Department of Natural Resources and Mines

Office of Groundwater Impact Assessment

Identification of gaining streams in the Surat Cumulative Management Area

Hydrogeological investigation report

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1 Introduction

1.1 Background

The Office of Groundwater Impact Assessment (OGIA) is responsible for the assessment of cumulative groundwater impacts from petroleum and gas (P&G) activities in the Surat Cumulative Management Area (CMA). This assessment includes regional groundwater flow modelling and the development of monitoring requirements for aquifers and groundwater dependent ecosystems (GDEs) – specifically, springs and gaining section of streams ('watercourse springs').

The collective assessments and management arrangements are reported in an Underground Water Impact Report (UWIR). Under the legislative framework, the UWIR is required to be updated every three years. This ensures any changes in P&G development scheduling and improvements in knowledge about the groundwater system are appropriately considered and incorporated.

The Surat UWIR (QWC, 2012 and OGIA, 2016a) identifies gaining streams based on the information available at the time of publication. The information is used in the UWIR for the development of a Spring Impact Management Strategy, which includes gaining streams. Under Queensland legislation, the term 'watercourse springs' in principle is a reference to gaining streams.

An increased confidence in the mapping of gaining streams in the Surat CMA is essential for improving the conceptual understanding of surface–groundwater interaction and for assessing impacts of CSG development on environmental values associated with those streams. OGIA has undertaken this project to remap potentially gaining streams across the Surat CMA using new datasets and information generated since the last such mapping was done by Australasian Groundwater and Environmental (AGE, 2005). Priority sites have also been validated as part of this project.

1.2 Gaining streams

Gaining streams are sections of watercourses where groundwater discharges to the streams through the streambeds. Discharge occurs as either permanent to ephemeral waterholes or as flowing sections of watercourses. These are often also known as 'baseflow fed' streams.

In the Surat CMA, a gaining stream may form as a result of the dissection of an outcropping aquifer by surface water flows, resulting in the unconfined aquifer being intersected by the streambed. This project focuses on such gaining streams receiving discharge from unconfined aquifers. In less common situations, faults may provide a conduit for groundwater to flow to the surface though confining formations. Such outflows are typically associated with springs and are not considered gaining streams for the purpose of this project.

1.3 Project scope

Broadly, the scope of this project is to remap gaining streams in the Surat CMA, based on new and contemporary datasets, and then to field-validate this mapping at selected priority sites. More specifically, the scope of the project includes:

- remapping of gaining streams in the Surat CMA using new datasets (since 2005);
- identification of priority sites based on predicted impacts from P&G development;
- literature review of field validation methods for gaining streams and development of a methodology for validation; and
- analysis and reporting.

The project is undertaken and led by OGIA. Field activities and isotope analysis have been undertaken in collaboration with Dr Axel Suckow and Dr Matthias Raiber from the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

1.4 Overview of the study area

The study area is the Surat CMA. It includes areas where more than 0.2 metres of groundwater pressure impact is predicted in the 2016 UWIR (OGIA, 2016a) as well as areas where aquifers outcrop to surface or subcrop below surficial sediments. The study area includes both the Upper Dawson and Condamine-Balonne catchments (**Figure 1-1**).

1.4.1 Hydrogeology

The surface geology for the study area is shown in (**Figure 1-1**) (OGIA, 2016b).

Aquifers include hydrostratigraphic units of the Great Artesian Basin (GAB) and Cenozoic aquifers. The main aquifers are the Precipice Sandstone, the Boxvale Sandstone of the Evergreen Formation, the Hutton, Springbok, Gubberamunda and Mooga sandstones and the Bungil Formation. These formations are typically laterally continuous and are extensively developed for groundwater use. The Walloon Coal Measures is one of the target formations for P&G development in the area. The major aquitards in the study area are the Evergreen, Westbourne, and Orallo formations.

Most recharge occurs to the outcrop areas in the north, north-west, north-east and east along the Great Dividing Range. Recharge is mainly by rainfall which either directly infiltrates the outcrop areas, or indirectly leaks from streams or overlying aquifers. While direct rainfall or diffuse recharge rates are low, generally less than 2.5 millimetres per year (Kellett et al., 2003), recharge through preferred pathway flow during high-intensity rainfall events, and localised recharge from stream or aquifer leakage, can provide up to 30 millimetres per year. Recharge water flows primarily along bedding planes and fractures from the recharge areas towards the south, south-west and west. Recent work (Hodgkinson et al., 2010, Smerdon & Ransley 2012, OGIA 2016b) suggests topographically driven groundwater flow towards the north and north-east in the Hutton and Precipice sandstone units in the area to the north of the Great Dividing Range. Natural discharge occurs via springs, rivers, vertical leakage and subsurface flow into adjoining areas.

Where sufficient thickness of alluvium is present, shallow unconsolidated deposits show significant groundwater yields. Alluvial groundwater quality in this area is generally fresh, with total dissolved solids (TDS) levels typically below 500 mg/L (OGIA 2016b).

1.4.2 Surface water and groundwater interaction

In unconfined aquifers (i.e. within GAB aquifer outcrops and within Cenozoic sediments), groundwater flow follows the surface water drainage pattern. Surface–groundwater interaction occurs in areas where outcropping aquifers have been dissected by surface water flows in the shallow watertable. Generally, the watertable is closer to the surface in the middle and lower reaches of surface water drainage systems (Winter, 1998).

The interaction between unconfined groundwater systems and surface water varies between the states of gaining, losing and/or intermittently transitioning between these states. This is common in outcrop areas for major aquifers of the Surat CMA (Hutton and Precipice sandstones) where erosion and dissection of the landscape by surface water flows has created a depression of sufficient depth to reach the watertable. A key challenge is the spatial and temporal variability of connectivity both within and along individual reaches.

