as in the Eastern Surat around the Undulla Nose and around Roma gas fields in the Northern Surat (Figure 6-7). Time series trend analysis of major ion chemistry indicates that the fresher water quality in the coal seams in these areas are pre-existing phenomena that predate CSG development and are unrelated to CSG-induced stresses.

8.2 Observed groundwater level trends

The following sub-sections describe the variety of groundwater level trends observed in the Hutton Sandstone in different hydrogeological settings across the Surat CMA. Figure 8-7 presents a spatial view of a selection of example hydrographs from outcrop/subcrop areas and from deeper in the basin, where CSG development is present. This figure provides a regional overview of the different types of trends throughout the basin and highlights some of the limitations associated with the short duration of monitoring at many locations. Appendix D provides group plots of groundwater levels and groundwater level trends for all Hutton Sandstone UWIR and non-UWIR company monitoring points in the Surat CMA.

There are 191 bores (101 UWIR and non-UWIR company monitoring points and 90 additional bores from the GWDB) that provide groundwater level data for the Hutton Sandstone across the Surat CMA. Of these 191 bores, 68 have groundwater level readings prior to 2010, with the remaining 123 sites only containing more recent groundwater level records (i.e. post-2010). Of the 68 sites with earlier records, 28 have one or more years with regular readings (i.e. at least four records per year) to allow for meaningful trend analysis.

8.2.1 Shallow outcrop and subcrop areas

8.2.1.1 Monitoring types and trends

Of the 28 sites with one or more years of continuous records (see section 7.1.5), 23 are situated in the outcrop area (or shallow subcrop) and have semi-continuous records prior to 2010 that can be analysed to broadly assess longer-term trends. There are also a further 14 Hutton Sandstone outcrop/subcrop monitoring points within the UWIR and non-UWIR company monitoring networks with sufficient temporal groundwater level data after 2010 (i.e. greater than 12 months of regular groundwater level data) to undertake a trend analysis assessment. Most monitoring points have less than four years of monitoring records.

A statistical trend analysis was undertaken for these 37 Hutton Sandstone monitoring points. The purpose of the trend analysis was to detect statistically significant increases or decreases in groundwater levels, using a modified Mann-Kendall trend test.

The locations of the 37 Hutton Sandstone outcrop/subcrop monitoring points and the interpreted groundwater level trends and trend rates over two main time periods (2000 to 2009 and 2010 to 2018) are shown on Figure 8-8. These time periods were rationalised as being representative of:

- the Millennium Drought (2000 to 2009) when CSG production in the basin was limited to only a few fields such as Talinga and Daandine
- a more recent period (2010 to 2018) when CSG production became much more widespread throughout the basin (especially during and after 2014) and cumulative CSG groundwater extraction increased exponentially
- the 2010 recharge event, which separated these two time periods, having influenced groundwater levels in both the Springbok Sandstone and Hutton Sandstone.

Table 8-1 provides a summary of the outcomes of the Hutton Sandstone groundwater level trend analysis. It is evident from Figure 8-7 and Figure 8-8 that decreasing trends are dominant in the outcrop area during both time periods, although as expected, there is also an increased number of sites with increasing trends in the period following the 2010 rainfall recharge period.

Table 8-1 Trend analysis results for monitoring points located in outcrop/subcrop

Hydrostratigraphic unit	Time period	Position in basin	Monitoring points	Groundwater level trend		
				Increasing	Decreasing	No trend
Hutton Sandstone	2000-2009	Outcrop/ subcrop	23	3	17	3
	2010-2018		37	10	18	9

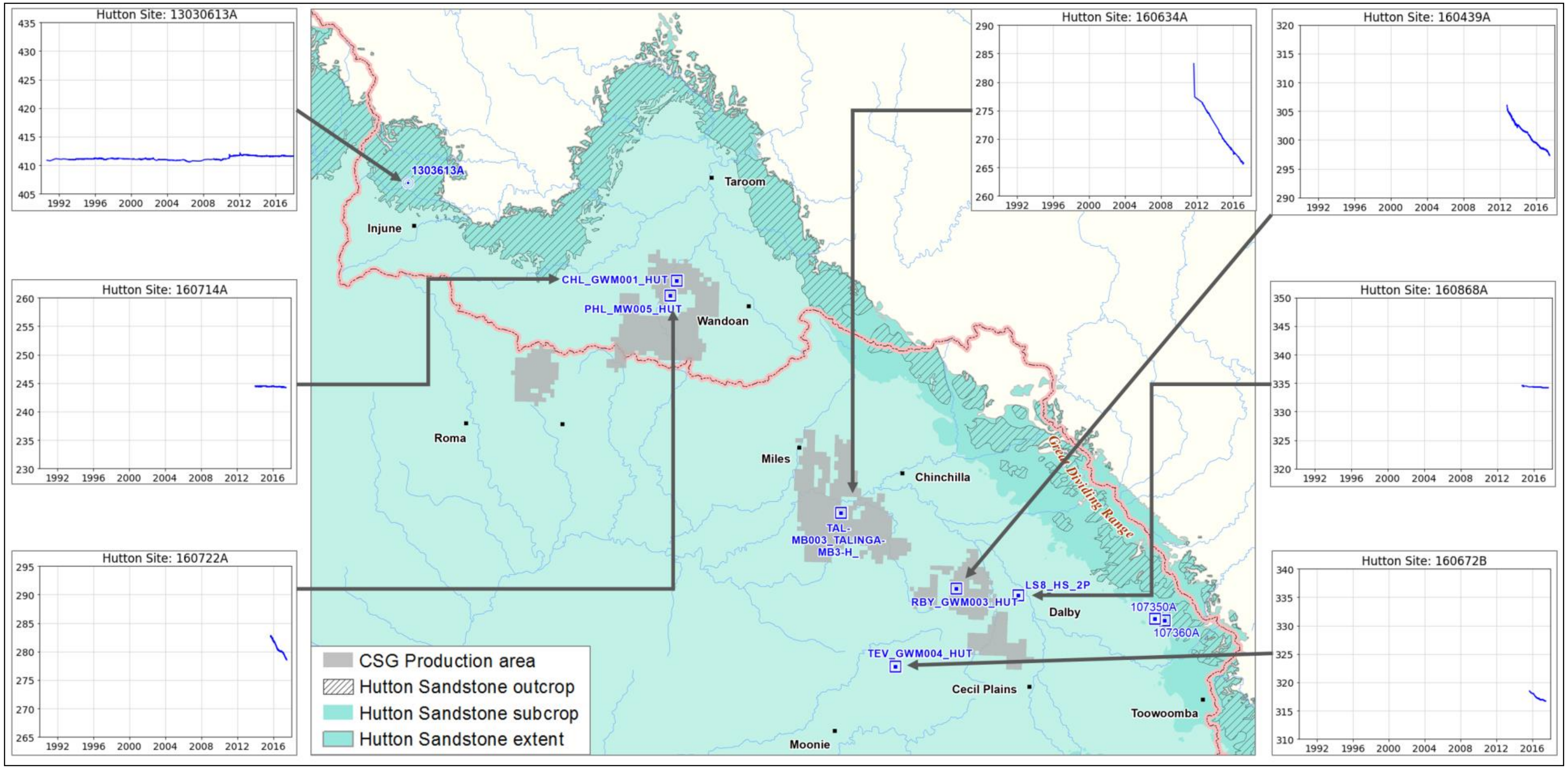

Figure 8-7 Selection of Hutton Sandstone hydrographs from different parts of the Surat CMA

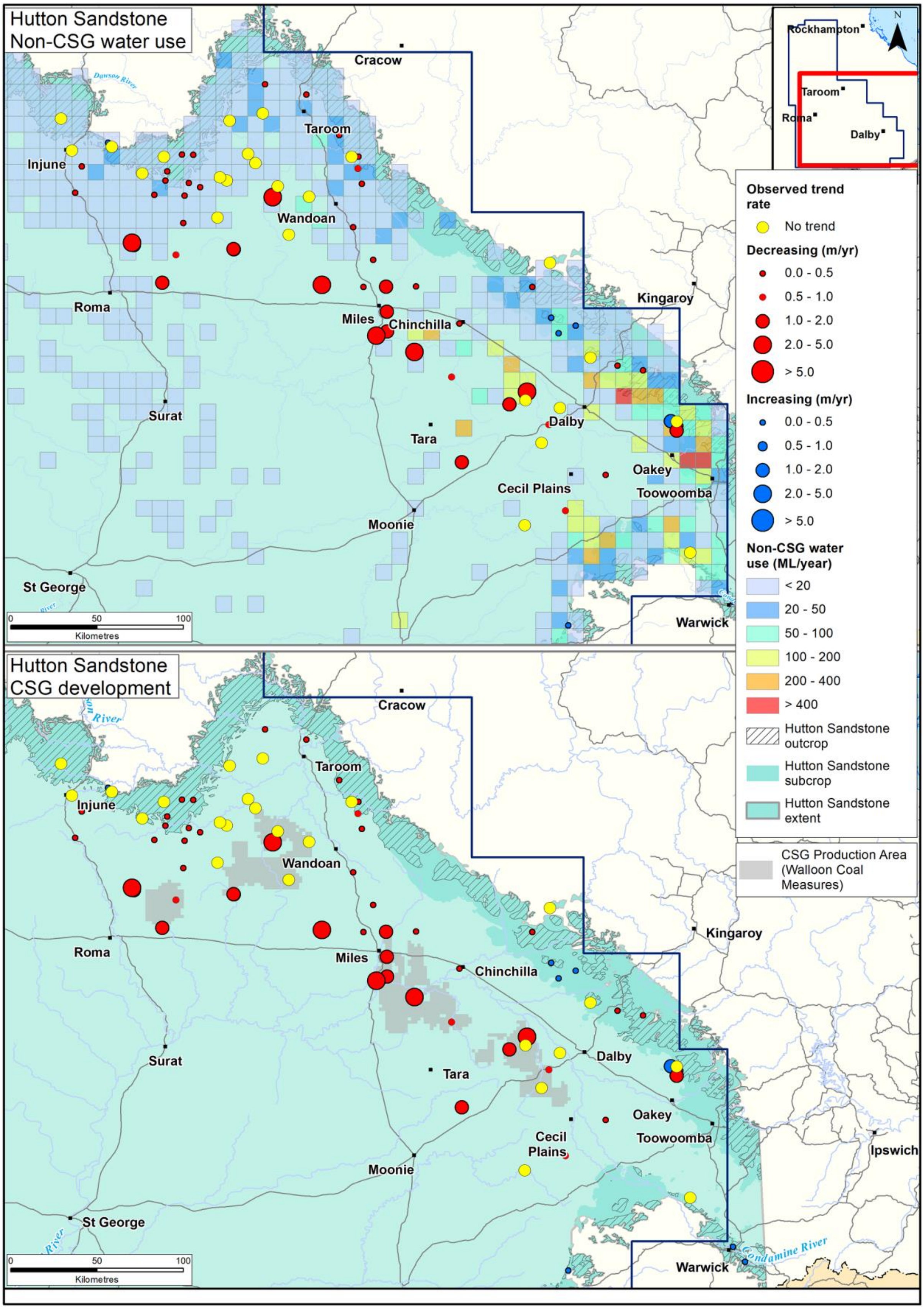

Figure 8-8 Hutton Sandstone groundwater level trends (2010 – 2018) with non-CSG water use (above) and current CSG production areas (below)

8.2.1.2 Example hydrographs

For this assessment, four Hutton Sandstone hydrographs have been selected at various locations across the Surat CMA, to provide an overview of basin-scale groundwater level trends in areas of Hutton Sandstone outcrop/shallow subcrop. The hydrographs for these four sites are provided in Figure 8-9 and their locations are shown in Figure 8-7.

RN13030613A is an existing DNRME monitoring bore screened in the lower Hutton Sandstone, towards the northwest of the basin. Semi-continuous daily data are available for this monitoring point from 1990 onwards. This site is located within the Hutton Sandstone outcrop and shows the groundwater levels fluctuate within a two-metre range, with extended periods of subtle rising and falling trends. Notably, groundwater levels consistently fall during the Millennium Drought and rapidly begin to rise after the December 2010 flooding event.

RN107350A and RN107360A are existing mine monitoring bores tapping the Marburg Sandstone (Hutton Sandstone equivalent) in the south-eastern outcrop/subcrop area, about 35 km north-east of Toowoomba. Semi-continuous groundwater level data for these two monitoring bores show declining levels during the Millennium Drought and recovering levels since the December 2010 flooding event. RN107360A has two facility roles listed: one being mine monitoring and the other being water supply purpose. The water supply extraction may explain the more pronounced drawdown (~20 m) observed at this site during the Millennium Drought.

RN42231563A is an existing DNRME monitoring bore located approximately 50 km east of Chinchilla. There is a stable groundwater level at this site during the Millennium Drought, followed by a four-metre rise in head after the December 2010 flooding event.

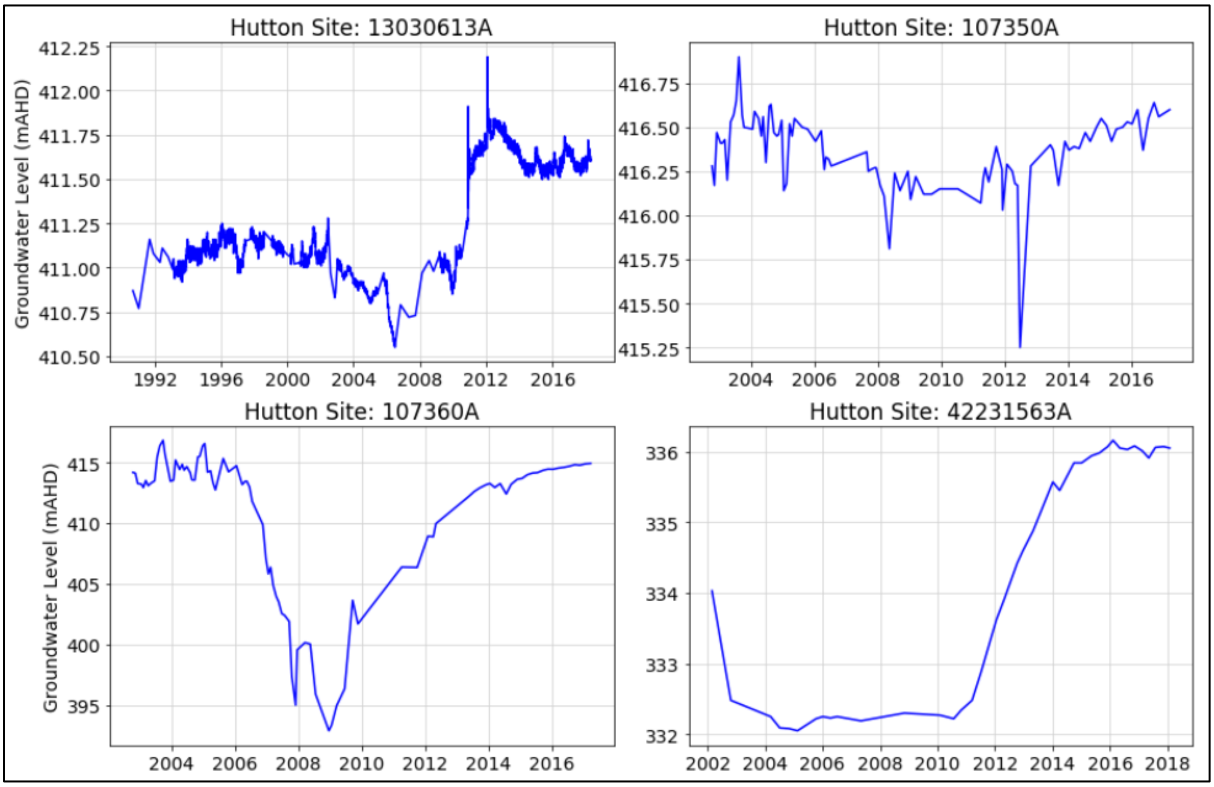

Figure 8-9 Hutton Sandstone site hydrographs from outcrop areas across the Surat CMA

8.2.2 Confined basin interior

8.2.2.1 Monitoring types and trends

As opposed to the outcrop areas where the GWDB is the primary source of groundwater level monitoring data, the UWIR and non-UWIR company monitoring network has more extensive spatial and vertical coverage in the interior of the basin, particularly in and around CSG development areas. The Hutton Sandstone in the basin interior underlies a number of other GAB aquifers and aquitards and consequently behaves as a confined aquifer system.

For the Hutton Sandstone, only five of the 28 sites with semi-continuous records prior to 2010 are situated in the deeper, confined basin. There are also a further 45 Hutton monitoring points within the UWIR and non-UWIR company monitoring network with sufficient temporal groundwater level data after 2010 (i.e. greater than 12 months of regular groundwater level data) to undertake a trend analysis assessment. Most of these monitoring points have less than five years of monitoring records.

A statistical trend analysis was undertaken for these 50 deeper-basin Hutton Sandstone monitoring points. The purpose of the trend analysis was to detect statistically significant increases or decreases in groundwater levels using a modified Mann-Kendall trend test (Mann 1945; Kendall 1975).

The locations of the 50 Hutton Sandstone outcrop/subcrop monitoring points and the interpreted groundwater level trends and trend rates over two main time periods (2000 to 2009 and 2010 to 2018) are shown on Figure 8-8. Table 8-2 provides a summary of the outcomes of the Hutton Sandstone groundwater level trend analysis.

Table 8-2 Trend analysis results for monitoring points located in confined areas

Hydrostratigraphic unit	Time period	Position in basin	Monitoring points	Groundwater level trend		
				Increasing	Decreasing	No trend
Hutton Sandstone	2000-2009	Deeper confined basin	5	0	3	2
	2010-2018		50	0	34	16

It is evident from Figure 8-8 and Table 8-2 that decreasing trends are dominant in the deeper confined parts of the formation during both time periods, with no instances of overall increasing trends. In some cases, individual hydrographs, particularly those from sites closer to outcrop areas, show increasing trends for short periods. However, the overall trend is downward in most cases, or null trend in some cases where the magnitude of the post-2010 increase is similar to the magnitude of the decrease seen in the remainder of the record.

8.2.2.2 Examples of declining trend

Figure 8-10 presents a selection of representative groundwater level trends (referenced to a zero metre datum), with two sites selected from each of the hydrogeological assessment areas. The locations of these six sites are shown in Figure 8-7. In the Eastern Surat, all Hutton Sandstone monitoring points show decreasing groundwater levels since 2011. TAL-MB003 (RN160634A) is presented in Figure 8-10 as it has the largest observed drawdown since 2011. The overall rate of decline is relatively consistent across this period, with no major inflections in the rate of drawdown that could be attributed to the timing of a particular stress (as described further in sections 8.3.2.2 and

8.3.3.2). Teviot GW4 (RN160672B) is situated more than 20 km to the south of the Eastern Surat hydrogeological assessment area and shows similar rates of drawdown, although over a shorter period of monitoring (i.e. post-2016).

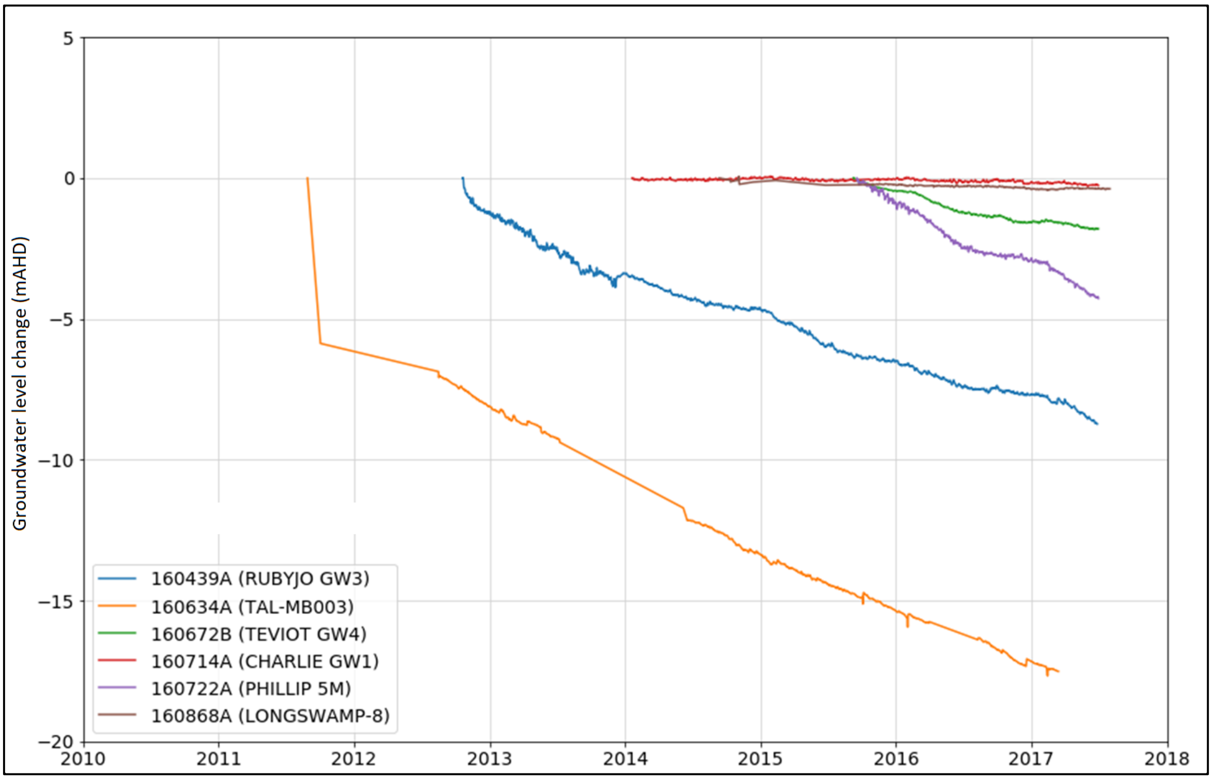

Figure 8-10 Selected Hutton Sandstone hydrographs in confined areas

In the South-eastern Surat, seven of the 13 monitoring sites show decreasing groundwater levels over the period of monitoring, with the six other sites showing no apparent trend. Figure 8-10 shows that RubyJo GW3 (RN160439A) has a slightly lower rate of observed groundwater level decline than TAL-MB003, while Longswamp 8 (RN160868A) shows a minor drawdown trend.

In the Northern Surat, eight of the 14 monitoring points show no apparent trend. These sites with no trend are mainly situated further north towards the Dawson River valley. Charlie GW1 (RN160714A) is one of those eight sites and is shown in Figure 8-10. Of the six sites that do show declining groundwater level trends, Figure 8-10 presents the groundwater level trend for Phillip 5M (RN160722A), which has a similar drawdown rate to TAL-MB003, although a much shorter length of record.

8.3 Analysis of groundwater level trends

This section provides a summary of the detailed analysis of Hutton Sandstone groundwater level trends and the potential influence of three water balance factors (section 4.2.1) – rainfall, non-CSG water use and CSG groundwater extraction. Only a number of selected example sites are shown in this section, in order to highlight important findings. Further details and examples are provided in Appendix E.

As described in section 7.3, the intention of the detailed correlation analysis is to consider the influence of each water balance factor in isolation and draw conclusions on which factors affect overall groundwater level trends, both in outcrop areas and deeper in the basin. This provides the basis for assessing the potential for CSG impact, using both statistical tools and hydrogeological judgement.

8.3.1 Correlation with rainfall trends

In this section, three hydrographs have been correlated with CDMMR from nearby weather stations, using the Spearman rank correlation method (Appendix G).

8.3.1.1 Shallow outcrop and subcrop areas

As described in section 4.2.1.1, it is expected that groundwater levels in outcrop areas will respond relatively rapidly to periods of above-average and below-average rainfall. The example given in this section (RN13030613A) provides continuous data over a 30-year period and confirms that groundwater levels show a strong correlation with long-term rainfall patterns in Hutton Sandstone outcrop areas.

Figure 8-11 presents the hydrograph for RN13030613A, an existing state monitoring bore tapping the lower Hutton Sandstone, and the Injune weather station CDMMR. This monitoring bore site is less than 3 km from Hutton Creek, which is mapped as a potentially gaining reach in the Hutton Sandstone outcrop area towards the northwest of the Surat CMA. This site is also on the northern side of the Great Dividing Range, which has a separate southwest to northeast groundwater flow system (Figure 8-7).

At this location, there is a strong correlation with the CDMMR for extended periods (Figure 8-11). The correlation is particularly strong for the last 18 years since around the year 2000 – declining groundwater levels are observed during the Millennium Drought and an apparent ‘resetting’ of groundwater level storage following the December 2010 rainfall event, where groundwater levels rise to well above the levels of the preceding decades.

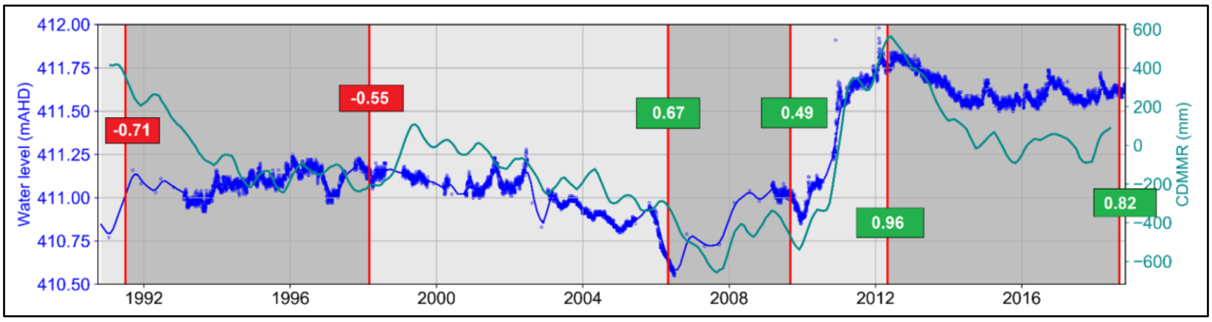

Figure 8-11 Spearman correlation, RN13030613A groundwater level and Injune weather station CDMMR

Further examples are provided in Appendix E.1.1.

8.3.1.2 Deeper basin interior

As described in section 4.2.1.1, it is expected that groundwater levels in deeper confined areas will show either a muted or null response to periods of above-average and below-average rainfall. As further described in section 8.2.2, for the period 2010-2018, there is a predominant representation of falling trends (68%) and minor representation of no trends (32%). Given below are two sites with falling trends from different geographic parts of the basin, suggesting that rainfall is having either no influence or a potential subtle delayed influence on groundwater level trends.

Figure 8-12 presents the Taroom weather station CDMMR and the hydrograph for Phillip 5M (RN160722A), an existing CSG monitoring point tapping the upper Hutton Sandstone. The nearest outcrop to this location is 40 km to the northwest. Data for this monitoring point show a monotonic decline since the start of the record in late 2015. There are subtle increases and decreases in the declining rate, with some flattening of the rate in the latter half of 2016 and 2017 approximately six months after above-average summer rainfall. Overall, there is a mixed correlation with rainfall, with inverse correlation during periods of above-average rainfall and positive correlation during below-average rainfall. This is mainly a function of the monotonic groundwater level trend and the short duration of monitoring. Of note, despite Phillip 5M being more than 150 km northwest of RubyJo GW3 and Teviot GW4 (Figure 8-7), the drawdown patterns seen at these sites are very similar: an overall monotonic declining trend, flattening in the latter half of each calendar year. This suggests that similar processes may be operating at these two locations.

Figure 8-12 Spearman correlation, Phillip 5M (RN160722A) groundwater level and Taroom weather station CDMMR

Figure 8-13 presents the hydrograph for TAL-MB003 (RN160634A), which is an existing UWIR monitoring point tapping the upper and lower Hutton Sandstone, and the Chinchilla weather station CDMMR. The nearest outcrop to this location is 51 km to the northeast. Data for this monitoring point suggest a monotonic decline in groundwater levels since late 2011. Overall, the correlation with rainfall is erratic, with periods of strong correlation – resulting from below-average rainfall in 2015 and 2017 – separated by periods of poor correlation during above-average rainfall periods.

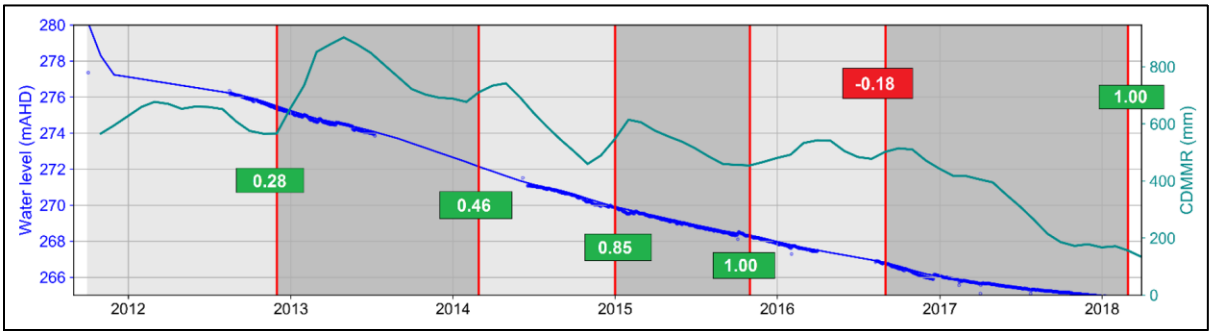

Figure 8-13 Spearman correlation, TAL-MB003 (RN160634A) groundwater level and Chinchilla weather station CDMMR

Compared to the previous example, the rate of decline at this site is more consistent (no apparent flattening periods), which may reflect this site being situated deeper into the basin with less obvious influence by recharge events.

Further examples are provided in Appendix E.1.2.

8.3.2 Correlation with non-CSG water use

As shown in Table 2-1, the Hutton Sandstone is an important water supply aquifer in the Surat CMA. The total estimated groundwater extraction of 13,755 ML/year from this formation represents around ~34% of the total estimated water (40,781 ML/year) extracted from all of the GAB formations in the Surat CMA. Further to this, around 10,150 ML/year of Hutton Sandstone extraction is for non-S&D purposes, including large agricultural, industrial, town water supply and stock-intensive uses that have significant operating water demands.

Figure 8-14 shows the Hutton Sandstone groundwater level trends compared with both non-CSG water use per 8×9-km grid cell and the CSG development footprint. There is a reasonable degree of spatial correlation between decreasing groundwater level trends and proximity to large non-CSG water use, which is further analysed below.

The three representative monitoring sites described in section 8.3.1 are again subjected to Spearman correlation analysis, however in this case, each groundwater level time series is correlated with OGIA's estimates of non-CSG water use for the Hutton Sandstone within 25 km of each monitoring point.

In all instances, the non-CSG water use predates the monitoring record (prior to the 1980s), which emphasises the long-term water budget influence of non-CSG water use on the Hutton Sandstone. However, as described in section 2.4, less than 1% of GAB water use in the Surat CMA is metered. As the water use in the Hutton Sandstone is largely estimated by OGIA, correlation analyses in this section are ascribed greater uncertainty than are the metered CSG groundwater extraction volumes described in section 8.3.3.

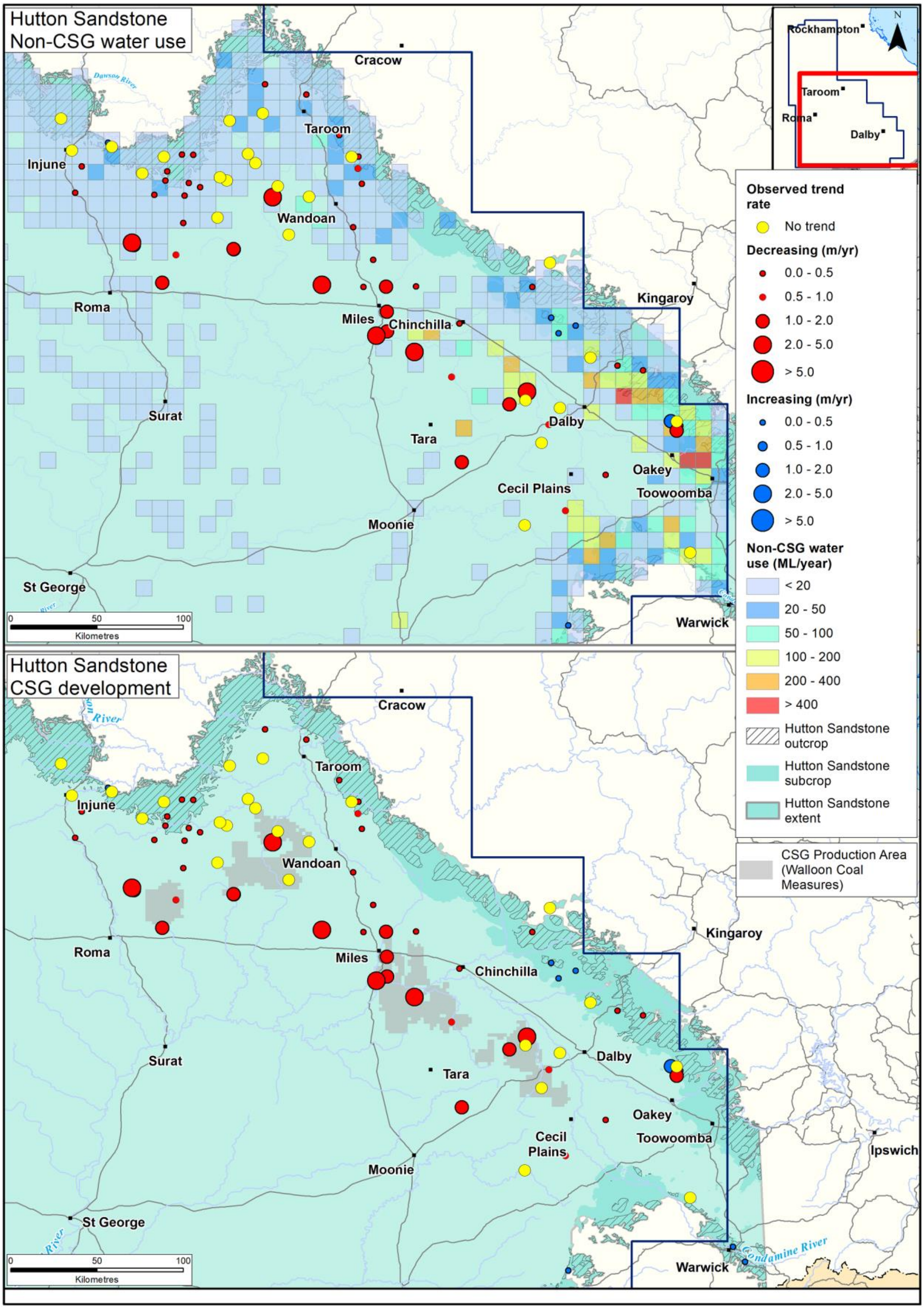

Figure 8-14 Hutton Sandstone groundwater level trends for the period 2010 to 2018, current non-CSG water use (upper frame) and CSG production areas as at 2018 (lower frame)

8.3.2.1 Shallow outcrop and subcrop areas

As described in section 8.3.2, the Hutton Sandstone is a major water supply aquifer in both outcrop areas and the internal, confined parts of the basin. For this reason, declining trends related to non-CSG water use are expected in areas of outcrop, in addition to the already demonstrated climatic influence described in section 8.3.1.1.

