Regional flow systems and potentiometry in Queensland's Surat and southern Bowen basins

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1 Introduction

1.1 About this document

To support the cumulative assessment of groundwater impacts from coal seam gas (CSG) and coal mining in the Surat Cumulative Management Area (CMA), the Office of Groundwater Impact Assessment (OGIA) collated and analysed the available groundwater pressure information to conceptualise the groundwater systems and support the calibration of the regional groundwater flow model. A summary of the groundwater flow directions is provided in the Underground Water Impact Report (UWIR) 2021 for the Surat CMA (OGIA 2021a).

This companion document supplements the UWIR 2021 with additional technical details on the available data sources, data treatment and methodology OGIA has applied to generate potentiometric surfaces for the major hydrostratigraphic units across the Surat CMA.

1.2 Context

Potentiometric surface maps are fundamental tools to support the development of a conceptual model for groundwater systems (Anderson & Woessner 2002; Barnett et al. 2012). These maps provide important insights on key groundwater flow processes such as:

- dominant groundwater flow directions, including horizontal and vertical flow components
- the location and influence of recharge and discharge features, including influences both natural (e.g. springs and rivers) and anthropogenic (e.g. water supply pumping)
- the influence of any boundaries (barriers or conduits) such as faults.

A detailed conceptualisation of the aquifers of the Surat CMA was completed in 2016 (OGIA 2016a) including the development of potentiometric surfaces for all major aquifers and aquitards. Updated potentiometric maps have been generated for key formations adjacent to the target resource development formations – the Walloon Coal Measures and the Bandanna Formation - to visualise and conceptualise potential for impacts from CSG and coal mine development.

2 Methodology

This section provides a summary of the data sources and methodology for the development of an integrated groundwater level dataset and potentiometric surface mapping in the Surat CMA.

2.1 Overall approach

The detailed methodology applied is provided in subsequence sections of this document. More broadly, the overall approach to potentiometric surface mapping included the following steps:

- Compilation of groundwater level data from various sources including Queensland Government and tenure holder monitoring (section 2.2).
- Quality assurance of the dataset to flag and remove erroneous data and bores where the data was considered potentially erroneous (section 2.3.1).
- Assignment of the records to aquifers based on OGIA's attribution for the water supply bore or monitoring point (section 2.3.2). Importantly, only those bores where there was only single contributing or dominant aquifer were included.

- Selection of data based on the aquifer and the period of record. This was initially completed automatically for data collected since 2018 – the current period (section 2.4.2).
- Review and trial of interpolation methods. The maps were prepared using the ArcGIS Pro function, 'Topo to Raster' (section 2.4).
- Review and finalisation of potentiometric maps (section 3). Where there was limited data, manual review of older data was undertaken and included where it was considered representative.

2.2 Data

2.2.1 Context

The availability of groundwater level data across the Surat CMA varies spatially and temporally, reflecting the evolution of groundwater management, monitoring and the stressors on the groundwater system through time.

Prior to the commencement of CSG development and related monitoring (pre-2006), the majority of the monitoring infrastructure in the Great Artesian Basin (GAB) and alluvium was established for managing groundwater use by the Queensland Government – the Department of Regional Development, Manufacturing and Water (DRDMW) and its predecessors. Reflecting this focus, pre-CSG infrastructure and data is therefore predominantly limited to outcrop areas away from CSG development, where groundwater was generally accessed at shallower depths for consumptive purposes.

Since 2010, there has been a significant increase in monitoring infrastructure in deeper formations within and adjacent to CSG tenures, with monitoring points established in response to previous UWIR requirements or for their own specific purposes (Chapter 9, OGIA 2021a).

2.2.2 Groundwater level data

In preparing potentiometric surfaces, OGIA has collated and compiled the available data to establish an integrated groundwater level dataset. The methodology and quality assurance measures used to develop the integrated groundwater level dataset are summarised in section 2.3.

Across the entire groundwater model domain for the Surat CMA (650×450 km), the complied dataset contains around 36,000 unique locations where groundwater level information is available, with approximately 2.6 million groundwater level records.

The integrated groundwater level dataset comprises the following data sources:

- **Water Monitoring Strategy (WMS)** – in accordance with the obligations under the UWIR, as well as Queensland and Australian government conditions of approval, tenure holders install, monitor and maintain an extensive groundwater network. This data is provided to OGIA every six months.
- **Baseline and baseline assessments** – OGIA maintains a database of tenure holder bore and baseline assessments of water supply bores. This dataset includes records of groundwater level measurements taken during these assessments.
- **Queensland groundwater database (GWDB)** – the Queensland Government's central repository for water bore information. Groundwater level information was compiled from various GWDB tables, including the water level, pump test, aquifer and stratigraphy tables.

2.2.3 Complementary data

In parallel with the integrated groundwater level dataset, the following are utilised as part of the methodology:

- **1-second Digital Elevation Model (1s DEM)** – a digital ground-surface model at a resolution of approximately 30×30 m. This surface is interpolated with the groundwater level data.
- **OGIA geological model** – a regional geological model developed and progressively refined to represent the lithostratigraphic-based conceptualisation of the Surat and Bowen basins. Currently comprising 22 stratigraphic surfaces (OGIA 2021b), the model is used to define the spatial extent of formations for the potentiometric surfaces.
- **Estimated pressure head at springs** – the pressure head for the spring (as observed or estimated by OGIA) provides a known piezometric level that can be prescribed to the source aquifer at that discrete location. This supplementary data provides localised definition of groundwater flow conditions at sites of local-scale natural discharge.

2.3 Data preparation

2.3.1 Quality assurance

Available groundwater level data may be unreliable due to a range of factors such as the construction of the water bore, influences on the bore at the time of the reading (i.e. pumping or record taken during construction), malfunctioning of the pressure transducer, or transcription errors in the field.

To identify and remove potentially erroneous data, OGIA has developed a series of functions to assign quality flags to groundwater level measurement at both a bore scale and at an individual groundwater level record scale. The complete list of quality flags developed by OGIA is provided in Appendix 2. In generating potentiometric surfaces presented in this report, the data quality flags listed in Table 2-1 were used to exclude data from the dataset.

Table 2-1: Applied data quality flags

Flag	Description	Type
1	Standing water level (SWL) is interpreted to be deeper than the base of the bore	
5	Default or null value	
11	The SWL is assigned to the 'X' pipe in the GWDB, indicating that the measurement was taken prior to the installation of casing	
16	GWDB code indicates the data is of poor quality (quality code 20)	
24	Identified as an isolated erroneous measurement in the UWIR WMS dataset	Record
25	Logger data where the groundwater level is interpreted to represent the logger reaching equilibrium and unrepresentative of groundwater level conditions	
26	UWIR WMS quality flag indicating that the monitoring point is no longer in use	
28	UWIR WMS quality flag indicating a flat line trend in groundwater level	
34	Artesian conditions exceeding 45 m, which are potentially erroneous	
29	UWIR WMS quality flag indicating that the entire record is erroneous	
30	UWIR WMS quality flag indicating the bore has a status of 'active and anomalous'	Bore
31	UWIR WMS status flag of 'Dry'	
32	UWIR WMS status flag indicating that there is a problem with the monitoring point	

Flag	Description	Type
33	UWIR WMS status flag indicating that the monitoring point is faulty	

2.3.2 Aquifer attribution

OGIA has developed an extensive method for the assignment of aquifers to water bores and monitoring across the CMA. Since the original workflow was developed in 2011, the aquifer attribution process has evolved in complexity. The approach incorporates OGIA's geological model, with bore construction and hydrostratigraphic information from GWDB aquifer and strata log tables, water licensing information, as well as from tenure holder-supplied datasets to assign a source aquifer to monitoring points. Additional information on the method is available in a companion document (OGIA 2021c). Overall approach includes two primary steps:

- Available datasets are collated for each RN–pipe combination. This step generates a master dataset of all available data for each RN–pipe.
- A hierarchical ruleset approach is applied to the master dataset to assign the contributing formation(s) to each RN–pipe combination. Highest confidence data and rulesets are applied first, with lower confidence datasets applied last.

Assumptions are made where necessary, such as the following:

- Where no depth information is available, a bore is assumed to be screened in the aquifer that is most frequently intersected by other water bores within five kilometres.
- Where information about the depth is available but the screened depth is not, the screened depth is assumed to be the same as other water bores constructed to similar depths and at similar times.
- In areas where the geological model has very limited or no control points, aquifer attribution recorded in the GWDB or licensing information is retained.

Importantly, where the bore is screened or open across multiple formations, the relative transmissivity of those formations is used to assign the dominant and secondary contributing aquifers. Only those water bores or monitoring points with primary aquifers that are ≥80% dominant are included in the generation of potentiometric surfaces.

2.3.3 Corrections

2.3.3.1.1 Data

For the generation of potentiometric surface maps, groundwater levels are converted to absolute (mAHD (Australian Height Datum)). Depending on the data source and format, data corrections vary and are summarised as follows:

- The tenure holder datasets (WMS UWIR) are provided in mAHD and are maintained.
- Data collated from the GWDB and tenure holder bore and baseline assessments may contain casing above ground ('stickup') and ground elevation information. Where this is available, a groundwater level is calculated (mAHD).
- Where this information is unavailable, the 1s DEM is used as the reference elevation to calculate a groundwater level (mAHD).

2.3.3.1.2 Density

Due to the geometry of the regional groundwater flow system (Surat and Bowen basins), some monitoring bores are installed at significant depths (>1,000 m), resulting in large variations of groundwater temperature, both within the boreholes themselves (between the water table and the screen intervals) and between individual monitoring points. Density variability is therefore observed both within individual formations and vertically across multiple formations.

Darcy's Law, a commonly applied differential equation used to describe flow in groundwater systems, does not consider variable-density environments and so the application of fluid density and atmospheric corrections should therefore be considered and applied where appropriate.

To accurately interpret groundwater flow conditions, it is necessary to correct pressure measurements for variations in temperature. While salinity also influences density, given the salinity ranges observed in the Surat Basin, this is not thought to dramatically influence water level measurements.

Two types of density correction are used in this workflow:

- **Water column correction** – accounting for the 'cooling head' effect on measured water levels, where water temperature within the water column differs from the screen interval. The difference in temperature causes a variation in density within the water column, which can result in a water level that is not representative of the formation pressure.
- **Conversion of hydraulic heads to reference heads** – when considering horizontal and vertical flow directions, it is important to convert all water level data to a common reference density. In this report, the reference density applied is freshwater at 20° C.

A detailed description of the equations used, and the application of this methodology to OGIA's integrated water level database, are presented in Appendix 1.

2.4 Data interpolation

2.4.1 Methodology

Groundwater conditions vary depending on the hydraulic conditions of the aquifer – confined versus unconfined. Measurement points have therefore been subdivided according to whether they source groundwater under either confined or unconfined conditions. For each major aquifer, the following steps are then applied:

1. Within the unconfined area, data points have been interpolated using co-kriging with the 1s DEM and then sampled at 250-m grid locations. The resulting raster surface is then converted to a point dataset.
2. The unconfined area point dataset is then interpolated with the measurement points in the confined part of the aquifer system. The ArcGIS Pro 'Topo to Raster' tool is applied.
3. Where interpolation in the unconfined area results in a potentiometric surface that extends below the base of the formation, the potentiometric surface has been limited (clipped) to where the potentiometric surface occurs above the base of the formation. This is interpreted to be the saturated extent of the formation.

2.4.2 Time steps

As a general hydrogeological principle, groundwater level data should only be contoured where it has been collected within a similar time period. As water balance factors in the groundwater system – recharge, groundwater pumping and discharge – can vary through time, using data from a similar time period seeks to normalise the potential temporal variability and influence of these factors on the observations and the resulting potentiometric surface.

This is a significant challenge in the Surat CMA, given the regional extent of the groundwater system. While current groundwater flow conditions are the primary focus for the UWIR, data from earlier time periods has been incorporated where data is considered representative. This is primarily used where data is necessary to constrain potentiometric surfaces where there is no data. Potentiometric surfaces have been produced, for information purposes, for several time periods as described in Table 2-2.