During high-flow surface water events, a rapid rise in surface water can also result in water moving from the stream into or over the stream bank (Winter, 1998). This water enters the groundwater system for a short period and may be returned to the stream in the following days or weeks, depending on the volume of bank storage (Winter, 1998).

1.5 This report

For context, Chapter 2 of this report provides a summary of previous assessments, data sources and details of the methodology and outputs from the remapping of potentially gaining streams in the Surat CMA. Chapter 3 details the approach to prioritisation of the identified potentially gaining reaches, followed by a summary of the field investigations and data collection methods in Chapter 4. Results, analysis and conclusions in relation to the project objective are in Chapters 5 and 6.

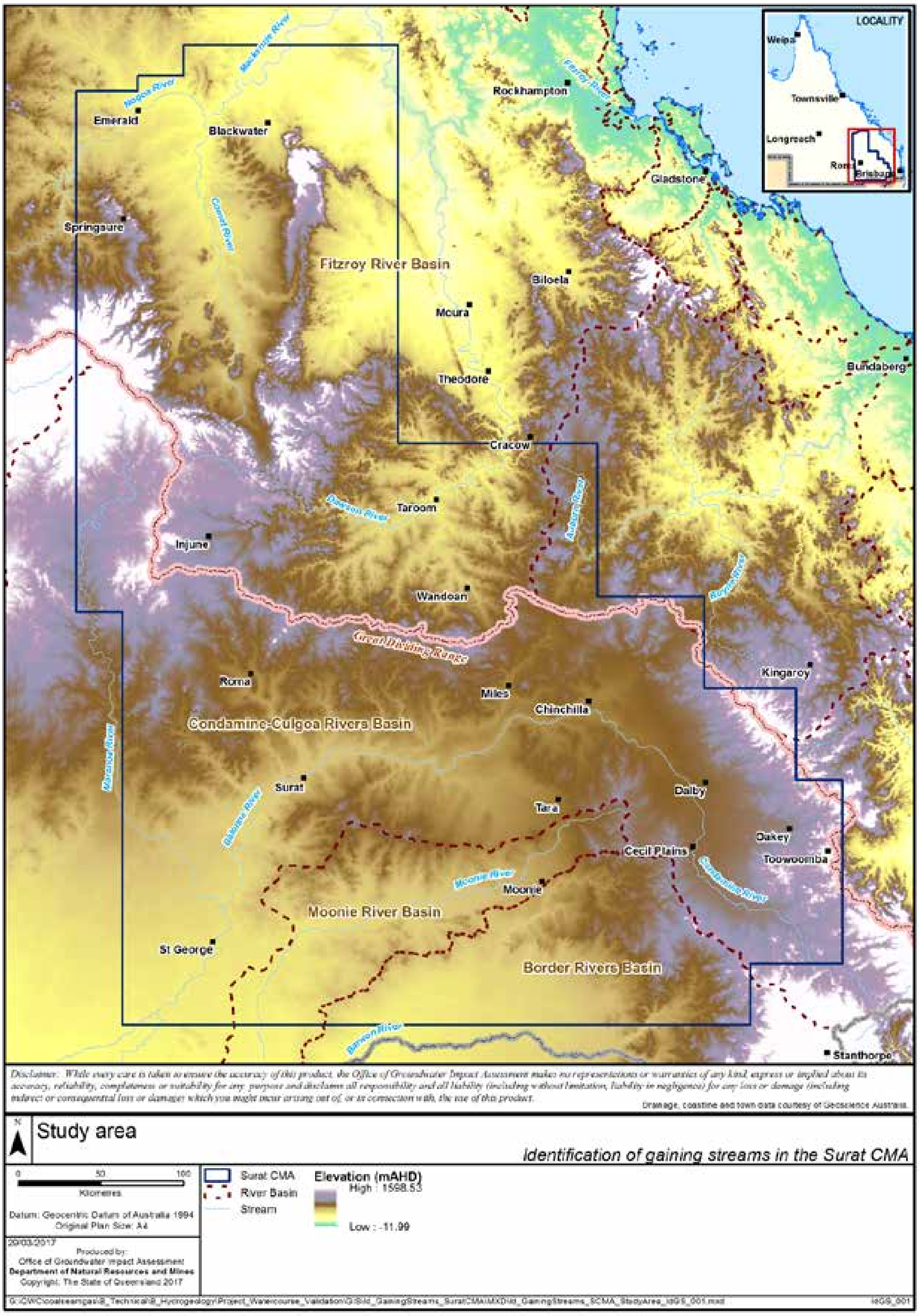

Figure 1-1 Study area

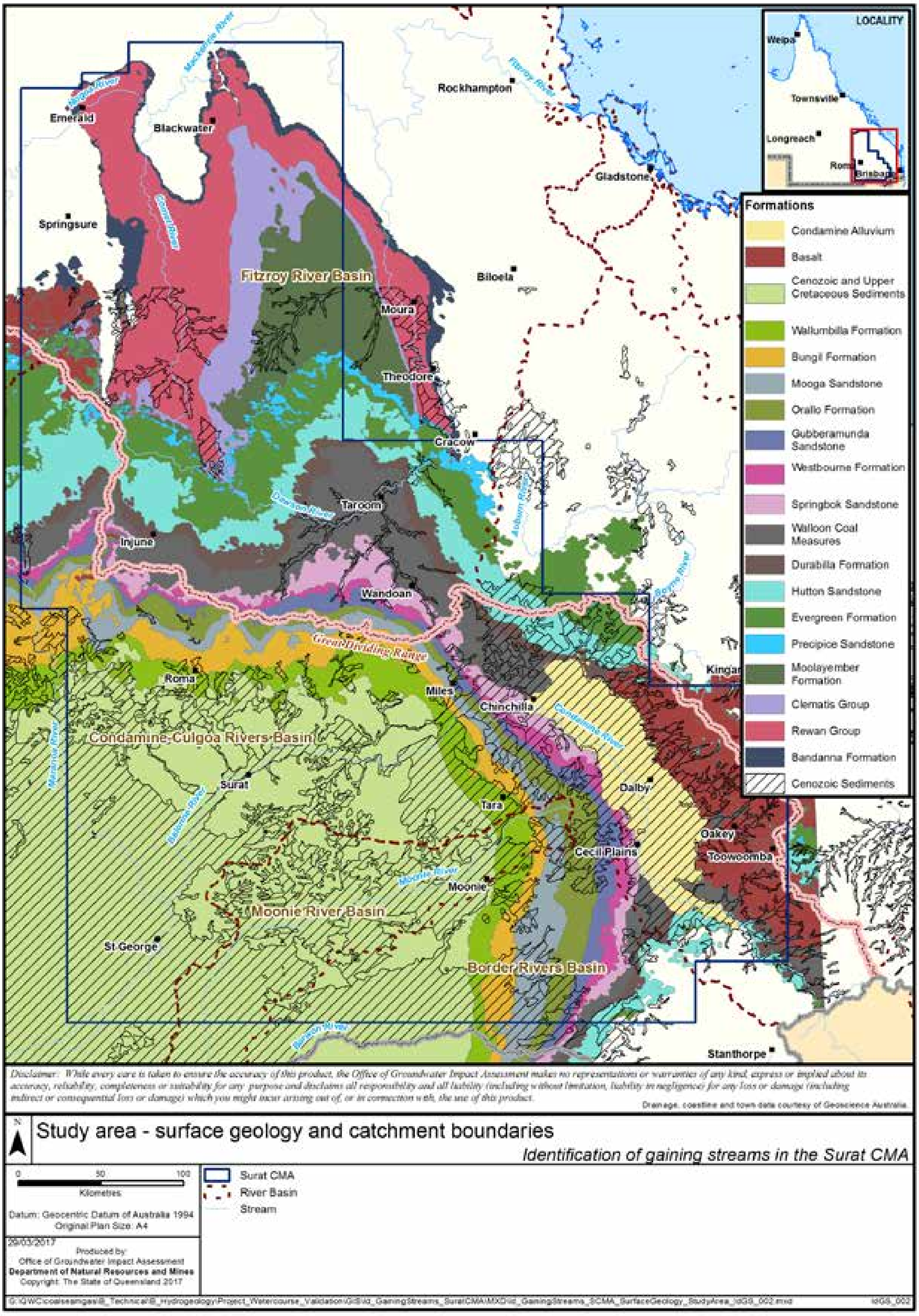

Figure 1-2 Surface geology and catchment boundaries

2 Remapping of gaining streams in the Surat CMA

2.1 Previous assessments and datasets

2.1.1 Potential river baseflow from aquifers of the GAB (AGE, 2005)

In 2005, AGE was engaged by the Department of Natural Resource and Mines (DNRM) to identify reaches of river systems where there was potential interaction with the groundwater of the GAB. Outcomes from this work were used to inform the *Water Resource (Great Artesian Basin) Plan 2006*.

The methodology applied under the project was a rapid desktop approach to prepare water level surfaces and then intersect those surfaces with topographic elevations (digital elevation model). This allowed for a broad assessment of any surface water systems that may be receiving baseflow. In parallel with the development of this dataset, the project incorporated other relevant datasets such as GAB springs, the nine-second digital elevation model (DEM) for Queensland and a literature review. As a minimum, where the depth to water was within 10 metres of the streambed, these reaches were identified as potentially gaining reaches. There were 43 potentially gaining streams identified in the Surat CMA from this assessment.