Figure 8-15 presents the hydrograph for RN13030613A, compared with annual non-CSG water use from the Hutton Sandstone within 25 km of that site. There are 111 water supply bores within 25 km, with total water use estimated to steadily grow from 150 ML/year in the early 1990s to nearly 200 ML/year in 2018. Non-CSG water use predates monitoring at this site.

The period between 1998 and 2006 shows a relatively strong negative correlation between falling groundwater levels and gradually increasing non-CSG water use. This period was also shown to correlate with below-average rainfall; this may indicate dry conditions and low recharge, coupled with increased groundwater extraction, leading to extended periods of groundwater level decline.

Post-2012, there is an inverse correlation between rising water use and overall declining groundwater levels. A rapid groundwater level recovery after 2010 has a positive correlation with water use, indicating other factors such as recharge were more influential during that period.

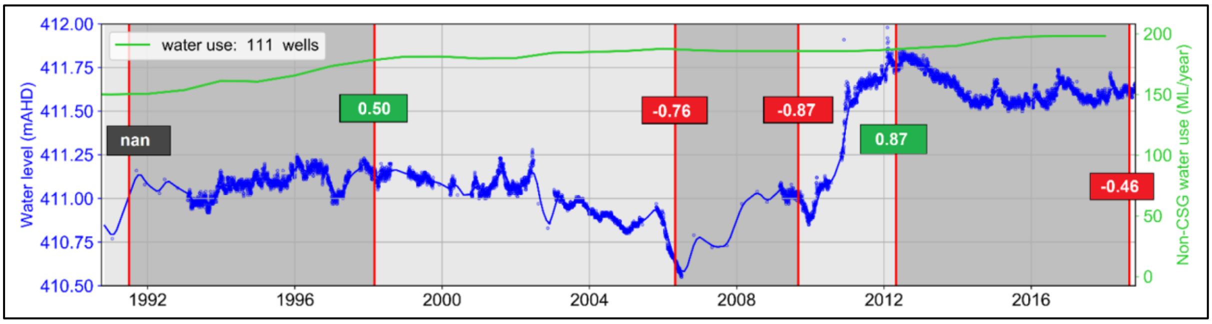

Figure 8-15 Spearman correlation, RN13030613A groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

Further examples are provided in Appendix E.2.1.

8.3.2.2 Deeper basin interior

The two representative Hutton Sandstone monitoring sites show contrasting correlations with non-CSG water use (Figure 8-16 to Figure 8-17) and are summarised as follows:

- Non-CSG water use predates monitoring at both locations.
- Non-CSG water use presents as a monotonic increasing trend at TAL-MB003 and a stable or slightly decreasing trend at Phillip 5M.
- Groundwater levels at both sites present as monotonic decreasing trends.
- At TAL-MB003, there is a perfect inverse correlation post-2013 that coincides with a three-fold increase in estimated extraction from the Hutton Sandstone within 25 km.
- At Phillip 5M, the data suggest a poor overall correlation between the two variables, largely due to a very slight reduction in estimated water use in the local area. This is a sustained stress acting on the Hutton Sandstone in this area.

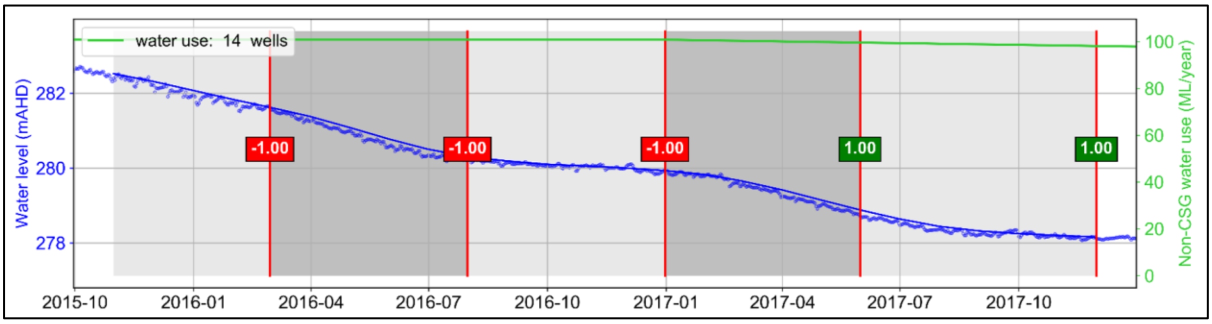

Figure 8-16 Spearman correlation, Phillip 5M (RN160722A) groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

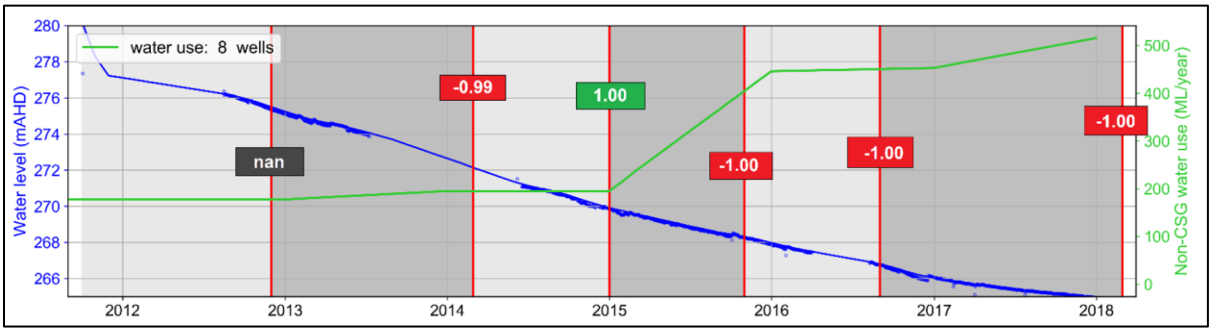

Figure 8-17 Spearman correlation, TAL-MB003 (RN160634A) groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

Further examples are provided in Appendix E.2.2.

8.3.3 Correlation with CSG groundwater extraction

8.3.3.1 Shallow outcrop and subcrop areas

Given the steep nature of the Walloon Coal Measures drawdown (section 6.3.2), significant impacts within the reservoir are expected to occur within 10 km of gas field areas. Currently, there are no CSG fields within 10 km of Hutton Sandstone outcrop areas. As expected, the representative Hutton Sandstone outcrop monitoring site at RN13030613A does not have any CSG wells in the Walloon Coal Measures within 10 km. For this reason, no correlation analysis between groundwater levels and CSG groundwater extraction was conducted at this site. In addition, none of the example outcrop sites in the Hutton Sandstone detailed in Appendix E have CSG groundwater extraction within 10 km.

8.3.3.2 Confined basin interior

Figure 8-18 presents the hydrograph for Phillip 5M (RN160722A) compared with monthly CSG groundwater extraction within 10 km of that site. This monitoring point is located within QGC's Phillip gas field, which commenced operations in 2017. There are 241 CSG wells within 10 km, with groundwater level monitoring predating CSG groundwater extraction at this site. The very small "background' level of CSG groundwater extraction prior to 2017 is a result of CSG wells 8–10 km from the monitoring point in the Portsmouth, Cameron and Kathleen gas fields (Figure 2-7). There are no operating CSG wells within 8 km of this monitoring point prior to 2017.

The data suggest a high level of inverse correlation between groundwater level decline and increasing CSG production during the period from 2017 onwards, indicating a possible relationship. However, the rate of observed decline during this period is similar to that observed during 2016 when there was minimal CSG groundwater extraction.

Figure 8-18 Spearman correlation, Phillip 5M (RN160722A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Figure 8-19 presents the hydrograph for TAL-MB003 (RN160634A) with the cumulative monthly CSG groundwater extraction within 10 km of that site. This monitoring point is located within APLNG's Talinga gas field, which commenced operations in 2009. There are 430 CSG wells within 10 km, with CSG groundwater extraction predating groundwater level monitoring at this site. The correlation coefficients are mixed over the six years of monitoring; this is largely related to the fluctuations in the CSG groundwater extraction rates. From a broader perspective, CSG groundwater extraction has remained constant, between 300 and 500 ML/month over this six-year period, while groundwater levels in the Hutton Sandstone have continued to decline.

Figure 8-19 Spearman correlation, TAL-MB003 (RN160634A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Further examples are provided in Appendix E.3.2.

8.3.4 Summary of correlation analyses

Sections 8.3.1 to 8.3.3 provide a summary of the degree of correlation between Hutton Sandstone groundwater levels at selected sites and three water balance stresses – rainfall, non-CSG water use and CSG groundwater extraction. Further examples are included in Appendix E. Table 8-3 below provides a summary of the outcomes of the correlation analyses for the Hutton Sandstone.

Table 8-3 Summary of Hutton Sandstone correlation analyses

Location	Monitoring site	Length of record (years)	Correlation with rainfall[1]	Correlation with non-CSG water use	Correlation with CSG groundwater extraction	Factors influencing groundwater levels
Shallow outcrop/ subcrop	RN13030613A	28	Yes (+)	Yes (-)	No	Rainfall and non-CSG water use.
	RN42231563A	16	Yes (+)	No	No	Rainfall.
	RN107350A	16	Yes (+)	Yes (-)	No	Rainfall and non-CSG water use.
Confined basin interior	RN160439A (RubyJo GW3)	5	Variable[2]	Yes (+)	No	Non-CSG water use. Uncertainty in water use estimates skew correlation; however, there is a large volume of localised non-CSG water use that coincides with sustained drawdown.
	RN160722A (Phillip 5M)	2	Variable[2]	Yes (+)	Yes (-)	Negative correlation within CSG once development commences; however, the same rate of drawdown in the monitoring point is observed for more than a year prior to CSG development.
	RN160634A (TAL-MB003)	6	No	Yes (-)	Mixed	Non-CSG water use. CSG groundwater extraction may be a contributing factor, but there is no evidence at this stage.

Table notes:

1. Sign shown in brackets indicates whether a persistent correlation is positive (+) or negative (-).
2. Potential recharge lag identified at these two sites, as well as other deeper, confined sites in the basin (e.g. Teviot GW4).

As emphasised in section 7.3.4, a persistent strong positive correlation of groundwater levels with rainfall would make it an influential factor for groundwater level trends, while a negative correlation with non-CSG water use and/or CSG groundwater extraction would make them influential factors. This is because rainfall is an input to the water budget (so groundwater levels tend to rise when rainfall increases and vice versa) and CSG groundwater extraction and non-CSG water use are outputs from the water balance (so groundwater levels tend to fall when extraction rises).

Key lessons include the following:

- When the monitoring length is greater than one decade (e.g. all three outcrop sites), the correlation with long-term rainfall trends is more apparent. Sites with longer records are also situated in outcrop areas, where groundwater levels are expected to be heavily influenced by rainfall-induced recharge.
- As expected, there is no correlation with rainfall for any of the deeper confined basin sites, although there may be a lag of approximately six months at two sites (i.e. they are correlated to some extent at RubyJo and Phillip gas fields).
- Data for five sites suggest a correlation with non-CSG water use, although two sites show an unusual positive correlation that is likely related to uncertainty in the water use estimates.
- Only one of the sites (Phillip 5M) shows a strong inverse correlation with CSG groundwater extraction across a single period. However, the same rate of drawdown in the monitoring point is observed for more than a year prior to CSG development, which suggests that the observed drawdown is related to a pre-existing stress, such as non-CSG water use.

8.3.5 Local-scale modelling

OGIA developed a detailed sub-regional groundwater model for the Talinga gas field in the Eastern Surat. This model was designed to test the hypotheses that CSG and non-CSG impacts could solely account for the declines in the Hutton Sandstone groundwater levels. Appendix A provides more detail on the model build, calibration and predictions. Key findings from this component of the assessment are as follows:

- It is unlikely that Hutton Sandstone drawdowns in the Eastern Surat are solely caused by CSG impacts, unless there are highly localised and highly permeable connectivity features that bypass the low formation-scale vertical permeability of the Durabilla Formation aquitard.
- Non-CSG water use stresses are capable of solely producing the observed Hutton Sandstone drawdown, assuming there is a high degree of connectivity within the upper Hutton Sandstone and the transmissivity of the formation is sufficiently high.

8.4 Conclusions

Key conclusions from the Hutton Sandstone groundwater level trend analysis are as follows:

- At this stage, there are no locations where CSG impacts are identified. At locations where drawdown is observed, there are other more plausible mechanisms to explain the drawdown impacts, such as non-CSG water use (as supported by sub-regional numerical testing).
- There are 191 groundwater level monitoring points completed in the Hutton Sandstone across the Surat CMA. Of these, only 28 sites have been used for pre-2010 groundwater level trend analysis, while 87 sites have been used for post-2010 trend analysis.
- Decreasing groundwater level trends are dominant in the outcrop area during both time periods (pre-2010 and post-2010), although as expected, a number of sites show short-term rising trends in the period following the 2010 rainfall recharge period.
- Decreasing trends are also common in the deeper confined parts of the formation during both the pre-2010 and post-2010 time periods, with no instances of overall increasing trends.

- Few connectivity features are likely to influence the observed groundwater level trends. This is attributed to both the presence of the Durabilla Formation (separating the two formations) and fewer occurrences of fault connectivity, multi-formation bores and wells.
- The Hutton Sandstone is a major water supply aquifer, with estimated extraction totalling one-third of the cumulative non-CSG water use from GAB formations in the Surat CMA. Non-CSG water use predates monitoring at both outcrop and confined basin sites.
- Detailed correlation analysis at outcrop/subcrop sites indicates the following:
    - There is a strong correlation with long-term rainfall trends in outcrop areas, and a potential lag response observed at a number of deeper monitoring points (e.g. RubyJo GW3 and Phillip 5M). During periods when rainfall is significantly above average, recharge is highly effective and becomes the dominant water budget component for several years afterwards.
    - There are no inflection points in the drawdown deeper in the basin and the length of record is very short. This makes analysis of correlation with recent stresses difficult to interpret. Further, both CSG groundwater extraction and non-CSG water use deeper in the basin tends to predate monitoring of the Hutton Sandstone groundwater levels at dedicated UWIR and company monitoring points.
    - At Phillip 5M, there is observed drawdown that predates CSG development within 8 km of the monitoring point.

9 Trend analysis – Condamine Alluvium

The ***Condamine Alluvium*** is a broad term used to describe the alluvial deposits of the Condamine River and its tributaries, located broadly between Warwick and Chinchilla. The alluvium is heavily used for water supply purposes including irrigation and town water supply (OGIA 2016a). The Condamine Alluvium is incised into the Walloon Coal Measures by up to 120 m, with potential for direct hydraulic interaction between the two formations.

In collaboration with Arrow Energy, OGIA undertook a comprehensive investigation project in 2013–2015 to improve understanding of the groundwater connectivity between the Condamine Alluvium and the Walloon Coal Measures. As part of the investigation, two sites for test-pumping and multi-level monitoring were established. Results of the investigation were reported in 2016 (OGIA 2016c).

A number of monitoring sites have been established along the western flank of the Condamine Alluvium in proximity to areas of current and proposed CSG development. This chapter presents emerging trends and analysis from up-to-date monitoring data in this area.

9.1 Formation characteristics

9.1.1 Stratigraphy and lithology

The basement for the Condamine Alluvium primarily comprises the Walloon Coal Measures, which underlies most of the central Condamine Alluvium, and the Springbok Sandstone, wedged between the Condamine Alluvium and the Walloon Coal Measures along the western margin. Figure 9-1 shows a schematic representation of the regional geological and hydrogeological setting.

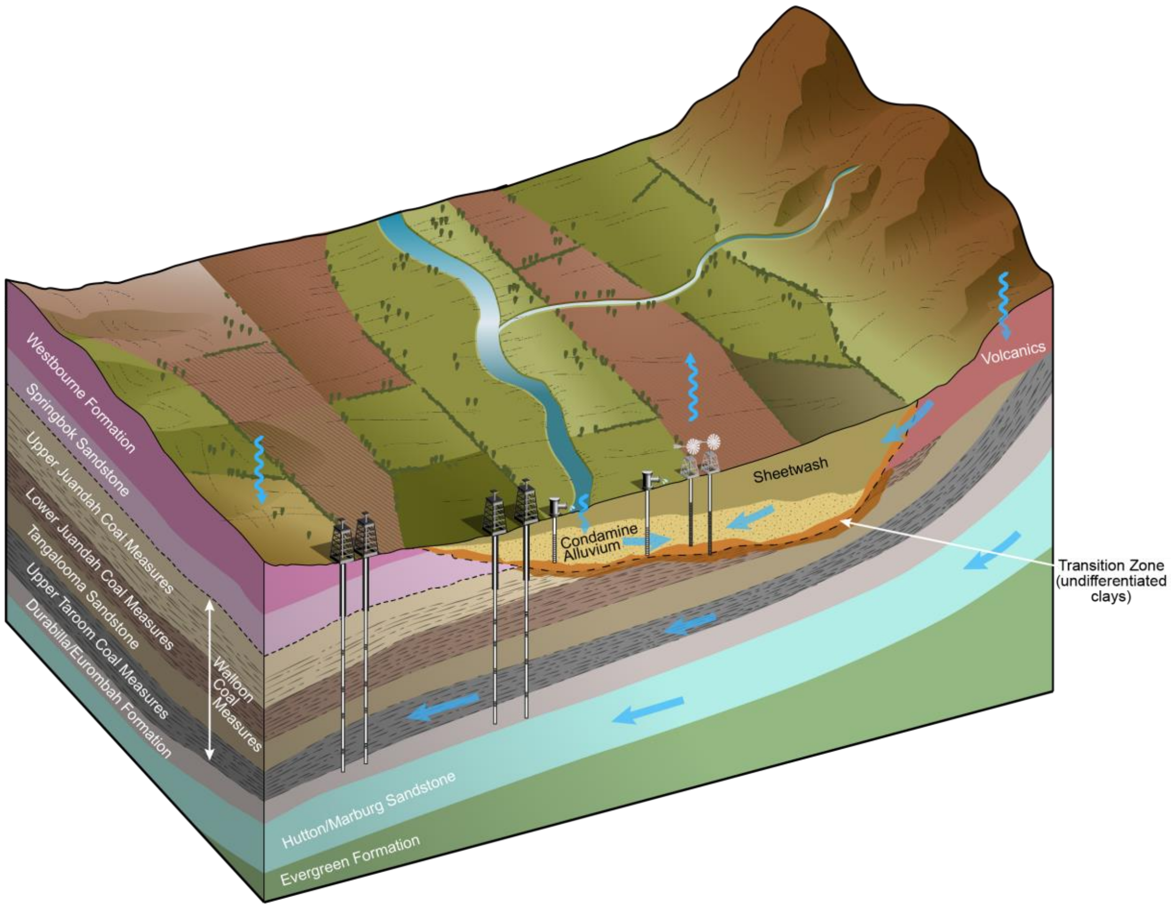

Figure 9-1 Schematic of the regional hydrogeological setting around the Condamine Alluvium

There are three hydrostratigraphic units within the Condamine Alluvium (OGIA 2016a):

- **Sheetwash** (including topsoil) occurs as a wedge of generally fine materials (silt and clay) or mixed sandy materials, abutting the eastern limits of the Condamine River plain and overlying the more varied granular alluvium aquifer. In many places, individual clay and silt horizons are more than 20 m thick.
- **Granular alluvium** underlies the sheetwash in most areas and typically presents as a wide range of relatively thin (less than 10 m), fine, mixed and granular (sand and gravel) horizons separated by clay lenses, representative of the complex depositional environment (riverine high-energy to lacustrine low-energy). There is generally an increase in fines content in the downstream direction, with much higher groundwater yields generally encountered in the coarser-grained deposits towards the south of the Condamine Alluvium footprint.
- **Transition zone** is the clay-dominated horizon at the base of the Condamine Alluvium. This is a combination of basal alluvial clays of the Condamine Alluvium and weathered Walloon Coal Measures. Where present, the transition zone ranges from less than 1 m to just more than 15 m in thickness.

9.1.2 Hydraulic properties

The hydraulic properties indicate spatial and vertical variability, which is reflective of the geology. Hydraulic conductivity estimates from the earlier pumping tests range between 1 and 781 m/day (OGIA 2016a). The majority of hydraulic conductivity values are derived from estimates of transmissivity, assuming saturated thickness. KCB (2011) conceptualised the Condamine Alluvium groundwater system as a two-layer system, calibrating the hydraulic conductivities as 0.2 to 2 m/day for the upper sheetwash layer and around 10 to 40 m/day for the lower alluvial/granular layer. Values obtained from recent pumping tests at two sites are consistent with these estimates (OGIA 2016c). The vertical hydraulic conductivity for the transition zone and the upper Walloon Coal Measures was estimated (OGIA 2016c) to range from 1×10^{-09} to 1×10^{-04} m/day across the Condamine Alluvium footprint, with 1×10^{-06} m/day being the most likely value at a regional scale. The horizontal hydraulic conductivity of this transition layer is likely to be two orders of magnitude higher.

9.1.3 Hydrochemistry

There is significant spatial variability in the water quality of the Condamine Alluvium, with total dissolved solids (TDS) ranging from fresh (550 mg/L) to highly saline (13,000 mg/L) and pH typically around 7.6 (OGIA 2016c). The water type in the Condamine Alluvium varies spatially with a number of hydrochemical domains evident, notably $Na\text{-}HCO_3$, Na-Cl and $Na\text{-}Cl\text{-}HCO_3$. The samples tend to indicate groundwater is of $Mg\text{-}HCO_3$ composition in upstream areas and most tributaries, with a gradual change to $Na\text{-}HCO_3$ composition further downstream (Huxley 1982).

OGIA (2016c) found that although there are similarities in some water chemistry parameters (i.e. TDS) between the Condamine Alluvium and the Walloon Coal Measures, their underlying chemical signatures are unique. The significant differences in hydrochemistry between the Condamine Alluvium and Walloon Coal Measures suggest that the two units evolved separately, with minimal regional-scale cross-formational flow of water.

It is acknowledged that, on average, recharge to the Condamine Alluvium is exceeded by outflow, the largest outflow being extraction from groundwater bores (Dafny & Silburn 2014). As a result, groundwater levels in the Condamine Alluvium have declined in many areas over the past 60 years.

9.1.4 Observed groundwater level trends

Groundwater levels in the Condamine Alluvium have declined across most of its footprint over the past 50 years (KCB 2010). The GWDB contains groundwater level data from a large number of bores within the Condamine Alluvium footprint, including long-term regular groundwater level records from hundreds of DNRME monitoring bores distributed across the area. The majority of these monitoring bores are screened exclusively in the Condamine Alluvium. Only a few monitoring bores with long-term records of groundwater levels reflect groundwater conditions in the underlying Walloon Coal Measures. Long-term groundwater level trends from selected bores in the Condamine Alluvium and the underlying Walloon Coal Measures (where available) were presented in OGIA (OGIA 2016c), with a revised version (including the latest data up to 2018) reproduced in Figure 9-2.

The following observations are made:

- In the southern area, groundwater levels in the Condamine Alluvium have been relatively stable over the past 40 years, fluctuating by less than five metres, with little or no seasonal variation.
- In the southern central area, to the south of Dalby and east of Cecil Plains, a significant groundwater depression began to form in the Condamine Alluvium in the 1960s as a result of non-CSG water use. Groundwater levels in this area fell by about 25 metres between 1965 and 2010, but appear to have stabilised in recent years.
- In the central area, around Dalby, a significant groundwater depression began to form in the Condamine Alluvium in the 1990s as a result of non-CSG water use. Levels in this area fell by up to 15 metres between 1960 and 2010 and have generally stabilised or recovered since 2007. This recovery is believed to be the result of decreasing extraction combined with increased recharge over this period (Dafny & Silburn 2014).

The western flank of the Condamine Alluvium is closest to CSG development and is the location where potential CSG impacts to the Condamine Alluvium might first appear. Nine dedicated Condamine Alluvium monitoring points at various points along this western flank were selected for detailed statistical analysis of groundwater level trends. The purpose of the trend analysis is to identify statistically significant increases or decreases in groundwater levels using a modified Mann-Kendall trend test.

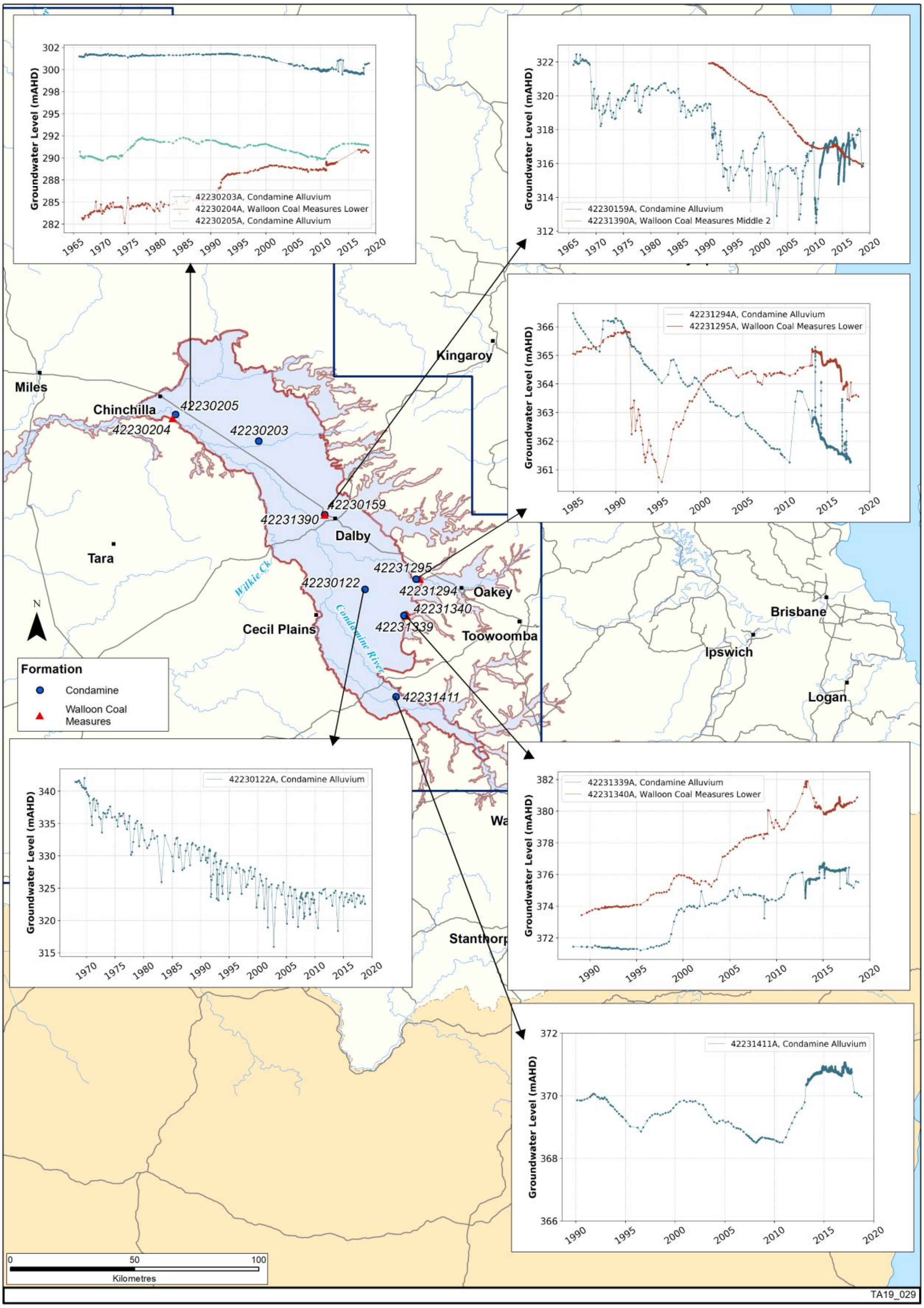

Figure 9-2 Long-term hydrographs for selected Condamine Alluvium and Walloon Coal Measures nested monitoring locations

The locations of the nine representative monitoring points and the interpreted groundwater level trends and trend rates over two main time periods (2000 to 2009 and 2010 to 2018) are shown in Figure 9-3. These time periods were rationalised as being representative of the following:

- the Millennium Drought (2000 to 2009) when CSG production in the basin was limited to only a few fields such as Talinga and Daandine
- a more recent period (2010 to 2018) when CSG production became much more widespread throughout the basin (especially during and after 2014) and cumulative CSG groundwater extraction increased exponentially
- the 2010 recharge event, which separated these two time periods, having influenced groundwater levels in the Condamine Alluvium.

Table 9-1 provides a summary of the outcomes of the Condamine Alluvium groundwater level trend analysis. It is evident from Figure 9-3 and Table 9-1 that decreasing trends are dominant in the period prior to 2010. In the more recent post-2010 period, there are mixed responses, with three increasing trends, one decreasing trend and five locations with no statistically significant trend.

Table 9-1 Summary of results from the OGIA 2018 groundwater level trend analysis assessment for the Condamine Alluvium

Hydrostratigraphic unit	Time period	Position in basin	Monitoring points	Groundwater level trend		
				Increasing	Decreasing	No trend
Condamine Alluvium	2000-09	Outcrop	5	0	5	0
	2010-18		9	3	1	5

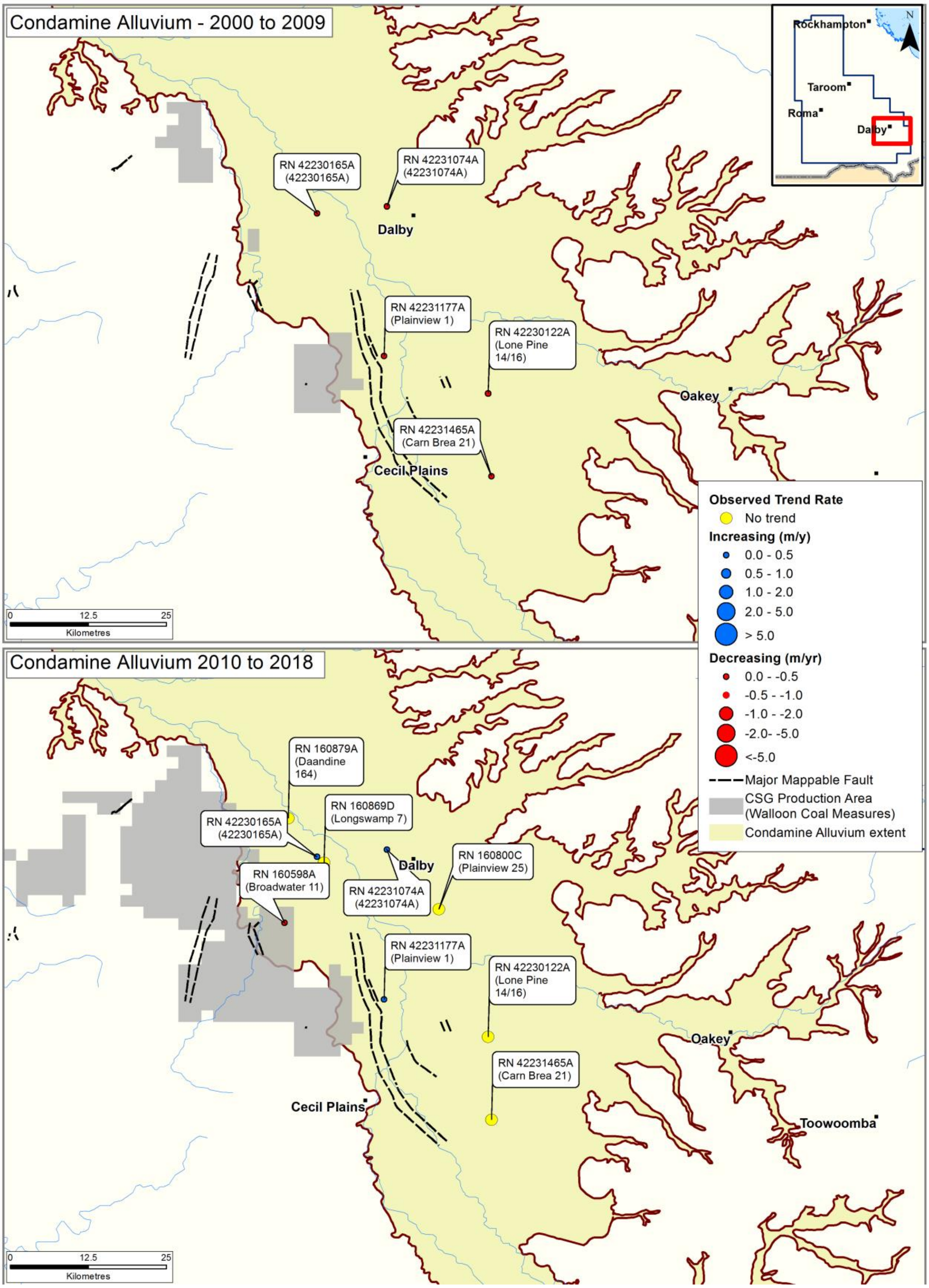

Figure 9-3 Condamine Alluvium groundwater level trends for 2000 to 2009 and 2010 to 2018

9.1.5 Connectivity with the CSG reservoir

9.1.5.1 Geological influences

OGIA's connectivity investigations (OGIA 2016c) concluded that there is a low level of connectivity between the Condamine Alluvium and the Walloon Coal Measures. The study identified a low-permeability 'transition zone' of undifferentiated clay (an aquitard) between the base of the Condamine Alluvium and the un-weathered Walloon Coal Measures (Figure 9-4). This sits above the firm mudstone/siltstone of the uppermost parts of the Walloon Coal Measures, which also typically forms an effective aquitard. Vertical flow and interaction between the Condamine Alluvium and the Walloon Coal Measures is therefore impeded by a combination of the transition zone and the firm mudstone/siltstone. The degree to which flow is impeded depends upon the combined thickness and vertical hydraulic conductivity of these two units.