Table 2-2: Time periods and data treatment

Time period	Description
Current (2018–2021)	Available data from the last three years (1/1/2018 to mid-2021). The latest available groundwater level record is used for the Walloon Coal Measures (WCM) and Bandanna Formation (BAN). Mean groundwater level record is used for all other formations.
2015	Available data between 1/1/2012 and 1/1/2015. This represents the period after a significant aquifer recharge event and prior to commencement of reinjection. The latest groundwater level record is used for both the WCM and BAN. Mean groundwater level record is used for all other formations.
2005	Available data from 1/1/1995 to 1/1/2005. This represents the pre-CSG period in the Surat Basin. The last record is used for the BAN. Mean groundwater level record is used for all other formations.
1995	Available data from 1/1/1947 to 1/1/1995. This represents the pre-CSG period in the Bowen Basin. The last record is used for the BAN. Mean groundwater level record is used for all other formations.
All time	Available data from 1900-01-01 to mid-2021. Mean groundwater level record is used for the BAN and mean groundwater level record is used for all other formations.

2.4.3 Assumptions

Key assumptions and limitations with the interpreted potentiometric maps are as follows:

- There are limited monitoring points in the deeper parts of the groundwater system. As a result, the potentiometric maps down-gradient of the CSG development areas have a low confidence.
- In unconfined aquifer areas, co-kriging is used to interpolate groundwater levels with topography. It is assumed that the water table in outcrop areas is a subdued expression of topography. The algorithm uses multivariate data analysis to interpolate groundwater levels by considering their relationship with surface topography in areas where minimal water level data exists.
- At known springs, the pressure heads for the springs (observed or estimated by OGIA) are assumed to represent the potentiometric surface of the springs' source aquifers.

3 Results and discussion

Potentiometric surfaces have been generated for the Condamine Alluvium, Springbok Sandstone, Upper Juandah Coal Measures, Lower Juandah Coal Measures, Taroom Coal Measures, Hutton Sandstone, Precipice Sandstone, Clematis Sandstone and Bandanna Formation. Potentiometric maps showing the interpreted groundwater flow directions for these formations are provided in the following sections.

3.1 Regional groundwater flow

A generalised map of groundwater movement in the Surat Basin is provided in Figure 3-1, as shown in the UWIR 2021. Across the Surat Basin, regional lateral groundwater flow directions north of the Great Dividing Range (the Range) are generally northward, with groundwater discharging into the Dawson River catchment. South of the Range, groundwater flow is generally southward, broadly consistent with the dip of the formation.

Vertically across the formations, the head gradients are generally downwards in outcrop areas where recharged water enters the system. Further downdip, in deeper parts of the system, these gradients reverse to upward. Local and subregional variations to this regional pattern occur in response to groundwater use, geological features and CSG development.

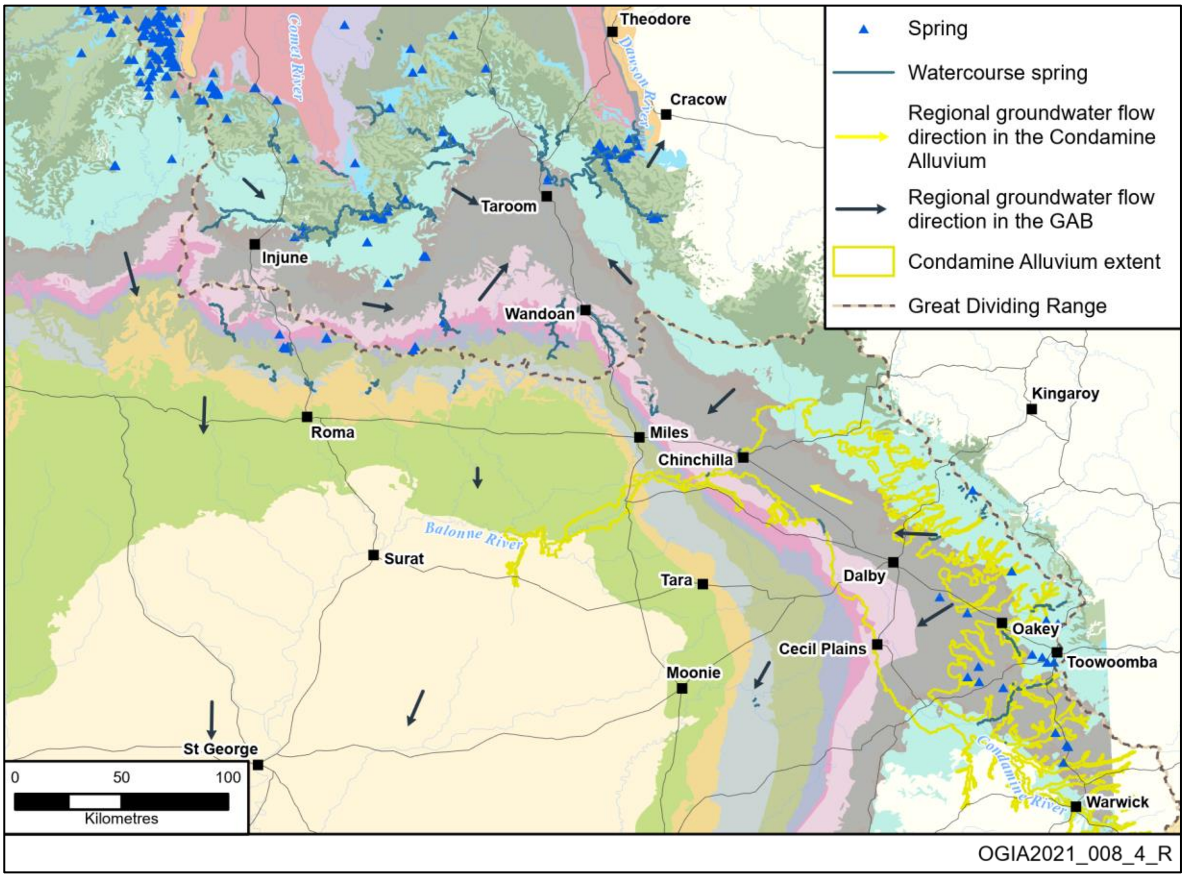

Figure 3-1: Representation of the main groundwater systems in the Surat CMA

3.2 Condamine Alluvium

The Quaternary Condamine Alluvium is incised into the Jurassic Surat Basin sequence. The Surat Basin (Springbok Sandstone and Walloon Coal Measures) subcrops beneath most of the central alluvium, forming the bedrock. The alluvial and sheetwash deposits of the Condamine River and tributaries form a broad plain between Millmerran and Chinchilla (OGIA 2016a).

3.2.1 Recharge and discharge

The Condamine Alluvium is primarily recharged from the Condamine River and its tributaries, with less significant recharge occurring via rainfall and irrigation. Streambed recharge is the primary recharge mechanism. The Condamine River is a losing stream, as groundwater levels in the surrounding alluvial aquifer have declined due to extraction and are consistently below the elevation of the streambed (OGIA 2016a).

Natural groundwater discharge is through a limited alluvial section downstream, with some lateral flows toward the western bounding aquifers and diffuse discharge via vegetation (Dafny & Silburn 2014). The main source of discharge is through water supply bores.

3.2.2 Groundwater flow

The Condamine Alluvium has been significantly developed for groundwater supply since the 1960s. Groundwater management has progressively increased, with the regulation of the drilling of additional bores and limitations on the take of water in intensively developed areas. A groundwater monitoring network was established to manage this development and is maintained by DRDMW.

Historically, a range of potentiometric surface have been prepared to support various studies on the Condamine Alluvium. Historical potentiometric surfaces in the Condamine Alluvium have also been prepared (KCB, 2010b) and are shown in Figure 3-2. It is evident that large depressions in the potentiometric surfaces gradually developed as a result of extensive groundwater use that began around the 1960s.

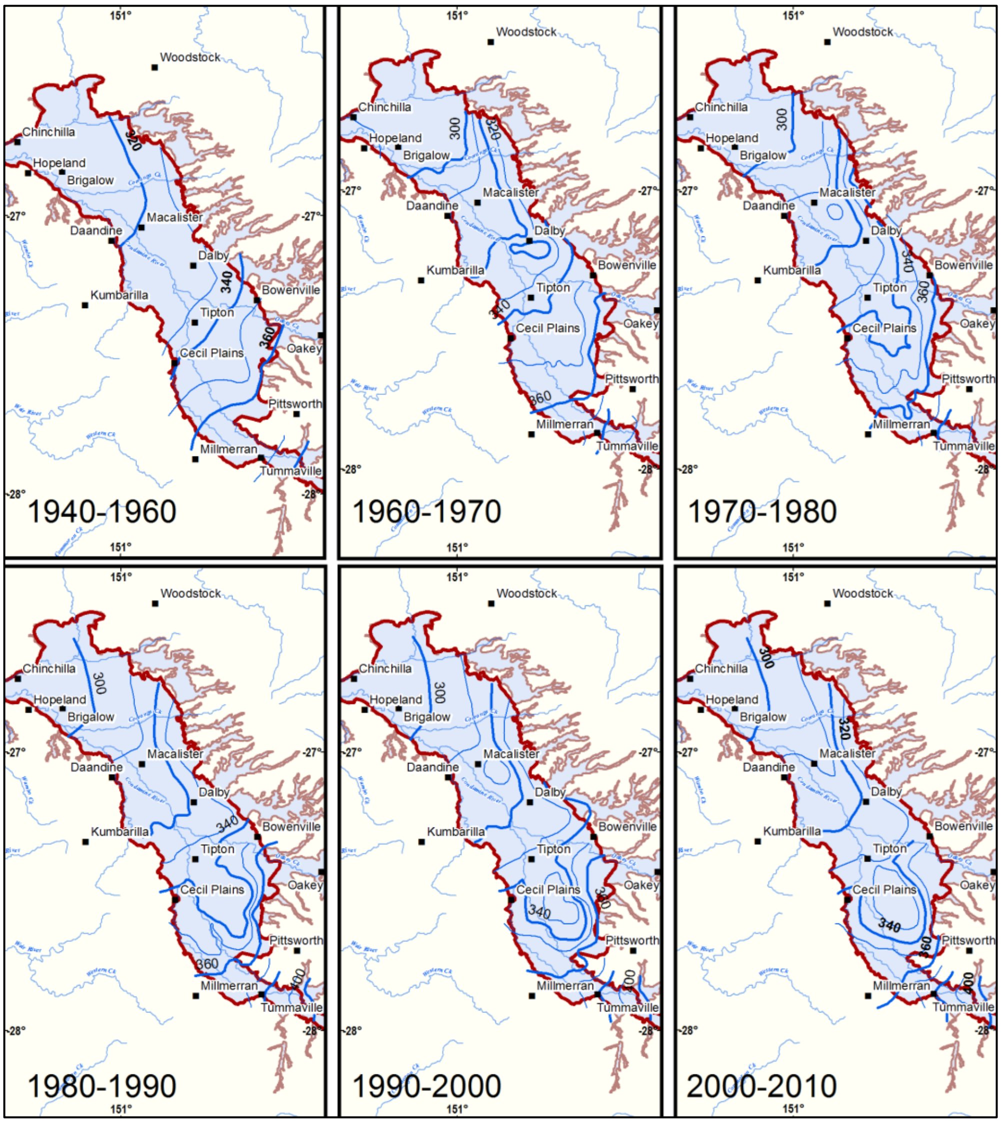

Figure 3-2: Historical groundwater levels in the Condamine Alluvium, 1940–2010 (OGIA 2016b)

The current potentiometric surface (2018–2021) for the Condamine Alluvium is shown in Figure 3-3. At the southern extent, groundwater levels of 400 mAHD are observed, down to less than 290 mAHD near Chinchilla in the north. Significant features of this surface are the large depressions east of Cecil Plains (~304 mAHD) and immediately east of Dalby (~320 mAHD). These depressions coincide with areas of high groundwater use.