Given the rapid nature and spatial extent of this project (70% of Queensland), AGE acknowledged a number of limitations with the outcomes. Although hydrogeological data from the Queensland groundwater database (GWDB) are available and relatively easy to manipulate into an assessment tool, the method is not expected to be highly accurate at a local scale. Errors with recorded water level data, limitations of the scale of the nine-second DEM in outcrop areas and interpolation over large areas are recognised as the key limitations.

This mapping by AGE (2005) of reaches of potentially gaining streams has been used by OGIA in preparing the 2012 UWIR and 2016 UWIR. This mapping is also used in the current project as a line of evidence in the remapping of potentially gaining reaches in the Surat CMA (**Figure 2-1**).

2.1.2 Depth to water table mapping (OGIA, 2017)

In 2017, OGIA developed a methodology for the development of regional depth to watertable maps in unconfined aquifer systems. The methodology was prepared to identify likely areas of shallow groundwater and to support the identification of GDEs in the eastern Murray–Darling Basin and the Fitzroy Basin.

The approach integrates water level information from the GWDB, OGIA's regional geological model and the one-second DEM. All available standing water level data was used regardless of the date of measurement. Depth to groundwater surface mapping was created using Co-Kriging. A strong correlation was noted between water level and topography (regression coefficient value (R^2) > 0.9). The process therefore uses information from the one-second DEM to guide the interpolation of the water levels.

As the project was focused on unconfined aquifer systems where aquifers are likely to receive rainfall recharge, it was recognised that groundwater levels may fluctuate seasonally. Depending on when a water level is measured, the water level could vary by several metres. Local groundwater pumping may also influence some measured water levels. For this reason and due to the nature of the interpolation process, depth to water level includes 'bands' of likely depth to groundwater, rather than single representative values (i.e. 5 metres, 5–10 m, 10–50 metres and > 50 metres (**Figure 2-1**)).