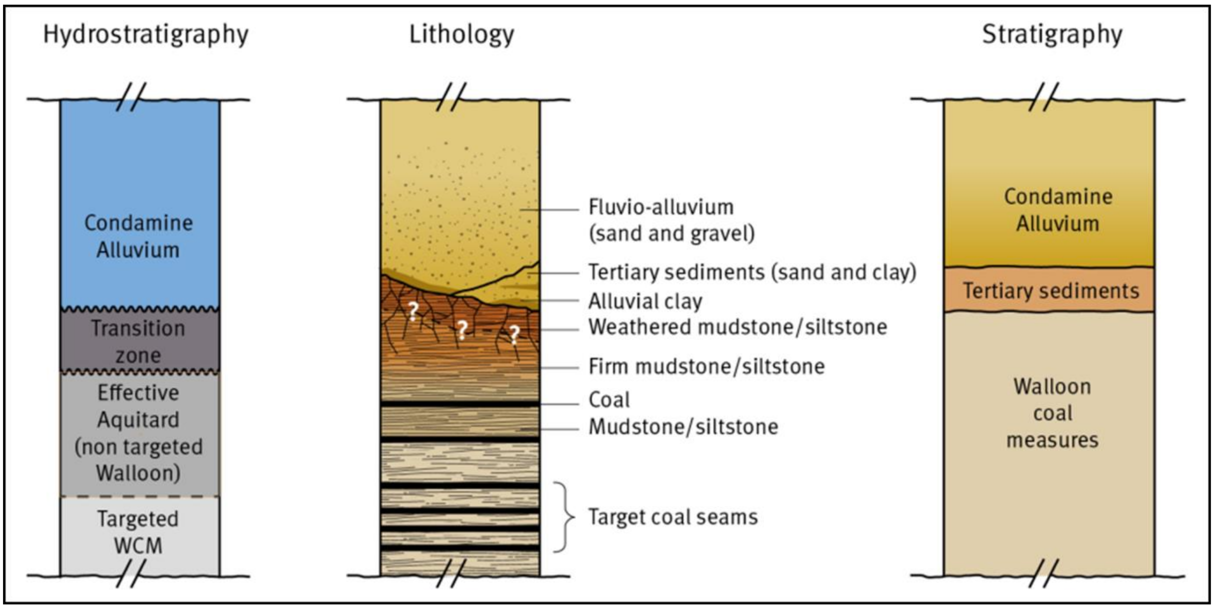

Figure 9-4 Conceptual schematic, Walloon Coal Measures and Condamine Alluvium interface

A map showing the subcrop geology, currently mapped fault locations and transition zone thickness is presented in Figure 9-5. Since the preparation of the UWIR 2016, there has been no change to the mapping of the transition zone, but the geology and mapping of faults have been updated (OGIA 2019c, 2019h).

Along the western flank in proximity to the areas where CSG development has occurred and pressure in the Walloon Coal Measures is depressurised, the transition zone is either absent or is relatively thin (less than 5 m). However, in this area, there is also a thin wedge of Springbok Sandstone that lies between the Condamine Alluvium and the Walloon Coal Measures.

Based on a detailed review of available seismic surveys, OGIA have also identified a number of mappable faults in close proximity to the Condamine Alluvium that could influence connectivity between the aquifer and the underlying Upper Juandah Coal Measures in this area – particularly the Horrane fault system and a further pair of north-south oriented faults west of the Horrane faults and close to the western margin of the Condamine Alluvium (OGIA 2019h). Figure 9-6 shows an interpreted seismic section through the Horrane Fault system which suggests displacements of up to 108 m.

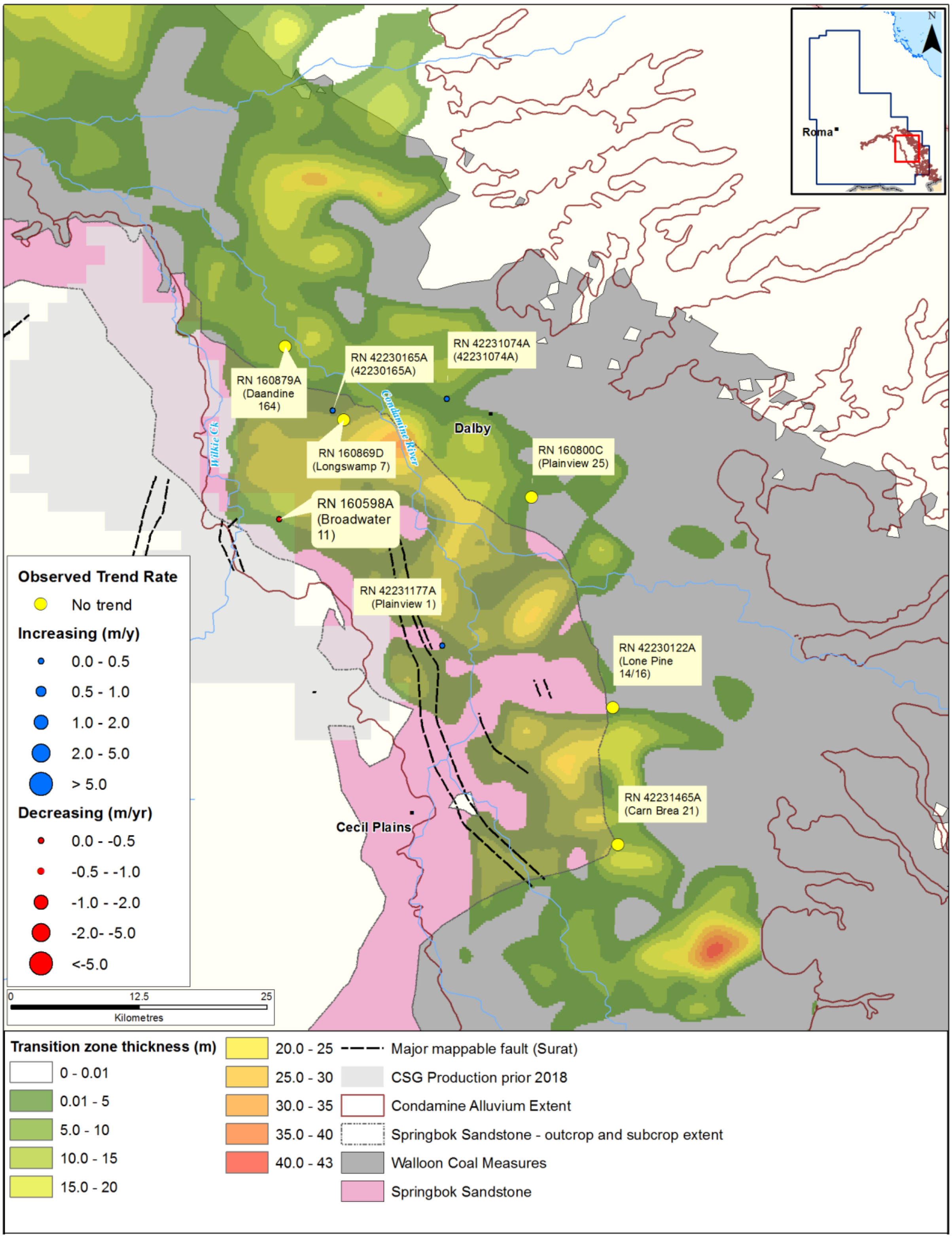

Figure 9-5 Geological influences on CSG impact propagation, Condamine Alluvium western flank

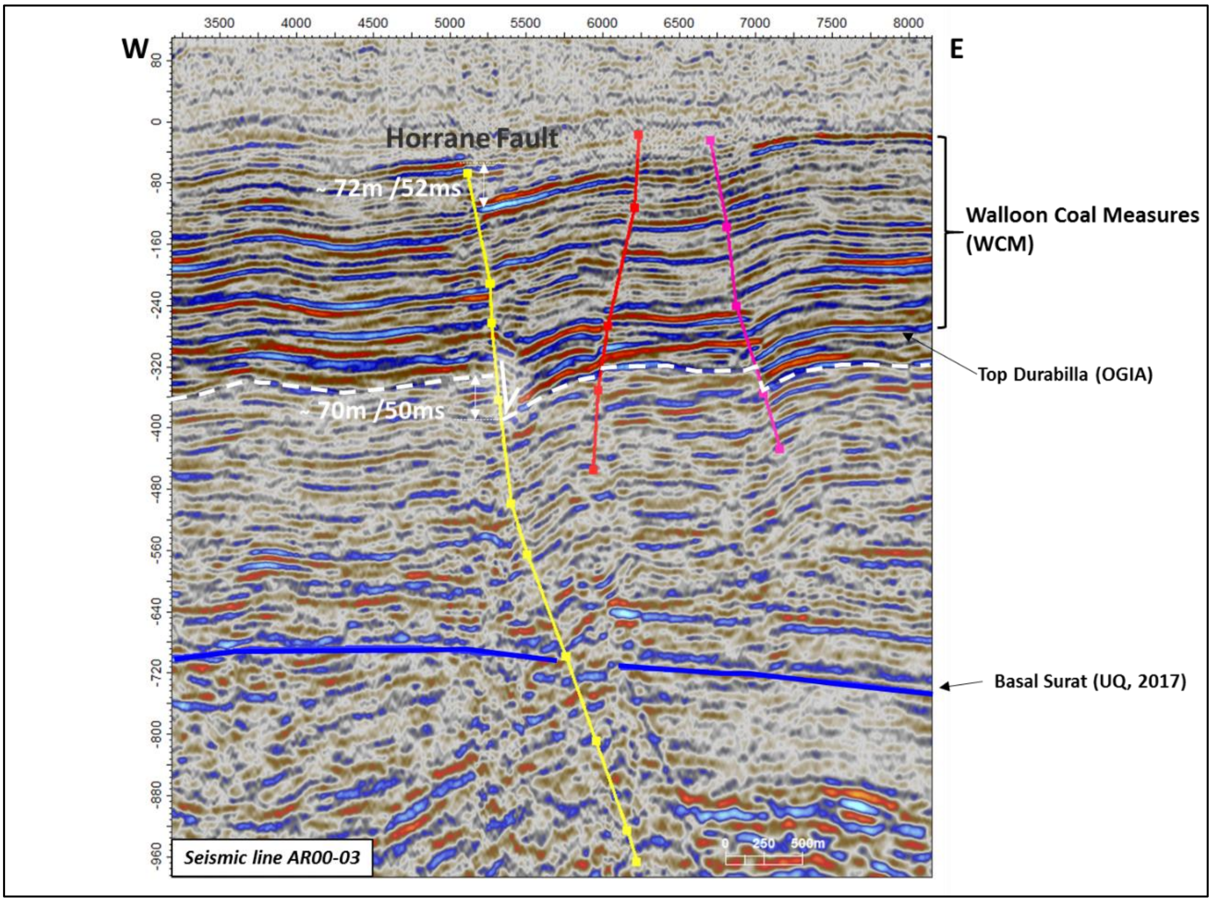

Figure 9-6 Seismic section, interpretation of the Horrane Fault (OGIA ref) and estimated throw at the top of Durabilla Formation and Walloon Coal Measures–Springbok Sandstone contact

The seismic profiles are characterised by poor resolution at shallow depths and hence provide no information about the effect of faulting on the contact between the Condamine Alluvium and the underlying Walloon Coal Measures. However, as described in section 9.1.4 and shown in Figure 9-3, the current monitoring of Condamine Alluvium groundwater levels to the east of Cecil Plains (where the Horrane Fault occurs) shows either increasing or no trends for the period 2010-2018. These trends are therefore not indicative of CSG impacts at this location. To provide further information on potential impacts in this area, further monitoring in the vicinity of this fault system is specified in the UWIR 2019.

9.1.5.2 Hydrochemistry signatures

Changes to groundwater chemistry, resulting from cross-formational flow and mixing of more than one type of water, can take a long time to develop. OGIA has nevertheless compared the groundwater chemistry difference in the Condamine Alluvium and the Walloon Coal Measures in CSG production areas, to assess if there are any emerging trends that could indicate cross-formational flow in these areas. Analysis suggests that few CSG wells show significant temporal trends or indications of inflow of Condamine Alluvium water into the Walloon Coal Measures (OGIA 2016c).

Figure 9-7 presents a comparison of major ion chemistry for CSG production wells and Condamine Alluvium bores. All CSG production well samples are characterised by Na^{+}+K percentages of greater than 97%, whilst the majority of Condamine Alluvium samples fall in the range of 47–90%. Chloride percentages and TDS concentrations in CSG production wells are also consistently higher than in the overlying Condamine Alluvium.

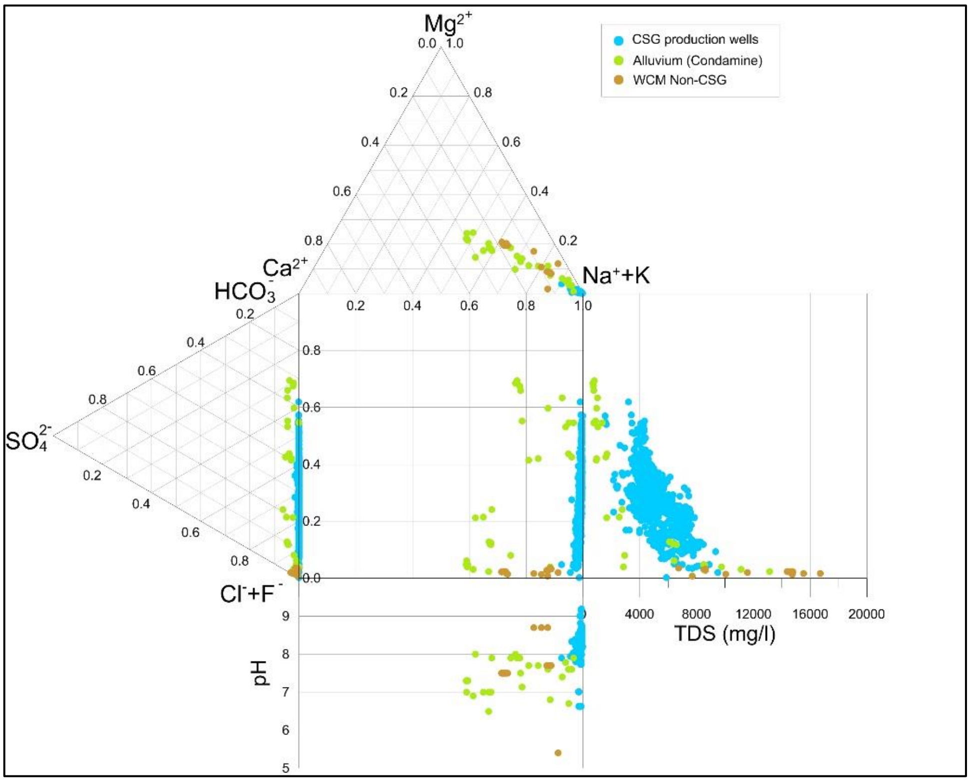

Figure 9-7 Durov plot, major ion chemistry, Condamine Alluvium and Walloon Coal Measures

A further illustration of the distinct differences between chemistry in the Condamine Alluvium and Walloon Coal Measures in the area is provided by plotting the ratio of sodium to chloride (Na/Cl) versus chloride (Figure 9-8). Groundwater samples taken from connected flow systems typically follow a predictable evolutionary path, gradually evolving from fresh recharge (relatively high Na/Cl ratios and low chloride concentrations) to ancient groundwater (low Na/Cl ratios and high chloride concentrations approaching seawater) (Eriksson 1985; Monjerezi et al. 2011). Figure 9-8 suggests that Condamine Alluvium samples (indicated by the red arrow) plot on quite different evolutionary pathways from samples drawn from Walloon Coal Measures CSG wells (orange arrow).

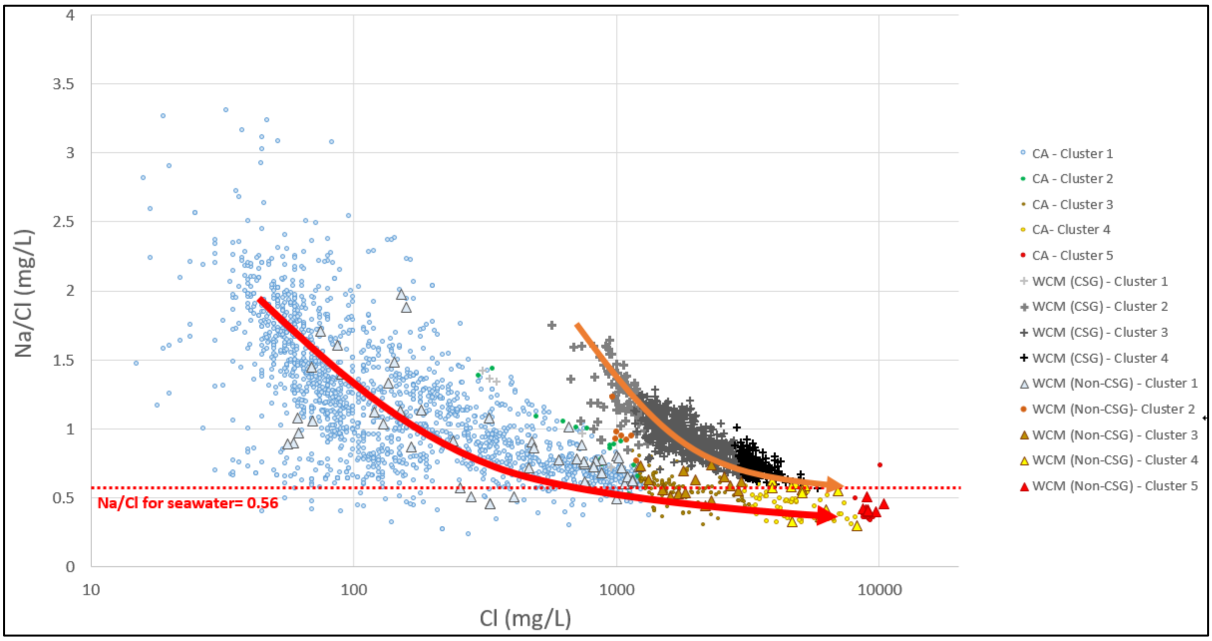

Figure 9-8 Na/Cl versus Cl - South-eastern Surat

9.2 Analysis of groundwater level trends

Groundwater levels are analysed at two monitoring sites towards the western flank of the Condamine Alluvium: RN42230159A (in the proximity of Longswamp 7) and RN42230165A. These sites are located to the west of Dalby, on either side of the Condamine River. RN42230165A is situated on the western side of Condamine River, near Arrow's Daandine gas field. RN42230159A is approximately 10 km to the east, on the eastern side of Condamine River (Figure 9-3). These two sites form an east–west transect towards Arrow's Daandine gas field. As for the Springbok Sandstone and Hutton Sandstone, hydrographs for these two representative sites have been correlated with rainfall trends as well as non-CSG water use and CSG groundwater extraction trends.

9.2.1 Correlation with rainfall trends

Previous investigations have established that the Condamine Alluvium is primarily an unconfined to semi-confined groundwater system that responds to direct recharge from rainfall and riverbed leakage and groundwater discharge through non-CSG water use (OGIA 2016c). It is therefore expected that the representative groundwater levels analysed in this section of the report will correlate with long-term rainfall trends.

In this section, Condamine Alluvium groundwater levels at two sites are correlated with long-term CDMMR from the Cecil Plains weather station over a 25-year period. This weather station is located on the western flank of the Condamine Alluvium (near areas of existing and proposed CSG development).

Figure 9-9 presents the hydrograph for RN42230165A, a Condamine Alluvium monitoring bore situated to the west of Dalby, with the Cecil Plains weather station CDMMR. Given both the long-term nature of the datasets and the noise in the groundwater level signal (due to unconfined aquifer and stress response to pumping), a 24-month rolling mean was applied to smooth out the groundwater level for correlation analysis. The actual groundwater level measurements are also provided on the plot to show that the overall structure of the data has been honoured through this smoothing process.

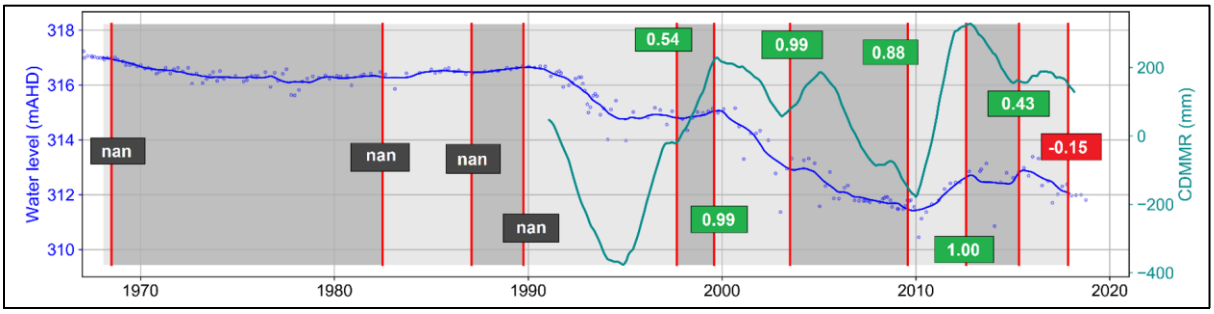

Figure 9-9 Spearman correlation, RN42230165A groundwater level and Cecil Plains weather station CDMMR

There is a steady, multi-year decline in groundwater levels from about 2000 to 2010, which correlates strongly to an extended below-average trend in rainfall over the same period (the Millennium Drought). This is followed by a subtle rising groundwater level trend from 2010 to 2013, which also strongly correlates with a corresponding sharp rise in CDMMR due to multi-year above-average rainfall. Importantly, there is a decline in groundwater level after 2013, which strongly correlates with below-average rainfall. Overall, this site shows a strong correlation with trends in rainfall.

Figure 9-10 presents the hydrograph for RN42230159A, a Condamine Alluvium monitoring bore situated near Dalby, with the Cecil Plains weather station CDMMR. Compared to the previous example, a longer (36-month) rolling mean was applied to smooth out the noisy groundwater level dataset for correlation analysis (the actual groundwater level measurements are again shown on the plot to visualise the effect of data smoothing). The three peaks in CDMMR around 2000, 2005 and 2011 all correlate well with increased groundwater levels, indicating that above-average rainfall leads to effective recharge of the unconfined to semi-confined alluvial aquifer. According to previous studies (e.g. OGIA 2016c), this is most likely recharge via the Condamine River.

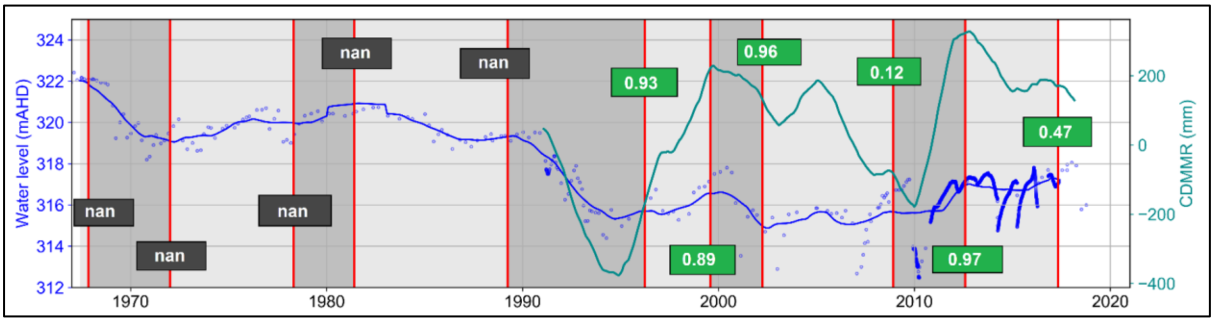

Figure 9-10 Spearman correlation, RN42230159A groundwater level and Cecil Plains weather station CDMMR

9.2.2 Correlation with non-CSG water use

Figure 9-11 shows the latest estimates for annual non-CSG water use from the Condamine Alluvium and tributaries (OGIA 2019b). This plot shows that water use climbed markedly over a three-decade period, from less than 20,000 ML/year in 1970 to around 100,000 ML/year in 2002. Since then, water use has declined to a current rate of less than 80,000 ML/year. Comparatively, this cumulative annual extraction volume is 4–5 times that of the Hutton Sandstone, and 100 times the Springbok Sandstone. This emphasises the scale of the stress that within-aquifer, non-CSG water use has on the Condamine Alluvium water budget. Given the scale of water use from this important high-yielding aquifer, it is expected that groundwater levels will exhibit a negative correlation with local extraction.

Figure 9-12 presents the cumulative annual non-CSG water use within 25 km of RN42230165A compared with the hydrograph for that site. There are 1,268 water supply bores within 25 km, with total cumulative extraction estimated to steadily grow from ~5,000 ML/year in the late 1980s to over 15,000 ML/year in 2004. Non-CSG water use predates groundwater level monitoring at this site. The period between 1988 and 1996 has a strong inverse correlation between falling groundwater levels and gradually increasing non-CSG water use. This correlation continues through to 2005, however, non-CSG water use then recedes until 2011, which diminishes the negative correlation between these two variables. Groundwater level rises post-2010, associated with an extended period of above average rainfall, leading to a poor correlation with non-CSG water use, highlighting the dominance of recharge processes during this time. After 2010, non-CSG water use again rises and coincides with more recent declines in groundwater levels.

Figure 9-13 presents the hydrograph for RN42230159A compared with the cumulative annual non-CSG water use within 25 km of that site. There are 1,535 water supply bores within 25 km, with total cumulative extraction estimated to steadily grow from ~5,000 ML/year in the early 1980s to nearly 20,000 ML/year in 2005. Non-CSG water use again predates groundwater level monitoring at this site. From 1980 to 2005, there is a predominant strong inverse correlation between rising non-CSG water use and falling groundwater levels, again emphasising the influence of water use on aquifer storage in the Condamine Alluvium. Post-2005, there is a period of reduced water use that broadly correlates with a slight recovery in groundwater levels.

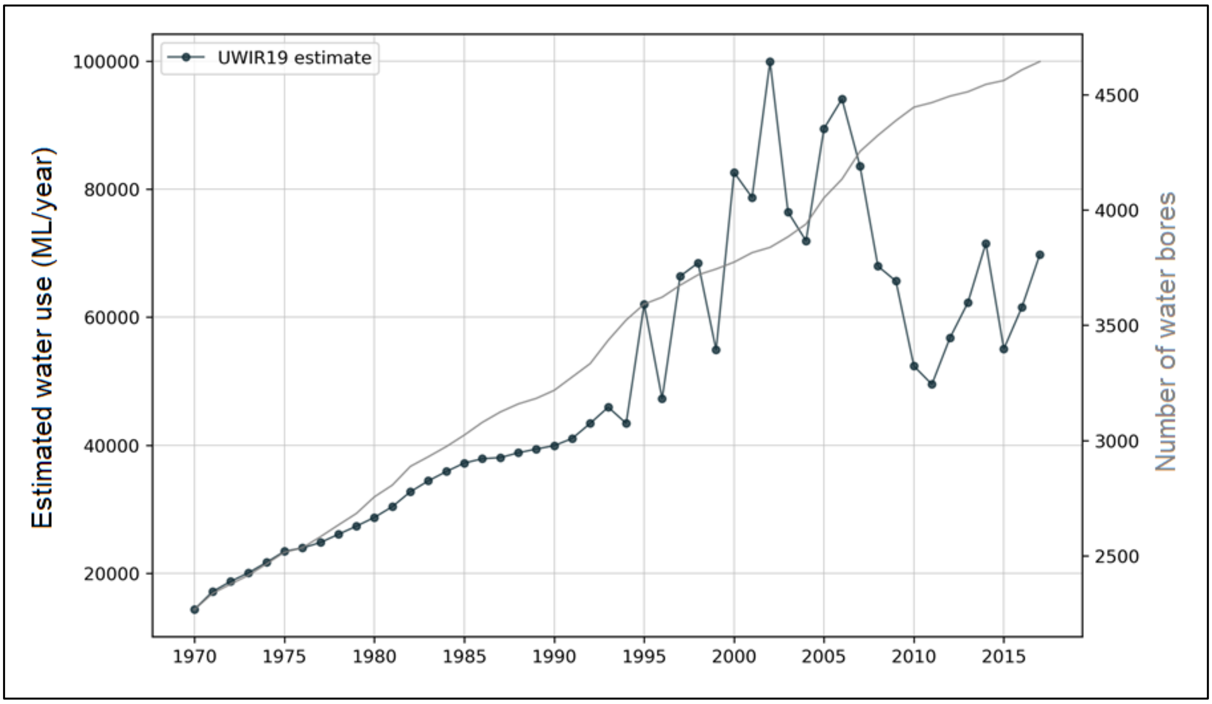

Figure 9-11 Temporal water use estimate for the Condamine Alluvium (after OGIA 2019b)

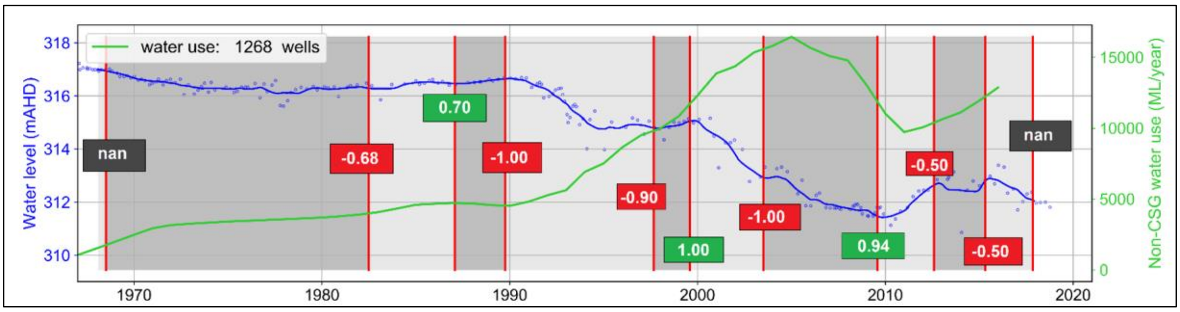

Figure 9-12 Spearman correlation, RN42230165A groundwater level and cumulative non-CSG water use from the Condamine Alluvium within 25 km

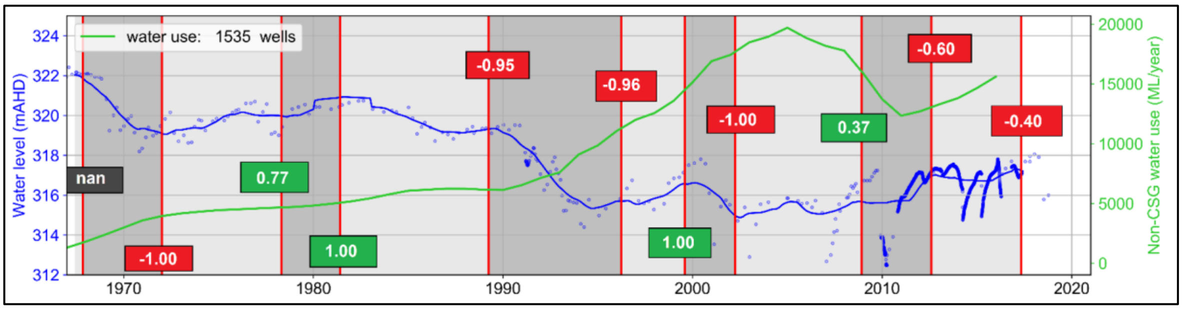

Figure 9-13 Spearman correlation, RN42230159A groundwater level and cumulative non-CSG water use from the Condamine Alluvium within 25 km

9.2.3 Correlation with CSG groundwater extraction

Figure 9-14 presents the hydrograph for RN42230165A compared with monthly CSG groundwater extraction within 10 km of that site. This monitoring point is located 8 km to the east of Arrow's Daandine gas field, which commenced operations in 2010. There are only 11 CSG wells within 10 km and groundwater level monitoring predates CSG groundwater extraction by more than 20 years. There is a reasonably strong inverse correlation post-2014, with rapidly increasing CSG groundwater extraction coinciding with a decreasing groundwater level trend. However, this period also coincides with decreasing rainfall trends and increasing non-CSG water use, which are more plausible explanations for the observed decline.

From a water budget perspective, within 25km of the monitoring point, peak annual CSG groundwater extraction is around 300 ML/year, representing around 2% of the ~12,500 ML/year non-CSG water use from the Condamine Alluvium. Hence, even if this CSG groundwater extraction was derived as an outflow from the Condamine Alluvium, it seems highly unlikely that this would result in the recent decline in groundwater level at this location, given the much larger non-CSG stress.

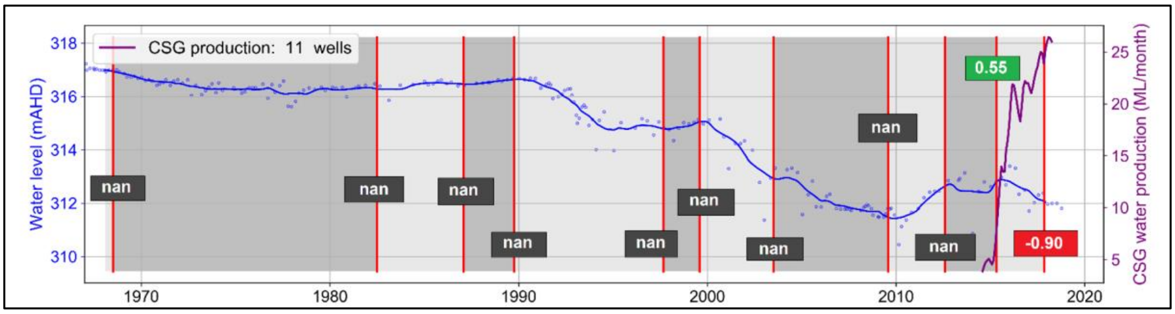

Figure 9-14 Spearman correlation, RN42230165A groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Figure 9-15 presents the hydrograph for RN42230159A compared with the cumulative monthly CSG groundwater extraction within 10 km of that site. There are no CSG wells within 10 km and therefore no CSG groundwater extraction volumes to correlate with groundwater level trends. CSG groundwater extraction is therefore not thought to be influencing groundwater levels at this site.