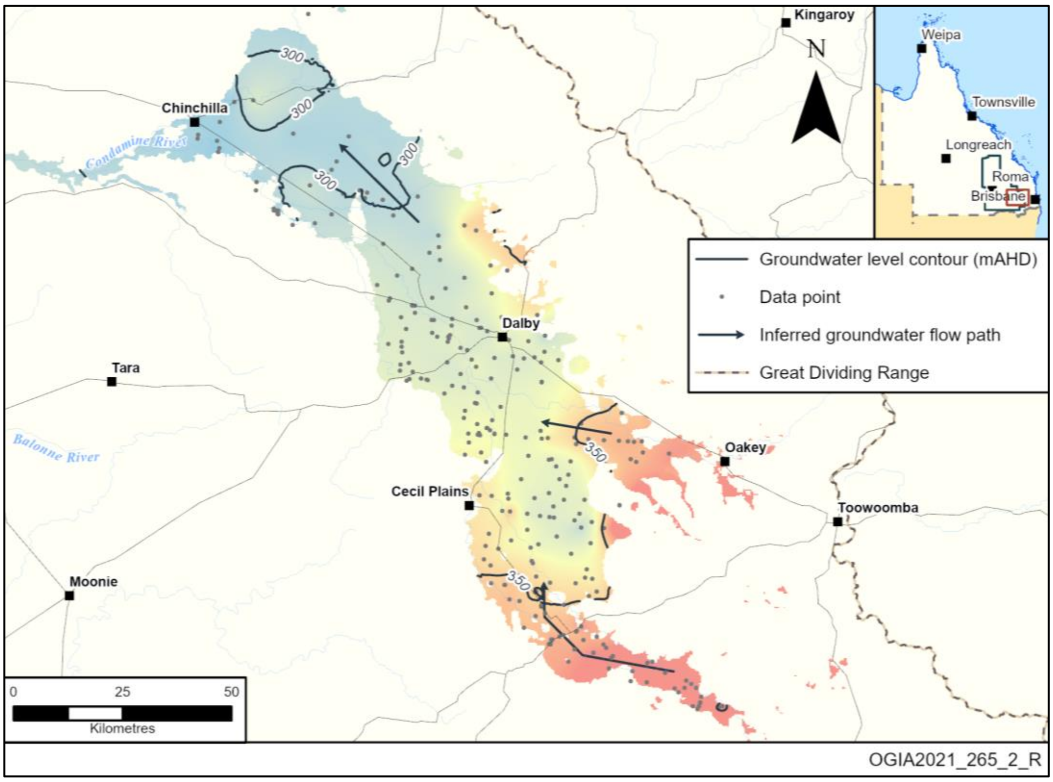

Figure 3-3: Condamine Alluvium groundwater levels, 2018–2021

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

For the majority of the area, the vertical hydraulic gradient is from the Walloon Coal Measures to the Condamine Alluvium. However, as CSG development occurs and depressurises the Walloon Coal Measures, the hydraulic gradient is progressively reversed – the vertical hydraulic gradient is towards the Walloon Coal Measures. At this stage, this is most prominent west of Dalby, where there has been substantial CSG development and gradients of more than 50 m towards the Condamine Alluvium are observed (OGIA 2021a).

3.3 Springbok Sandstone

The Springbok Sandstone overlies the Walloon Coal Measures, underlies the Westbourne Formation and comprises medium to fine-grained, feldspathic to lithic sandstone with minor pebbly layers, siltstone, mudstone and occasional thin bentonite and coal lenses. The formation has a typical thickness ranging from 70 to 200 m and attains a maximum thickness of around 300 m in the Mimosa Syncline (OGIA 2019a). Despite the relatively high sandstone composition of this formation, the

Springbok Sandstone is classified as a tight aquifer (OGIA 2021a) due to its low horizontal permeability.

3.3.1 Recharge and discharge

The potentiometric surface maps indicate the Springbok Sandstone is primarily recharged in the outcrop areas in the north-western (near Injune) and eastern (south of Dalby) parts of the basin. Estimated recharge is about 5.7 GL/year, or 1.3 mm/year using the chloride mass balance (CMB) method (OGIA 2019b).

Although considered a minor water supply aquifer, discharge from the Springbok Sandstone is primarily through water bores and wells (OGIA 2021a). There are about 166 water supply bores for stock and domestic (S&D) and agricultural purposes, with a total estimated use of around 369 ML/year, proximal to active resource development areas (area of interest). The majority is for S&D purposes, located within and adjacent to the formation outcrop. There are few water supply bores in the deeper confined parts of this aquifer. The formation has limited groundwater use compared to other aquifers such as the Gubberamunda, Hutton and Precipice sandstones.

OGIA compared CSG well screen intakes against the geological formations to assess the potential for direct extraction of associated water from surrounding aquifers (OGIA 2021d). Analysis suggests that approximately 16% of the CSG wells are partially completed into the Springbok Sandstone, but an analysis of water production data suggests that 97% of wells partially completed into the Springbok Sandstone do not extract materially higher volumes of water compared to wells in the same gas fields that are exclusively completed into the Walloon Coal Measures.

The Springbok Sandstone is interpreted to support several watercourse springs where the formation outcrops on the northern side of the Range. Terrestrial groundwater-dependent ecosystems (GDEs) may also occur where the formation has been dissected by surface-water flows, the water table is shallow and deep-rooted vegetation is present (section 4.4.9, OGIA 2021a).

3.3.2 Groundwater flow

The current potentiometric map for the Springbok Sandstone is shown in Figure 3-4. The formation extends predominantly south of the Range. The map incorporates data from 89 locations, 52 of which are tenure holder monitoring points and the remainder (37) being GWDB bores. There is reasonable coverage of tenure holder monitoring in the Springbok Sandstone across the gas field areas.

The groundwater flow system is interpreted to be multi-directional and deviates from the traditional concept of groundwater flow directions in the GAB. This is interpreted to a combination of the natural variability in the formation properties, groundwater use and localised CSG impacts.

The major groundwater flow systems observed include the following:

- Regional flow directions northwest-to-southeast from Injune to Goondiwindi and east-to-south from Dalby to Goondiwindi. These two regional flow systems appear to converge along the Mimosa Syncline, but may be influenced by the available data density in these areas.
- A groundwater divide, coincident with the Range, to the north of Roma and Miles.
- A local west-to-east system along the north-western margin of the Condamine River floodplain and to the south of the river. OGIA has assessed that localised drawdown at a monitoring point (Kenya East GW4) is a CSG impact in this area (OGIA 2019c, 2019d, 2019e). There are also plausible mechanisms for more direct connectivity between the reservoir and the aquifer at this location, with an apparent stress–response relationship.

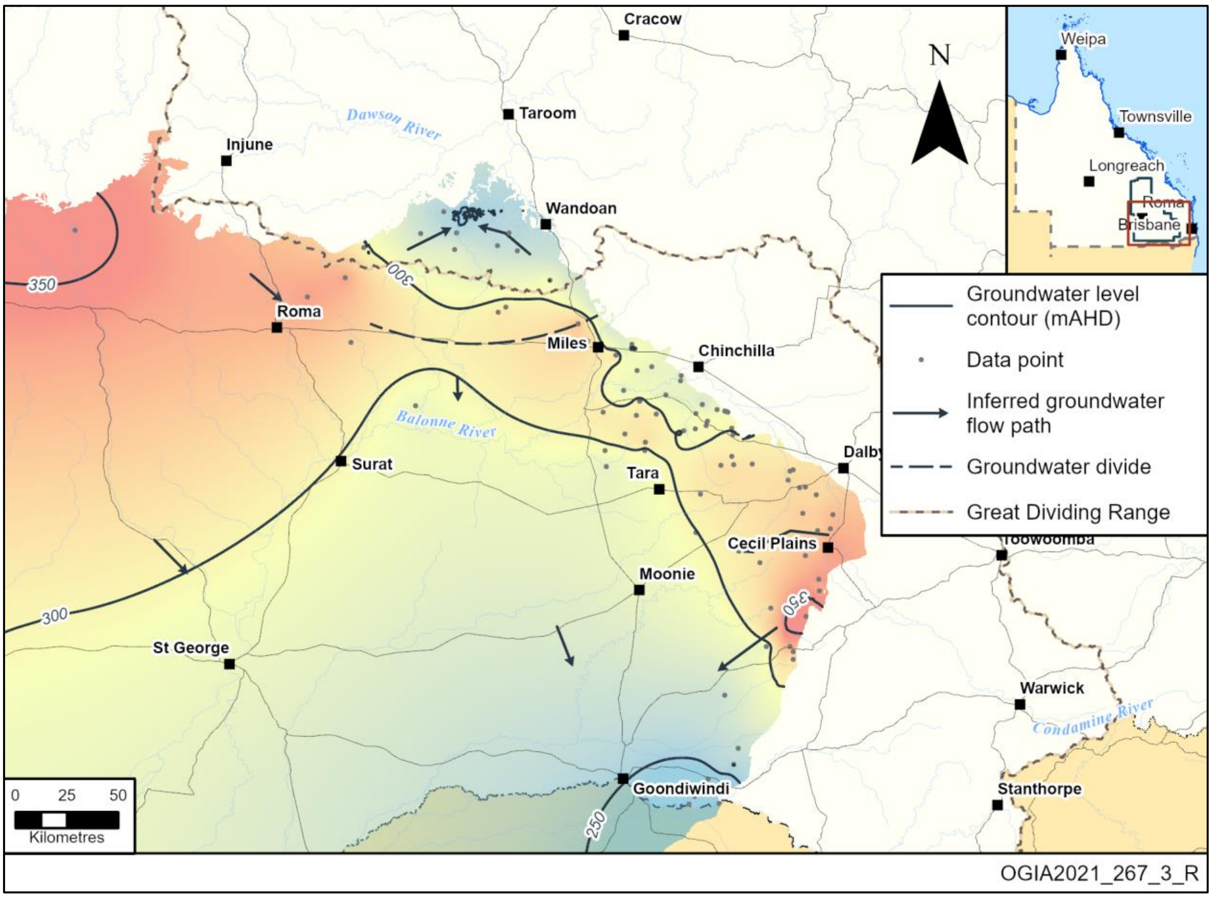

Figure 3-4: Interpreted groundwater flow directions in the Springbok Sandstone, 2018–2021

- A south-to-north flow system in the northern Surat gas fields area with localised convergence of flow along Horse Creek. A moderate concentration of groundwater use in this area may also be contributing locally to the drawdown observed.

The Walloon Coal Measures and Springbok Sandstone are highly stratified and include significant proportions of siltstone and mudstone. Based on core permeability tests and formation-scale numerical permeameter results, the estimated vertical permeability is much lower than in the horizontal direction (section 4.4.3, OGIA 2021a).

In areas of CSG development, large vertical pressure gradients are now observed from the Springbok Sandstone towards the Walloon Coal Measures – induced by CSG depressurisation.

3.4 Walloon Coal Measures

The Walloon Coal Measures is the primary Surat Basin target formation for CSG extraction and coal mining, ranging in thickness from 300 to 350 m within the CSG production areas. It comprises mostly thin, discontinuous coal seam layers, siltstone, mudstone and fine to medium-grained lithic sandstone, deposited over millions of years from rivers and in lakes and swamps across the Surat and Clarence-Moreton basins (Scott et al. 2004).

The two coal-dominated subunits within the Walloon Coal Measures are the Juandah Coal Measures in the upper part and the Taroom Coal Measures in the lower part. The Walloon Coal Measures is unconformably overlain by the Springbok Sandstone and is separated from the underlying Hutton Sandstone by the Durabilla Formation – a regionally extensive aquitard (see Figure 4-4, OGIA 2021a).

3.4.1 Recharge and discharge

The long-term mean recharge rate derived from the CMB approach is estimated to be 1.3 mm/year (OGIA 2019b). Similar to other GAB formations, a high proportion of this recharge is rejected through outflows to streams and rivers during model calibration.

Discharge is primarily through water bores and CSG groundwater extraction. There are more than 794 water supply bores used for S&D and agricultural purposes within 15 km of resource development areas – mainly in outcrop areas – taking an estimated 2,375 ML/year (see Table 3-1, OGIA 2021a). In comparison, CSG groundwater extraction associated with depressurisation is about 54,000 ML/year (see section 2.3.5, OGIA 2021a). A relatively very small volume (less than 1,000 ML/year) is extracted during dewatering of operational coal mines.