The regional depth to groundwater level contours developed through this process do not account for shallow groundwater levels resulting from local hydrogeological heterogeneity, such as perched aquifers or structural- or fault-related groundwater expressions.

For this project, depth to water table mapping has been used to identify areas of shallow groundwater, including areas of potentially gaining streams. The depth to watertable mapping for the study area is shown in **Figure 2-1**.

2.1.3 Groundwater dependent ecosystem mapping (DSITI, 2015)

The Queensland Herbarium has established a peer-reviewed method for mapping GDEs in Queensland (DSITI, 2015). On a catchment-by-catchment basis, the methodology integrates available spatial datasets and elicitation from local expert knowledge in a range of disciplines.

The methodology incorporates facilitated workshops and the development of GDE mapping rule sets which are applied across the catchment to identify potential areas of surface expression, terrestrial and subterranean GDEs. Importantly, the identified GDEs are attributed with a confidence rating which reflects the level of verification, assessment or confidence that the technical experts have with the individually mapped features.

OGIA funded and worked collaboratively with the Queensland Herbarium to apply the methodology across the Surat CMA in 2015/16. The products have been included in this project as a line of evidence in the remapping of potentially gaining streams in the Surat CMA. The surface expression depth to watertable mapping for the study area is shown in **Figure 2-1**.

2.1.4 Commonwealth assessments (CSIRO, 2012 and Welsh et al., 2014)

The GAB Water Resource Assessment (CSIRO, 2012) was a GAB-wide study commissioned by the Australian Government to assess the status of the groundwater resource, identify the potential impacts of resource development and fill key knowledge gaps. Within the study area, the assessment noted areas of shallow groundwater and potential areas of gaining streams (e.g. the Dawson River).

The Australian Government's Bioregional Assessment for the Condamine-Balonne subregion (Welsh et al., 2014) mapped connectivity between surface water and groundwater in the southern portion of the study area. Within the study area, the assessment identified losing conditions in the Condamine River and gaining conditions in the Balonne River.

The outcomes from these Commonwealth assessments have been included in this project as a line of evidence in the remapping of potentially gaining reaches in the Surat CMA.

2.1.5 Water observations from space (WOfS)

WOfS is a web service displaying historical surface water observations derived from satellite imagery for all of Australia from 1987 to present day. WOfS displays the detected surface water from the Australia-wide Landsat 5 and Landsat 7 satellite imagery archive. In this project, WOfS was used as a line of evidence to identify areas where surface water persisted during drought periods and is therefore potentially connected to the groundwater system.