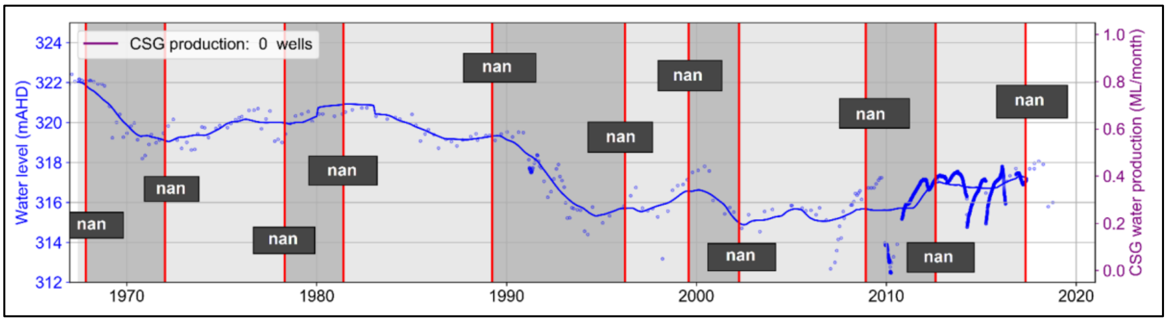

Figure 9-15 Spearman correlation, RN42230159A groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

9.2.4 Summary of correlation analyses

Sections 9.2.1 to 9.2.3 provide a summary of the degree of correlation between Condamine Alluvium groundwater levels at selected sites and three water balance factors – rainfall, non-CSG water use and CSG groundwater extraction. Table 9-2 provides a summary of the outcomes of the correlation analyses for the Condamine Alluvium. As previously emphasised in section 7.3.4, a persistent strong positive correlation of groundwater levels with rainfall would make it an influential factor for groundwater level trends, while a negative correlation with non-CSG and/or CSG would make them influential factors.

Key observations from the analysis:

- Condamine Alluvium groundwater levels on the western flank tend to show a positive correlation with rainfall, such that below-average rainfall periods coincide with declining levels and above-average periods with subtle rising levels. This is interpreted to represent a combination of the occurrence or absence of recharge events and resulting water use practices on the observed groundwater levels (i.e. during high rainfall periods, water use is reduced).
- Non-CSG water use in the local study areas match the general trends presented for the regional aquifer (as shown in Figure 9-11), with a rapid increase in extraction between 1990 and 2005. There are strong negative correlations between groundwater levels and non-CSG water use over this same time period, reflecting the local drawdown of the aquifer in response to pumping. As extraction decreases after 2005, correlations are less prominent.
- There is a negative correlation with CSG at RN42230165A after 2015, such that the rapid increase in associated CSG groundwater extraction coincides with decreases in groundwater levels. However, this period also coincides with decreasing rainfall trends and increasing non-CSG water use, which are more plausible explanations for the observed decline.

Table 9-2 Summary of Condamine Alluvium correlation analyses

Location	Representative monitoring site	Length of record (years)	Correlation with rainfall[1]	Correlation with non-CSG water use	Correlation with CSG groundwater extraction	Factors influencing groundwater levels
Condamine Alluvium	RN42230165A	50	Yes (+)	Variable (-)	Yes (-)	Rainfall and non-CSG water use. Negative correlation with non-CSG water use is strongest up until 2005, after which extraction is reduced in this area. Negative correlation with CSG groundwater extraction is not supported by water budget analysis and occurs when non-CSG water use is increasing and rainfall trends decreasing.
	RN42230159A	50	Yes (+)	Variable (-)	No	Rainfall and non-CSG water use. Negative correlation with non-CSG water use is strongest up until 2005, after which extraction is reduced in this area.

Table notes:

1. Sign shown in brackets indicates whether a persistent correlation is positive (+) or negative (-).

9.2.5 Nested site analysis

As shown in Table 9-3, significant drawdown is observed in the Walloon Coal Measures at the Broadwater GW11 and Stratheden 4 sites due to nearby CSG groundwater extraction. This drawdown has resulted in downward head gradients of up to 30 m from the Condamine Alluvium to the underlying Upper Juandah Coal Measures. However, there has been no obvious response in the Condamine Alluvium at either location.

A small amount of drawdown (less than two metres) has also been observed in the Walloon Coal Measures at the Daandine 164 and Tipton 197 sites, located just to the west of the Condamine River. In these two cases, there is also some evidence of drawdown in the Condamine Alluvium. However, given the relatively small drawdowns and the minor head differences at this location, it is considered more likely that the observed drawdowns are a combination of non-CSG water use from the Condamine Alluvium and the downward trend in CDMMR.

The Daandine 164 site was also one of two pumping test sites investigated as part of the Condamine Connectivity study (OGIA 2016c). During this test, drawdowns of up to 20 m were induced in the Condamine Alluvium and there was little to no observed response in the underlying Walloon Coal Measures. The fluctuations in groundwater levels near Daandine 164 observed during the testing period were instead attributed to the combined effects of mechanical loading and regional trends in the Walloon Coal Measures (OGIA 2016c). Given these findings, it is considered unlikely that the observed declining levels in the Condamine Alluvium are caused by the recent minor decline in the Walloon Coal Measures.

Table 9-3 Summary of groundwater level observations at nested sites with monitoring in the Condamine Alluvium

Monitoring site	Distance to nearest CSG production well	CSG production start	Maximum observed drawdown, WCM (m)	Groundwater level trend rate, Condamine Alluvium (m/yr)	Total observed drawdown, Condamine Alluvium (m)	Head difference, Condamine Alluvium–WCM (m)	Potential CSG Impact, Condamine Alluvium
Broadwater GW11	Within CSG area	2014	>200	0	0[1]	18 ↓	No, no observed drawdown
Stratheden 4	Within CSG area	2008	>40	-0.15	-0.3	30 ↓	No, no significant observed drawdown
Tipton 197	5 km	2005	0	-0.2	-6	-3 ↑	No, no significant observed drawdown in WCM
Plainview 1	6 km	2005	0	0.2	2	-16 ↑	No, no observed drawdown
Daandine 164	8 km	2008	2	-0.5	-1.5	0 -	No, no significant observed drawdown in WCM

Table notes

1. Negligible drawdown rate of 2 cm/year (0.02 m/year) noted.

9.3 Conclusions

Key conclusions from the Condamine Alluvium groundwater level trend analysis are as follows:

- At this stage, based on the available data, there are no locations where CSG impacts are identified. At locations where drawdown is observed, there are other more plausible mechanisms to explain the observed drawdown, particularly the non-CSG water use.
- The Condamine Alluvium and tributaries comprise a major water supply aquifer, with extraction estimates up to 100,000 ML/year in the early 2000s. Large parts of the aquifer have experienced tens of metres of drawdown since the 1960s.
- Groundwater level trends have been analysed at nine representative Condamine Alluvium monitoring points along the western flank of the alluvial aquifer, in relatively close proximity to current CSG development areas. Groundwater level trends in the decade prior to 2010 are consistently declining, reflecting the long-term non-CSG water use in this area coupled with reduced recharge during the Millennium Drought. In the period post-2010, groundwater level trends are mixed: one declining trend, three rising trends and five sites where statistically significant trends could not be established, owing to fluctuating groundwater levels.
- Two specific monitoring locations (RN42230159A and RN42230165A) have been selected for detailed groundwater level correlation analysis. Situated in the central area to the west of Dalby, towards the western flank of the central Condamine Alluvium, these sites are close to Arrow’s Daandine gas field, which commenced operation in 2005. Correlation analyses indicates that:
    - Rising and falling groundwater levels tend to correlate positively with periods of above-average and below-average rainfall, indicating that this unconsolidated alluvial aquifer is strongly influenced by climatic events.
    - At both sites, non-CSG water use predates groundwater level monitoring, with three-fold increases in extraction between the 1980s and 2005 within 25 km. Both sites experienced declining groundwater levels during the Millennium Drought (2000 to 2010) when less recharge, coupled with increasing water use, impacted storage in the aquifer. Increases in non-CSG water use more recently (after 2016) have resulted in periods of subtle declining groundwater levels in RN42230165A.

10 Overall conclusions

10.1 Introduction

A multiple-lines-of-evidence approach is applied, including both qualitative and quantitative methods, to establish the nature of trends and determine the likely causes of those trends in the Surat CMA with a particular focus on the extent to which CSG impacts may have influenced those trends. This involves statistical methods (Mann-Kendall and Spearman for correlation with water balance factors), contextualisation with sub-regional and local-scale hydrogeological conceptualisation, and validation through numerical modelling. The outcomes from these individual methods are then integrated to assess the potential for CSG impacts.

This assessment is focussed on understanding the influence of CSG groundwater extraction from the Walloon Coal Measures on adjacent aquifers – the Springbok Sandstone, Hutton Sandstone and Condamine Alluvium. This chapter summarises overall conclusions of the assessment presented in this report.

10.2 Walloon Coal Measures

The Walloon Coal Measures is the primary reservoir for CSG development in the Surat CMA. The formation is an interbedded aquifer comprising the Upper and Lower Juandah coal measures, the Tangalooma Sandstone and the Taroom Coal Measures.

Across the development area, there are broadly consistent trends in groundwater level response to CSG development. The magnitude of drawdown within each sub-unit of 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.

A comparison of observed groundwater level decline with distance to nearest active CSG well indicates declines of more than 10 m are largely limited to areas within 10 km of CSG production wells. This also suggests that although there are declines of 200–300 m 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 relatively flatter cone of depression in the lower part of the Walloon Coal Measures.

10.3 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 drawdown in the Springbok Sandstone immediately overlying the Walloon Coal Measures. This formation is considered a tight aquifer and has very low estimated water use and permeability compared to other aquifers.

Monitoring points show highly variable groundwater level 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. 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 production areas, impacts from CSG groundwater extraction are most apparent in Kenya East GW4 (RN160525A), 30 km south of Chinchilla. This monitoring site shows relatively static groundwater 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 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. 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).

Overall, there are variable groundwater level trends in the Springbok Sandstone. Consistent with previous predictions, there is evidence of CSG impact 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-water balance factors.

10.4 Hutton Sandstone

The Hutton Sandstone underlies the Walloon Coal Measures in the Surat Basin, separated from the CSG reservoir by the intervening Durabilla Formation aquitard. Unlike the Springbok Sandstone, there are relatively few features (including faults and bores) which may act to enhance connectivity.

Within and adjacent to the outcrop areas, groundwater levels in the Hutton Sandstone are relatively stable and show a strong correlation with rainfall. In areas away from the outcrop areas and closer to the CSG fields, there is no obvious correlation with rainfall.

Declining groundwater level trends are observed in the Hutton Sandstone across the majority of the Surat CMA – close to outcrop and deeper within the basin, inside and outside CSG production areas, before and after the commencement of CSG groundwater extraction. Where declining trends are observed, these appear to correlate strongly with local non-CSG water use and rainfall events in some locations.

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 (Appendix A). 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.

Overall, the widespread declining groundwater level trends in available data correlate well with rainfall patterns, particularly in outcrop areas, and with non-CSG water use from 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 groundwater extraction in the overlying Walloon Coal Measures. Non-CSG water use in 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.

10.5 Condamine Alluvium

The Condamine Alluvium is a major water supply aquifer. As a result, in the southern central area of intensive development (south of Dalby and east of Cecil Plains), groundwater levels have been depressed by around 25 m since the 1960s. Over time, the trends in groundwater level have also been predominantly downward until about 2010, with some stabilisation in recent time.

Along the western flank of the Condamine Alluvium, in close proximity to areas of current CSG development, the trends in the Condamine Alluvium correlate reasonably well with longer-term dry and wet periods in the CDMMR as well as long-term non-CSG water use. In contrast, the trends in the underlying Walloon Coal Measures in the same area show clear declining trends that do not correlate with trends in the Condamine Alluvium, although the length of record is short. Consistent with previously reported findings, it is considered unlikely that the trends in the Condamine Alluvium are influenced by CSG groundwater extraction from the Walloon Coal Measures at this stage.

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Appendix A Sub-regional modelling

A.1 Objectives and purpose

A sub-regional numerical groundwater flow model was developed by OGIA in 2017 for a portion of the Eastern Surat hydrogeological assessment area. This area was selected as it included:

- the earliest CSG gas fields targeting the Walloon Coal Measures (i.e. Talinga)
- significant non-CSG water use from the Hutton Sandstone
- significant declining groundwater levels in the Hutton Sandstone
- available Hutton Sandstone monitoring data in the post-CSG commencement period
- uncertainty as to the potential for CSG development to affect the Hutton Sandstone.

Specifically, the objective of the model was to evaluate the potential for either CSG groundwater extraction or non-CSG water use to influence observed groundwater level responses.

A.2 Model geometry

The sub-regional model was an extract from the regional groundwater flow model prepared to support the UWIR 2016 (see OGIA 2016d). The model code used is MODFLOW-USG (Panday et al. 2017) and adopts the same 1,500×1,500-m cell size as the UWIR 2016 regional groundwater model. The extent of the sub-regional model is approximately 65 by 70 km (~ 4,500 km^2). The cell tops and bottoms for each layer are also adopted from the regional model.

The sub-regional model was reduced vertically to include only six layers: the lower Walloon Coal Measures, Durabilla Formation, upper Hutton Sandstone, lower Hutton Sandstone, Evergreen Formation and Precipice Sandstone.

The model grid and cells sizes are shown three-dimensionally in Figure A-1. The model contains 43 columns and 47 rows, for a total of 2,021 cells per layer and 12,126 active cells.

A.3 General head boundaries

The uppermost layer (lower Walloon Coal Measures) and entire bottommost layer (Precipice Sandstone) were established as General Head Boundary (GHB) conditions to essentially ‘force’ the head conditions present in the regional model for these layers. By forcing the head in these layers, the vertical flow system is honoured between these layers and the Hutton Sandstone (layers 3 and 4). In addition, GHB heads are established on the outer edges of the aquitards in layers 2 (Durabilla Formation) and 5 (Evergreen Formation) and for layers 3 and 4. By forcing the heads on the outer edges of the model in layers 3 and 4, the appropriate lateral flow conditions in the Hutton Sandstone and sub-regional head gradients are established.

These outer GHB heads were based on OGIA’s interpretation of pre-CSG (1995) mapped groundwater levels for the Hutton Sandstone. This combination of boundary conditions and layers establishes sufficient lateral and vertical flow constraints to allow prediction of heads in the Hutton Sandstone that factor both lateral flow within the formation and vertical exchange with immediately overlying (Walloon Coal Measures) and underlying (Precipice Sandstone) aquifers.

A.4 Model calibration

The model was calibrated in steady-state mode (to pre-CSG 1995 heads at selected Hutton Sandstone monitoring points) and in transient mode (to head changes in the Hutton Sandstone for a 21-year period). This transient calibration period was from January 1995 to December 2015, with 252 monthly stress periods adopted in this simulation.

The initial heads were derived from the coupled steady-state simulation, such that one model output provides the input for the second model. The GHB boundaries in layers 1 and 6 were varied monthly, based on the transient monthly outputs from the regional model, to reflect the changing head conditions in the Walloon Coal Measures and Precipice Sandstone. Importantly, the widespread depressurisation of the coal seams could be implemented, such that heads in layer 1 reduced in development areas through time (see Figure A-2 for spatial distribution of December 2015 depressurised heads in Layer 1).

The lateral GHBs in layers 2 to 5 were also varied temporally to allow for the gradual evolution of heads from an interpreted 1995 state to a 2015 state. Historical non-CSG water use from the Hutton Sandstone was simulated in this transient mode, using dedicated Connected Linear Node (CLN) boundary conditions that allow pumping from multiple layers in each well. The CLN boundary condition also enforces restriction of flow to the well as head conditions reduce in the well, providing for numerical stability and avoiding unnecessary over-pumping of the aquifer when heads don't support continued flux to the well.

A.5 Simulations

Three separate calibration simulations were established to align with the three hypotheses for groundwater level trends in the Hutton Sandstone:

1. A 'CSG-only' case with CSG stresses only – layer 1 GHB heads are adjusted to represent CSG activity. Non-CSG water use in the Hutton Sandstone is not simulated.
2. A 'non-CSG water use' case with non-CSG water use stresses in layers 3 and 4 only – layer 1 GHB heads reflect 1995 pre-CSG heads (i.e. no CSG activity simulated) and therefore non-CSG water use in the Hutton Sandstone represents the main extraction stress.
3. A 'base' case with both CSG and non-CSG stresses operating concurrently.

Each model was calibrated using the model-independent PEST software. For this model, PEST used calibration targets for both steady-state Hutton Sandstone heads and changing Hutton Sandstone heads during the transient simulation. PEST employed pilot points in combination with geostatistics (kriging) to optimise horizontal and vertical hydraulic conductivity and specific storage properties for each model layer.

PEST fundamentally seeks to produce the best match between measured and modelled heads by iteratively adjusting material properties within specified bounds and rating the performance of the calibration match using a global objective function, which it strives to minimise. PEST will sometimes run hundreds or thousands of iterations until an optimal calibration is achieved. This process of automated calibration is a powerful tool to interrogate the adequacy of the conceptual model, as it explores parameter uncertainty and provides feedback on whether the conceptual understanding of parameter fields can actually result in modelled groundwater levels that closely reflect reality. Used properly, errors in the conceptual model that are often critical are identified by PEST during the calibration process.

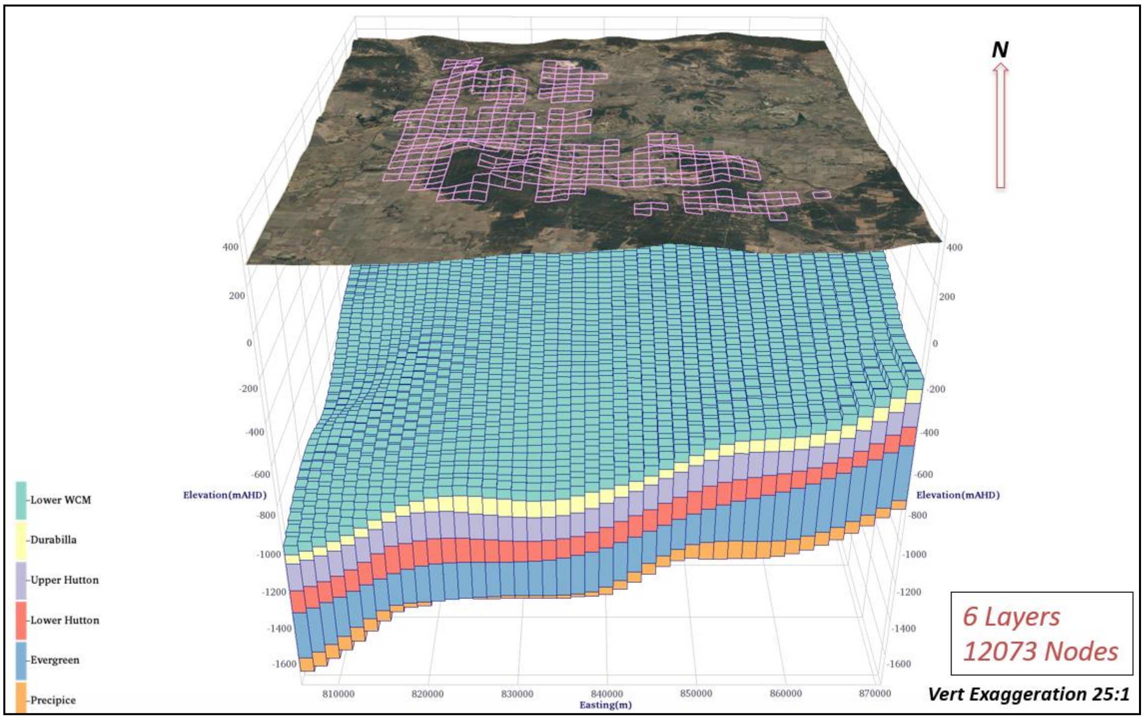


Figure A-1 Three-dimensional perspective of the numerical model grid looking south to north

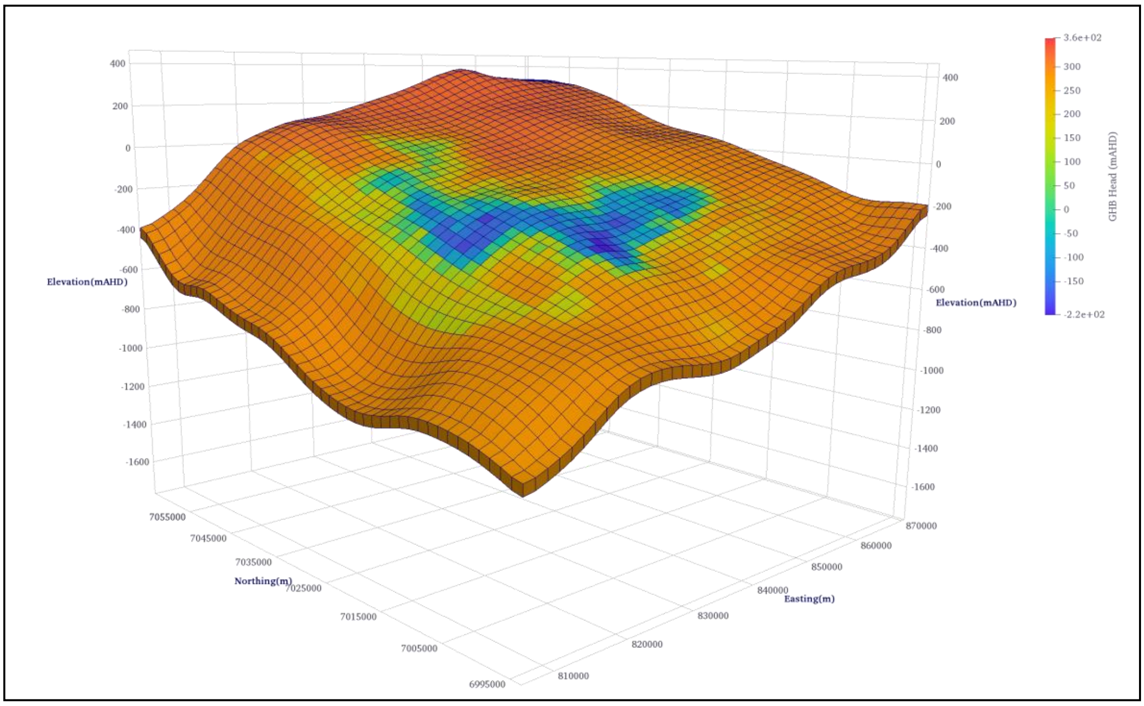


Figure A-2 Depressurised heads in model layer 1 (lower Walloon Coal Measures) at December 2015 as enforced by GHB conditions across every cell of the layer

A.6 Results and discussion

In terms of interpreting the mechanisms for observed groundwater level trends in the Hutton Sandstone, the key results for each of the three calibrated models are discussed in terms of two parameters:

- Hydraulic properties:
    - Hutton Sandstone Kh for the non-CSG water use case (compared to the base case)
    - Durabilla Formation Kv for the CSG-only case and base case (compared to the non-CSG water use case).
- Hydraulic heads:
    - The modelled Hutton Sandstone heads in steady-state
    - The change in Hutton Sandstone heads during transient simulation (all three cases).

For the non-CSG water use case, to reproduce the observed groundwater level trends, the Hutton Sandstone Kh must be sufficiently high to enable radial propagation of within-aquifer drawdown. In this case, the drawdown must result entirely from non-CSG water use and therefore drawdown is required to propagate tens of kilometres from the larger extraction points, situated along the Condamine River valley, to monitoring points north and south of the river.

Table A-1 presents the calibrated Kh statistics for the Hutton Sandstone layers in the base case and non-CSG water use case. The zones of transmissivity of the Hutton Sandstone (a function of Kh multiplied by saturated thickness) that will largely control propagation of drawdown are likely to be best represented by the higher percentiles, rather than the lower percentiles. For this reason, the central tendency values, the P95 and the maximum have been highlighted in bold in Table A-1 to draw attention to these values (with additional purple shading applied to the base case and blue shading applied to the non-CSG water use case).

When comparing these two cases, it is evident that the median and mean are similar for both the upper and lower Hutton Sandstone layers. Interestingly, the base case tends to have higher Kh values for the upper Hutton Sandstone at the P95 and maximum values, which is not immediately intuitive, as it would be expected that the non-CSG water use case would require more transmissive Hutton Sandstone to promote internal drawdown within this layer.

For both cases, the Kh statistics are noticeably reduced when compared to the field-derived test pumping Kh statistics for this formation (see section 8.1.2). For comparison, 35 pumping tests completed in the upper Hutton Sandstone across the basin yielded a median Kh of 0.64 m/day, a P75 of 5.8 m/day and a maximum of 174 m/day. Based on this comparison, it appears that PEST has probably not sufficiently increased the transmissivity of the upper Hutton Sandstone for the non-CSG water use case, which may limit the lateral propagation of drawdown.

Table A-1 Calibrated Kh statistics, Hutton Sandstone layers, base case and non-CSG case

Model layer	Model case	Hydraulic property (units)	Minimum	P5	Median	Mean	P95	Maximum
Upper Hutton Sandstone	Base	Kh (m/day)	4.56E-04	2.40E-03	**7.09E-03**	**1.41E-02**	**4.15E-02**	**7.41E-01**
Lower Hutton Sandstone	Base	Kh (m/day)	1.54E-04	8.69E-04	**1.45E-03**	**1.62E-03**	**2.27E-03**	**6.04E-02**
Upper Hutton Sandstone	Non-CSG	Kh (m/day)	1.43E-04	3.18E-03	**7.37E-03**	**9.67E-03**	**2.09E-02**	**2.98E-01**
Lower Hutton Sandstone	Non-CSG	Kh (m/day)	3.55E-04	9.29E-04	**1.51E-03**	**1.84E-03**	**2.19E-03**	**1.79E-01**

The Durabilla Formation aquitard separates the Walloon Coal Measures from the Hutton Sandstone. Its vertical hydraulic conductivity (Kv) and thickness will dictate how readily groundwater will flow upwards from the Hutton Sandstone into the overlying depressurised coal seams, assuming a sufficient hydraulic gradient. As the thickness is constant between the three model cases, the variable that controls the difference in vertical flow is the Kv of the intervening Durabilla Formation.

The Durabilla Formation Kv statistics for all three model cases are presented in Table A-2. As with the previous table, the most relevant statistics are the higher Kv percentiles, reflecting more permeable aquitard zones that will allow more rapid Hutton Sandstone vertical fluxes towards the reservoir. These more relevant statistics are highlighted in bold and shaded purple (base and CSG cases) and blue (non-CSG water use case).

Table A-2 Calibrated Kv statistics, Durabilla Formation layer, all model cases

Model layer	Model case	Hydraulic property (units)	Minimum	P5	Median	Mean	P95	Maximum
Durabilla Formation	Base	Kv (m/day)	1.04E-08	3.73E-08	8.08E-08	**1.58E-06**	**2.59E-07**	**1.00E-03**
Durabilla Formation	CSG	Kv (m/day)	1.04E-08	3.15E-08	7.43E-08	**1.96E-06**	**2.68E-07**	**1.00E-03**
Durabilla Formation	Non-CSG	Kv (m/day)	1.26E-08	3.11E-08	8.24E-08	**1.11E-07**	**2.70E-07**	**3.51E-06**

In addition, Figure A-3 presents a three-dimensional image of the Durabilla Formation Kv field for the CSG-only case. Together, Figure A-3 and Figure A-4 show that in order to produce the necessary drawdown in the Hutton Sandstone at TAL-MB003 and CON-MB009, the Durabilla Kv must be locally increased to approach the maximum threshold of 1.0E-03 m/day.

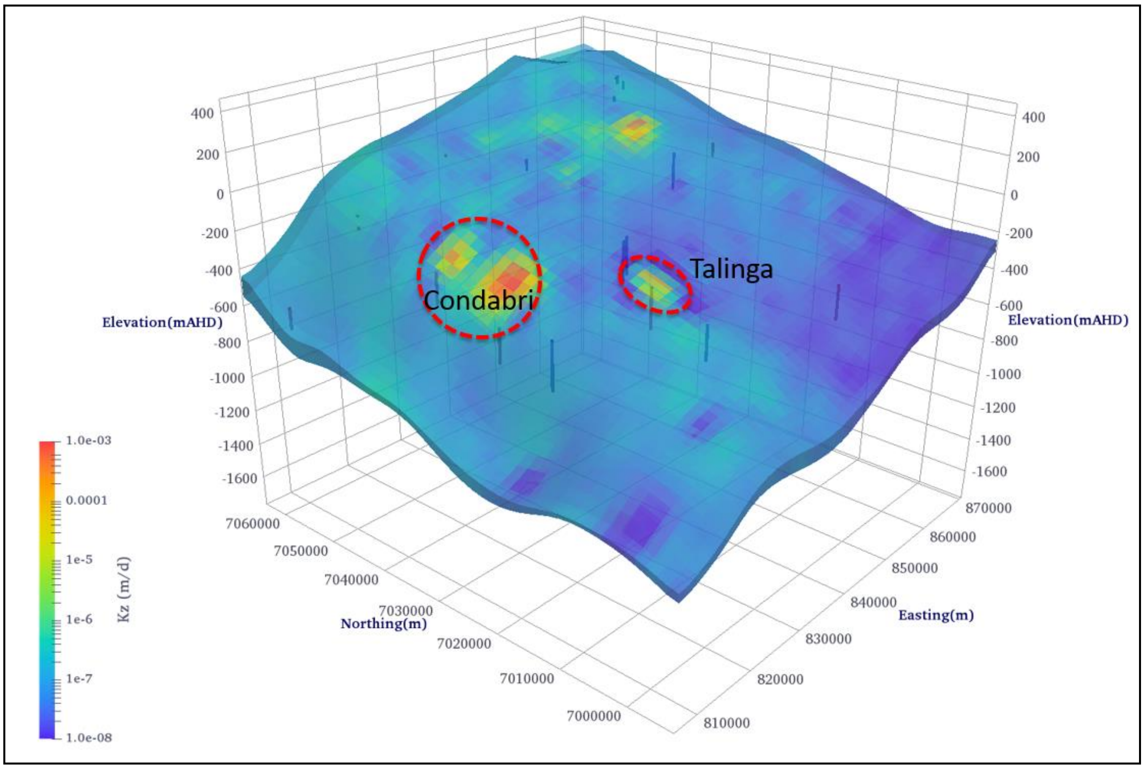


Figure A-3 Calibrated Kv field, model layer 2 (Durabilla Formation), CSG-only case

Red ellipses in this figure highlight areas where Durabilla Formation Kv values approach the 1.0E-03 m/day maximum threshold – a value that is five orders of magnitude higher than the median Kv for that same layer and four orders higher than the P95 value. Of note, the maximum Kv value in the non-CSG water use case is 3.51E-06 m/day, which is three orders of magnitude lower in the area of TAL-MB003 and CON-MB009 in the base and CSG cases. PEST has created these localised structures in the Durabilla Formation at these locations to enable the necessary drawdown to replicate the observed groundwater levels trends at the TAL-MB003 and CON-MB009 monitoring points.

Hydrographs of the simulated drawdowns for each model case are shown in Figure A-4, with the locations of each of these monitoring points shown in Figure A-5. All three model cases are able to replicate the necessary drawdown at TAL-MB003 and CON-INJ001.

The far-field drawdowns are less accurate for the non-CSG water use case, suggesting that either the GHB boundary conditions are influencing model predictions on the edges of the model, or the upper Hutton Sandstone Kh is generally too low in the non-CSG water use case. Regardless, the modelling shows that both CSG and non-CSG stresses are capable of producing the observed drawdowns in the Hutton Sandstone. In order to do so, the base case and CSG-only case require highly localised, high Kv structures directly adjacent to the monitoring points.

These theoretical features are not pervasive; if they were, drawdowns similar to TAL-MB003 would be observed everywhere in the model layer.