Natural groundwater discharge appears to be into the outcrop areas to the north of the Range and potentially into the Dawson River (OGIA 2016c). Some discharge is also likely to occur through evapotranspiration in outcrop areas.

3.4.2 Groundwater flow

Groundwater flow in the Walloon Coal Measures is represented separately for the Taroom, Upper Juandah and Lower Juandah coal measures in Figure 3-5 and Figure 3-6. Taroom Coal Measures (Figure 3-5) potentiometric surface was generated from 154 data points, the Upper Juandah Coal Measures was generated from 135 data points (Figure 3-6 upper) and the Lower Juandah Coal Measures was generated from 123 data points (Figure 3-6 lower). There is extensive data coverage in the major development areas across the subunits of the Walloon Coal Measures.

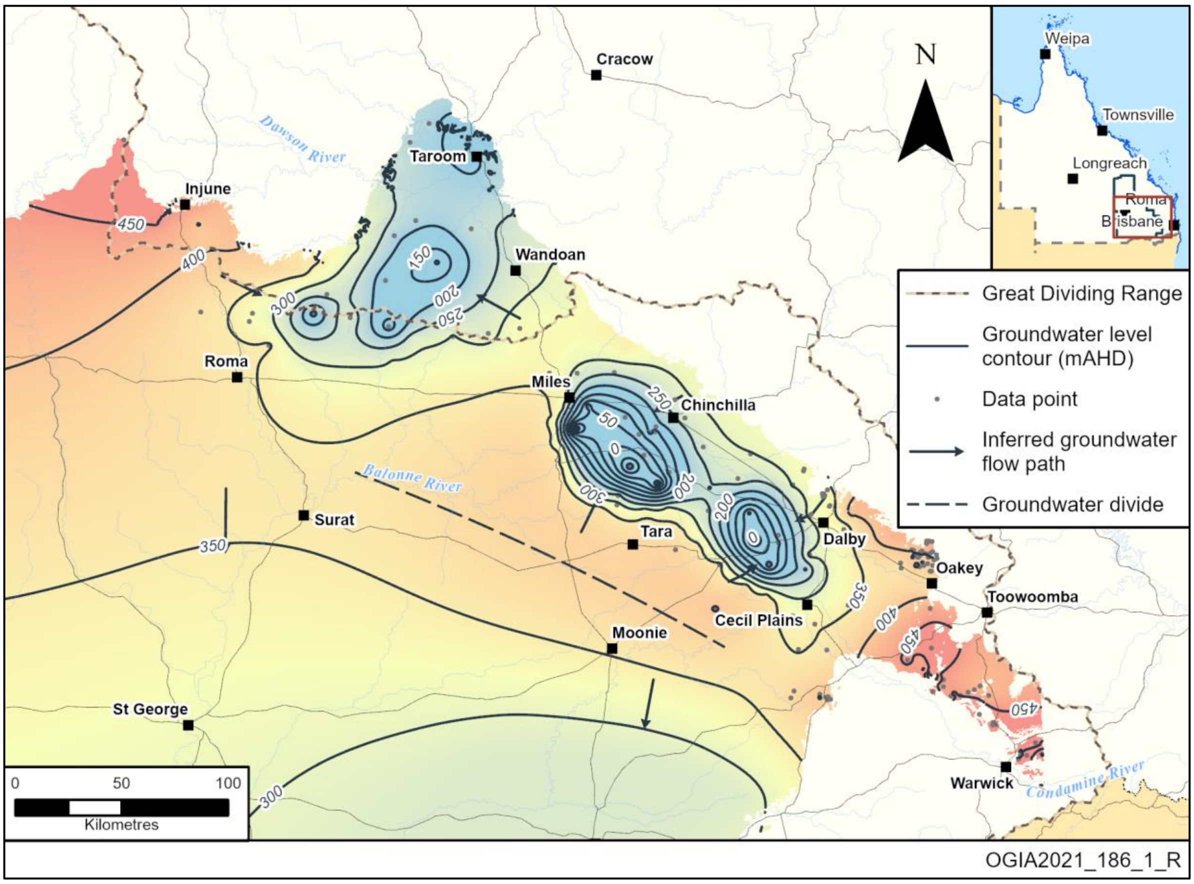

Figure 3-5: Interpreted groundwater flow directions in the Taroom Coal Measures, 2018–2021

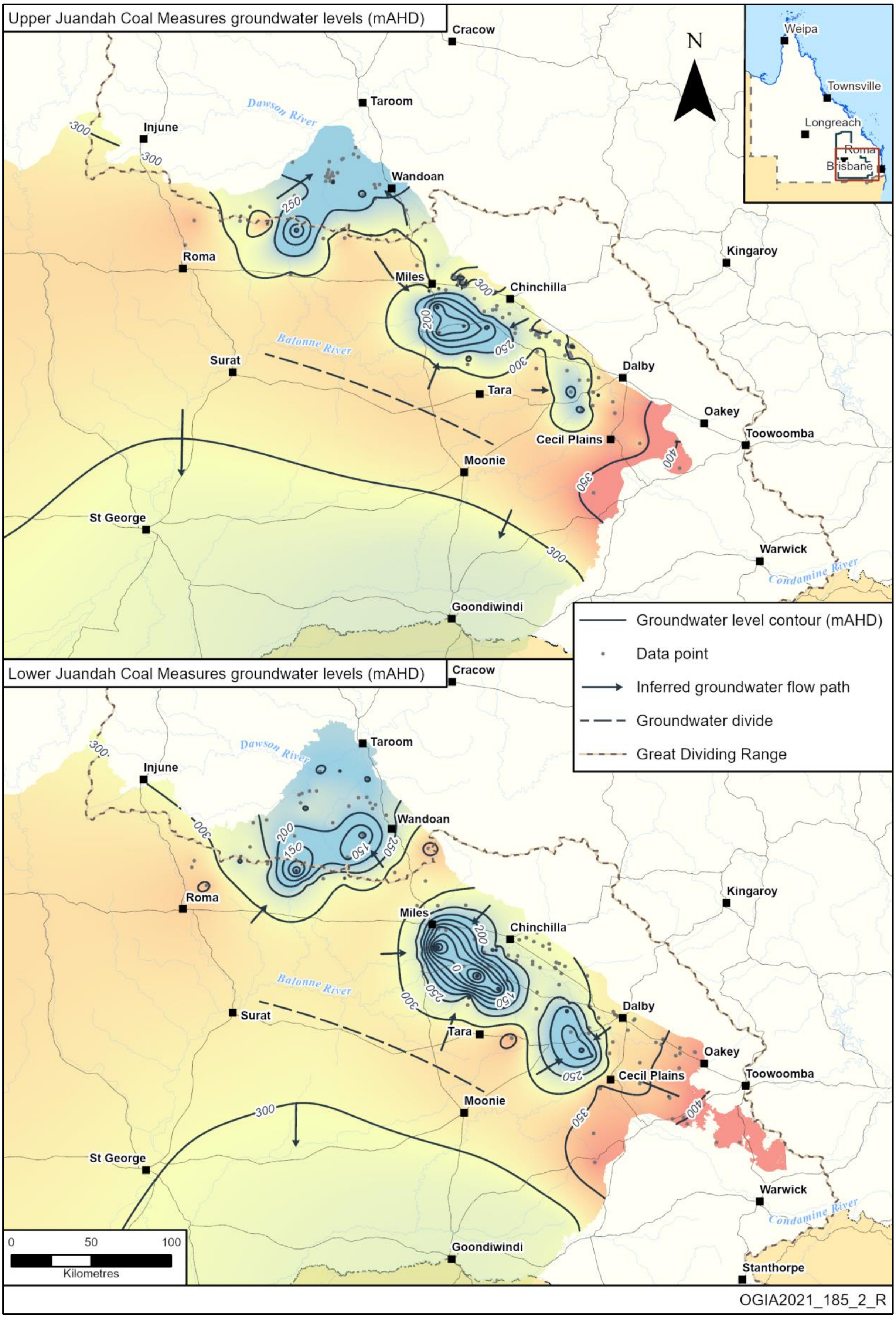

Figure 3-6: Interpreted groundwater flow directions in upper and lower Juandah coal measures, 2018–2021

The regional groundwater flow systems are largely aligned with those observed in the overlying Springbok Sandstone; southwest to southeast system from near Injune; an east-to-south system from near Dalby; and a south-to-north system on the northern side of the Range, towards Taroom. Large radially convergent drawdown patterns observed in the CSG development areas are exceptions to this alignment. This is particularly evident in the eastern areas where up to 200 m of drawdown is observed locally. The observed drawdown in the CSG areas appears to be very steep, with little drawdown observed outside of the operating fields. This is likely to reflect the discontinuous nature of the coal in these gas fields and low effective horizontal permeabilities.

The regional and local flow systems in the Taroom Coal Measures are generally consistent with the Upper Juandah Coal Measures and Lower Juandah Coal Measures, however the magnitude and extents of drawdown in CSG areas is appreciably greater. This tends to confirm that depressurisation has impacted this deeper formation more intensely and has produced a general downwards flow potential within the Walloon Coal Measures in these gas field areas. As with the Upper Juandah Coal Measures, the drawdown cones are steep away from active CSG fields, such that diminished drawdown is observed more than 10 km from the operating gas fields.

In terms of vertical hydraulic gradients, under pre-development conditions, similar to the relationship observed between formations, an upward gradient would be expected between the subunits of the Walloon Coal Measures – from the Taroom Coal Measures to the Juandah Coal Measures. Due to the high permeability contrast between the coal and the matrix (or interburden), horizontal flow dominates within these formations, with vertical flow being restricted.

CSG development has altered, and will continue to alter, the vertical flow regime by significantly lowering the pressure in the formation. As CSG groundwater extraction advances, the pressure difference between the coal seams and the interburden will gradually increase, causing some flow from the interburden to coal seams, while the release of gas within the coal seams provides additional resistance to the flow of water (section 4.4.2, OGIA 2021a).

Following the commencement of CSG development, larger pressure declines are generally observed in the Taroom Coal Measures, with declines subsequently observed in the Juandah Coal Measures. This delay in the vertical propagation of pressure decline reflects the heterogeneity of the formation and the dominance of lateral flow.

3.5 Hutton Sandstone

The Hutton Sandstone is the most extensive Jurassic aquifer within the Surat Basin and is separated from the overlying Walloon Coal Measures by the Durabilla Formation. Thicknesses of the formation typically range between 150 and 200 m, reaching up to 400 m along the axis of the Mimosa Syncline. Comprising sandstone interbedded with siltstone, shale, minor mudstone and coal, the formation is highly heterogeneous and has significant lateral and vertical facies changes, especially towards the eastern margin of the Surat CMA (OGIA 2016a). The permeability of this formation is highly variable (Figure 3-7, OGIA 2021a).

3.5.1 Recharge and discharge

The Hutton Sandstone is primarily recharged in the outcrop areas in the north-western (near Injune) and eastern (east of Dalby) parts of the basin, along the Range. The long-term mean recharge rate derived from the CMB method is 3.2 mm/year, resulting in an annual estimate of recharge of about 39.6 GL/year (OGIA 2019b). Similar to other formations, the model-calibrated recharge is lower because most of the recharge is rejected as losses to local groundwater discharge features in the outcrop zone, e.g. stream baseflow as well as evaporation and transpiration (OGIA 2019b). This conclusion is supported by other recent studies (Raiber & Suckow 2017).

Discharge is primarily though water supply bores. The Hutton Sandstone is extensively developed, with more than 1,200 water bores and a total estimated water use within the area of interest of about 7,800 ML/year for stock-intensive, S&D, irrigation, town water supply and industrial and agriculture purposes (Table 3-1, OGIA 2021a). Most of this use is in areas where the formation is either at outcrop or at depths of less than 500 m. Significant groundwater use in the southern part, between Toowoomba and Miles, occurs within the same footprint as existing CSG development.