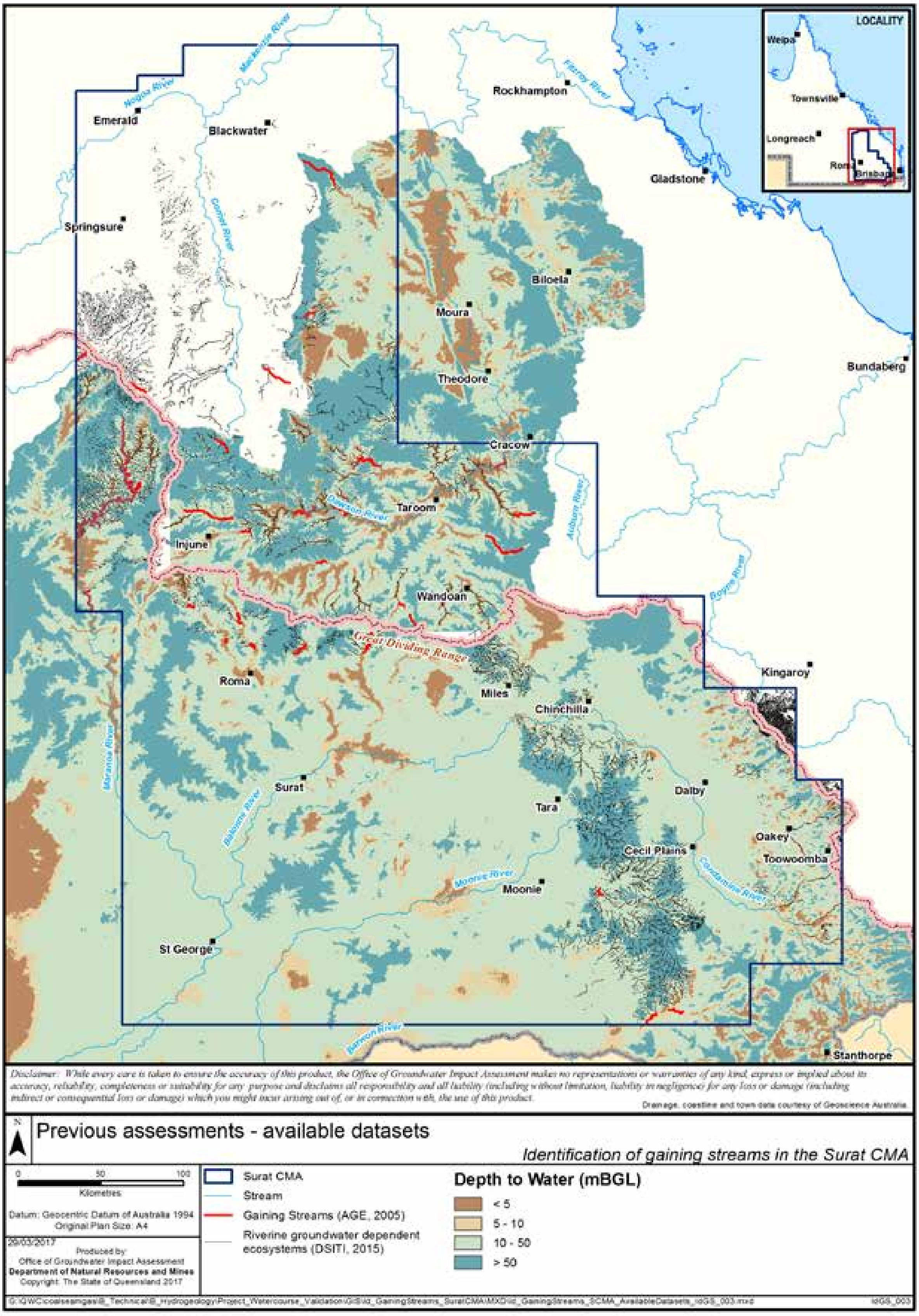

Figure 2-1 Previous assessments: gaining streams (AGE, 2005), depth to watertable mapping (OGIA, 2017) and GDE mapping (DSITI, 2015)

2.2 Methodology

The following section provides an overview of the method applied to remap gaining streams in the Surat CMA for the purpose of this project. The methodology builds on AGE (2005), incorporating recently generated datasets and understanding of the groundwater system, in a multiple lines of evidence approach to determine areas of streams and rivers likely to be under gaining conditions.

Using the depth to watertable mapping (OGIA, 2017), areas of shallow groundwater were identified. The one-second DEM was subtracted from the mapping to provide an estimate of the depth to groundwater. From this process, areas where the watertable was less than 5 m below ground level were considered potential areas of surface water and groundwater connectivity.

Using the depth to watertable mapping and pressure contours, streams were assessed to determine their connectivity regime with the adjacent groundwater system (i.e. losing, gaining, intermittent).

Additional lines of evidence were then incorporated to provide a measure of confidence in the identified potentially gaining streams. These included:

- The Queensland Herbarium GDE mapping products, including riverine wetlands interpreted to be dependent on groundwater. Only those wetlands mapped as moderate or high confidence were used in this assessment.
- The WOfS dataset, integrated with the gaining streams to increase confidence with the identified reaches. Only moderate confidence was applied to this dataset as this is based on Landsat imagery with a 25 x 25 m resolution.
- Aerial imagery during drought periods, assessed to determine permanency of surface water and identify sampling locations for the field-validated reaches.

2.3 Results of remapping

Areas of potentially gaining streams in the Surat CMA were identified using the methodology described in Section 2.2. The outcomes from this assessment for the Surat CMA are shown in **Figure 3-1**.

In comparison to the AGE (2005) assessment, there are new areas of potentially gaining streams that have been identified using this method. The majority of the identified potentially gaining streams are in the Dawson River catchment. In particular, on the northern slopes of the Great Dividing Range between Wandoan and Roma, additional potentially gaining streams have been identified along Sugarloaf Creek, Barton Creek, Kangaroo Creek, Horse Creek, Woleebee Creek, Juandah Creek and Downfall Creek.

The updated mapping also identified a wider extent of gaining streams than was identified by AGE (2005). The sections of gaining streams associated with the Dawson River, the Maranoa River, Hutton Creek, Cockatoo Creek, Robinson Creek and Bungeworgorai Creek have been mapped to occur over a larger extent than the original assessment (AGE, 2005).

At some locations, the new mapping suggests some previously identified gaining streams (AGE, 2005) are less likely. For example, the revised mapping suggests that shallow groundwater conditions do not occur within previously identified reaches along Mimosa Creek tributary, Bungaban Creek, the Dawson River (NW), Horse Creek (East Branch) and Western Creek. Field validation is required to confirm these conclusions.

3 Prioritisation for field validation

Field validation of gaining streams was necessary to improve confidence and further refine the mapping. Given the large spatial extent of the study area, the magnitude of predicted impacts from P&G development (OGIA, 2016a, 2016c) was used as a first filter for further prioritisation. This initial filter captures all potentially gaining streams located within the 0.2-metre drawdown extent (OGIA, 2016a).

Relatively greater confidence is needed in the mapping of gaining streams in those impact areas for the purpose of developing monitoring and management strategies. The following sections provide detail of the methodology and outcomes of the prioritisation.

3.1 Methodology

Following the application of the initial drawdown filter, two additional criteria were applied:

- *Magnitude* of drawdown at the location of the gaining stream; and
- Level of *confidence* in the presence of the gaining stream based on existing mapping.

For each gaining stream, the magnitude of predicted drawdown for the underlying aquifer from the OGIA regional groundwater model was used as the first criterion (**Table 3-1**).

Table 3-1 Predicted drawdown groups

Description	Group
> 1 metre drawdown in the source aquifer at the location of the gaining steam	1
0.2–1 metre drawdown in the source aquifer at the location of the gaining steam	2
< 0.2 metre drawdown in the source aquifer at the location of the gaining stream	3

The second criterion applied was the level of confidence in the identified gaining stream. The scoring system used to determine the level of confidence is summarised below and calculated in **Table 3-2**:

- *Depth to water* – The assigned score relates to the continuous length of stream overlying shallow groundwater (< 5 metres below ground level). Reaches with > 15 km of length associated with shallow groundwater are assigned a 3; in contrast, reaches with < 5 km are assigned a 1.
- *GDE confidence* – Each GDE riverine wetland is attributed a confidence level. This relates to the degree of confidence in the presence of the mapped GDE: low, moderate and high confidence. Low-confidence GDEs are assigned a 1 while high-confidence GDEs are assigned a 3.
- *WOfS* – This dataset maps the historical surface water recurrence in the landscape. Streams where continuous sections of surface water have been identified are assigned a 3 and streams where no visible surface water is recorded are assigned a 1.
- *Surface water observations from aerial imagery* – Historical aerial imagery was reviewed to identify occurrence of surface water. Streams with extensive, long and continuous sections of surface water are assigned a 3. Streams with no visible surface water are assigned a 1.
- *Previously identified gaining streams (AGE, 2005)* – This dataset identifies streams where shallow depth to groundwater (<10 metres) within the GAB formations was determined. An additional confidence score of 1 is assigned to each stream if it has been previously mapped in this dataset.