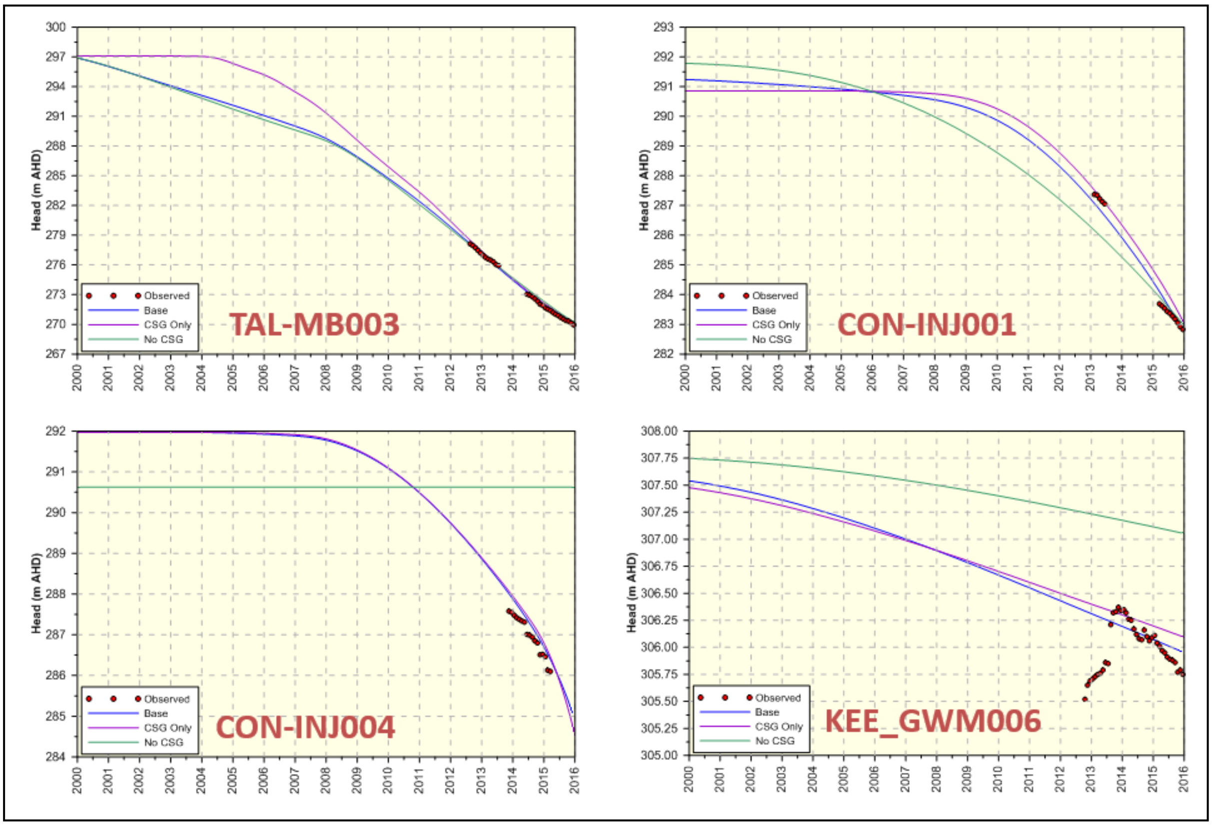


Figure A-4 Simulated drawdown, selected Hutton Sandstone monitoring points, all model cases

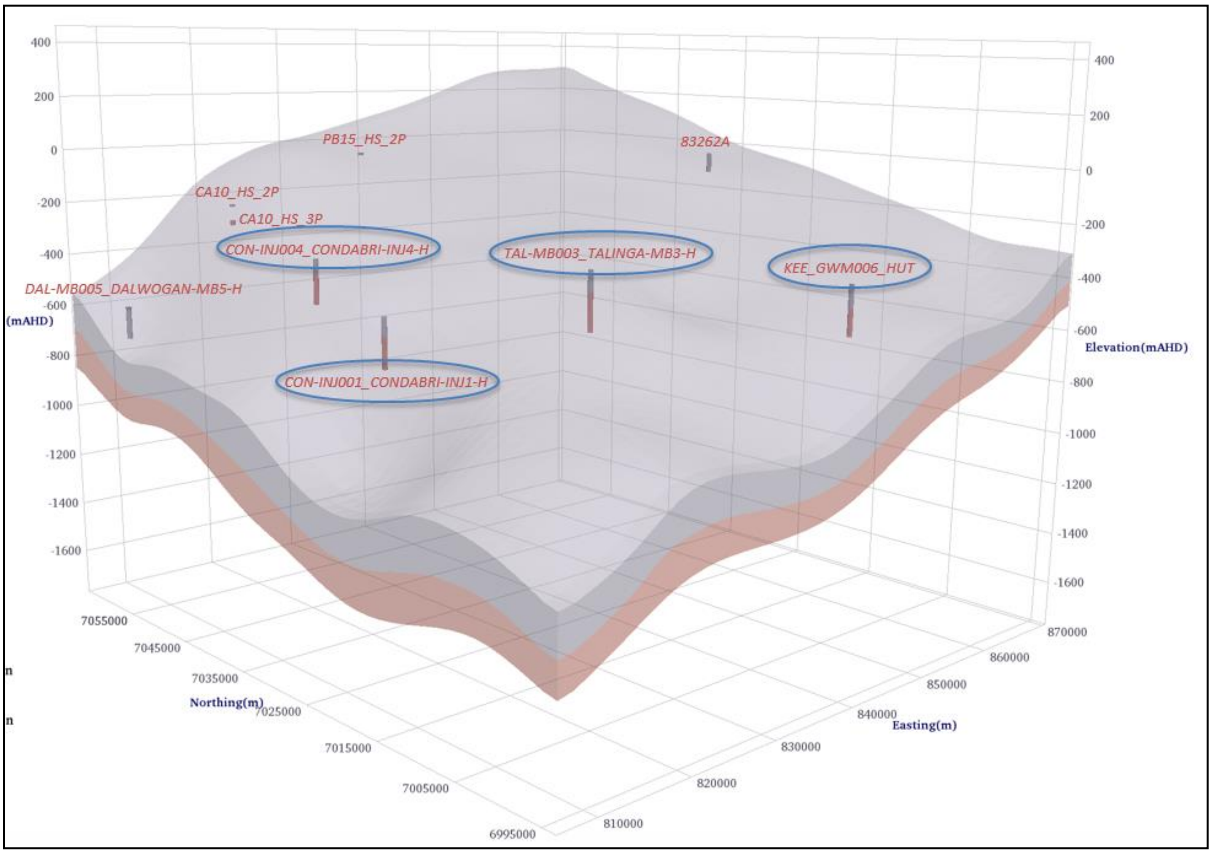


Figure A-5 Hutton Sandstone monitoring point locations within model layers 3 and 4; circled monitoring points are featured in Figure A-4

Therefore, overall it is unlikely that Hutton Sandstone drawdowns in the Eastern Surat can be solely caused by CSG impacts, unless there are highly localised connectivity features that bypass the low formation-scale Kv of the Durabilla Formation aquitard – this contradicts findings from investigations i.e. there are very few connectivity features in this area.

It is also evident that non-CSG water use is capable of solely producing the observed Hutton Sandstone drawdown, assuming there is a high degree of connectivity within the upper Hutton Sandstone and the effective Kh of the formation is sufficiently high. The Kh needs to be higher than what has been modelled in the non-CSG water use case to ensure both near-field (e.g. Talinga) and far-field (e.g. Kenya East) drawdown responses.

Appendix B Springbok Sandstone groundwater level trends

B.1 Observed trends in CSG areas

In this appendix, the groundwater level data have been processed so that each individual monitoring point commences at a zero metres groundwater level datum and subsequent changes in groundwater levels are plotted as cumulative deviation from that zero datum. This allows for transparent comparison of each individual monitoring point and simplifies detection of rising and falling trends and trend rates.

The following six figures present group plots of groundwater levels and groundwater level trends for each of the three sub-regional areas.

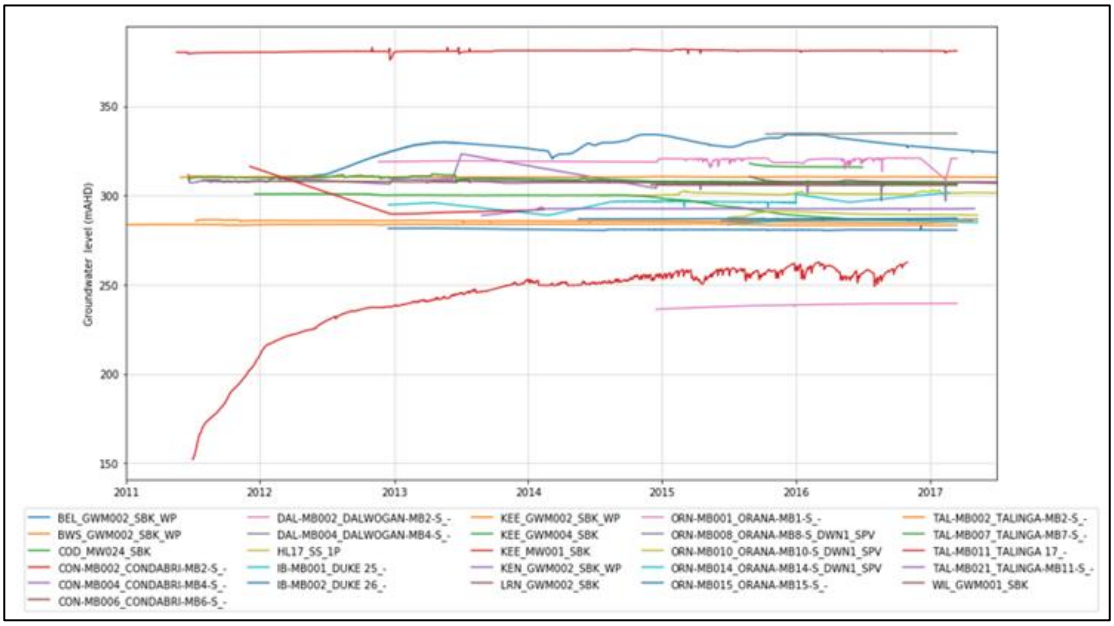


Figure B-1 Springbok Sandstone groundwater levels – Eastern Surat

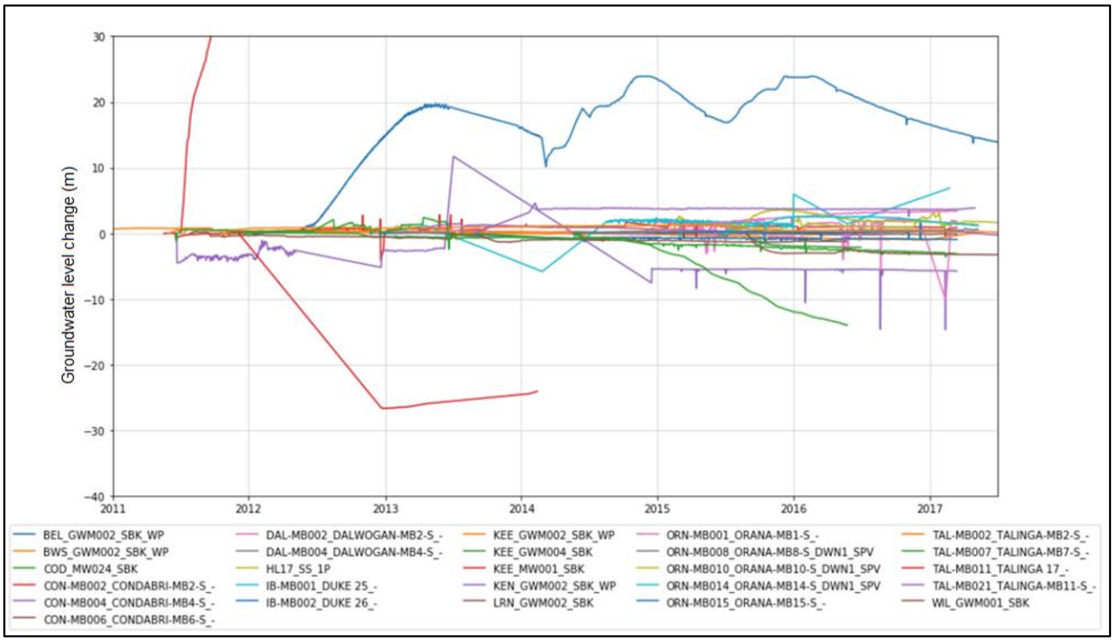


Figure B-2 Springbok Sandstone groundwater levels – Eastern Surat

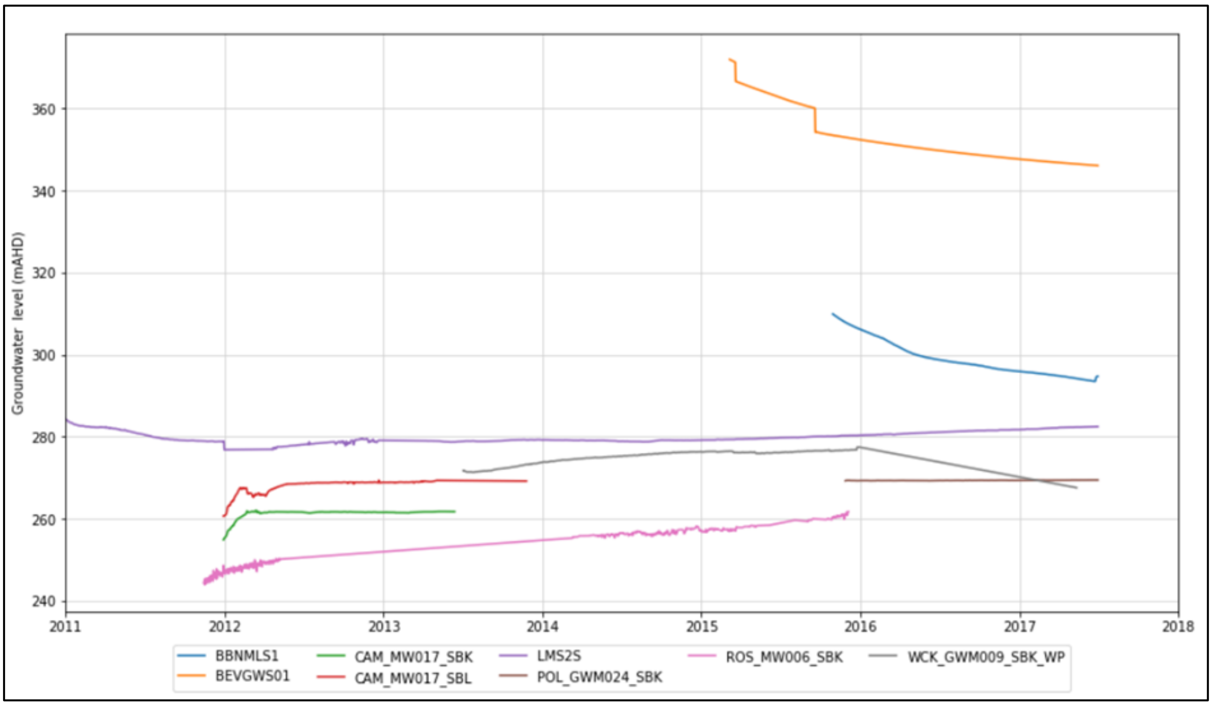


Figure B-3 Springbok Sandstone groundwater levels – Northern Surat

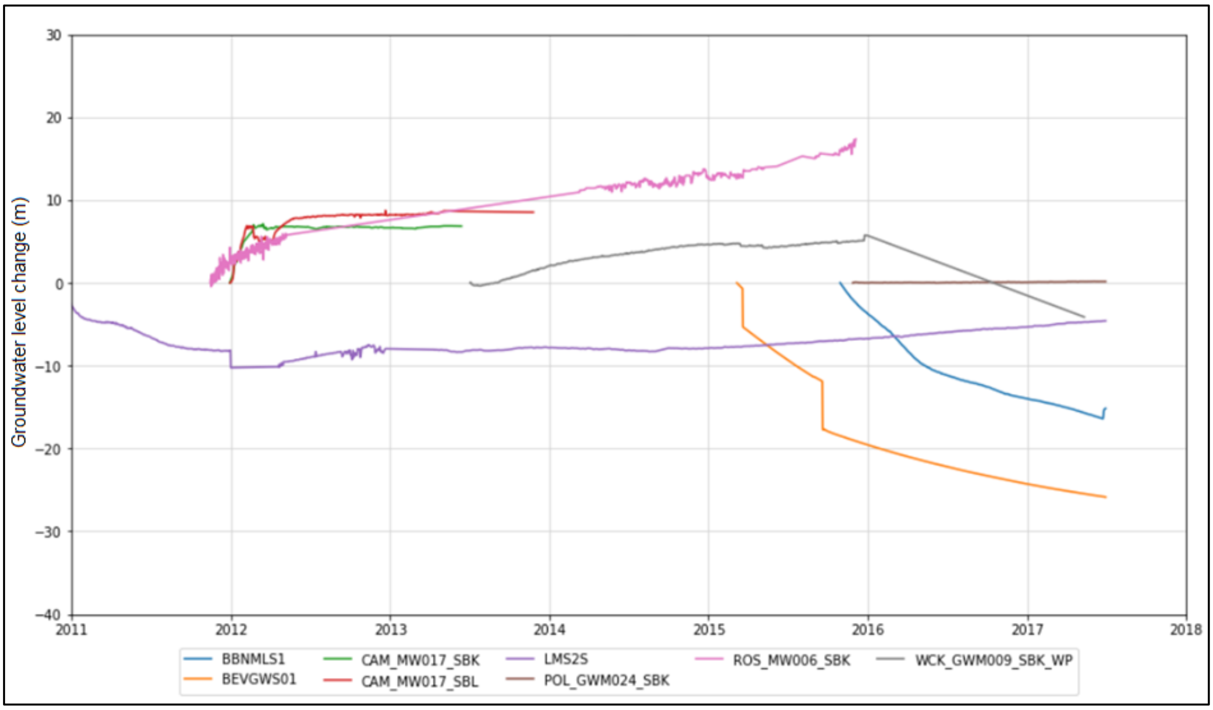


Figure B-4 Springbok Sandstone groundwater levels – Northern Surat

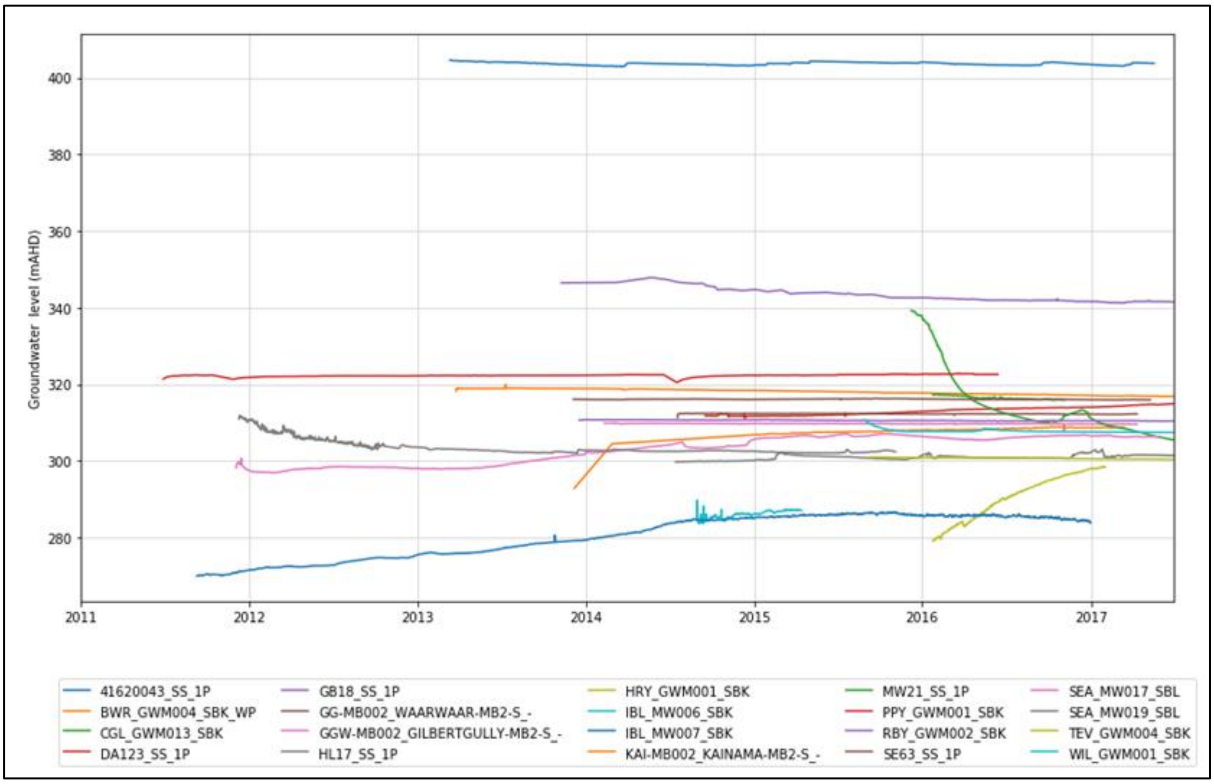


Figure B-5 Springbok Sandstone groundwater levels – South-eastern Surat

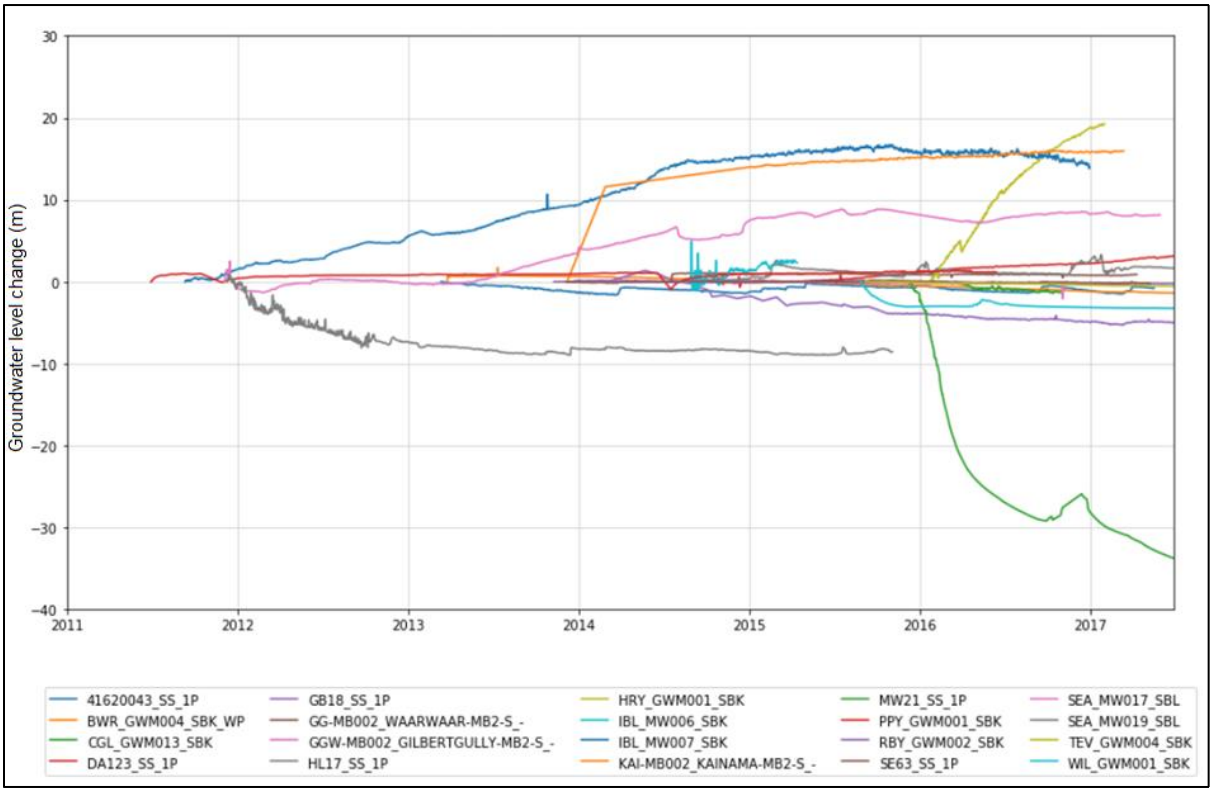


Figure B-6 Springbok Sandstone groundwater levels – South-eastern Surat

B.1.1 Inside CSG production areas

The Springbok Sandstone groundwater level trends inside operating CSG fields in the three hydrogeological assessment areas are plotted in Figure B-7. It is apparent from this plot that Springbok Sandstone groundwater level trends are highly variable since 2011.

Increasing groundwater levels are common trends observed in all three areas, up to a maximum of 25 m rise as observed at BEL_GWM002 in the Eastern Surat. As noted in chapter 7, a number of Springbok Sandstone observation points in recharge areas, situated well away from CSG development, have rapidly recovering groundwater levels post-2010. This sudden rise in levels correlates with a significant decade-scale rainfall event in late 2010 that triggered a large volume recharge event, which effectively 'reset' the aquifer storage after decades of storage depletion. It is therefore plausible that the December 2010 recharge signal may propagate deeper into the basin over a period of several years and subsequently lead to rising groundwater levels, as observed in Figure B-7. Further to this, most of the rising groundwater level sites are situated closer to outcrop (where recharge occurs) than the sites recording declining trends or no trend. Continued monitoring is necessary to better evaluate whether these increasing levels are in response to recharge or whether some other mechanism is responsible, such as gas migration up-dip of CSG development.

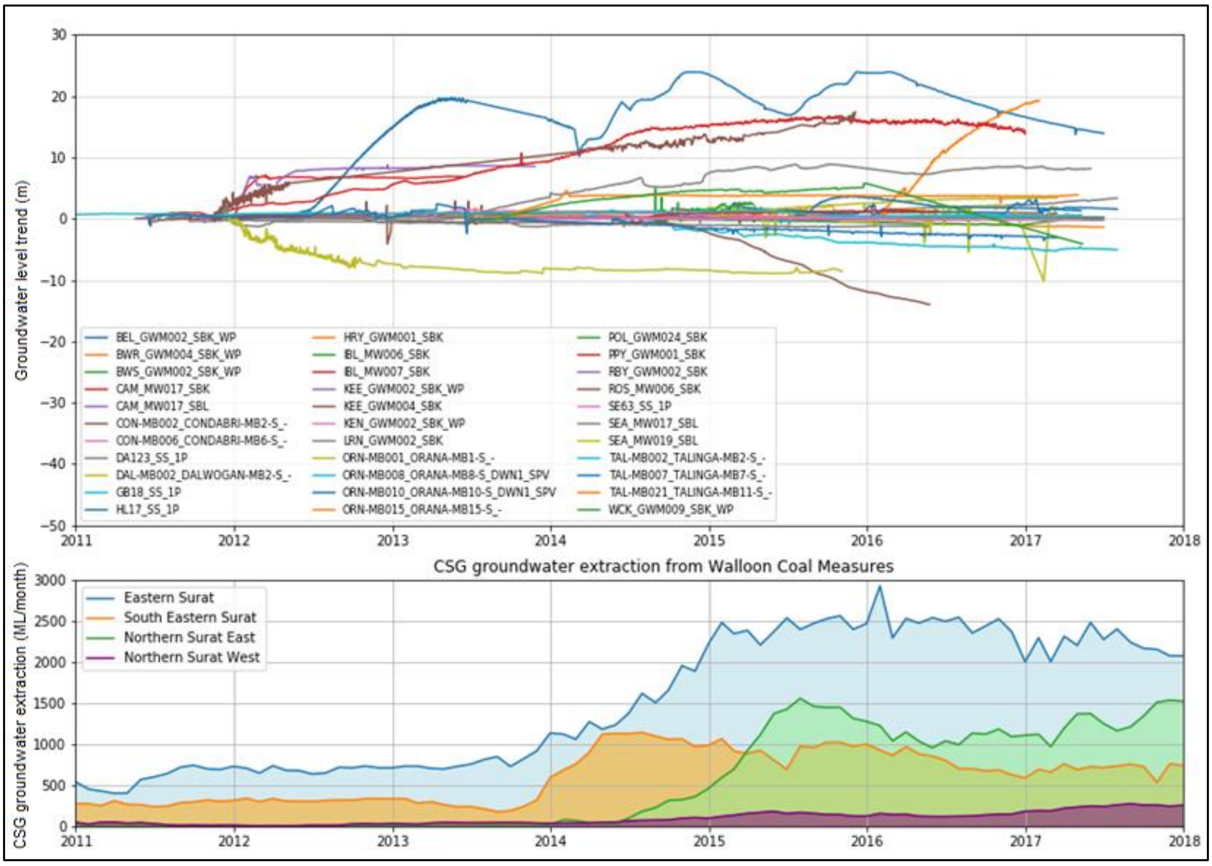


Figure B-7 Springbok Sandstone groundwater levels and CSG groundwater extraction within operating CSG areas

There are also a number of decreasing groundwater levels observed in the Springbok Sandstone within CSG development areas. KEE_GWM004, situated in the Kenya East gas field in the Eastern Surat, has been recognised as a site that is likely to be impacted by CSG development. Prior to 2014, the groundwater levels at this site are stable, and the sudden drawdown is commensurate with the onset of localised CSG depressurisation. More than 13 m of drawdown has been observed at this site, at a rate of decline of approximately 6.75 m/year. Interestingly, KEE-GWM002, situated less than 2 km away, shows no apparent drawdown over the same period – although this monitoring point is situated in the upper Springbok Sandstone, whereas KEE-GWM004 is 60 m deeper in the lower Springbok Sandstone. This disparity in trends over such a small distance suggests that impacts in the Springbok Sandstone at this location are currently localised in the lower Springbok Sandstone.

B.1.2 Outside CSG production areas

The Springbok Sandstone groundwater level trends outside operating CSG fields in the three hydrogeological assessment areas are plotted in Figure B-8. A comparison between Figure B-7 and Figure B-8 shows consistent Springbok Sandstone groundwater level trends both inside and outside of CSG production: generally subtle background increasing and decreasing trends, with a few instances of larger rates of decline and increase that suggest localised impacts.

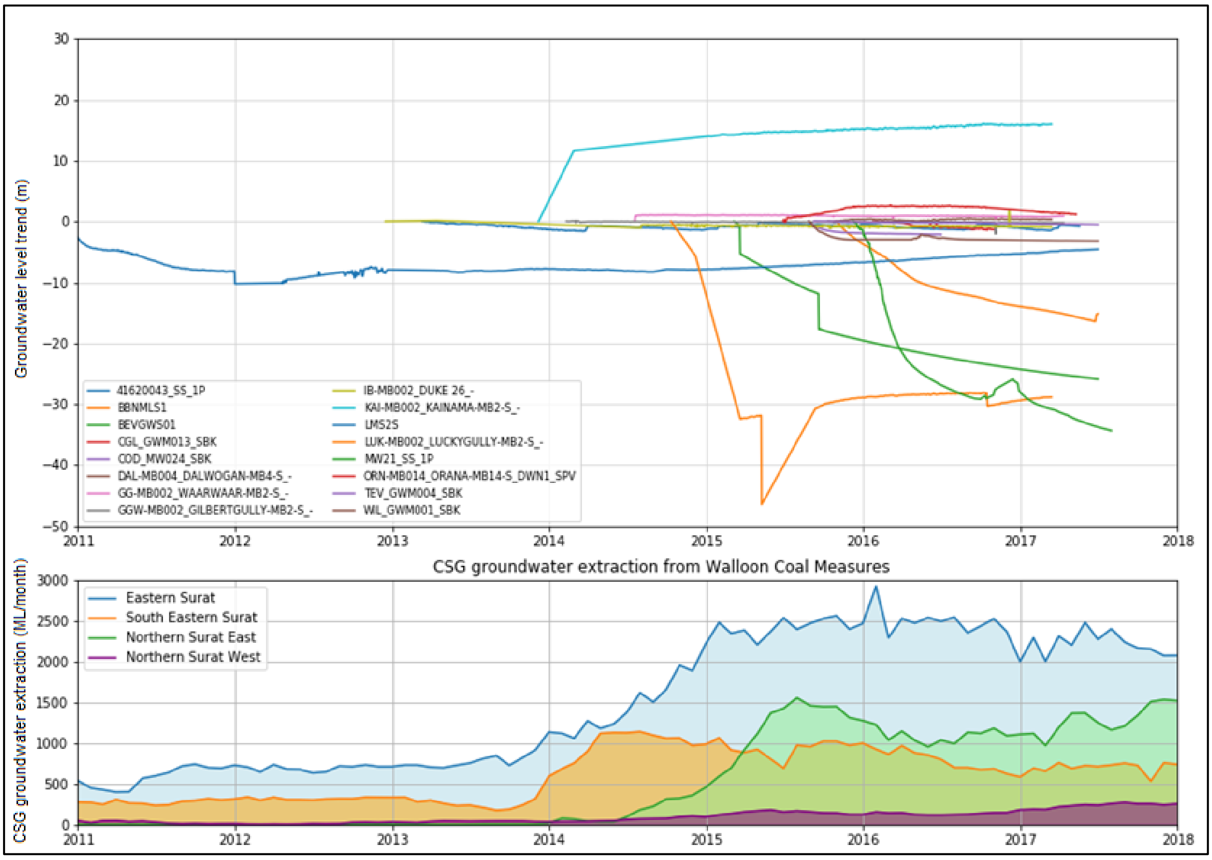


Figure B-8 Springbok Sandstone groundwater levels outside operating CSG areas

In the South-eastern Surat, most sites have subtle (i.e. < 5 m total groundwater level change) increasing and decreasing trends, with two exceptions where trend rates are more substantial. The first, Kainama-MB2-S, shows progressively rising groundwater levels since 2014 with more than 15 m of increase over a three-year period. The second is MW21_SS_1P, which shows sudden drawdown in early 2016, with more than 30 m of decline by mid-2017.

In the Northern Surat, although most of the sites have increasing trends, three sites have recorded large drawdowns in recent years. In the western sub-area between Thornhill and Wallumbilla, two sites – Binbinette (BBNMLS1) and Beverley GW bore (BEVGWS01) – show large drawdowns. Binbinette has a total observed drawdown of 16 m with a declining trend rate of 8.8 m/year, while Beverley GW bore has a total observed drawdown of 13 m with a declining trend rate of 8.2 m/year. In the eastern sub-area, a third site (LUK-MB002-S) also shows a large drawdown, however, this is likely associated with a post-drilling period of equilibration to formation pressures. Following this early period of equilibration, the monitoring point is now in a slow period of recovery, with occasional instances of localised pumping impacts in mid-2015 and late 2016.

Appendix C Springbok Sandstone correlation analyses

C.1 Correlation with rainfall

C.1.1 Shallow outcrop and subcrop areas

For this assessment, three outcrop monitoring sites (locations previously shown on Figure 7-7) have been selected to undertake more detailed correlation analysis with nearby rainfall trends, to gain an appreciation of potential recharge influences on shallow groundwater level trends. Each hydrograph has been correlated with the CDMMR from a nearby weather station, using the Spearman rank correlation method.

Figure C-1 presents a hydrograph for RN107698A, an existing water supply bore situated in outcrop in the Eastern Surat and the Chinchilla weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, resampled at monthly intervals. The bore shows approximately 13 m of decline between separate readings in 2001 and late 2008. This period of decline coincides with an extended dry period, where below-average rainfall conditions persisted. However, there are too few data points to confidently confirm this trend. In early 2011, the groundwater levels commence a two-metre recovery that coincides with above-average rainfall conditions, as shown by 0.65 positive correlation. Confidence in the trend over this post-2010 period is higher, as there are more data points.

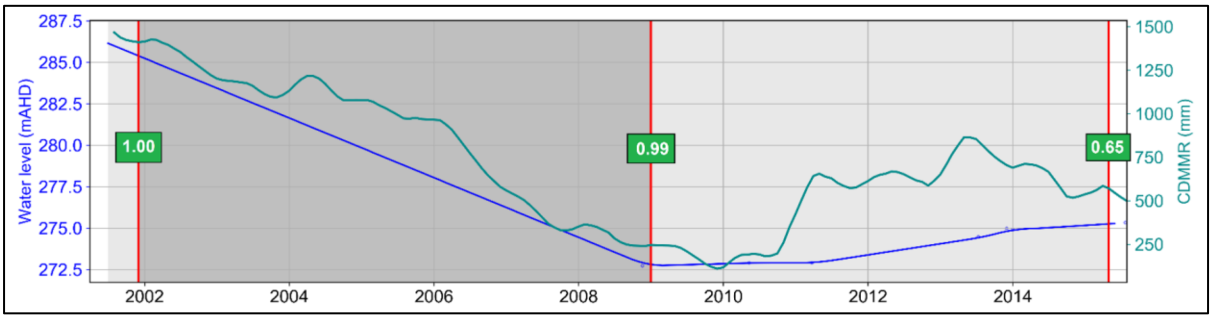


Figure C-1 Spearman correlation, RN107698A groundwater level and Chinchilla weather station CDMMR

Figure C-2 presents a hydrograph for Daandine 123 SS (RN160347E), an upper Springbok Sandstone monitoring point situated at the Daandine gas field in the South-eastern Surat, and the Condamine Plains weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, resampled at monthly intervals. This monitoring site shows a monotonic rising trend of approximately four metres over three years. The correlation coefficient erratically shifts between positive and negative numbers, with no apparent hydrogeological correlation.