Extensive areas of known groundwater discharge to surface-water systems are located in the north and north-eastern outcrop areas, particularly around the Dawson River and upper reaches where eroded and incised landscape exposes the water table, resulting in areas of permanent water and surface expression. In addition to areas of relatively diffuse discharge to watercourses and other features, a number of spring complexes are anticipated to receive groundwater flow from the unconfined part of the aquifer within areas of topographic lows (OGIA 2016c).

3.5.2 Groundwater flow

The potentiometric map for the Hutton Sandstone is shown in Figure 3-7. This surface was generated from 461 data points, including 92 tenure holder monitoring points, 349 GWDB bores and 20 spring locations. In terms of data distribution, there is an abundance of groundwater level data within and adjacent to the outcrop in the northern and eastern extent of the formation. In these areas, the Hutton Sandstone is relied upon as a significant water supply aquifer. In the deeper confined parts of the aquifer system, tenure holder monitoring points are the primary data source. Southwest of CSG development areas, there are few data points to inform the basin-scale groundwater flow dynamics.

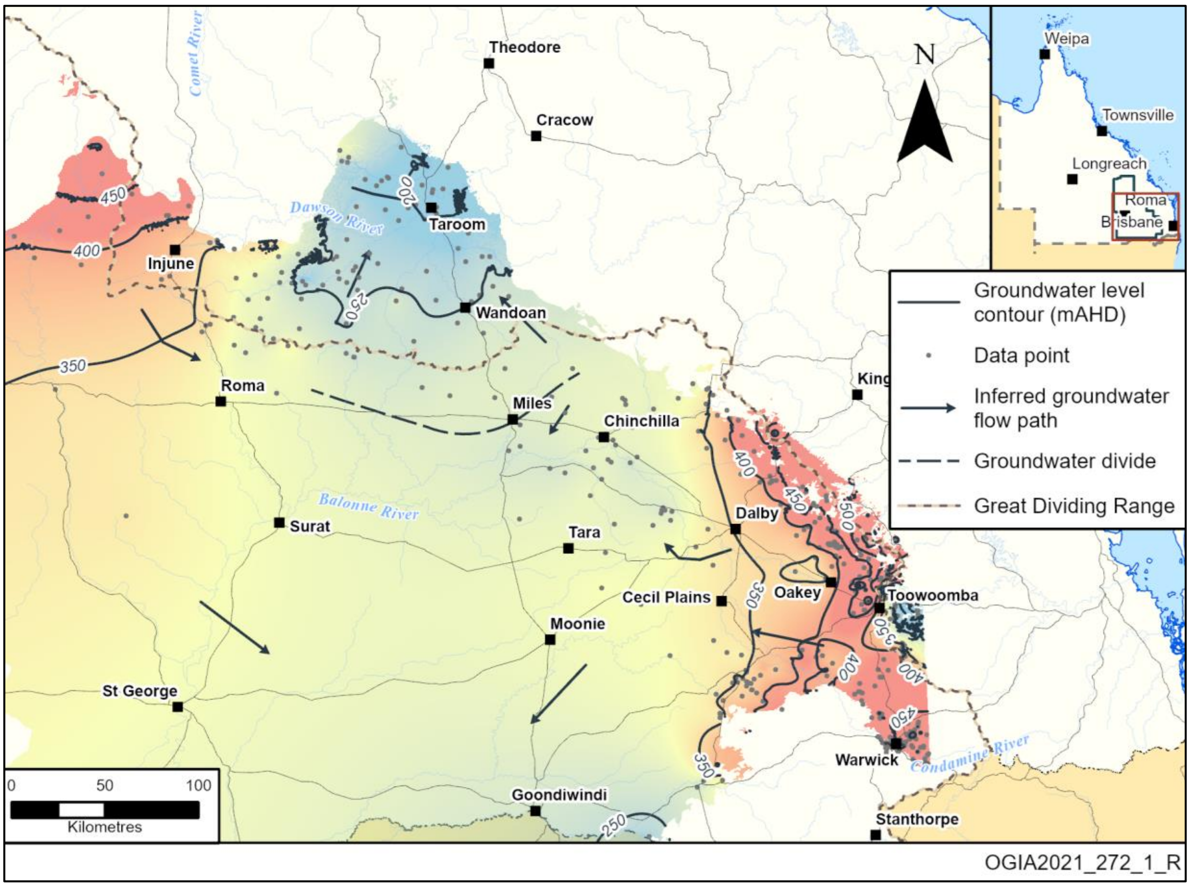

Figure 3-7: Interpreted groundwater flow directions in the Hutton Sandstone, 2018–2021

The potentiometric surface indicates the Hutton Sandstone is a multi-directional aquifer system with recharge in the northwest (Injune) and the east of the basin, with an east–west groundwater divide south of the Range. North of this divide, the Hutton Sandstone aquifer appears to flow northward towards the Dawson River valley where a number of springs and watercourses are supported by discharge from the Hutton Sandstone. South of the Range, groundwater flow directions are interpreted to be to the south, although there is limited data in these areas. The interpreted flow directions are consistent with hydrochemical evolutionary pathways reported in other studies (Raiber & Suckow 2017).

South of the Range in the eastern CMA, groundwater flow in the Hutton Sandstone is generally from the Range (escarpment) to the southwest, however, there is also minor flow to the southeast, into the Clarence–Moreton Basin. The change in flow direction may be associated with an abrupt change in topography to the west of Toowoomba, sufficient to override the subtle dip of the formation over the Helidon Ridge (Ransley & Smerdon 2012).

Groundwater use from the Hutton Sandstone is widespread throughout the northern and eastern extent of the formation. In addition, there are a number of large (>100 ML/year) irrigation, industrial and stock-intensive extractions surrounding the lower Condamine River floodplain between Dalby and Chinchilla. There are corresponding drawdown patterns observed in the regional potentiometric surface in the same general areas as these larger groundwater users.

Groundwater levels range from about 610 mAHD, along the Range beneath the Main Range Volcanics, decreasing to 200 mAHD – near Taroom in the north, towards the Dawson River, and near Toowoomba in the southeast. The potentiometric surfaces and flow directions are consistent with previous interpretations (Hodgkinson, Hortle & McKillop 2010).

Contrary to this, an assessment using natural environmental tracers concluded the main direction of flow in the Hutton Sandstone north of the Range is from north to south (Suckow et al. 2016). However, the assessment highlighted that the Hutton Sandstone flow system is complex – with several recharge areas, flow pathways and discharge zones – noted the discrepancy between the flow directions derived from regional heads and from tracer studies, and postulated that the groundwater flow regime in the area north of the Range may be in a transitional phase. The interpolated groundwater level data could reflect changes driven by climate and groundwater extraction and the tracers would reflect the natural flow system prior to development (Suckow et al. 2016).

In terms of vertical hydraulic potential, under pre-development conditions in outcrop areas, the Walloon Coal Measures would be expected to have a higher hydraulic head than the underlying Hutton Sandstone. Within confined areas, it would be expected that this relationship would be reversed, with the Hutton Sandstone generally having a higher hydraulic head.

Following CSG development, there are areas of substantial gradient towards the Walloon Coal Measures – more than 200 m head difference in some locations. The Hutton Sandstone is physically separated from the Walloon Coal Measures by the Durabilla Formation, a regional aquitard which has an average thickness of about 55 m across most of the area (Figure 4-5, OGIA 2021a). However, impacts are predicted in the Hutton Sandstone in the long term (OGIA 2021a).

3.6 Precipice Sandstone

The Precipice Sandstone unconformably overlies the Bowen Basin and is confined by the overlying Evergreen Formation. It is the most laterally consistent and least heterogeneous aquifer in the Surat

Basin. The thickness of this formation ranges from 40 to 110 m and has the highest horizontal permeability of all aquifers (Figure 3-7, OGIA 2019f).

3.6.1 Recharge and discharge

The long-term mean recharge rate derived from the CMB method is 26.6 mm/year, equivalent to an annual recharge volume of about 32.8 GL/year (OGIA 2019b). This higher recharge rate is attributed to a higher-rainfall outcrop area and the formation's relatively high permeability. However, similar to other formations, a large proportion of estimated recharged is rejected through streams and other discharge features in outcrop areas.

A managed aquifer recharge scheme is established by Origin Energy to reinject treated CSG water into the Precipice Sandstone. Since the commencement of the scheme in 2015, more than 30,000 ML has been reinjected – currently averaging around 4,500 ML/year (OGIA 2021a). This has resulted in pressure responses at significant distances (>80 km) from the reinjection facility.

The Precipice Sandstone has a moderate level of groundwater use – about 2,225 ML/year from more than 186 water bores within the area of interest, primarily for town water supply and stock-intensive purposes (Table 3-1, OGIA 2021a). Conventional oil and gas is produced from the Precipice Sandstone, particularly at the Moonie field, which has operated since 1964 and has an annual associated water extraction of around 1,000 ML.

North of the Range where the formation outcrops, there are areas of significant groundwater discharge to surface-water systems and as discrete spring locations, where the Evergreen Formation persists, and as baseflow to the Dawson River. In addition to the surface expression of groundwater, extensive low-lying and dissected areas in the outcrop of the Precipice Sandstone are associated with terrestrial GDEs. At these locations, the water table is shallow and deep-rooted vegetation is likely to be accessing groundwater (OGIA 2016c).

3.6.2 Groundwater flow

The potentiometric surface map for the Precipice Sandstone is shown in Figure 3-8. This map was generated using 239 data points, 61 tenure holder monitoring points, 50 GWDB bores and 128 spring elevations. The majority (196) of the data points are north of the Range in the vicinity of spring complexes and along major regional gaining reaches of the Dawson River and Cockatoo Creek. There are fewer data points south of the Range and the deeper parts of the basin, resulting in lower confidence in these areas.

The Precipice Sandstone regional flow system is unique; there are two major natural recharge zones in the northwest (northeast of Injune) and east (between Chinchilla and Miles, along the Range) and two distinct flow patterns:

- A northwest-to-northeast regional flow pattern traverses the Range and is interpreted to be driven by groundwater discharge within the Dawson River (springs and baseflow).
- A northwest-to-southeast regional flow pattern tends to concentrate discharge in the Moonie and Dalby areas. Moonie has been the site of active conventional development from the Precipice Sandstone since 1964. There are a number of large groundwater users (non-CSG) southeast and southwest of Dalby, which may also be inducing flow to this area.