For each stream, the drawdown group and level of confidence have been used to prioritise sites for field validation.

3.2 Results

The prioritisation outcomes for the identified gaining streams are provided in **Table 3-2** and mapped in **Figure 3-1**

The purpose of the field verification is to confirm the presence of gaining conditions and support the continued refinement of the methodology used to map gaining streams across the Surat CMA. High-confidence gaining streams affected by predicted drawdown are prioritised for field validation.

Juandah Creek, Downfall Creek, Horse Creek and Woleebee Creek were identified as high-priority streams for field validation. The approach also identified Eurombah Creek and the Dawson River as high-priority streams; however, as these sites are known gaining reaches and are currently being monitored, they were therefore excluded from the prioritisation process.

For the initial round of field validation, high-priority streams and those streams with significant differences between previous mapping (AGE, 2005) and the current methodology are considered.

The prioritisation stage identified two sites for initial field validation:

- **Juandah Creek.** The regional groundwater model predicts > 1 metre drawdown in the Springbok Sandstone. Shallow groundwater is interpreted to occur (< 5 metres below ground) and there is a high level of confidence in the occurrence of gaining conditions.
- **Bungaban Creek.** The regional groundwater model predicts approximately 1 metre drawdown in the Hutton Sandstone at this location. The depth to groundwater is > 10 metres below ground and there is moderate confidence that gaining conditions exist.

Bungaban Creek has been selected for field validation. The AGE (2005) assessment identified Bungaban Creek as a gaining stream, while the current methodology does not identify the Bungaban Creek as a potentially gaining stream. Field validation of Bungaban Creek and Juandah Creek will assist in validation of the AGE (2005) assessment and current methodology for the identification of potentially gaining streams.

Table 3-2 Prioritisation of potentially gaining streams for field validation

Potentially gaining streams	**Datasets**						**Confidence level**	**Drawdown group (Table 3-1)**
	Watertable mapping (Section 2.1.2)	**GDE mapping (Section 2.1.3)**	**WOfS (Section 2.1.5)**	**Aerial imagery**	**Gaining streams (AGE, 2005)**	**UWIR monitoring site**		
Juandah Creek	3	2	2	3	0	No	High	1
Downfall Creek	3	2	2	3	0	No	High	1
Horse Creek	3	2	2	3	0	No	High	1
Woleebee Creek	3	2	2	3	0	No	High	1
Blyth Creek	2	2	2	2	1	No	Moderate	2
Condamine River	1	2	3	3	0	No	Moderate	3
Rocky Creek	1	2	3	3	0	No	Moderate	3
Wilkie Creek	1	2	3	3	0	No	Moderate	1
Yuleba Creek	2	2	2	2	1	No	Moderate	2
Bungaban Creek*	1	2	1	3	1	No	Moderate	2
Horse Creek (East Branch)*	1	2	1	1	1	No	Low	2
Sugarloaf Creek	1	2	1	1	0	No	Low	1
Dawson River	2	3	3	3	1	Yes	High	1
Eurombah Creek	1	2	3	3	1	Yes	High	1
Kangaroo Creek	3	2	1	2	0	Yes	Moderate	1
Barton Creek	1	2	1	1	0	Yes	Low	1
** Gaining conditions not mapped during current the mapping process*	*3 = Extensive* *2 = Moderate* *1 = Short*	*3 = High* *2 = Moderate* *1 = Low*	*3 = Continuous* *2 = Discontinuous* *1 = Nil*	*3 = Continuous* *2 = Discontinuous* *1 = Nil*	*1 = Mapped* *0 = Not mapped*			