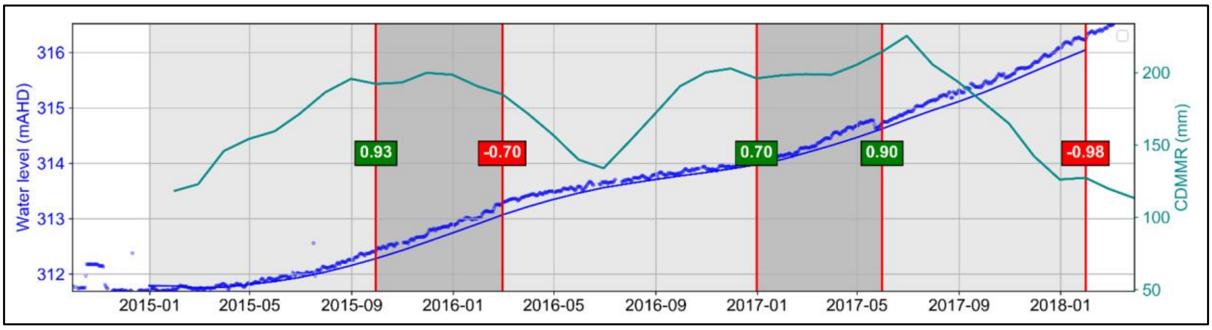


Figure C-2 Spearman correlation, RN160347E (Daandine 123 SS) groundwater level and Condamine Plains weather station CDMMR

C.1.2 Confined basin interior

As described in section 4.2.1.1, it is expected that groundwater levels in deeper confined areas will show either a muted or no response to periods of above-average and below-average rainfall. As further described in section 7.2.2, there is an even mix of rising, falling and no trends for the post-2010 period. Of the falling trends, only three have pronounced inflection points in drawdown that identify the onset of impact. One of these three sites, Kenya East GW4, is used as an example site.

As mentioned in section 7.3.1, Kenya East GW2 (upper Springbok Sandstone) is situated approximately 2 km from Kenya East GW4 (lower Springbok Sandstone) but shows no apparent and sustained drawdown response over the same period of monitoring. Kenya East GW4 is a good example of the fluctuating 'no trend' that is seen at around 26% of sites.

Gilbert Gully MB2-S is a lower Springbok Sandstone monitoring site in the South-eastern Surat that, despite being situated some distance from current CSG development areas, shows a declining groundwater level trend.

Figure C-3 presents a hydrograph for Kenya East GW2 (RN160519A), an upper Springbok Sandstone monitoring point located in the Kenya East gas field, and the Chinchilla weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, resampled at monthly intervals. This monitoring site shows very subtle fluctuating trends of ~0.1 m/year, with no apparent monotonic rising or falling trend. Although this site shows a reasonably good positive correlation with rainfall in the period after 2016, there is a near-inverse correlation in the four years prior. There may be a time lag in the recharge response here, such that the peak in CDMMR in early 2013 presents in the hydrograph in early 2015. However, at this point in time, there seems to be little value in further exploring this possible delayed recharge response until more monitoring data are available at this site.

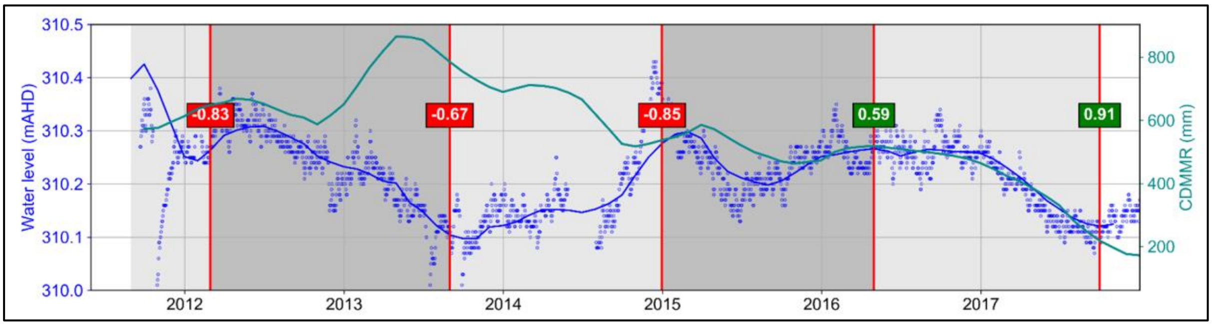


Figure C-3 Spearman correlation, RN160519A (Kenya East GW2) groundwater level and Chinchilla weather station CDMMR

Figure C-4 presents a hydrograph for Gilbert Gully MB2-S (RN160728A), a lower Springbok Sandstone monitoring point in the southern regions of the South-eastern Surat, and the Cecil Plains weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, resampled at monthly intervals. Once the noise is removed from the groundwater level signal, this monitoring point shows very subtle declining trends. There is a very erratic correlation with rainfall across each of the breakpoint time periods, making meaningful interpretation difficult over this short time period. Overall, however, there is not a pervasive declining rainfall trend that might explain the subtle decreasing groundwater level trend.

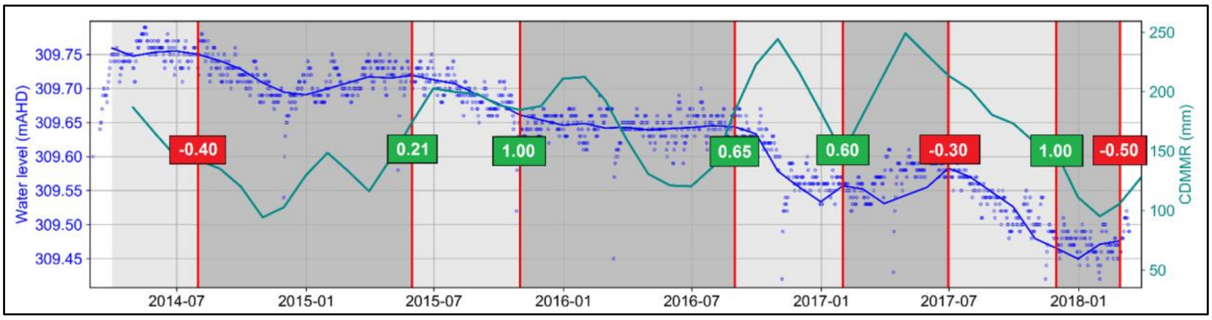


Figure C-4 Spearman correlation, RN160728A (Gilbert Gully MB2-S) groundwater level and Cecil Plains weather station CDMMR

C.2 Correlation with non-CSG water use

Table C-1 lists the current non-CSG water use for the Springbok Sandstone across the Surat CMA (OGIA 2019b) and the Hutton Sandstone estimates of water use for context, given that the Hutton Sandstone is a major water supply aquifer in the GAB. Comparing the two formations, it is evident that the Springbok Sandstone has far fewer bores and that most are for minor stock and domestic (S&D) purposes. The total estimated groundwater extraction of 515 ML/year makes up ~1% of the cumulative estimated water (40,781 ML/year) extracted from all of the collective GAB formations in the Surat CMA. This ranks the Springbok Sandstone as the ninth aquifer formation out of ten in the GAB, in terms of total estimated water supply volume for non-CSG purposes. Only those formations that are classified as aquitards (Wallumbilla, Durabilla, and Moolayember formations) or are spatially limited aquifers (i.e. the Boxvale Sanstone Member) produce less water each year.

Table C-1 Estimated current water use, Springbok Sandstone and Hutton Sandstone (after OGIA 2019b)

Formation	Number of bores			Groundwater use (ML/year)		
	Non-S&D	S&D	Total	Non-S&D	S&D	Total
Springbok Sandstone	13	194	**207**	150	364	**514**
Hutton Sandstone	348	2,697	**3,045**	10,159	3,596	**13,755**

Figure C-5 also shows the temporal growth in the number of bores and estimated water use volumes since 1970. The estimated “average” profile, which includes metered data, shows a slow reduction in water use from ~1,000 ML/year in 1970 to ~400 ML/year in 1996. The large reduction in water use in 1995 is related to the capping of an uncontrolled artesian bore (RN 2822). Non-CSG water use stresses have been present since before the 1970s and have slowly increased.

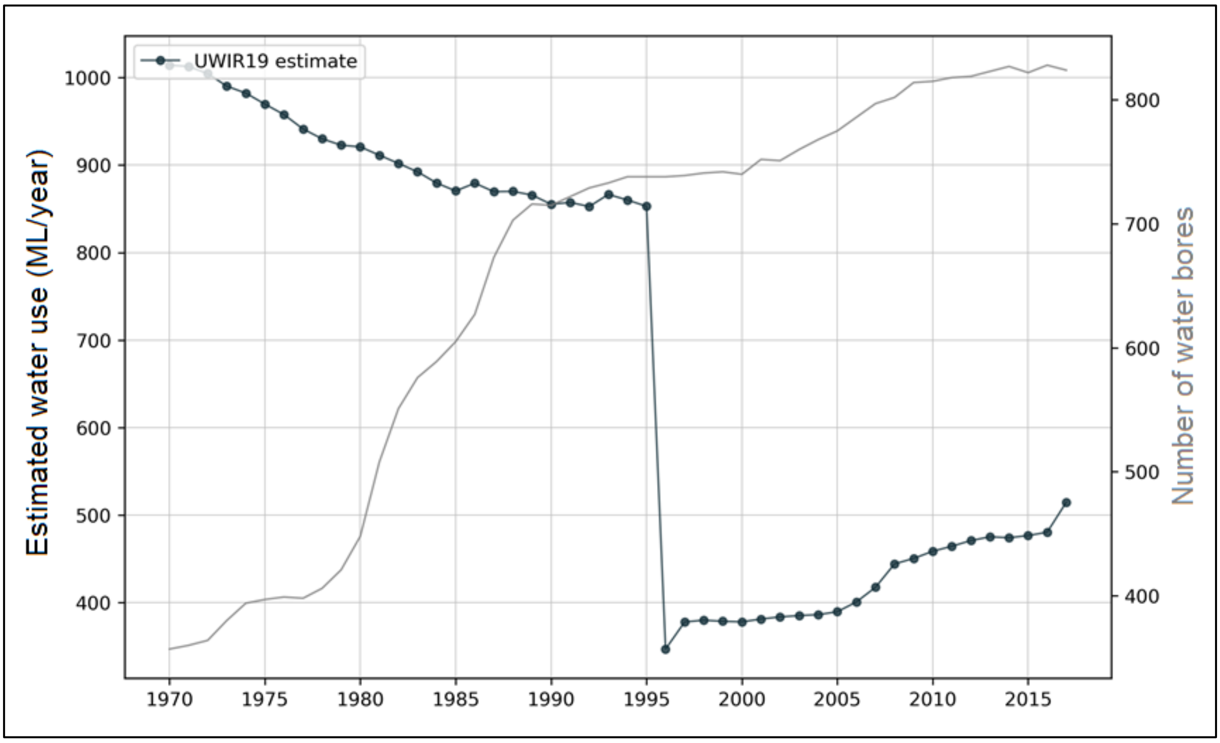


Figure C-5 Temporal water use estimate – Springbok Sandstone (after OGIA 2019b)

C.2.1 Shallow outcrop and subcrop areas

The three representative outcrop and subcrop monitoring sites described in section 7.3.1 are again subjected to Spearman correlation analysis, however in this section, each groundwater level time series is correlated with estimates of non-CSG water use. A radial search function within Python is implemented to cumulatively add the total extraction volumes per annum for every water supply bore within the specified 25-km radius. As these water use estimates are at an annual resolution, the correlation is temporally coarser than the monthly correlation with CDMMR described in the previous section. This is particularly influential for short time series.

In all instances, the non-CSG water use predates the monitoring record (prior to the 1960s), which emphasises the long-term water budget influence of non-CSG water use in the GAB. This is the case even for the Springbok Sandstone, which is one of the least used aquifers in the basin. It is not possible to determine a true background groundwater level trend without first de-trending non-CSG water use from the groundwater level record. For this analysis, however, de-trending was not undertaken, as an accurate climate model and measured non-CSG water use records are not available to underpin meaningful analysis. Very few bores outside of the Condamine Alluvium groundwater system are metered and therefore there is considerable uncertainty in these estimates. Given this limitation in the input datasets, the correlation analyses has a comparatively lower confidence than the measured CSG groundwater extractions (section 7.1.5).

Figure C-6 presents the hydrograph for Daandine 123 SS (RN160347E) compared with the cumulative annual non-CSG water use within 25 km of that site. In this case, a continuous increasing non-CSG water use trend perfectly correlates with a monotonic groundwater level rise. There is no plausible explanation whereby increased groundwater extraction leads to increased groundwater levels in a single-phase groundwater flow system. It therefore seems unlikely that non-CSG water use can explain these rising trends.

Figure C-6 Spearman correlation, RN160347E (Daandine 123 SS) groundwater level and non-CSG water use from the Springbok Sandstone within 25 km

C.2.2 Confined basin interior

Figure C-7 presents the hydrograph for Kenya East GW2 (RN160519A) compared with the annual non-CSG water use within 25 km of that site. The cumulative non-CSG water use trend from 73 nearby water supply bores indicates a very slight sustained increase over the period of monitoring. As the groundwater level subtly increases or decreases, the correlation coefficient erratically switches between positive and negative values and, overall, indicates that it is not having a consistent influence on the groundwater level.

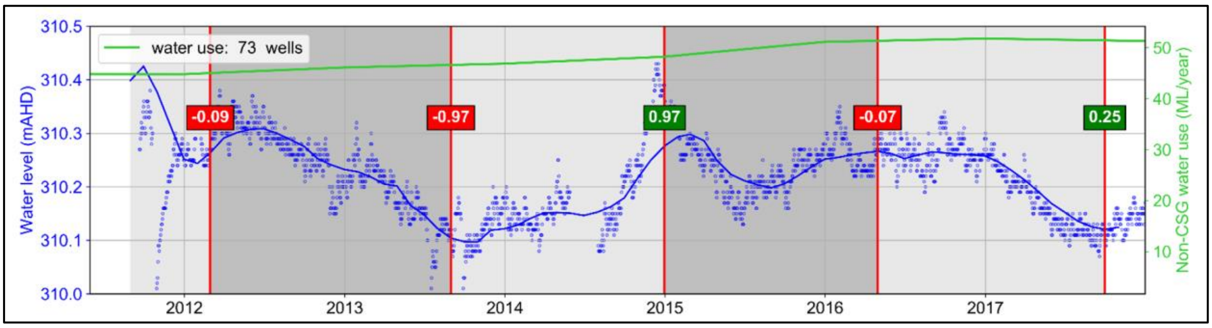


Figure C-7 Spearman correlation, Kenya East GW2 (RN160519A) groundwater level and non-CSG water use from the Springbok Sandstone within 25 km

Figure C-8 presents the hydrograph for Gilbert Gully MB2-S (RN160728A) compared with the cumulative annual non-CSG water use within 25 km of that site. At this location in the South-eastern Surat, there are six water supply wells with a cumulative extraction of around 40 ML/year, with this stress predating groundwater level monitoring. The correlation coefficient irregularly switches between positive and negative values, reflecting the subtle rising and falling groundwater level trends within an overall declining trend. A wider rolling mean may allow for a better correlation. From a water budget perspective, the overall declining trend can plausibly be explained by sustained long-term non-CSG water use.

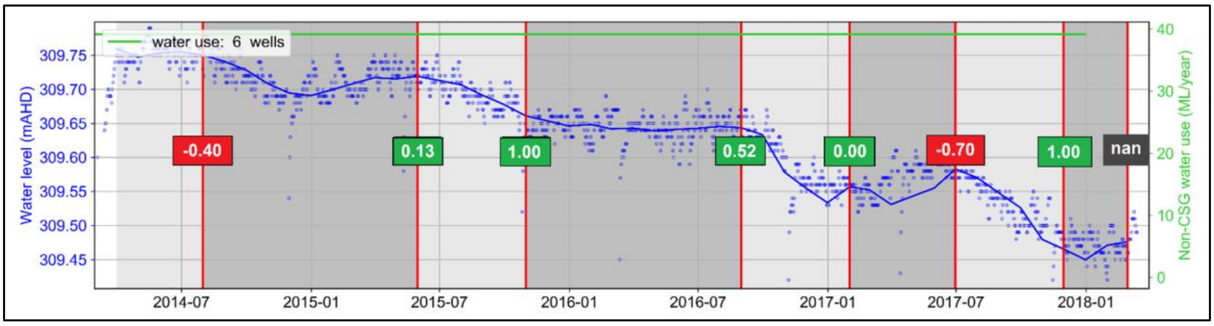


Figure C-8 Spearman correlation, Gilbert Gully MB2-S (RN160728A) groundwater level and non-CSG water use from the Springbok Sandstone within 25 km

C.3 Correlation with CSG groundwater extraction

This section of the report correlates localised cumulative CSG groundwater extraction from the Walloon Coal Measures with groundwater level trends for the same suite of outcrop, subcrop and basin-interior monitoring points described in the sub-sections above.

C.3.1 Shallow outcrop and subcrop areas

Figure C-9 presents the hydrograph for RN107698A compared with monthly CSG groundwater extraction within 10 km of that site. There are 118 CSG wells within 10 km of this site, with a rapid rise in extraction during early 2014. The correlation coefficient is 1.00 for the period after 2010. This correlation has little hydrogeological meaning though, because the groundwater levels are recovering (following large-scale recharge to the aquifer) during a period when CSG groundwater extraction increases.

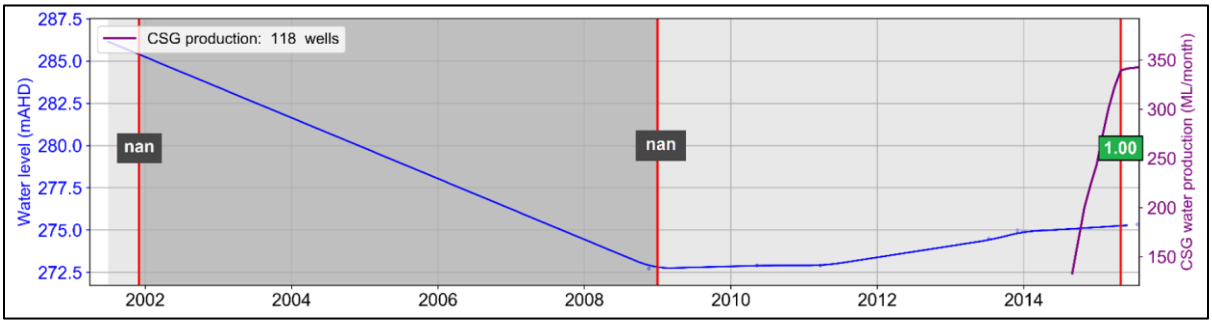


Figure C-9 Spearman correlation, RN107698A groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Figure C-10 presents the hydrograph for Daandine 123 SS (RN160347E) compared with the cumulative monthly CSG groundwater extraction within 10 km of that site. Over the three years of monitoring, a steadily declining CSG groundwater extraction rate and steadily increasing groundwater level results in a strong inverse correlation. The short duration of monitoring again makes it difficult to interpret these rising groundwater levels and how CSG groundwater extraction may be influencing them. The timing of when levels began increasing would help to establish a causal link with the responsible stress. This was demonstrated in other outcrop sites, where rising levels after late 2010 could be tied to a large flooding event in the basin, resulting in highly effective aquifer recharge. Unfortunately, most of the increasing trends observed in the UWIR and non-UWIR company monitoring networks are pre-existing trends without defined points of inflection in groundwater levels.

Figure C-10 Spearman correlation, RN160347E (Daandine 123 SS) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

C.3.2 Confined basin interior

Figure C-11 presents the hydrograph for Kenya East GW2 (RN160519A) compared with the cumulative monthly CSG groundwater extraction within 10 km of that site. This site has a fluctuating groundwater level with no apparent overall trend. This somewhat erratic groundwater level trend has short periods that correlate very well with CSG groundwater extraction and other periods that correlate poorly. Overall, there is no long-term declining trend in groundwater level to correlate with increased CSG groundwater extraction.

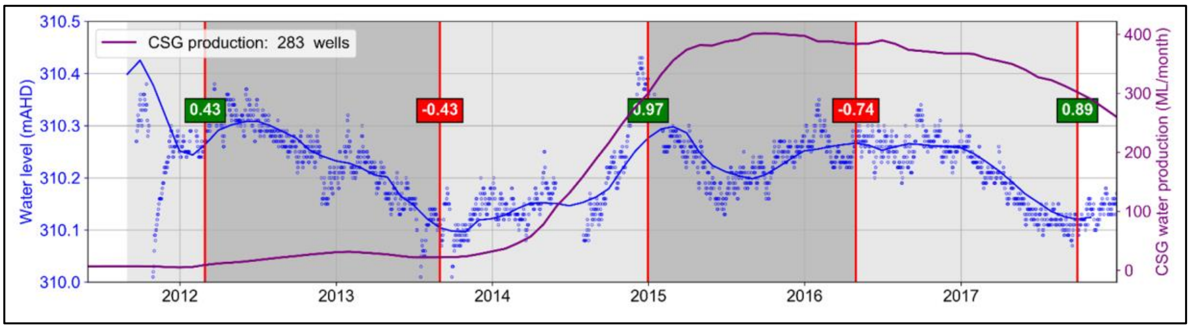


Figure C-11 Spearman correlation, Kenya East GW2 (RN160519A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Figure C-12 presents the hydrograph for Gilbert Gully MB2-S (RN160728A) compared with the cumulative monthly CSG groundwater extraction within 10 km of that site. There are zero CSG wells within 10 km, therefore there is no extraction trend to correlate with groundwater levels and no likely influence of CSG on groundwater level trends at this site. As the subtle declining groundwater level trend does not correlate with rainfall and there is a sustained non-CSG water use that predates monitoring, it follows that this site is being impacted solely by within-aquifer non-CSG water use stresses.

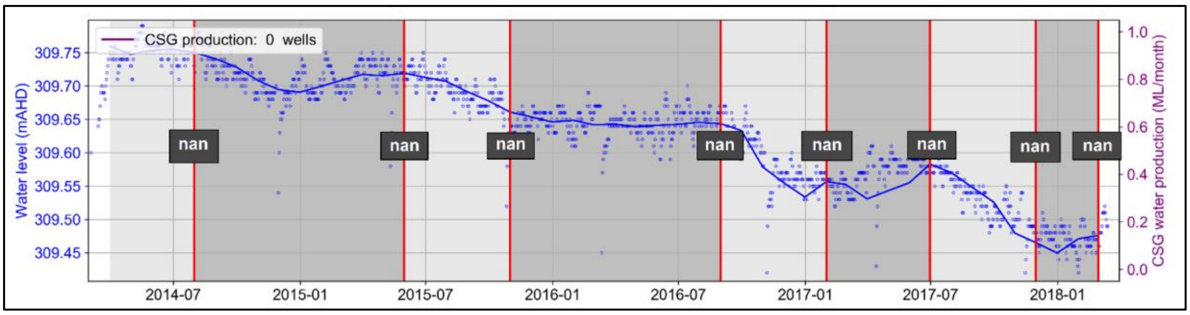


Figure C-12 Spearman correlation, Gilbert Gully MB2-S (RN160728A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Appendix D Hutton Sandstone groundwater level trends

D.1 Observed trends in CSG areas

Compared to outcrop areas, the UWIR and non-UWIR company network has a more extensive spatial and vertical coverage in the interior of the basin where most GAB formations are buried at greater depths and behave as confined aquifer systems. This section of the report will review Hutton Sandstone groundwater level trends within the basin interior, based primarily on data from company monitoring networks. This review will consider whether the monitoring points are situated within or outside of currently operating CSG fields, to evaluate whether there are any notable trends in groundwater levels in close proximity to presently depressurised coal seams.

In this appendix, the groundwater level data have been processed so that each individual monitoring point commences at a zero metres groundwater level datum and subsequent changes in groundwater levels are plotted as cumulative deviation from that zero datum. This allows for transparent comparison of each individual monitoring point and simplifies detection of rising and falling trends and trend rates.

The following six figures present group hydrograph plots for each of the three hydrogeological assessment areas.