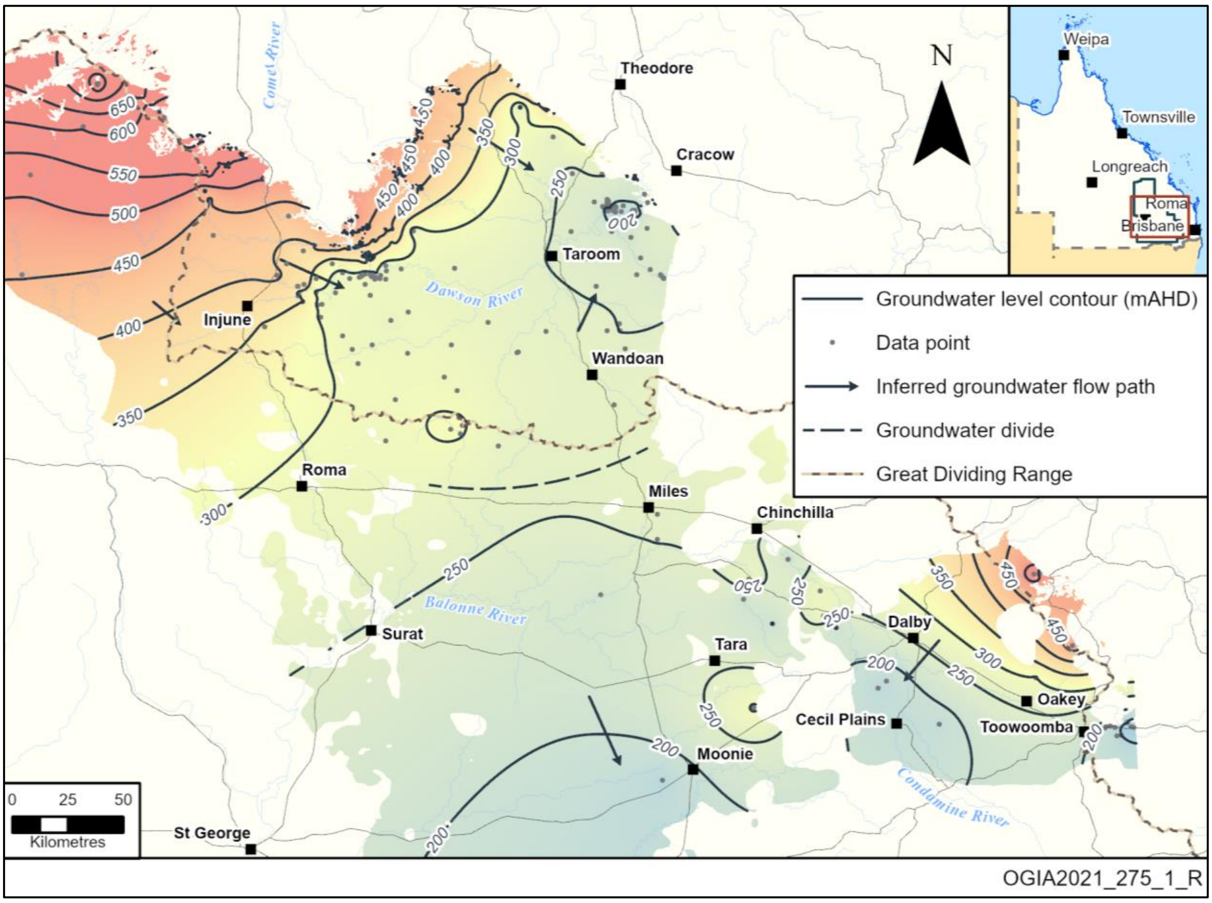

Figure 3-8: Interpreted groundwater flow directions in the Precipice Sandstone

Groundwater heads range from 700 mAHD in outcrop areas in the northwest, to 220 mAHD around Taroom in the northeast – an area of known groundwater discharge. North of the Range, groundwater flow is from west to east. The interpreted flow directions are consistent with previous assessments such as Hodgkinson, Hortle & McKillop (2010).

Although the spatial extent of available data south of the Range is limited, the direction of groundwater flow is interpreted to be from north to south. The Kumbarilla Arch, marking the boundary between the Surat and Clarence–Moreton basins, does not appear to be related to a groundwater divide. However, further to the east, it is likely that the Helidon Ridge controls groundwater flow in both the Precipice Sandstone and Evergreen Formation, creating a groundwater divide (Ransley & Smerdon 2012).

Groundwater discharge to the east, from the Precipice Sandstone near Toowoomba, is thought likely to be a manifestation of a change in formation dip that occurs in this area. The groundwater contours also suggest a groundwater depression southeast of Chinchilla; this coincides with an area of significant groundwater development.

Another feature of the Precipice Sandstone regional flow system is the mounding that occurs at the Reedy Creek and Spring Gully gas fields in the northern Surat Basin. This is the site of Origin Energy's Precipice reinjection program; subsequent mounding has spread for tens of kilometres in all directions in this part of the basin. The extensive lateral propagation of mounding tends to reinforce the permeable nature of this productive aquifer system.

In terms of potential connectivity, the overlying Evergreen Formation limits the interaction with Surat Basin units. However, there are localised areas of potential interaction where the Precipice Sandstone is interpreted to be in direct contact with the Bandanna Formation of the underlying Bowen Basin.

One area of these areas is east of the Hutton–Wallumbilla Fault, where the geological formations were uplifted and subsequently eroded away prior to the deposition of the Precipice Sandstone, bringing this formation into direct contact with the Bandanna and Cattle Creek formations (section 4.4.8, OGIA 2021a). Another contact zone occurs adjacent to the Leichhardt–Burunga Fault, where the area of potential connectivity is much smaller compared to the western contact zone.

In these areas, following CSG depressurisation, there is a significant hydraulic gradient from the Precipice Sandstone towards the Bandanna Formation.

3.7 Clematis Group

The Clematis Group is an important regional aquifer of the Bowen Basin. The typical thickness of this unit ranges from 20 to 300 m, but can reach 1,000 m within the Taroom Trough. Overlain by the Moolayember Formation, it is separated from the Bandanna Formation by a thick sequence of fine-grained, low-permeability siltstones and mudstones of the Rewan Group (OGIA 2021a).

The formation typically comprises medium- to coarse-grained, quartzose to sublabile, micaceous sandstone, siltstone, mudstone and granule to pebble conglomerate deposited by braided and meandering streams (Exon 1976). It is also heterogeneous and displays rapid lateral and vertical variations in texture and hydraulic properties (Cadman, Pain & Vukovic 1998).

3.7.1 Recharge and discharge

The long-term mean recharge rate derived from the CMB method is 16.2 mm/year, equating to an annual volume of about 61.3 GL/year. Similar to the Precipice Sandstone, the higher recharge rate of the Clematis Group is attributed to the higher rainfall outcrop areas and porous quartzose sandstone resulting in lower chloride in the groundwater (OGIA 2016a), but a large proportion of the recharge is rejected in outcrop areas.

The Clematis Group is not extensively developed for groundwater use and has a total estimated water use of only about 28 ML/year from some 26 water bores within the area of interest (Table 3-1, OGIA 2021a). Much of the groundwater use occurs in the northwest around outcrop areas, with minor extraction estimated in the south, between Roma and Surat. Elsewhere, the unit is deep and not easily accessible for water supply purposes. Conventional oil and gas is produced from the Clematis Sandstone or the equivalent Showground Sandstone (OGIA 2019g).

Discharge is interpreted to occur to surface-water systems within outcrop areas in the Expedition and Blackdown Tableland national parks, where the formation has been significantly dissected and eroded and the water table is exposed, resulting in areas of permanent water and surface-expression GDEs within these drainage lines. In addition to diffuse areas of discharge, a number of spring complexes receive groundwater flow from the unconfined areas of this aquifer (OGIA 2016c).

3.7.2 Groundwater flow

The potentiometric surface for the Clematis Sandstone is presented in Figure 3-9. This map was generated from 184 data points, primarily from the GWDB, spring locations – mostly north of the Range where the formation occurs. Due to the limited spatial distribution of these data points, formation depth was used to guide the interpolation.

Groundwater levels are higher in the western and northern outcrop areas, driving the predominant flow from west to east, consistent with the regional dip of the formation into the Taroom Trough. Locally, groundwater flows into the Arcadia Valley on the western side of the outcrop areas and from Blackdown Tableland National Park towards Moura plain. Artesian conditions exist in the Clematis

Group between the western and eastern outcrop areas. Natural groundwater discharge also occurs where local creeks are incised into the formation.

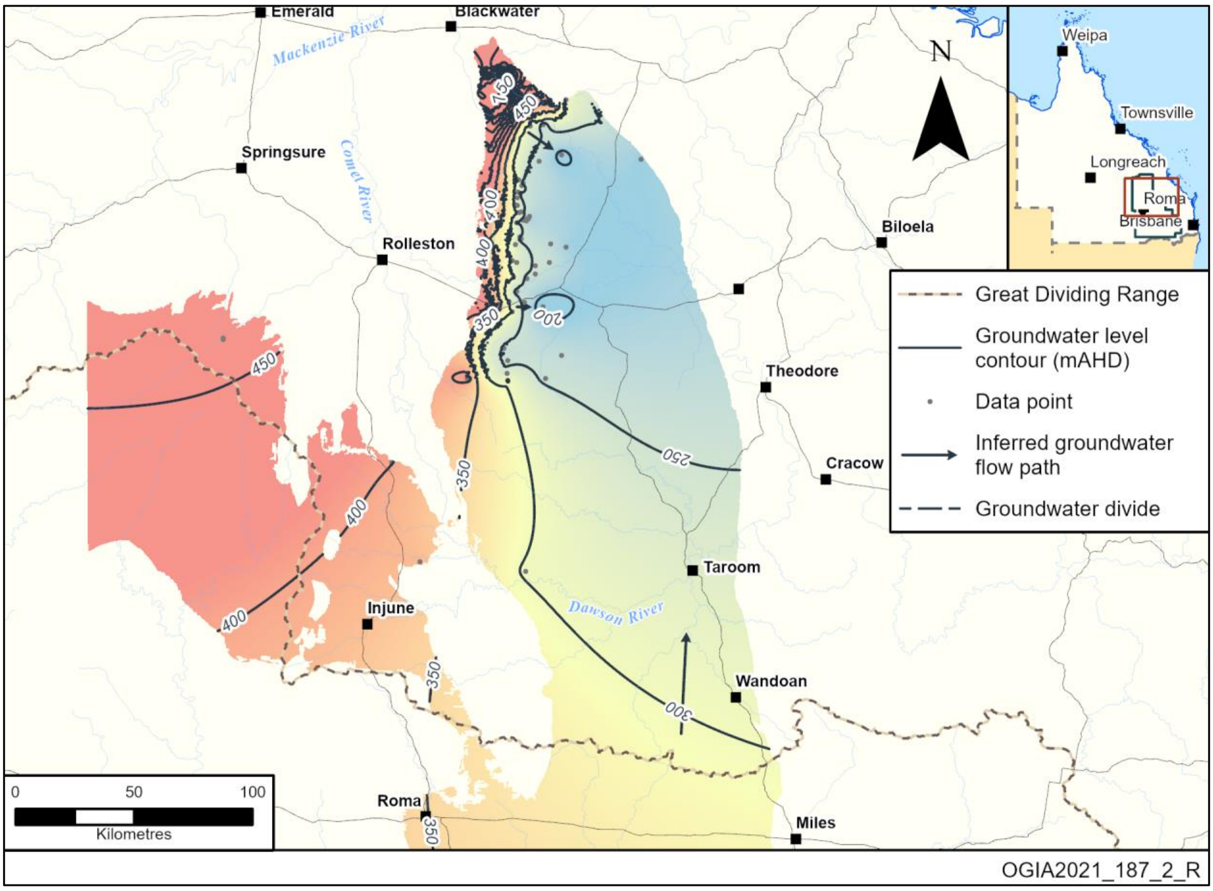

Figure 3-9: Interpreted groundwater flow directions in the Clematis Sandstone, 2018–2021

In terms of vertical hydraulic potential, the overlying Moolayember Formation and underlying Rewan Group are tight aquitards that limit interaction between the Clematis Group and other aquifer units, except at some locations where the Moolayember Formation has been eroded away – such as towards east of the Hutton–Wallumbilla Fault – providing direct connection with the overlying Precipice Sandstone (OGIA 2016a). There is limited data in this area to conceptualise the hydraulic relationship between these units but the gradient is likely to be from the Clematis Group towards the Precipice Sandstone.

3.8 Bandanna Formation

The Bandanna Formation and the equivalent Rangal and Baralaba coal measures are the uppermost coal-bearing reservoirs in the Bowen Basin. Overlying the Black Alley Shale towards the west of the basin and the Gyranda Subgroup towards the east, the formation conformably underlies the Rewan Group, a tight aquitard. However, close to the Hutton–Wallumbilla Fault in the west and the Leichhardt–Burunga Fault in the east, the Rewan Group and other Late Triassic units have been partially eroded such that the Bandanna Formation is in direct contact with the Precipice Sandstone.

The Bandanna Formation typically comprises interbedded, brown to black, carbonaceous mudstones, coal, siltstone and minor clayey sandstone thought to have been deposited in fluvio-deltaic environments. The thickness of the Bandanna Formation varies from 70 to 250 m. Similar to the Walloon Coal Measures, the coal seams are generally the more permeable units, sitting within a lower-permeability sequence of mainly mudstones, siltstones or fine-grained sandstones.

3.8.1 Recharge and discharge

Recharge for the Bandanna Formation is estimated to be 1.48 mm/year, with an annual volume of about 1 GL/year, most of which is rejected in outcrop areas.

Very little groundwater is extracted for agricultural or other purposes from this formation, potentially due to the poorer water quality, yields and accessibility of the resource. There are only 14 water supply bores with a total water use of 27 ML/year in the area of interest (Table 3-1, OGIA 2021a) and extraction is primarily occurring in the northern outcrop area.