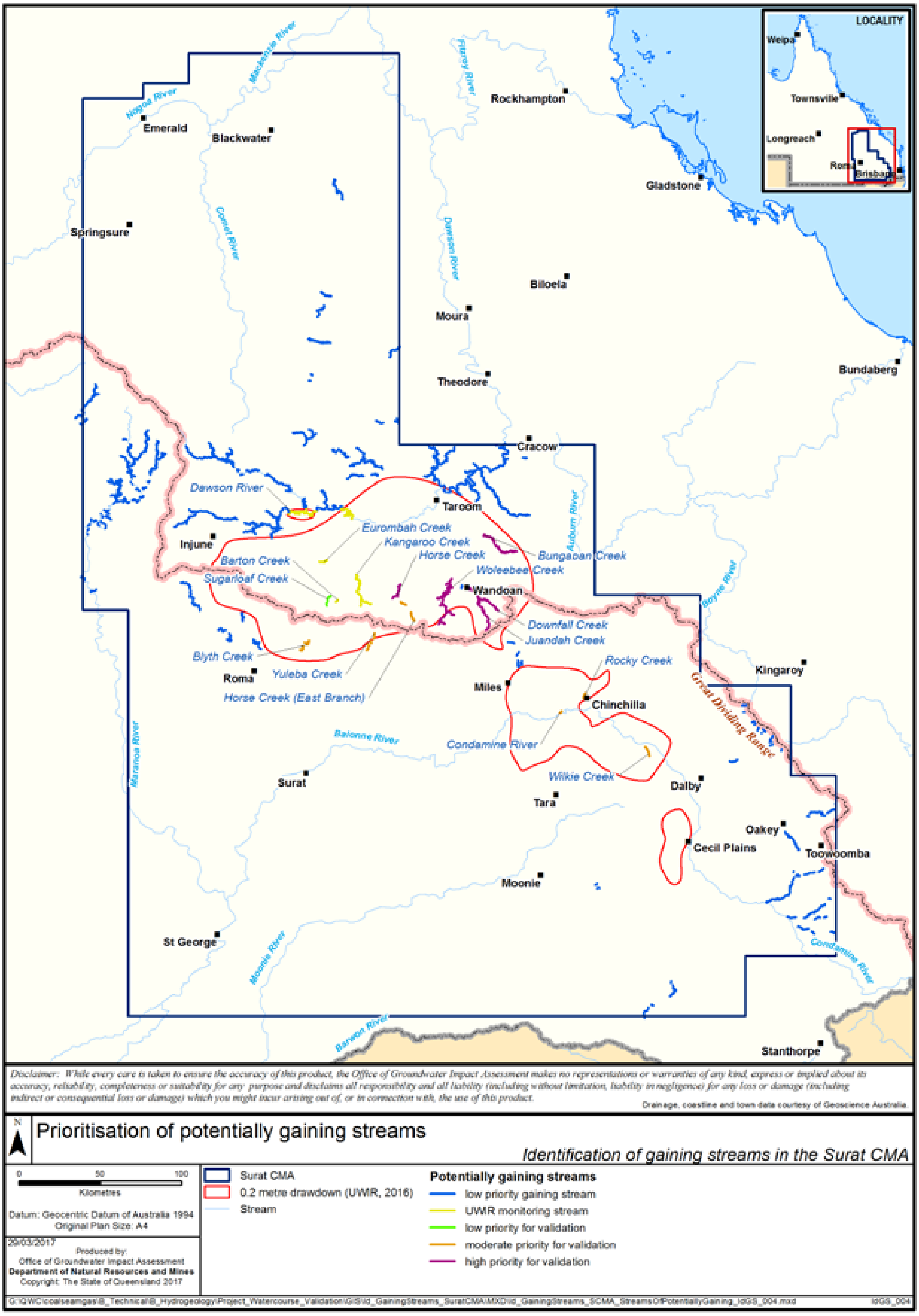

Figure 3-1 Prioritisation of potentially gaining streams

4 Field investigations

Fieldwork at Bungaban Creek and Juandah Creek was completed between 5 and 7 December 2016. OGIA undertook field activities and CSIRO provided support to OGIA during this project through assistance with isotope sampling and laboratory analysis. This Chapter provides a summary of the conceptual understanding of the sites visited and field data collected during the campaign.

4.1 Juandah Creek

Juandah Creek is an upper tributary of the Dawson River approximately 10 km south-east of Wandoan (**Figure 3-1**). The headwaters of this creek are further south and east along the Great Dividing Range. The creek flows north towards Wandoan into the Dawson River. As shown in **Figure 4-4**, the surface geology along this section of the creek includes the Springbok Sandstone, the Walloon Coal Measures and alluvium. Surface water and bores sampled during the project are also shown. There are no existing or historical surface water gauging stations along this reach of Juandah Creek.

4.1.1 Climate

The closest rainfall stations to the site are Shelbourne (042033), Giligulgul (035029) and Giligulgul TM (035039). The Giligulgul TM station provides the most complete dataset. The closest weather station with total climate information is the Taroom Post Office (35070). **Figure 4-1** shows the average climate statistics from this station, based on daily climate measured over the period 1870 to 2017. Daily rainfall records for the period September to December 2016 for the Giligulgul TM station are shown in **Figure 4-2**.

As shown in **Figure 4-2**, 8.4 mm of rainfall was recorded at the Giligulgul rainfall station in the month prior to the field activities. This rainfall was recorded over six separate events and is unlikely to have contributed significant surface water flows into Juandah Creek during the collection of field data.

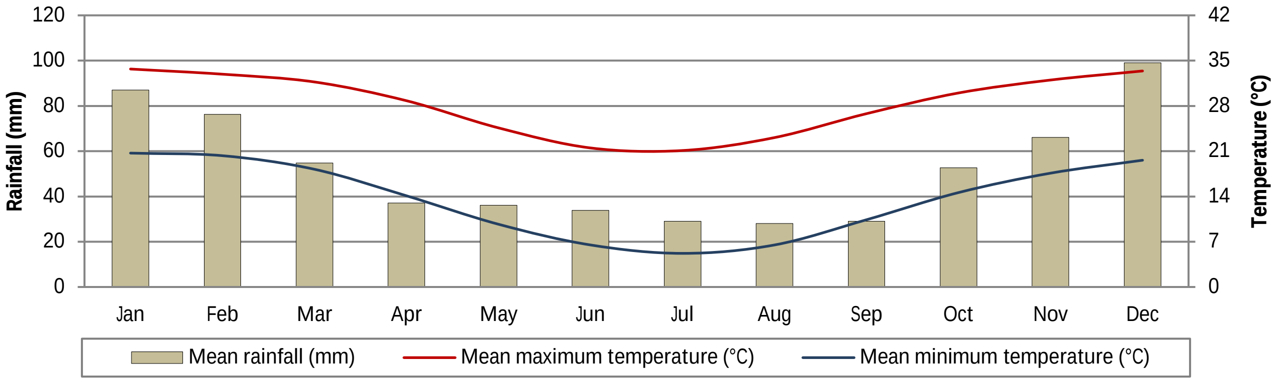

Figure 4-1 Average climate statistics at Taroom (35070) for the period 1870 to 2017