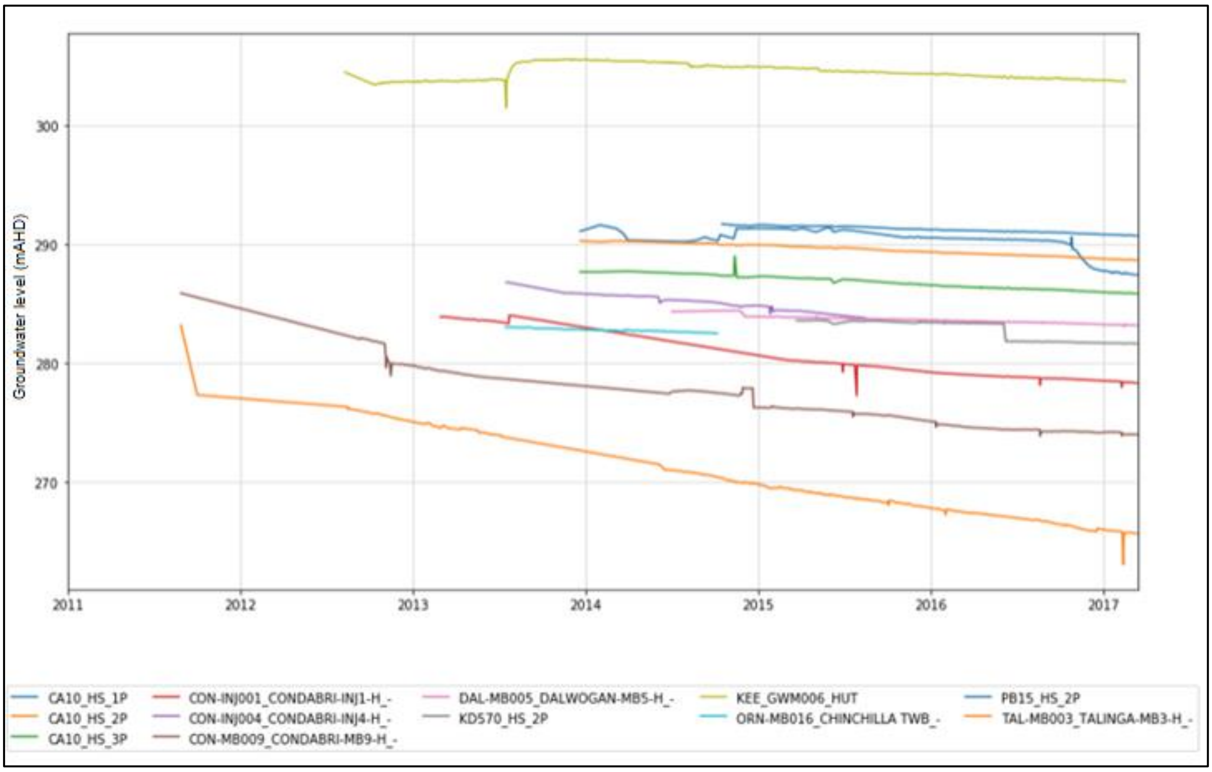


Figure D-1 Hutton Sandstone groundwater levels – Eastern Surat

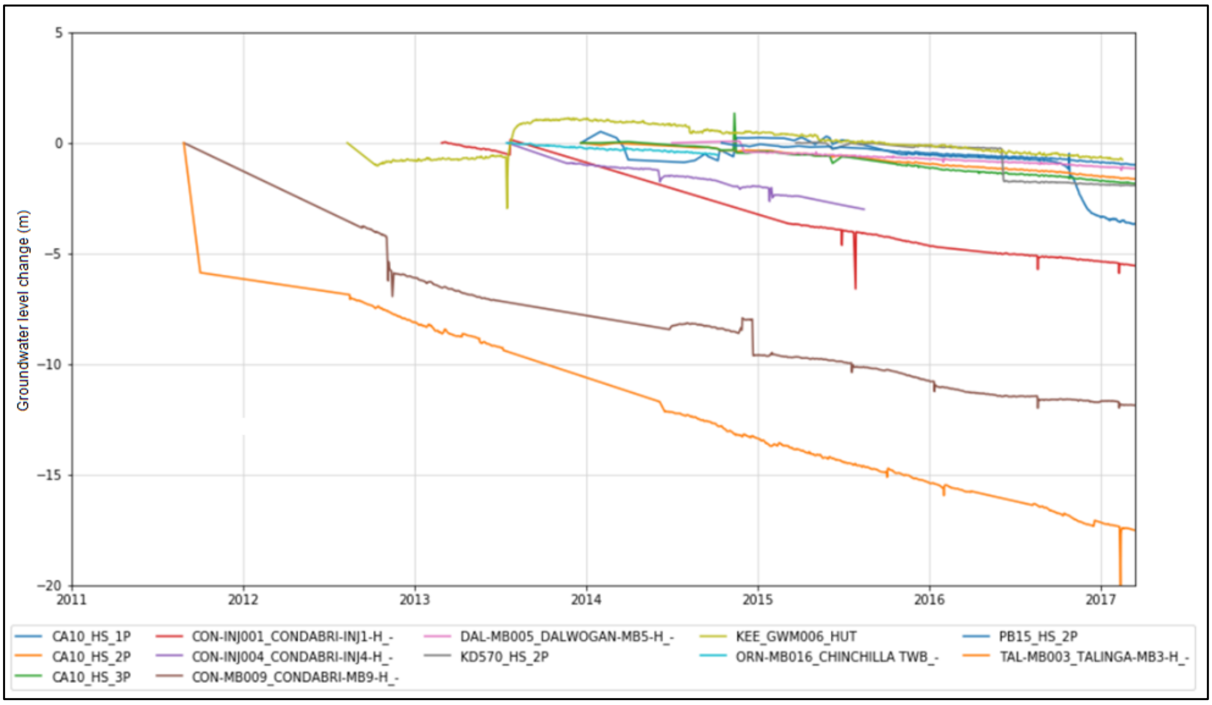


Figure D-2 Hutton Sandstone groundwater level trends – Eastern Surat

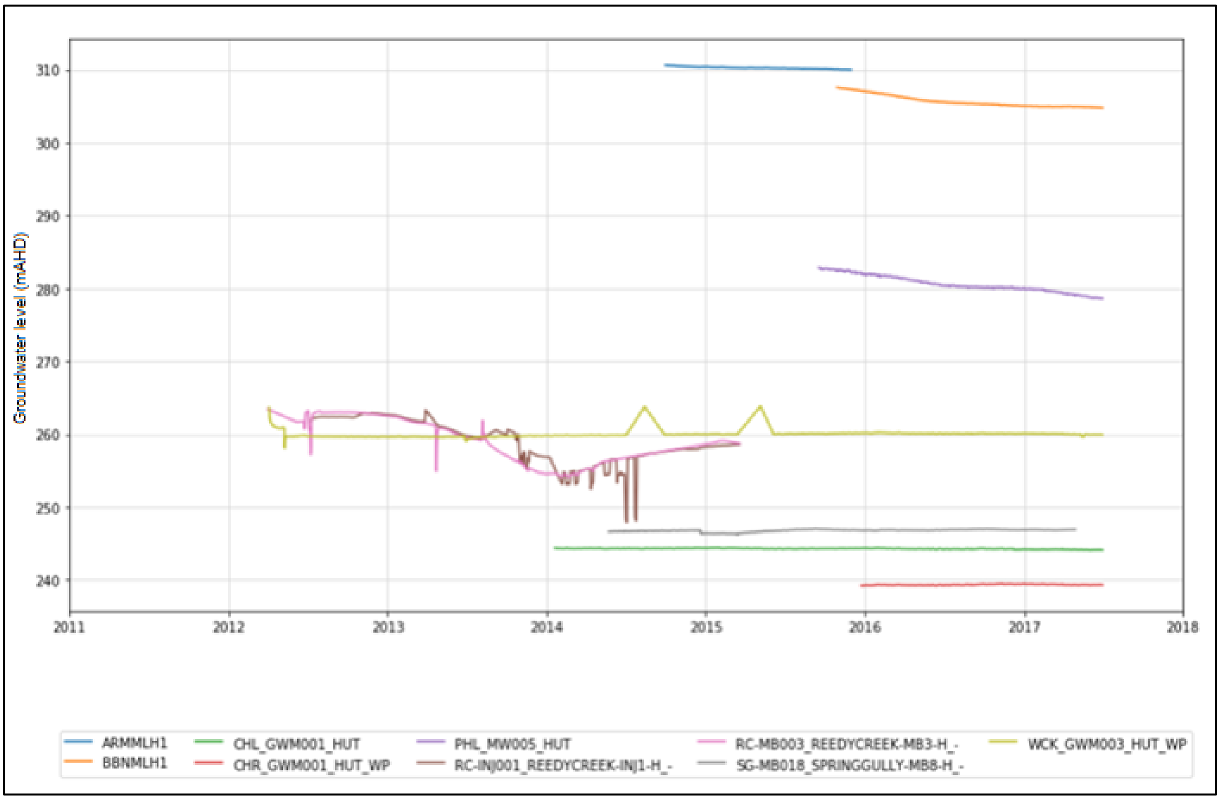


Figure D-3 Hutton Sandstone groundwater levels – Northern Surat

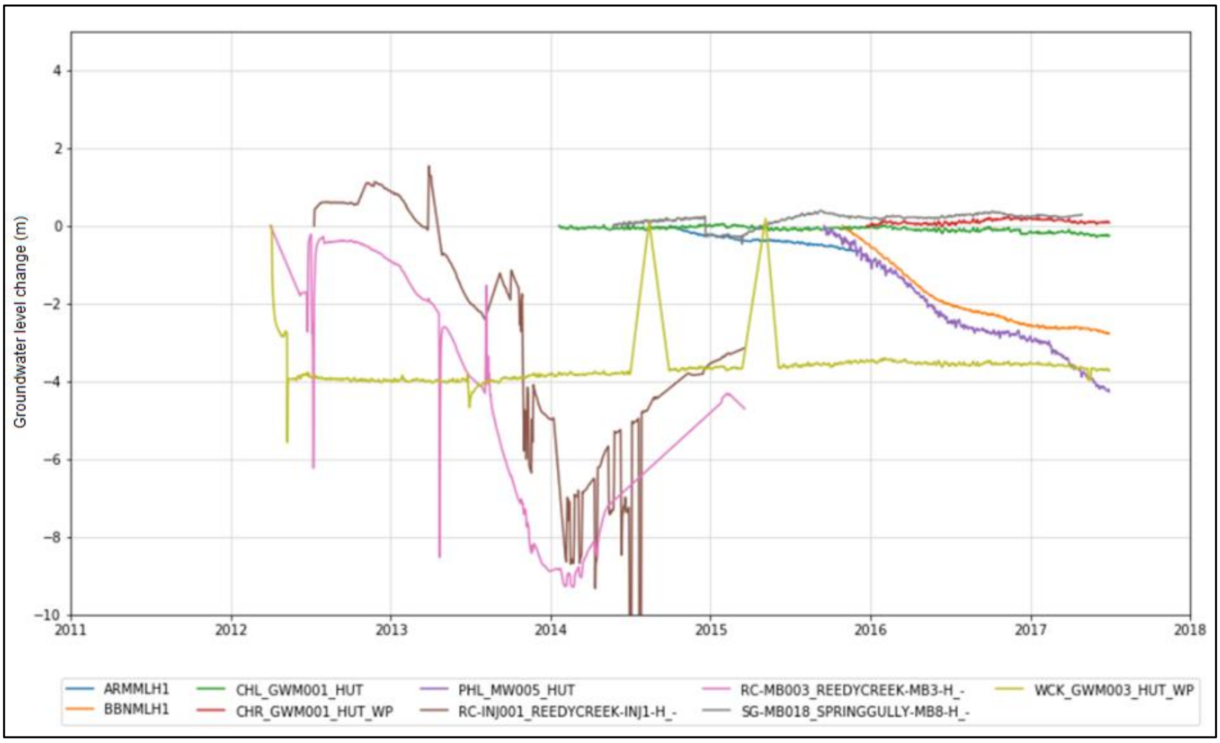


Figure D-4 Hutton Sandstone groundwater level trends – Northern Surat

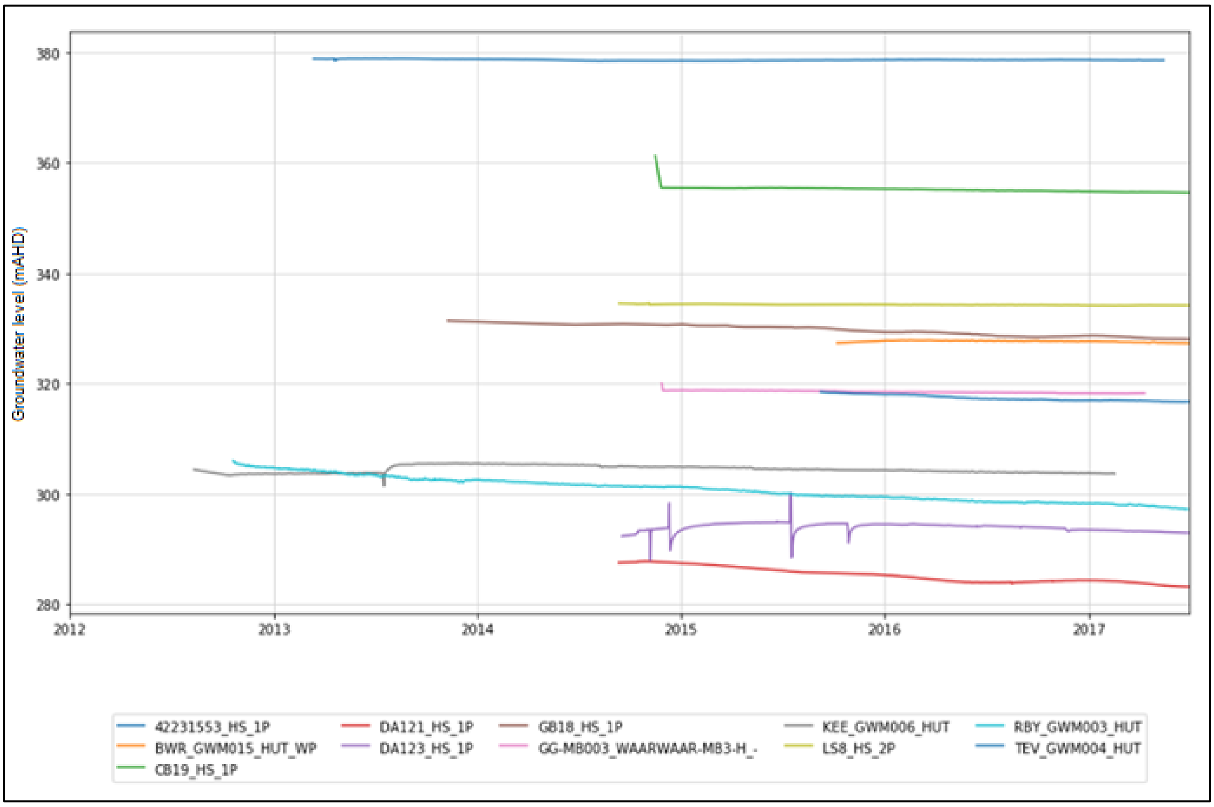


Figure D-5 Hutton Sandstone groundwater levels – South-eastern Surat

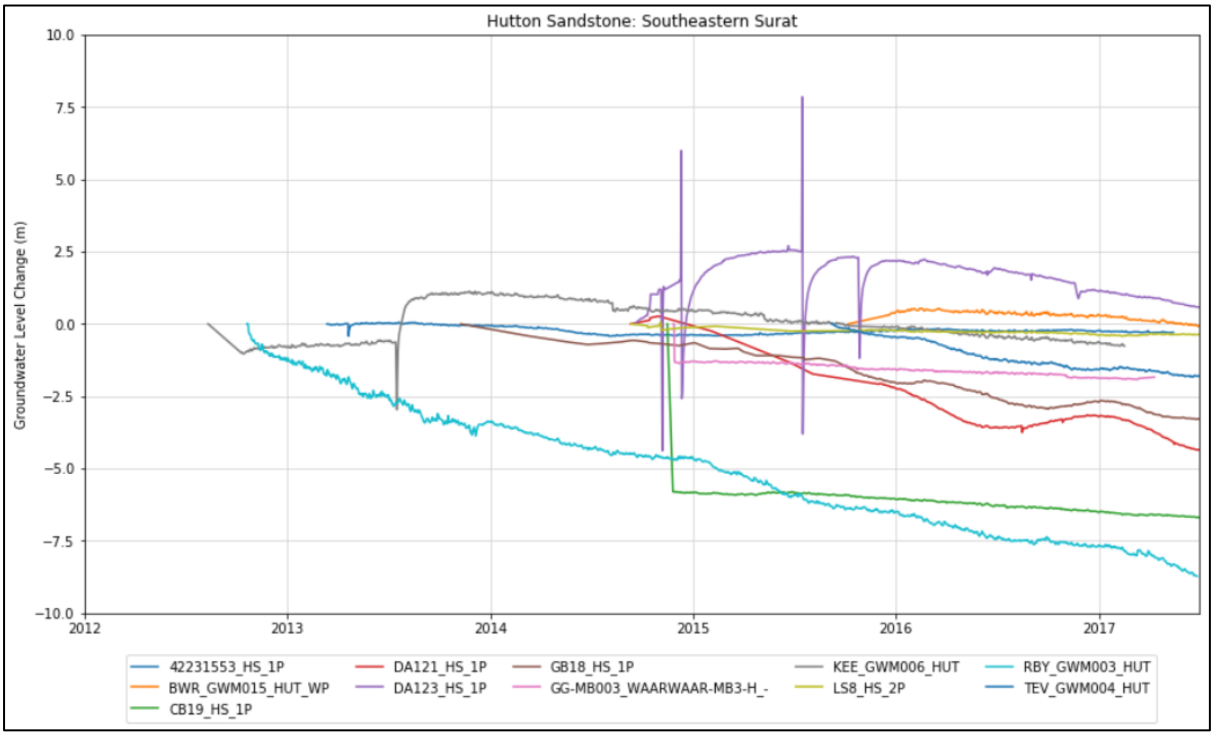


Figure D-6 Hutton Sandstone groundwater level trends – South-eastern Surat

D.1.1 Inside CSG production areas

The Hutton Sandstone groundwater level trends inside operating CSG fields in the three hydrogeological assessment areas are plotted in Figure D-7. It is apparent from this plot that the Hutton Sandstone groundwater level trends are systematically declining within CSG production areas, with the main variable being the rate of decline. Declining trends are far more common in the Eastern and South-eastern Surat, whereas in the Northern Surat, there is a tendency for generally static trends (57%).

In the Eastern Surat, there are three sites with more pronounced observed rates of drawdown:

- TAL-MB003: more than 16 m of drawdown observed at a rate of decline of 2.4 m/year
- CON-MB009: more than 11 m of drawdown observed at a rate of decline of 2.3 m/year
- CON-INJ001: more than 5 m of drawdown observed at a rate of decline of 1.57 m/year.

In the South-eastern Surat, there are two sites with more pronounced rates of drawdown:

- RBY_GWM003_HUT: more than 8 m of drawdown at a rate of decline of 1.7 m/year
- DA121_HS_1P: more than 3.5 m of drawdown at a rate of decline of 2.2 m/year.

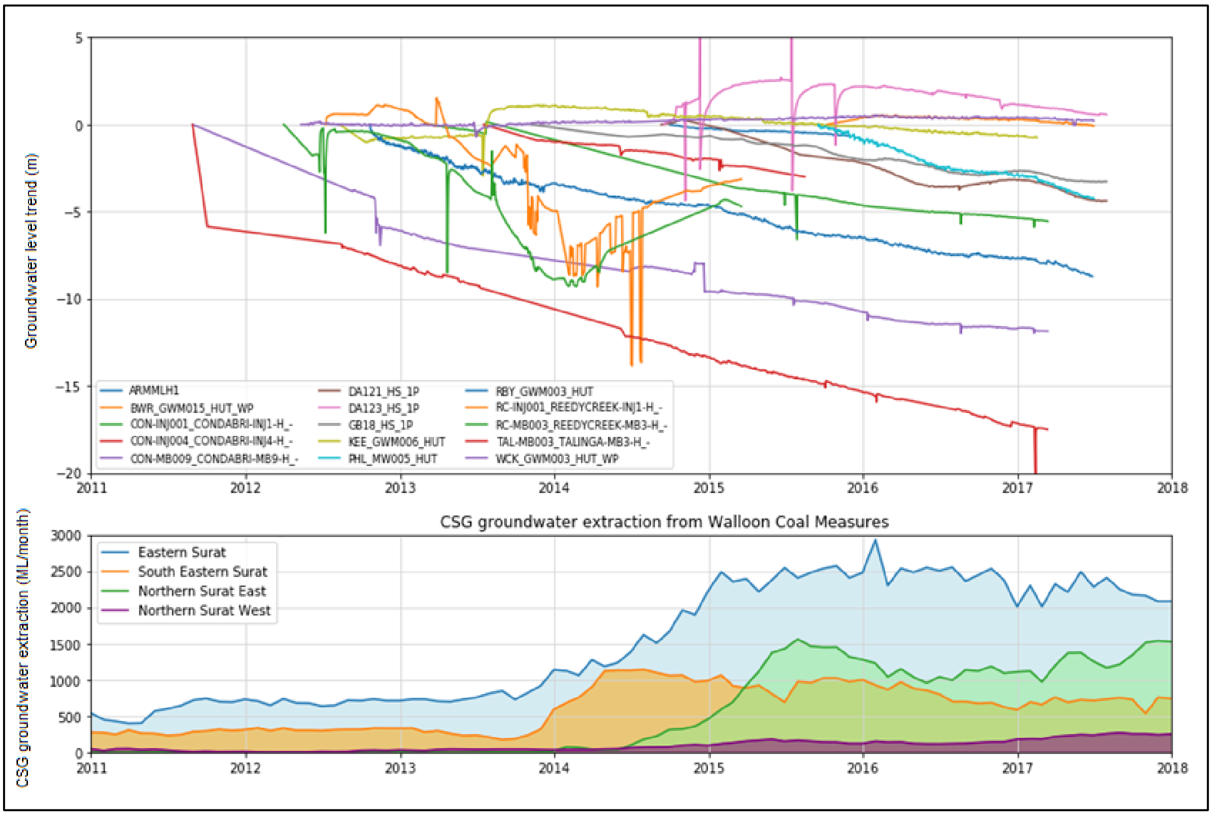


Figure D-7 Hutton Sandstone groundwater level trends within operating CSG areas

D.1.2 Outside CSG production areas

The Hutton Sandstone groundwater level trends outside operating CSG fields in the three hydrogeological assessment areas are plotted in Figure D-8. A comparison between Figure D-7 and Figure D-8 shows a dramatic contrast in trends, with groundwater level trends outside CSG areas typically showing static to very low rates of drawdown, whereas inside CSG areas, there are far more instances of pronounced drawdown.

Without further interrogation, the differences in the groundwater level trends tends to suggest that CSG impacts are occurring in the Hutton Sandstone. However, as described in the following sections, there is another factor to consider when evaluating groundwater level trends in this formation.

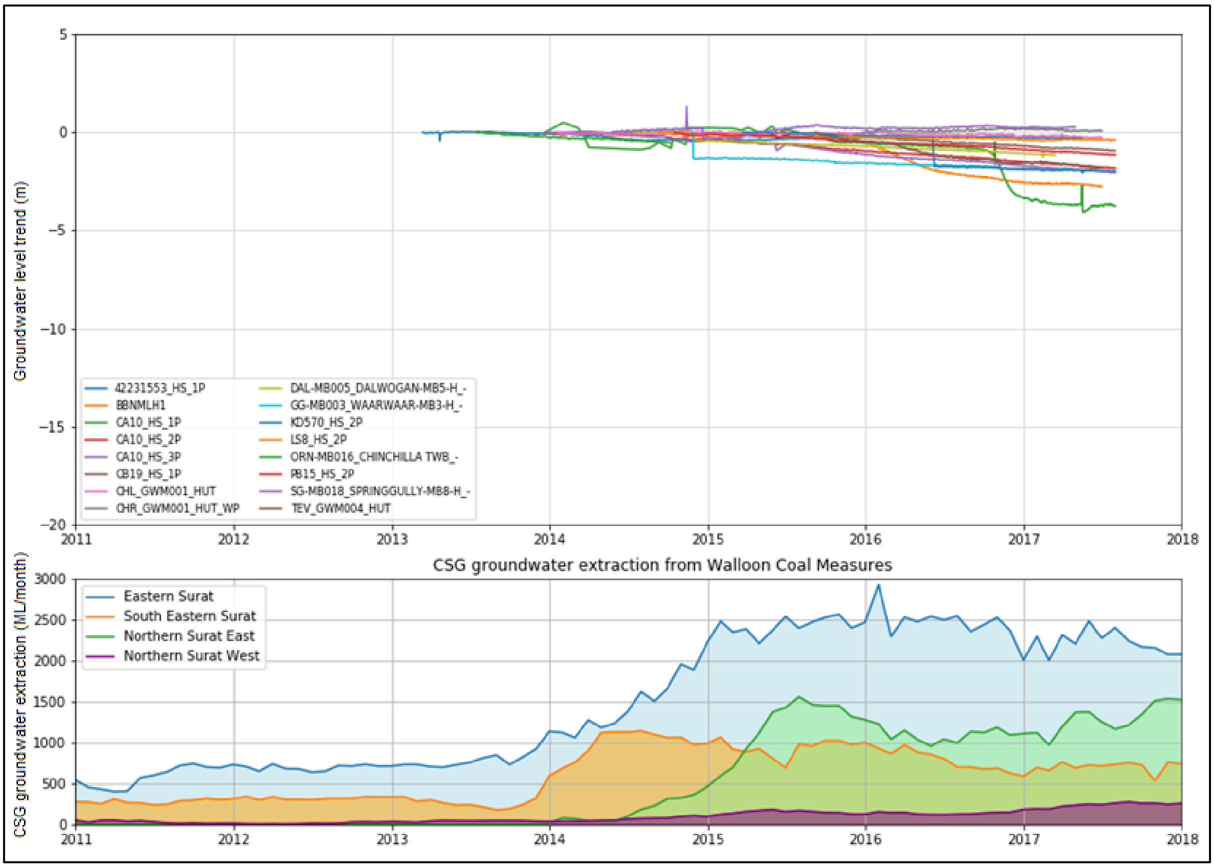


Figure D-8 Hutton Sandstone groundwater level trends outside operating CSG areas

D.1.3 Proximity to large, within-aquifer, non-CSG water use

The noticeable difference in Hutton Sandstone groundwater level trends inside and outside CSG development areas does not provide a complete picture of potential contributing stresses. There is also a very good correlation between larger rates of drawdown and proximity to major within-aquifer pumping stresses in the Hutton Sandstone.

As shown in Figure 8-14 of the main report, there are a large number of users of non-CSG water from the Hutton Sandstone that occur in the same areas as CSG development in the Eastern and South-eastern Surat. To further evaluate this alternative hypothesis – that major within-aquifer stresses are primarily influencing Hutton Sandstone groundwater level trends – the Hutton Sandstone groundwater level trends were re-plotted: rather than grouping by proximity to CSG areas, those monitoring points within 10 km of large (>100 ML/year) non-CSG water users from the Hutton Sandstone were grouped together, as shown in Figure D-9. The remaining Hutton Sandstone monitoring points (those situated further than 10 km from large non-CSG water users) were grouped together in Figure D-10.

These two alternative plots show a striking correlation between larger rates of drawdown and proximity to within-aquifer, non-CSG water use, and smaller drawdown rates further away from within-aquifer stresses. To further illustrate and compare with previous plots, those sites that are within CSG development areas are denoted as dashed lines. In doing so, it is apparent that both sets of stresses occupy the same geographic parts of the basin.

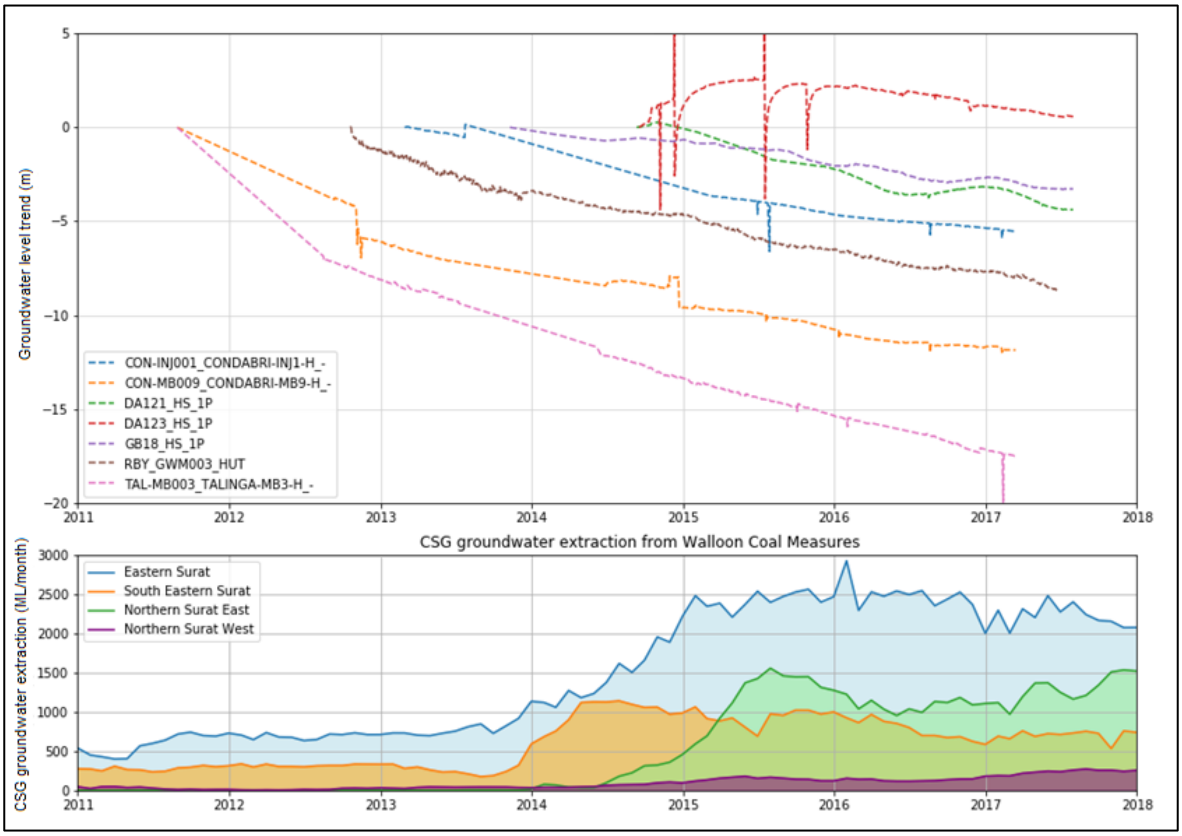


Figure D-9 Hutton Sandstone groundwater level trends within 10 km of large Hutton Sandstone non-CSG water users; dashed hydrographs are within CSG development areas

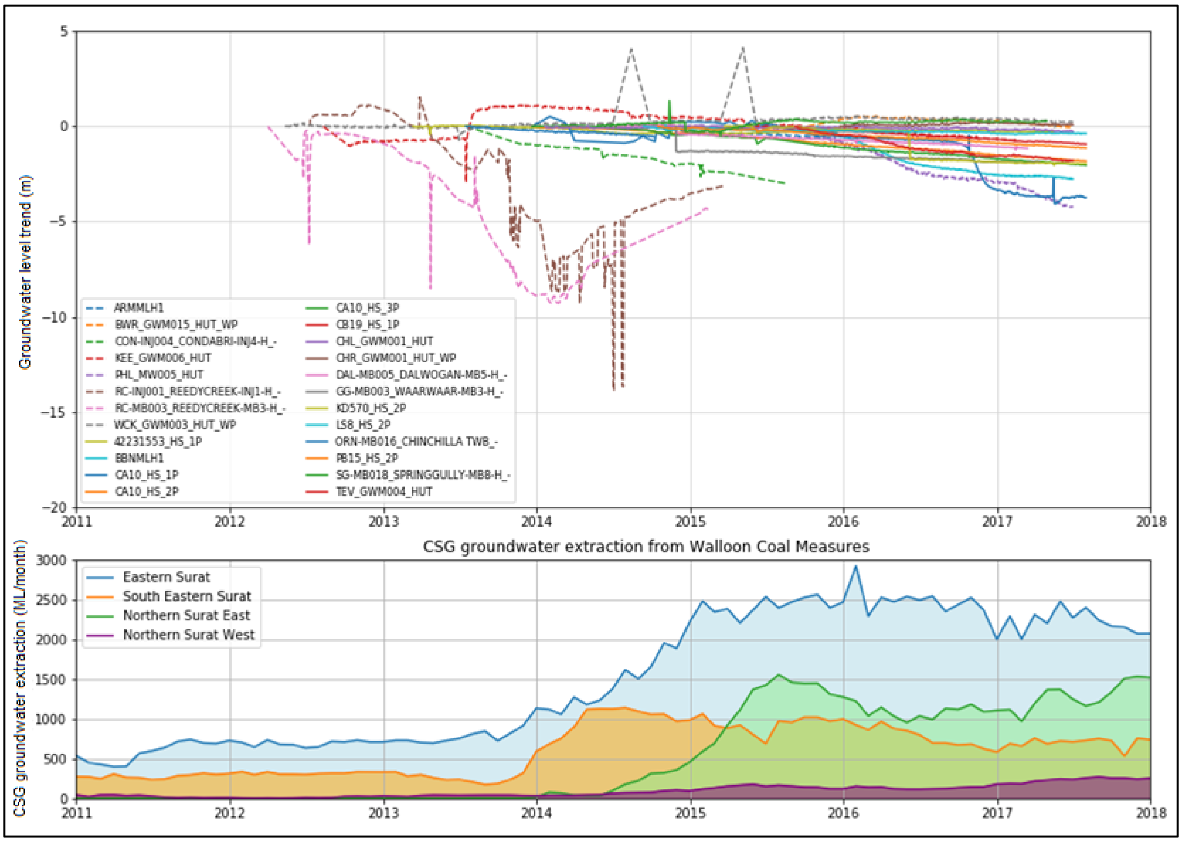


Figure D-10 Hutton Sandstone groundwater level trends more than 10 km from large Hutton Sandstone non-CSG water users; dashed hydrographs are within CSG development areas

Appendix E Hutton Sandstone correlation analyses

E.1 Correlation with rainfall trends

E.1.1 Shallow outcrop and subcrop areas

Figure E-1 presents the hydrograph for RN42231563A, an existing DNRME monitoring bore tapping the Hutton Sandstone, and the Cecil Plains weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a six-month rolling average, used in correlation analysis. This monitoring bore is situated in outcrop, 50 km east of Chinchilla. Below-average rainfall conditions in this part of the basin from 2002 to 2010 have translated as generally stable groundwater levels with mixed positive and negative correlation coefficients, suggesting no apparent influence during this drier period. There are no apparent groundwater level rises in response to annual summer rainfall periods during this dry period. A significant recharge event in late 2010 produced a four-metre rise in recorded groundwater levels over the next two to three years, with a strong positive correlation of 0.72. However, despite below-average rainfall conditions since 2013, groundwater levels continue to rise. Overall, this site only correlates with rainfall following above-average conditions, such as the flooding event in late 2010.

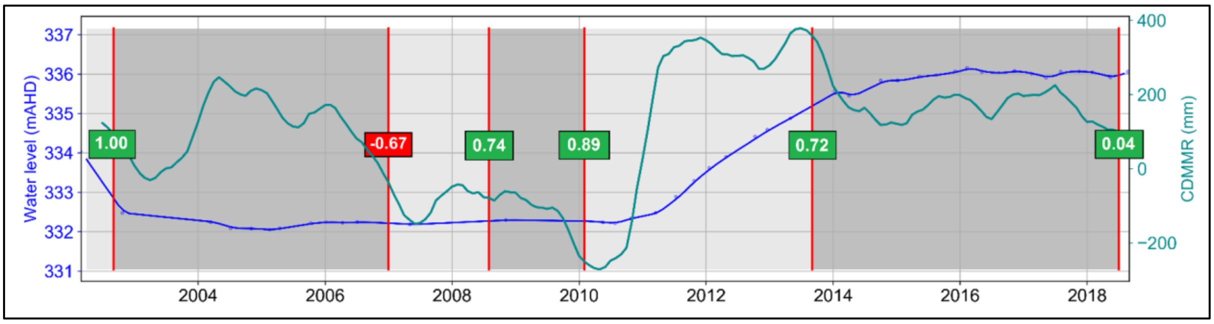


Figure E-1 Spearman correlation, RN42231563A groundwater level and Chinchilla weather station CDMMR

Figure E-2 presents the hydrograph for RN107350A – an existing mine monitoring bore tapping the Marburg Sandstone (Hutton Sandstone equivalent) in outcrop, directly to the northwest of Toowoomba on the western side of the Range – and the Cecil Plains CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a nine-month rolling average, used in correlation analysis. Above-average rainfall events in late 2010 also coincide with sudden increases in groundwater levels, with correlation coefficients of 0.41 into early 2012. After 2013, however, groundwater levels continue to rise despite below-average rainfall conditions. These rising levels since 2010 have essentially reset the aquifer groundwater levels to before the Millennium Drought.

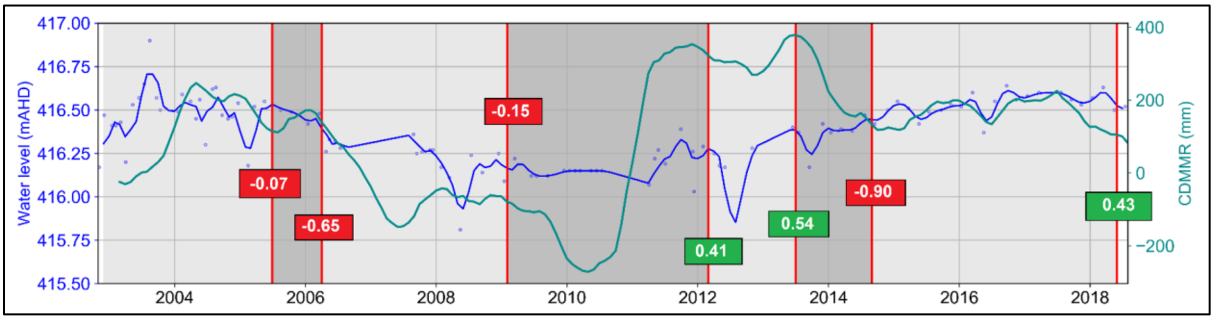


Figure E-2 Spearman correlation, RN107350A groundwater level and Cecil Plains weather station CDMMR

E.1.2 Confined basin interior

Figure E-3 presents the hydrograph for RBY_GWM003_H (RN160439A), an existing UWIR monitoring point tapping both the upper and lower Hutton Sandstone, and the Cecil Plains CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, used in correlation analysis. Nearest outcrop is 40 km to the northeast. The groundwater level trend at this site is a monotonic decline since late 2012. There are subtle increases and decreases in the declining drawdown rate, with some flattening of the rate in the latter half of years 2013 to 2017. Also noticeable on this plot is that above-average rainfall tends to occur in the months immediately before and after each new year (i.e. the summer rainfall months). Consequently, each period separated by breakpoints in the groundwater level record has a poor correlation with rainfall. Future iterations of this analysis should consider a lag time of approximately six months between rainfall occurring and these instances of flattening of the groundwater level. One hypothesis may be that some form of discharge is the dominant stress influencing groundwater levels in this deep part of the basin, and that the recharge periods are merely reducing the drawdown in periods in which there is increased influx (as throughflow) to the aquifer. The period of monitoring at this location is too short to determine how the aquifer responded to the significant December 2010 recharge event that influenced the outcrop and subcrop bores described above.

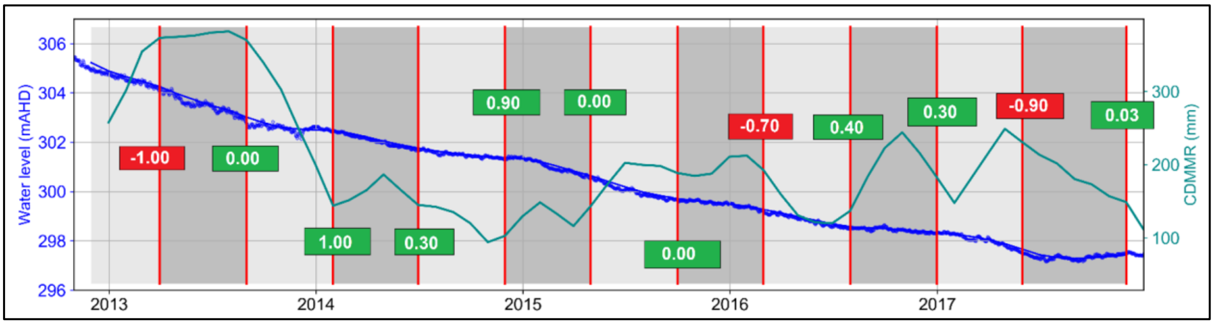


Figure E-3 Spearman correlation, RBY_GWM003_H (RN160439A) groundwater level and Cecil Plains weather station CDMMR

Figure E-4 presents the hydrograph for PHL_MW005_HUT (RN160722A), an existing UWIR monitoring point tapping the upper Hutton Sandstone, and the Taroom weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, used in correlation analysis. Nearest outcrop is 40 km to the northwest. The groundwater level trend at this site is a monotonic decline since late 2015. There are subtle increases and decreases in the declining rate, with some flattening of the rate in the latter half of 2016 and late 2017. Overall, there is a mixed correlation with rainfall, with inverse correlation during above-average rainfall and reasonable correlation during periods of below-average rainfall. This is mainly a function of the monotonic groundwater level trend and the short duration of monitoring.

Interestingly, despite PHL_MW005_HUT being 170 km to the northwest of RBY_GWM003_H, the consistencies in the drawdown patterns are very similar: an overall monotonic declining trend with flattening in the latter parts of 2016 and 2017. Both sites are 40 km from nearest outcrop and may be reflecting similar processes, i.e. dominant discharge causing groundwater levels to decline, punctuated by periods of subordinate recharge lessening the drawdown impact.

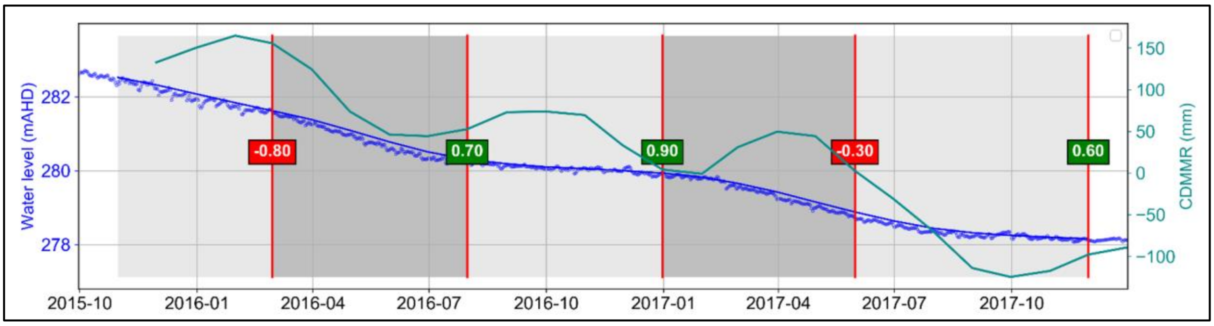


Figure E-4 Spearman correlation, PHL_MW005_HUT (RN160722A) groundwater level and Taroom weather station CDMMR

Figure E-5 presents the hydrograph for TAL-MB003-H (RN160634A), an existing UWIR monitoring point tapping the upper and lower Hutton Sandstone, and the Chinchilla weather station CDMMR. The groundwater level scatter plot shows actual measured groundwater levels, while the groundwater level line graph shows a 12-month rolling average, used in correlation analysis. Nearest outcrop is 51 km to the northeast. The groundwater level trend at this site is a monotonic decline since late 2011. Overall, the correlation with rainfall is erratic, with periods of strong correlation as a result of below-average rainfall in 2015 and 2017, separated by periods of poor correlation during above-average rainfall periods.