Most of the groundwater (about 8,200 ML/year for 2020) extracted from the Bandanna Formation is taken in the process of depressurisation for CSG production. There are numerous established mines, but they are located further north, away from CSG production areas.

Although natural groundwater discharge areas from the Bandanna Formation are unknown, based on the groundwater flow directions, there is potential interaction with shallow groundwater systems and terrestrial GDEs in the low-lying and dissected outcrop areas along the north-eastern margin of this formation (OGIA 2016c).

3.8.2 Groundwater flow

A potentiometric map for the Bandanna Formation is presented in Figure 3-10. Data coverage is significantly limited to outcrop areas – from water supply and some mine monitoring bores – and CSG production areas around the Arcadia, Fairview and Spring Gully gas fields. This map was generated from 59 data points, including 15 tenure holder monitoring points and 44 GWDB bores.

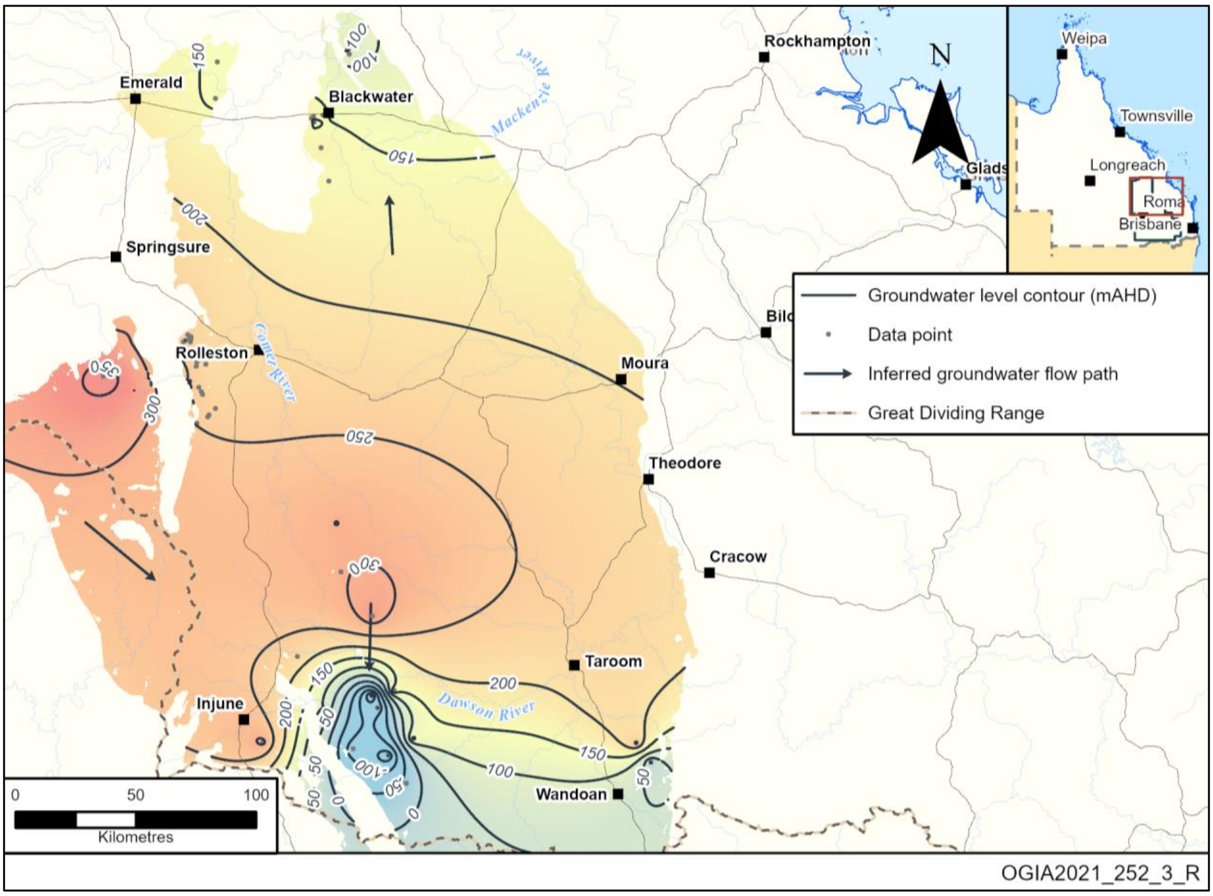

Figure 3-10: Interpreted groundwater flow directions in the Bandanna Formation, 2018–2021

The main regional groundwater flow is west-to-northeast, from high topographic ranges toward the Moura area and the Dawson River. Local-scale flow systems are also observed, for example, a south-to-north system from Rolleston toward Emerald, along the Comet River valley. Obvious departures from the Bandanna Formation regional trend are the large radially convergent drawdown patterns observed in the Fairview and Spring Gully development areas, with more than 200 m of drawdown observed in some locations. Similar to groundwater flow in the Walloon Coal Measures, the cone of depression from CSG activity in the Bandanna Formation is steep but not laterally extensive, with little drawdown observed outside of the operating fields.

In terms of vertical hydraulic potential, the Bandanna Formation overlies the deeper Permian formations and is overlain by the Rewan Group. These overlying and underlying formations are dominated by low-permeability sediments that restrict induced flow from depressurisation of Bandanna coal seams, except where the coal seams come in contact with the Precipice Sandstone.

Recent work further refined the contact zones (section 3.5.6, OGIA 2019f). Origin has recently acquired new 3D seismic data in the area of the Peat Gas field, providing new information on the eastern contact zone between the Precipice Sandstone and the Bandanna Coal Measures. This new data has been reviewed by OGIA as consistent with the current conceptualisation and will be used in to refine the geological model in the future.

In the western contact zone, east of the Hutton–Wallumbilla Fault, water pressures have fallen in the Bandanna Formation by more than 200 m due to depressurisation for CSG production, with limited evidence, at this stage, of impact on the Precipice Sandstone (section 5.6.2.4, OGIA 2021a). The eastern contact zone occurs adjacent to the Leichhardt–Burunga Fault where potential connectivity is much smaller compared to the western contact zone. However, minimal data on groundwater pressure or chemistry are available at this location, limiting the assessment of the degree of connectivity.

3.9 Regional hydraulic gradients

Connectivity between CSG target formations and adjacent aquifers requires both a pathway – a fault, well or geological contact – and a pressure gradient between the formations. Vertical pressure gradients highlight the areas where there is potential for movement between formations.

Vertical hydrographs are tools developed by OGIA to visualise local hydraulic gradients by integrating geological model and pressure data (mean annual hydraulic head) to illustrate changes in groundwater pressure and gradients over time. Example vertical hydrographs at representative locations are shown in Figure 3-11 and are summarised as follows:

- **RN160989** – approximately 40 km to the northeast of Roma, within Senex's Western Surat Gas Project. The site includes five nested monitoring points from the Springbok Sandstone to the Hutton Sandstone. Following CSG development in the Walloon Coal Measures in 2017, progressive declines are observed within Lower Juandah Coal Measures. As a result, the vertical gradients from the underlying Hutton Sandstone and overlying Springbok Sandstone have progressively increased since that time.
- **RN160846** – approximately 28 km west of Dalby, within the existing CSG production area of QGC's Isabella gas field. The site includes six nested monitoring points from the Springbok Sandstone to the Hutton Sandstone. Following development of the Walloon Coal Measures, the hydraulic heads are significantly lower than the overlying Springbok Sandstone and

underlying Hutton Sandstone. As a result, the hydraulic gradient occurs towards the Walloon Coal Measures and has progressively increased over time.

RN160941 – approximately 22 km southwest of Cecil Plains, outside the existing CSG production footprint. The site includes six nested monitoring points from the Springbok Sandstone to the Hutton Sandstone. At this location, the Walloon Coal Measures shows a short period of depressurisation in response to nearby production testing, followed by gradual recovery to pre-development levels. Hydraulic heads within the Walloon Coal Measures, specifically the Taroom Coal Measures, are higher than the underlying Hutton Sandstone, indicating a gradient from the Taroom Coal Measures to the Hutton Sandstone.

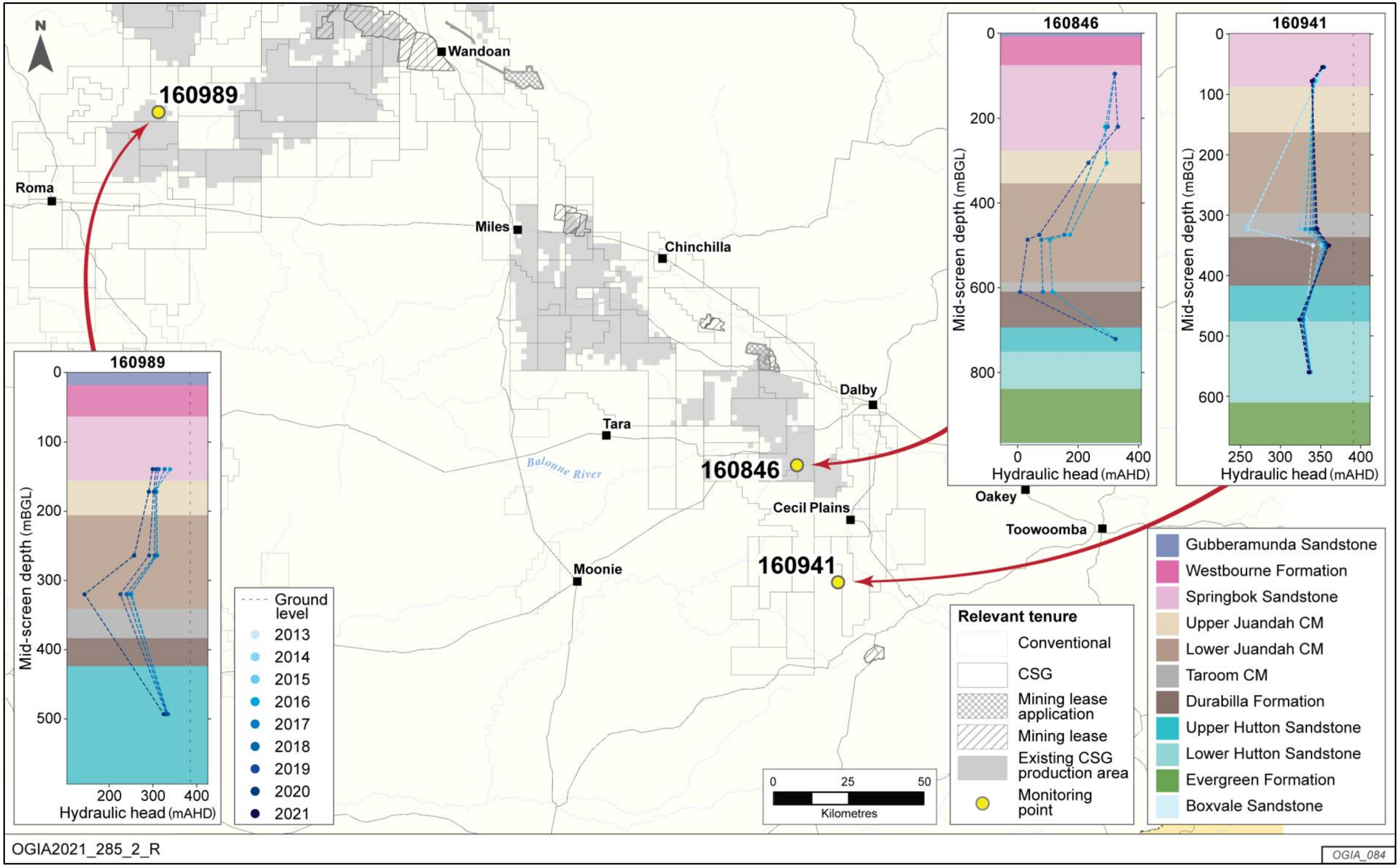

Figure 3-11: Vertical hydrographs at representative location

4 Conclusion

To support the assessment of resource development impacts on the groundwater systems, OGIA has developed a method for integration of available data, quality assurance and the generation of potentiometric maps across the Surat CMA. The approach applied to data preparation, quality assurance and treatment are more broadly applicable to other groundwater systems.