Compared to the previous two examples, the rate of decline at this site is more consistent (no apparent flattening periods) and this may reflect this site being situated deeper into the basin, with less immediate influence by rainfall recharge.

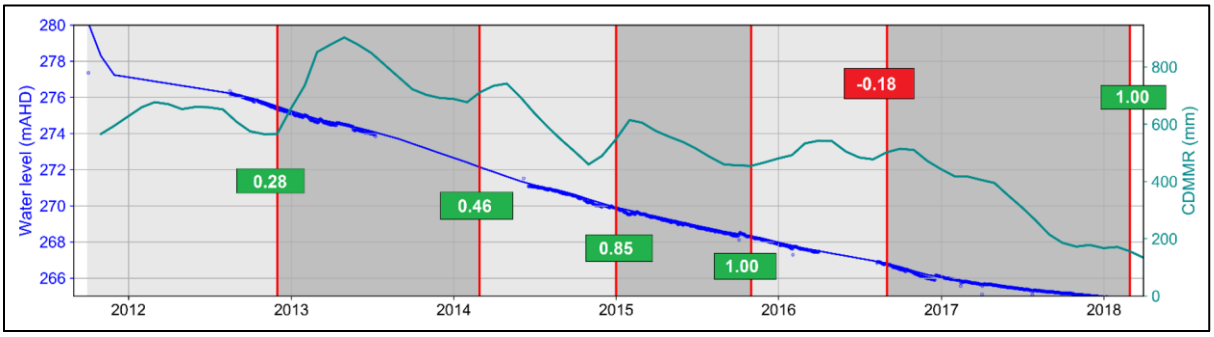


Figure E-5 Spearman correlation, TAL-MB003-H (RN160634A) groundwater level and Chinchilla weather station CDMMR

E.2 Correlation with non-CSG water use

Table C-1 summarised the current estimates of non-CSG water use for the Hutton Sandstone across the Surat CMA (OGIA 2019b). That table showed that the Hutton Sandstone is a major water supply aquifer in the Surat Basin, with nearly 14,000 ML extraction per year. Apart from being a major source for smaller-scale stock and domestic purposes (~2,700 ML/year), the Hutton Sandstone also supports major stock-intensive, town water supply, agriculture, industrial and irrigation projects to a total of 10,159 ML/year. This heavy reliance on the Hutton Sandstone represents around 34% of the total estimated non-CSG water use from the GAB formations in the Surat CMA.

Figure E-6 also shows the temporal growth in the number of bores and estimated water use volumes since 1970. The estimated "average" profile, including metered data, shows a rapid growth in water use, from ~3,500 ML/year in 1970 to ~14,000 ML/year in 2017. Non-CSG stresses have been present since before the 1970s and have slowly increased as more bores are drilled.

From a water balance perspective, the long-term, non-CSG water use from the Hutton occurs over a longer timeframe than the observed declining heads observed in the three representative outcrop bores described above. It is therefore entirely plausible that any storage decline observed in these early hydrographs may be related to within-aquifer, non-CSG water use stresses.

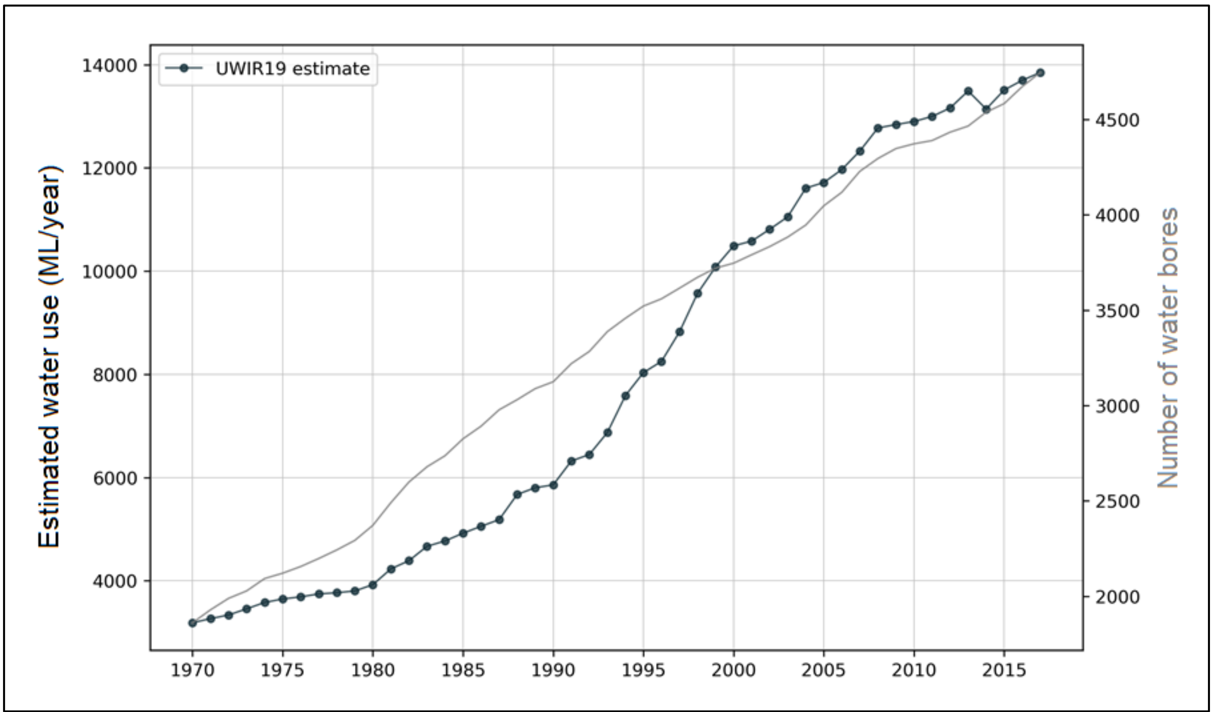


Figure E-6 Temporal water use estimate – Hutton Sandstone (after OGIA 2019b)

E.2.1 Shallow outcrop and subcrop areas

The three representative outcrop and subcrop monitoring sites described in section 8.3.1 are again subjected to Spearman correlation analysis, however in this section, each groundwater level time series is correlated with estimates of non-CSG water use for the Hutton Sandstone. A radial search function within Python is implemented to cumulatively add the total extraction volumes per annum for every bore within the specified 25-km radius. As these water use estimates are at an annual resolution, the correlation is temporally coarser than the monthly correlation with CDMMR described in the previous section. This is particularly influential for short time series.

For the three representative outcrop sites across the Surat CMA considered, it is evident that non-CSG water use within 25 km presents as either a relatively stable or slowly increasing monotonic trend. This monotonic water use trend is easily correlated with any other monotonic variable, such as groundwater level (either as a positive or inverse correlation), and does not necessarily confirm causation. Caution must therefore be taken when drawing inferences from this analysis and this approach is therefore more suited to hypothesis generation than validation of the causes of a specific impact.

In all instances, the non-CSG water use predates the monitoring record (prior to the 1980s), which emphasises the long-term water budget influence of non-CSG water use in the GAB. This is especially the case for the Hutton Sandstone, which is one of the most used aquifers in the basin. It is not possible to determine a true background groundwater level trend without first de-trending non-CSG water use from the groundwater level record. For this analysis, however, de-trending was not undertaken for reasons previously outlined in section 7.3.2 (mainly owing to uncertainty in climate and non-CSG water use inputs).

Figure E-7 presents the hydrograph for RN42231563A compared with annual non-CSG water use within 25 km of that site. There are 213 wells within 25 km, with a total estimated use volume of nearly 500 ML/year. This site shows a consistent positive correlation with non-CSG water use, which is contrary to the negative correlation expected if pumping were affecting groundwater levels. For this reason, it appears that this false correlation is not a plausible explanatory variable for the groundwater levels observed in this area.

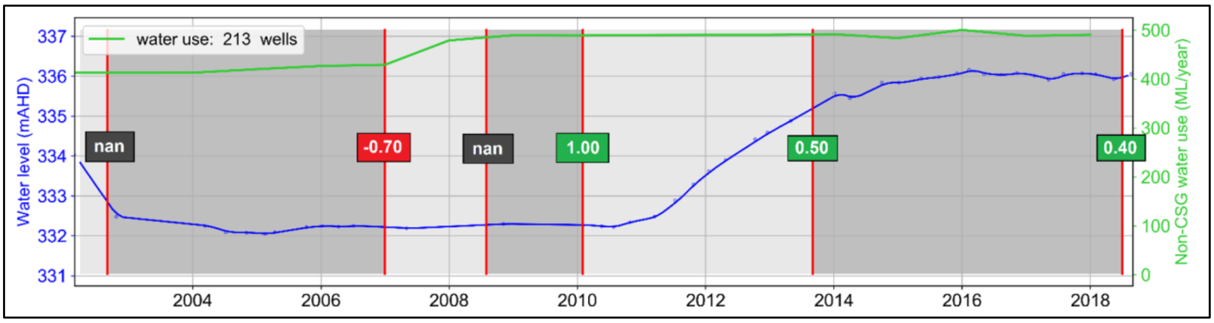


Figure E-7 Spearman correlation, RN422315563A groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

Figure E-8 presents the hydrograph for RN107350A compared with the cumulative annual non-CSG water use within 25 km of that site. There are 942 Hutton Sandstone water supply bores within 25 km, with a total estimated annual use volume that exceeds 3,000 ML since 2018. This is a heavily developed part of the Hutton Sandstone within the Surat CMA, which helps to explain the strong inverse correlation between declining groundwater levels and increasing water use (from 2006 to 2009) during the Millennium Drought. Rising groundwater levels post-2010 are obviously not explained by the sustained non-CSG pumping, with another stress (i.e. recharge) more likely to be responsible.

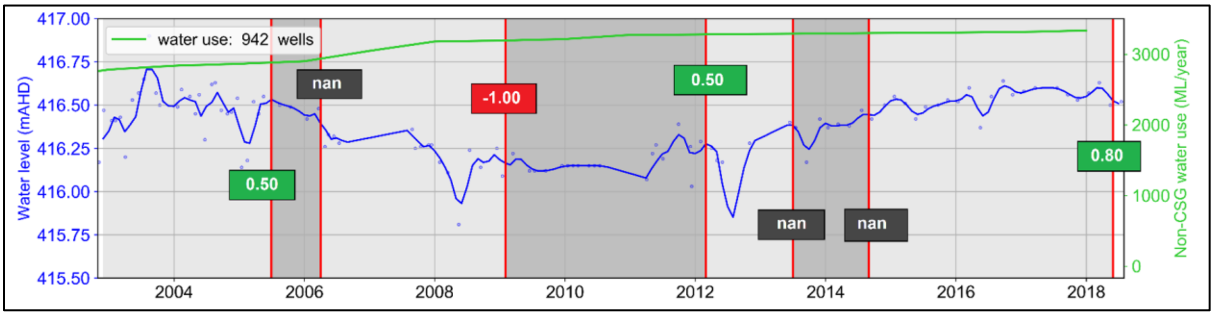


Figure E-8 Spearman correlation, RN107350A groundwater level and non-CSG water use from the Hutton Sandstone within 25 km

E.2.2 Confined basin interior

The three representative Hutton Sandstone monitoring sites show very similar correlations with non-CSG water use (Figure E-9 to Figure E-11) and are summarised together here:

- Non-CSG water use predates monitoring at all three parts of the basin.
- Non-CSG water use presents as a monotonic increasing or slightly decreasing trend at all three sites.
- Groundwater levels presents as monotonic decreasing trends.
- The comparison of the two monotonic trends lead to perfect correlation coefficients.
- The rates of Hutton Sandstone drawdown are larger for similar or lower rates of Hutton Sandstone extraction in the outcrop areas. This is likely related to the more confined storage of the aquifer, deeper in the basin.
- There are no changes in non-CSG water use to explain the flattening in drawdown observed in the latter half of each calendar year at RBY_GWM003_H and PHL_MW005_HUT.

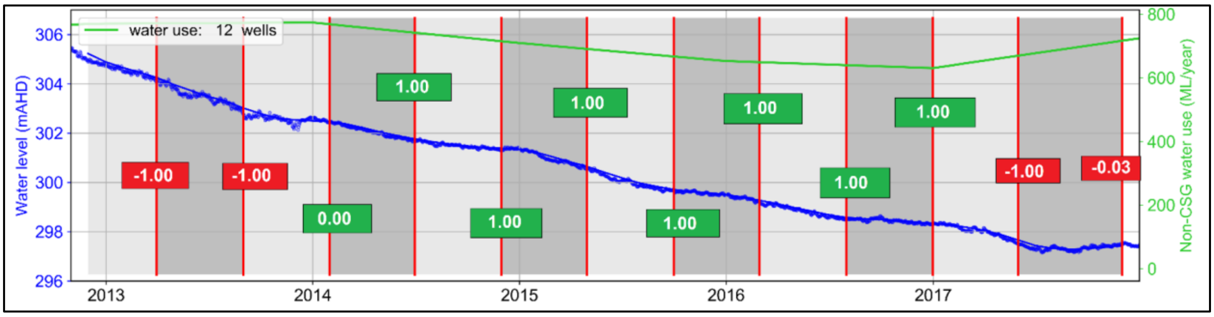


Figure E-9 Spearman correlation, RBY_GWM003_H (RN160439A) groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

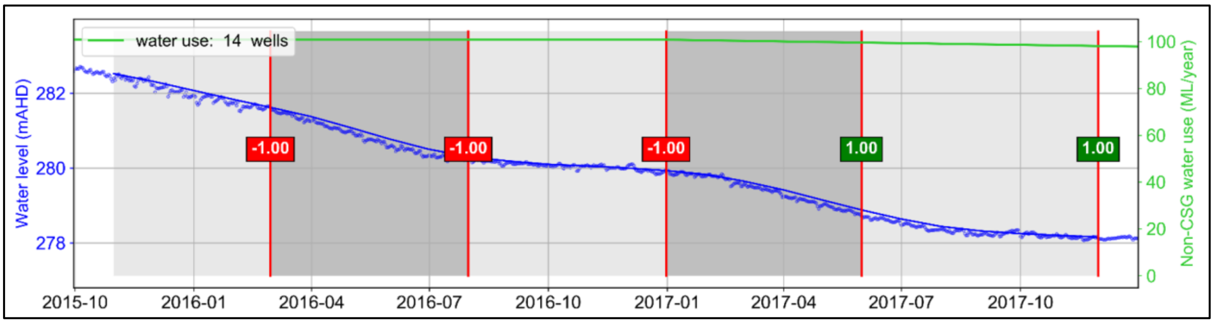


Figure E-10 Spearman correlation, PHL_MW005_HUT (RN160722A) groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

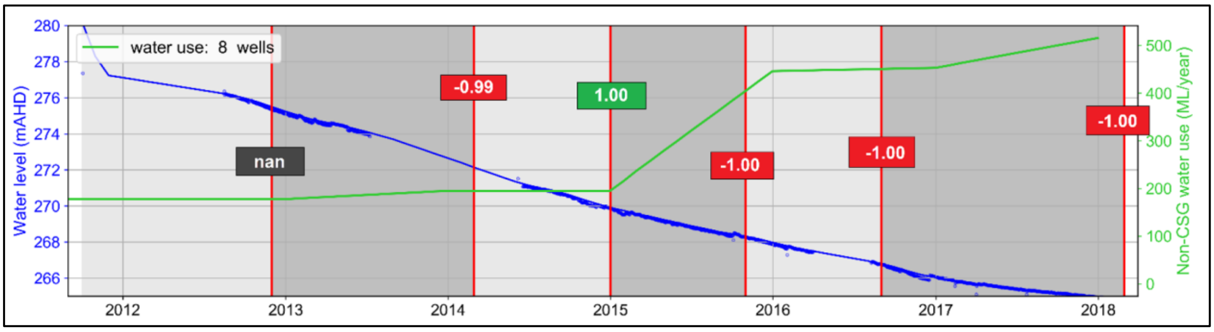


Figure E-11 Spearman correlation, TAL-MB003-H (RN160634A) groundwater level and cumulative non-CSG water use from the Hutton Sandstone within 25 km

E.3 Correlation with CSG groundwater extraction

E.3.1 Shallow outcrop and subcrop areas

None of the three representative Hutton Sandstone outcrop monitoring sites have any CSG wells in the Walloon Coal Measures within 10 km of the monitoring point. For this reason, no correlation analysis between groundwater levels and CSG groundwater extraction was conducted for these sites.

E.3.2 Confined basin interior

Figure E-12 presents the hydrograph for RBY_GWM003_H (RN160439A) compared with the cumulative monthly CSG groundwater extraction within 10 km of that site. This monitoring point is located within QGC's RubyJo gas field, which commenced operations in 2012. There are 321 CSG wells within 10 km, with CSG groundwater extraction predating groundwater level monitoring. There are periods of strong positive and negative correlation between these two variables, mainly related to the fluctuating CSG groundwater extraction volumes through time. There are no obvious changes in CSG groundwater extraction volumes that could explain the flattening of the drawdown rate in the latter half of years 2013 to 2017.

At this site, the volumes of water (~100 ML/month) extracted from the Walloon Coal Measures are similar in magnitude to the non-CSG water use (~100 ML/month) from the Hutton Sandstone. It is unlikely that a significant proportion of CSG-extracted water around this site is derived from inter-aquifer leakage from the Hutton Sandstone. As such, the dominant outflow component from the Hutton Sandstone is expected to be non-CSG water use from within the aquifer.

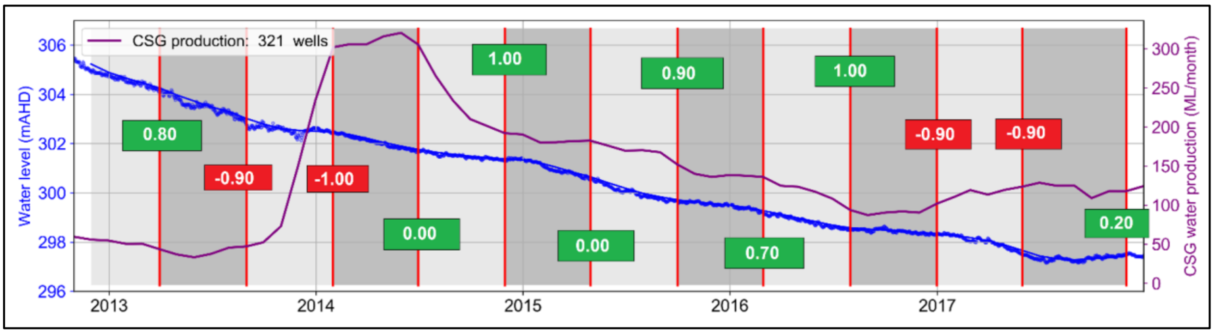


Figure E-12 Spearman correlation, RBY_GWM003_H (RN160439A) groundwater level and CSG groundwater extraction from the underlying Walloon Coal Measures within 10 km

Appendix F Groundwater level density corrections

F.1 Density corrections

As presented in OGIA (2016b), this appendix describes the methods applied by OGIA for the preparation of raw groundwater level data for analysis. The topics presented below are limited to data treatment methods for the purposes of this report.

F.2 Theoretical basis for density corrections

Darcy's Law is a commonly applied equation to describe groundwater flow though porous media; however, it does not consider variable density environments. To adequately assess both vertical and horizontal flow directions, conversion of raw groundwater level data to a common reference density is required.

For example, for a fluid of constant salinity, as fluid temperature rises, density decreases. In contrast, a rise in salinity increases the density of a fluid, where temperature remains constant. Groundwater systems characterised by variable temperature and/or salinity conditions therefore require a density correction to a reference density (typically freshwater).

F.3 Conversion for temperature influences on water density

Where uniform groundwater salinity exists, or where salinity is close to that of freshwater, density at a given temperature is determined by the Thiesen-Scheel-Diesselhorst Equation (McCutcheon et al. 1992):

$$\boldsymbol{Density}\left(\frac{\boldsymbol{kg}}{\boldsymbol{m^3}}\right) = \mathbf{1000} \times \frac{(\mathbf{1} - (\boldsymbol{T} + \mathbf{288.94})}{(\mathbf{508929.2} \times (\boldsymbol{T} + \mathbf{68.13}))} \times (\boldsymbol{T} - \mathbf{3.99})^{\mathbf{2}}$$

$\boldsymbol{T}$ is the water temperature (^{0}C) and salinity = 0 mg/L.

F.4 Correction for temperature and salinity influences on density

McCutcheon et al. (1992) provide an equation to correct for the combined influence of temperature and salinity on fluid density:

$$\boldsymbol{Density}\left(\frac{\boldsymbol{kg}}{\boldsymbol{m^3}}\right) = \boldsymbol{\rho o} + \boldsymbol{AS} + \boldsymbol{BS}^{\frac{3}{2}} + \boldsymbol{CS}^{\mathbf{2}}$$

$\boldsymbol{A}$ = $8.25\mathrm{e}^{-1} - 4.09\mathrm{e}^{-3} \times \mathrm{T} + 7.64\mathrm{e}^{-5} \times T^2 - 8.25\mathrm{e}^{-7} \times T^3 + 5.37\mathrm{e}^{-9} \times T^4$

$\boldsymbol{B}$ = -5.72e^{-3} + 1.02e^{-4} $\times$ T - 1.66e^{-6} $\times$ T^2

$\boldsymbol{C}$ = 4.83e^{-4}

$\boldsymbol{S}$ is salinity in g/kg (where 1 g/kg = 1 ppt = 0.001 mg/L = 0.001 ppm)

$\boldsymbol{T}$ is Temperature (^{0}C)

$\boldsymbol{\rho o}$ is pure water density as a function of temperature (Appendix F.3).

F.5 Conversion to equivalent hydraulic heads

In order to compare hydraulic head measurements of variable density, a correction is required to normalise hydraulic head data to a common reference elevation and density, often referred to as 'reference heads' or 'equivalent hydraulic heads' (Welsh 2007)(Rousseau-Gueutin et al. 2014). For the purposes of this project, a freshwater reference density (Salinity = 0 mg/L) (Post, Kooi & Simmons 2007) was used to correct hydraulic head measurements relative to the Australian Height Datum (AHD), as determined using the following equation:

$$hf \quad = \quad z + \frac{\rho A}{\rho F} \times \frac{P}{\rho A \times g} = \quad z + \frac{\rho A}{\rho F} \times h$$

hf is equivalent freshwater hydraulic head or reference head (mAHD)

z is elevation head at the screen mid-point (Post, Kooi & Simmons 2007)

ρA is aquifer density (kg/m^3)

ρF is density of freshwater or reference density (kg/m^3)

P is groundwater pressure (kPa)

g is gravitational acceleration (g = 9.81 m/s)

h is the hydraulic head at the measurement point (m).

F.6 Correction of water column length

In situations where the measurement point is above the screen interval, the temperature (density) of water within the water column will differ relative to the screen interval; the pressure head or measured groundwater level will therefore not be representative of the formation. Depending upon the monitoring point location and measurement method, there may be a need to undertake a correction prior to calculating equivalent hydraulic heads:

$$\mathit{Corrected\ water\ column\ length} = \left(\frac{\rho B}{\rho F}\right) \times ha$$

ρB is the average water column density (kg/m^3)

ρF is the density of groundwater in the formation (kg/m^3)

ha is the initial water column length (m).

The above equation represents the density corrected hydraulic head (h) from Appendix F.5.

Appendix G Summary of statistical methods

G.1 Modified Mann-Kendall analysis

Groundwater level data were analysed for trends using a modified Mann-Kendall (M-K) technique.

Given the irregularity of some of the data (in some cases, both daily and yearly sampling is observed), a linear interpolation function was applied simultaneously with a monthly resampling using a mean. This produces a continuous monthly time series for each monitoring point and ensures consistency between datasets. A rolling mean was then applied to remove the influence of seasonal variability and noise. This yields the trend component $M_{(t)}$ which detects changes in data (either upward or downward) over a period of time.

The trend component was used in an M-K analysis to identify if a statistically significant trend is observed in the data. The M-K analysis technique seeks to determine differences in trend directions (or signs) between later and earlier data points.

The M-K analysis is a simple non-parametric test and, as such, is not affected by the magnitude of the data or any distribution assumptions. Given that the M-K test does not take into account seasonal effects, the decomposed $M_{(t)}$ was used to determine when to reject a null hypothesis (H_0) and accept the alternative hypothesis (H_a).

The initial assumption of the M-K test is that the H_0 is true and that the data must show a statistically significant trend before H_0 is rejected and H_a is accepted. The M-K test was implemented in a Python model using the following steps:

1. List data in order of increasing time, x1,x2, . . . ,xn (where n is the total number of data points).
2. Calculate the differences between each data point and every point preceding it. The number of differences in the dataset can be expressed as n(n-1)/2 and is calculated using x_j- x_k, where x_k is the data point preceding x_j (j=k+1). As every value in the dataset is compared to all values preceding it, relatively small datasets can yield a high number of pairwise comparisons.
3. Determine the sign of all x_j- x_k such that sgn(x_j- x_k) is either -1, 0 or 1, for x>0, x=0 or x<0 respectively.
4. Calculate S statistic, which is the number of positive differences minus the number of negative differences (if S is positive then the date value later in the time period is larger than those earlier on; if S is negative then the data value later in the time period is smaller):

$$\boldsymbol{S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sgn(x_j - x_k)}$$

5. Calculate the Variance of S as follows:

$$\boldsymbol{VAR(S) = \frac{1}{18}[n - (n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5)]}$$

$\boldsymbol{g}$ is the number of tied groups

$\boldsymbol{t_p}$ is the number of observations in the pth group.

6. Calculate the Mann Kendall ZMK statistic such that:

$$\boldsymbol{Z_{MK}} = \frac{\boldsymbol{S-1}}{\sqrt{\boldsymbol{VAR(S)}}}\ \boldsymbol{if\ S > 0}$$

$$\boldsymbol{Z_{MK} = 0\ if = 0}$$

$$\boldsymbol{Z_{MK}} = \frac{\boldsymbol{S+1}}{\sqrt{\boldsymbol{VAR(S)}}}\ \boldsymbol{if\ S < 0}$$

If ZMK >0 or <0 then a trend increases or decreases accordingly.

A two-tailed test is then used to calculate the p value to investigate the significance of the trend where:

$$\boldsymbol{p = 2(1 - (PZ_{|MK|} \leq Z_{|MK|}))}$$

$\boldsymbol{p}$ is the significance

$P\mathbf{Z}_{|\mathbf{MK}|} \leq \mathbf{Z}_{|\mathbf{MK}|}$ is the probability of ZMK being less or equal to the observed value.

From here, a trend is assigned as follows:

$$\boldsymbol{If\ \left\{Z_{MK} < 0\ and\ Z_{|MK|} > PPF\left(\frac{1-0.05}{2}\right)\right\}\ then\ trend = decreasing}$$

$$\boldsymbol{If\ \left\{Z_{MK} > 0\ and\ Z_{|MK|} > PPF\left(\frac{1-0.05}{2}\right)\right\}\ then\ trend = increasing}$$

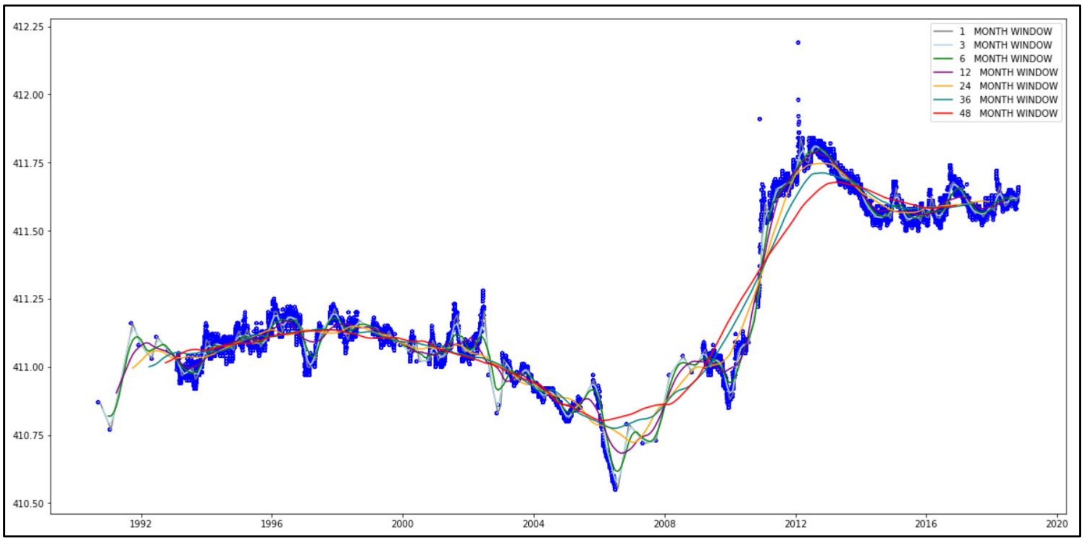
$$\boldsymbol{otherwise\ trend = No\ Trend}$$

where $\boldsymbol{PPF}$ is the point percent function in SciPy which returns the inverse of the Cumulative Density Function and so PPF gives the value of the variate for which the cumulative probability has the given value.

G.2 Breakpoint detection

The following custom breakpoint detection workflow was developed for the purposes of this report:

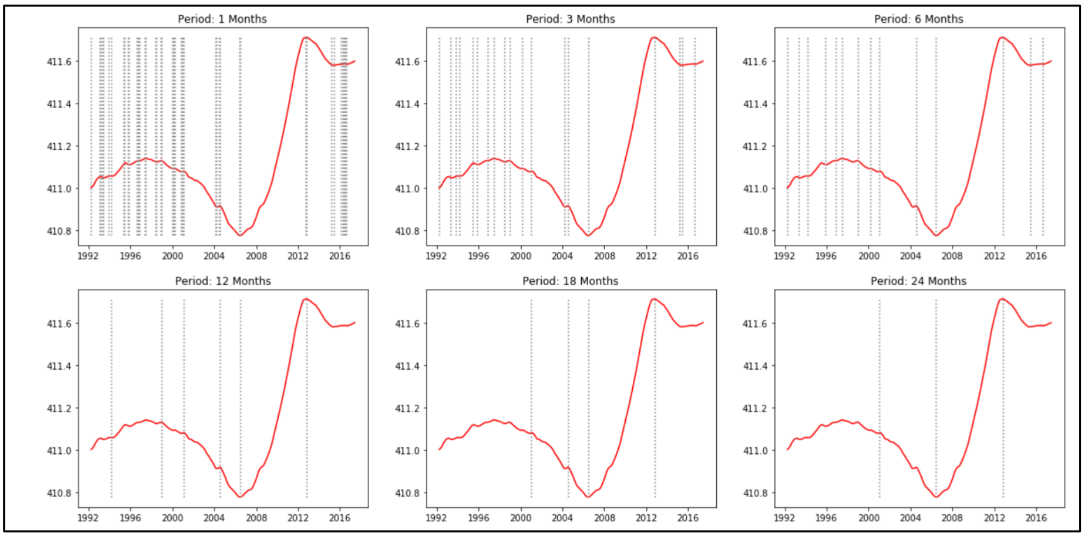
1. The groundwater level records are initially resampled monthly with a mean. A moving window size is selected for each site in order to smooth out any noise in the data or potential seasonal effects. This term is referred to as the trend component (Mt).



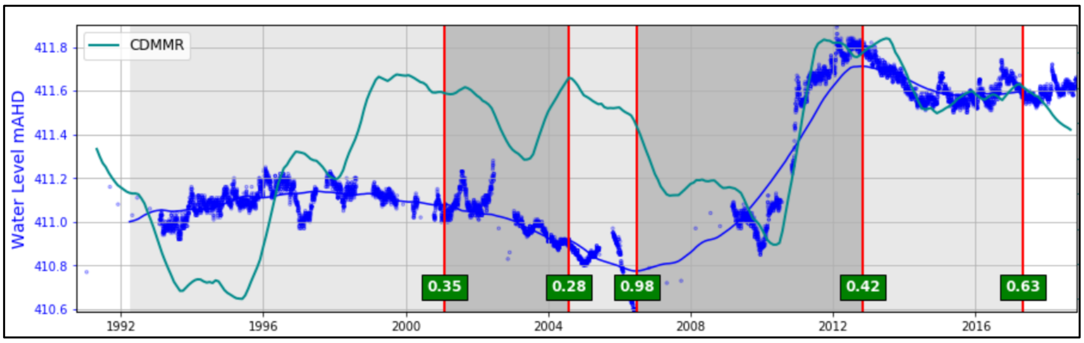
2. Pairwise differences Xdiff for all x in n (the number of observations) are calculated such that:

$$X_{diff} = [x_2 - x_1, x_3 - x_2, \dots, x_n - x_{n-1}]$$

3. The sign of all values in Xdiff is determined such that the sign is either -1, 0 or 1.
4. Groups are then formed where consecutive values have the same trend.
5. Breakpoints are then selected based on a minimum period (months) of consecutive trend. This parameter is set manually, based on visual inspection.



6. The data are then split into monotonic components, based on the identified breakpoints.



In some situations, additional breakpoints were added manually to better show the influence of climatic or extraction breakpoints that did not necessarily correspond to groundwater level breakpoints.

G.3 Cross correlation analysis

Once monotonic periods were isolated using the breakpoints analysis described in section G.2, a cross-correlation analysis was performed in order to correlate groundwater level trends with CDMMR, non-CSG water use and CSG groundwater extraction.

A Spearman correlation was used to identify monotonic correlation between these variables. The spearman coefficient (ρ_s) was calculated using the inbuilt .corr() function in the Pandas module of Python. The Spearman coefficient is defined by:

$$\boldsymbol{\rho_s = 1 - (\frac{6\sum d_i^2}{n(n^2-1)})}$$

Where d_i is the difference between the two ranks of each variable and n is the number of observations. A coefficient of 1 implies perfect positive correlation, 0 implies no correlation and -1 implies perfect inverse correlation.