The potentiometric surfaces and discussion:

- provide a contemporary understanding of groundwater flow directions in the Surat CMA
- advance the understanding of CSG-induced change in hydraulic gradients
- highlight foundational components of the groundwater flow system, including areas of recharge, discharge and regional groundwater flow divides.

Unique challenges in preparing potentiometric surfaces in the Surat CMA include the following:

- Spatial and temporal data availability – groundwater use and monitoring is typically concentrated in shallower parts of the groundwater system. Data availability in the deeper confined area – south-western Surat CMA – is limited or only available from a historical time period. This results in lower-confidence interpretations of groundwater flow in these areas.
- Magnitude of CSG-induced drawdown – CSG-induced drawdown results in substantial (up to 300 m) changes in hydraulic head within 15 km of active CSG wells. This presents a challenge for interpolation, with significant dependence on limited data points leading to unrealistic contours in these areas, requiring manual intervention.

As new information, data and knowledge is available, OGIA will refine the current potentiometric surfaces maps. Key areas of future work will include the following:

- Research and investigation to develop an approach to generate synthetic groundwater level and head difference control points in the southern and south-western Surat CMA for the major formations.
- Local area-focused potentiometric surfaces such as the Dawson River, hydraulic gradients around the Precipice Sandstone and the Bandanna Formation contact zone, and the Condamine Alluvium.

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Appendix 1 Methodology for density correction

Darcy's Law is a commonly applied equation to describe groundwater flow though porous medium, 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. Given the variability in monitoring bore construction across the Surat CMA, monitoring bores have been classified into three monitoring types based on their measurement point location and instrumentation, as illustrated in Figure A1-1 and discussed below.

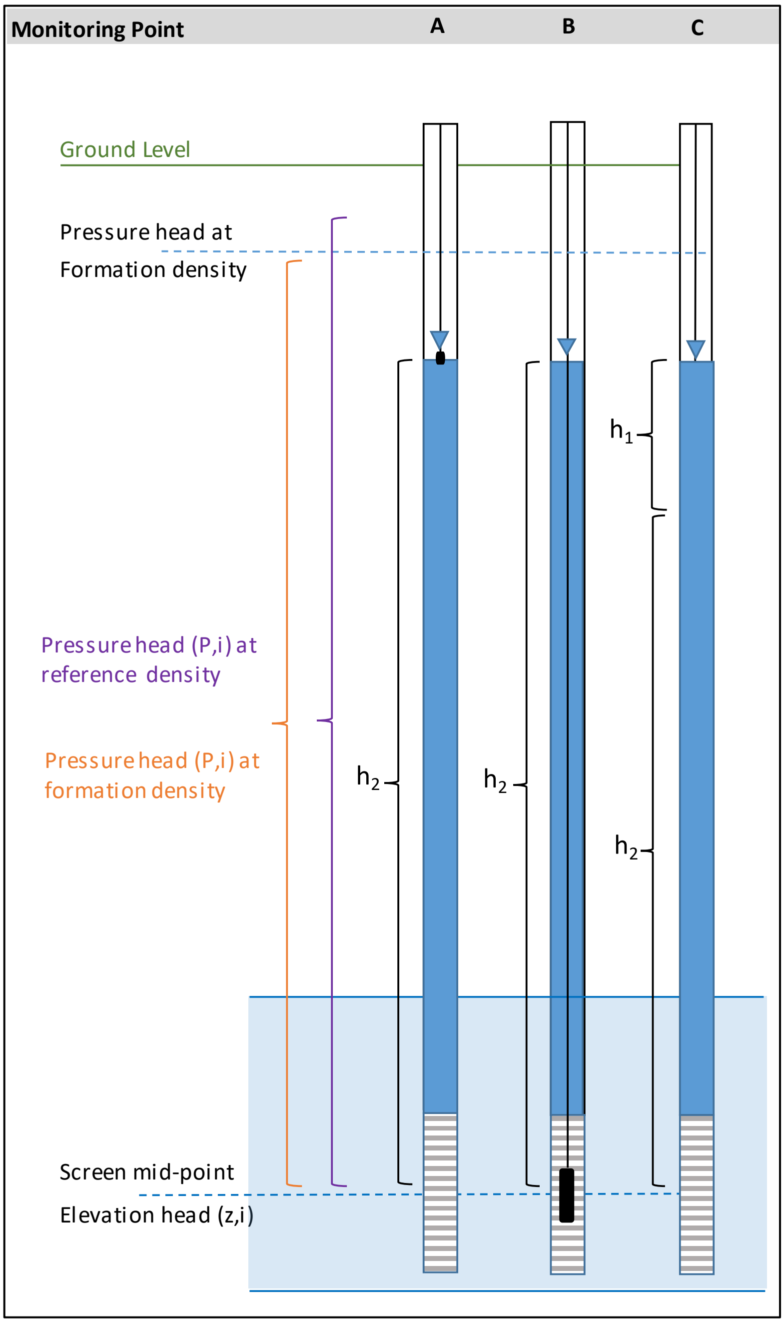

Figure A1-1: Measurement method types

Measurement point at the top of a water column (method A)

This monitoring type includes subartesian wells where the water column is measured via manual dipping. In this situation, a water column correction is required due to the cooling affect within the water column. The water within the water column is not representative of formation density at the screen interval. The corrected water column height is then converted to an equivalent hydraulic head at a reference density.

Average water column density is calculated using the temperature of the mid-point of the water column, applying the 'all-data' depth vs temperature relationship ($y = 0.023x + 28.797$).

Corrected water column = $\text{Measured water column length x} \frac{\text{Average water column density}}{\text{Reference density}}$

Equivalent hydraulic head = $\text{Elevation head (z)} + \text{corrected water column length}$

Measurement point at the screen mid-point (method B)

This monitoring type applies to all bores where pressure is measured directly from within the screen interval via a pressure transducer or equivalent. A water column correction is not required for this monitoring type. The GWDB provides a pressure conversion factor of 1 kPa = 0.10215507 that integrates the density of water at 20° C and 0 mg/L total dissolved solids.

Corrected pressure head = $\text{Measured pressure (kPa)} \times \text{GDWB conversion factor}$

Equivalent hydraulic head = $\text{Elevation head (z)} + \text{corrected pressure head}$

Measurement point within the water column (method C)

This monitoring type applies to bores where pressure is measured from a pressure transducer above the screen interval. Pressure is measured directly at the pressure transducer and a water column correction does not apply above the pressure transducer. For the section of water column between the pressure transducer and the interval, a water column correction is required prior to the correction to equivalent hydraulic heads.

Corrected pressure head above the sensor (h_1) = $\text{Pressure (kPa)} \times \text{GDWB conversion factor}$

Corrected water column below the sensor (h_2) = $\text{WC length} \times \frac{\text{Average water column density}}{\text{Reference density}}$

Equivalent hydraulic head = $h_1 + h_2 + \text{elevation head (z)}$

Appendix 1.1 GWDB bores

The GWDB reports water levels in metres below a reference point (either top of casing (R) or Natural Surface (N)). Reported water levels vary by measurement method, as follows:

- manual dips – the reported value relates to the depth of water in the bore

- loggers – the reported value is calculated from pressure (kPa) and corrected to freshwater head at 20° C as part of logger data processing routines.

The correction applied depends on the measurement method and depth of monitoring equipment with respect to the screen, however, no information is currently available to determine the installation depth of various monitoring equipment for GWDB data. As such, all GWDB bores have been density corrected for the full water column length as outlined in **method A.**

Where no information was available for the screen interval, no density correction was applied.

Appendix 1.2 WMS bores

OGIA's WMS database captures groundwater level data for different measurement methods and corrections were applied as follows:

- Manual Dip (M) reported in elevation (mAHD), **method A**.
- Pressure Gauge (G) reported as freshwater-corrected head elevation (mAHD), **method B**.
- Logger (L) reported as freshwater-corrected head elevation (mAHD), **method B or C**.
- Air Line (A) reported as freshwater-corrected head elevation (mAHD), **method B or C**.

Appendix 2 Quality assurance flags

A series of functions have been included to assign quality flags at both bore and record levels. Selected flags used in the development of potentiometric surfaces are presented in section 2.3.1.

Table A2-1: Quality assurance flags

Flag	Description	Scale
1	Standing water level (SWL) is interpreted to be deeper than the base of the bore.	Record
2	SWL interpreted to be below the bottom of the open interval.	
3	Facility type of the bore is artesian (i.e. 'AC', 'AF', 'AU', 'AS', 'AB'), but the SWL is below ground level (i.e. negative value).	
4	Facility type of the bore is subartesian ('SF'), but the SWL is above ground level (i.e. positive value).	
5	Default GWDB null groundwater level records (9999.99, 999.9, 99.99, 0, None, -99.99, -999.9 and -9999.99).	
6	Artesian conditions recorded (+ve) that are >20 m and are potentially erroneous.	
7	SWL is significantly deep and potentially erroneous (>100 mbgl).	
8	WL measurements sourced from the GWDB Aquifer and Strata tables, indicating an 'As Drilled' WL reading. WL is potentially unrepresentative of groundwater conditions due to WL decline associated with bore development.	
9	Data source is the pump test table, method is in 'ART' or 'F/F' (Artesian or Free-Flowing), but the SWL is negative (-ve), indicating subartesian conditions.	
10	Pump test table record, method code is 'PUM' (indicating pumping), but the SWL is positive (+ve) indicating artesian conditions.	
11	'X' pipe groundwater level reading (SWL taken prior to casing installation). Pipes with a value of X refer to a borehole before it is completed with a Pipe. An example would be a conductivity measurement taken during drilling.	
12	WL reading taken on the same day as the drill date. Where this occurs, there is greater potential for the WL measurement to be inconsistent with the true groundwater level in the aquifer.	
13	GWDB WL QUALITY CODE 160: Data is of suspect quality.	
14	GWDB WL QUALITY CODE 255: A system auto-entry where missing data / a gap in a data record is detected.	
15	GWDB WL QUALITY CODE 60: Data is estimated.	
16	GWDB WL QUALITY CODE 20: Data is of poor quality.	
17	Bore is marked as "D" (Dry) in the 'REMARK' field of the GWDB Water Level table.	
18	Bore marked as 'P' in the 'REMARK' field of the GWDB Water Level table (indicating nearby pumping).	
19	Bore marked as 'B' in the 'REMARK' field of the GWDB Water Level table (bore purged).	
20	UWIR WMS monitoring 'QUALITY_Code' 4 (indicating pumping).	
21	Consecutive values within ±1 cm based on a five-period rolling mean calculation, which is performed with the timeseries in ascending and descending order to capture end members.	

Flag	Description	Scale
22	Assigned bore elevation have a variance of ±10 m relative to the 1s DEM. This may indicate inaccurate elevation or location information.	Bore
23	Bore has been constructed with steel casing, which is more than 100 years old. These are likely to have rusted significantly.	
24	UWIR WMS ‘QUALITY_Code’ flag of 1 indicating an isolated erroneous measurement.	Record
25	UWIR WMS ‘QUALITY_Code’ flag of 2 indicating an equilibrium period at the start of monitoring.	
26	UWIR WMS ‘QUALITY_Code’ flag of 3 indicating that the MP is no longer in use.	
27	UWIR WMS ‘QUALITY_Code’ flag of 4 indicating that record is representative of a Sampling/Pumping event. This is considered correct, but for local effect only.	
28	UWIR WMS ‘QUALITY_Code’ flag of 5 indicating a flatline trend. Likely due to an incorrect GWL Elevation calculation.	
29	UWIR WMS ‘QUALITY_Code’ flag of 6 indicating that the entire record is erroneous.	
30	UWIR WMS ‘Updated_Status’ of ‘Active_Anomalous’.	Bore
31	UWIR WMS ‘Updated_Status’ of ‘Active_Dry’.	
32	UWIR WMS ‘Updated_Status’ of ‘Active_Problem’.	
33	UWIR WMS ‘Updated_Status’ of ‘Faulty_MP’.	
34	Variation of Flag_6. Artesian conditions recorded (+ve) that are >45 m and are potentially erroneous.	Record

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