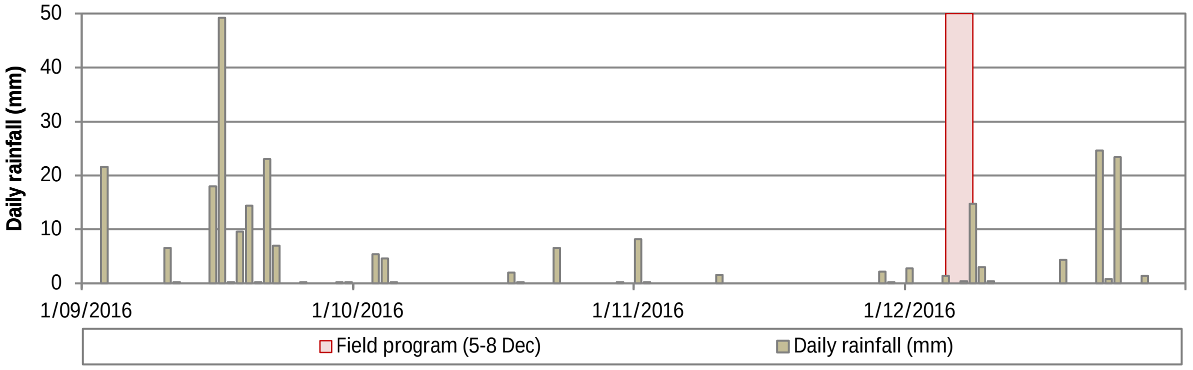

Figure 4-2 Giligulgul TM (035039) rainfall statistics for the period September to December 2016

4.1.2 Hydrogeology

At this location, Juandah Creek conforms to the geological contact between the Springbok Sandstone and the Walloon Coal Measures. The creek is overlain by significant Cenozoic alluvial and surficial sediments to an estimated depth of 10 metres. An east–west cross-section of the creek and underlying geology, using the OGIA geological model and GSQ surface geological mapping, is shown in **Figure 4-3**.

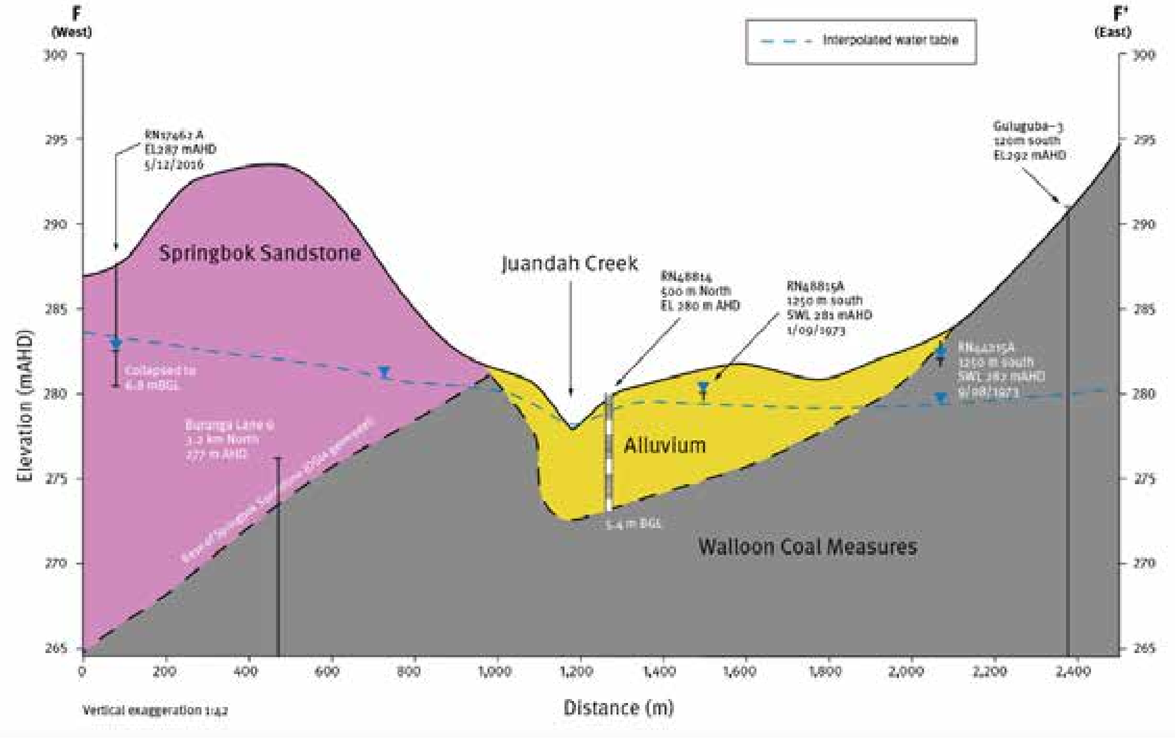

Figure 4-3 Cross-section of Juandah Creek showing the underlying geology and stratigraphic water level controls. The depth to water table mapping (OGIA, 2017) is also included in the section.

The locations of field-collected data and historical datasets are shown in **Figure 4-4**.

The interpreted regional groundwater level indicates groundwater flow towards the creek, suggesting the alluvium may be a discharge point for surrounding aquifers. This is shown with both the interpreted depth to watertable mapping (OGIA, 2017) and the locally available water level data: RN44215A (Walloon Coal Measures), RN17462A (Springbok Sandstone), RN48815A (Alluvium) and RN48814 (Alluvium). It is likely that the watertable in the alluvium responds to local recharge events more rapidly than the surrounding consolidated formations.

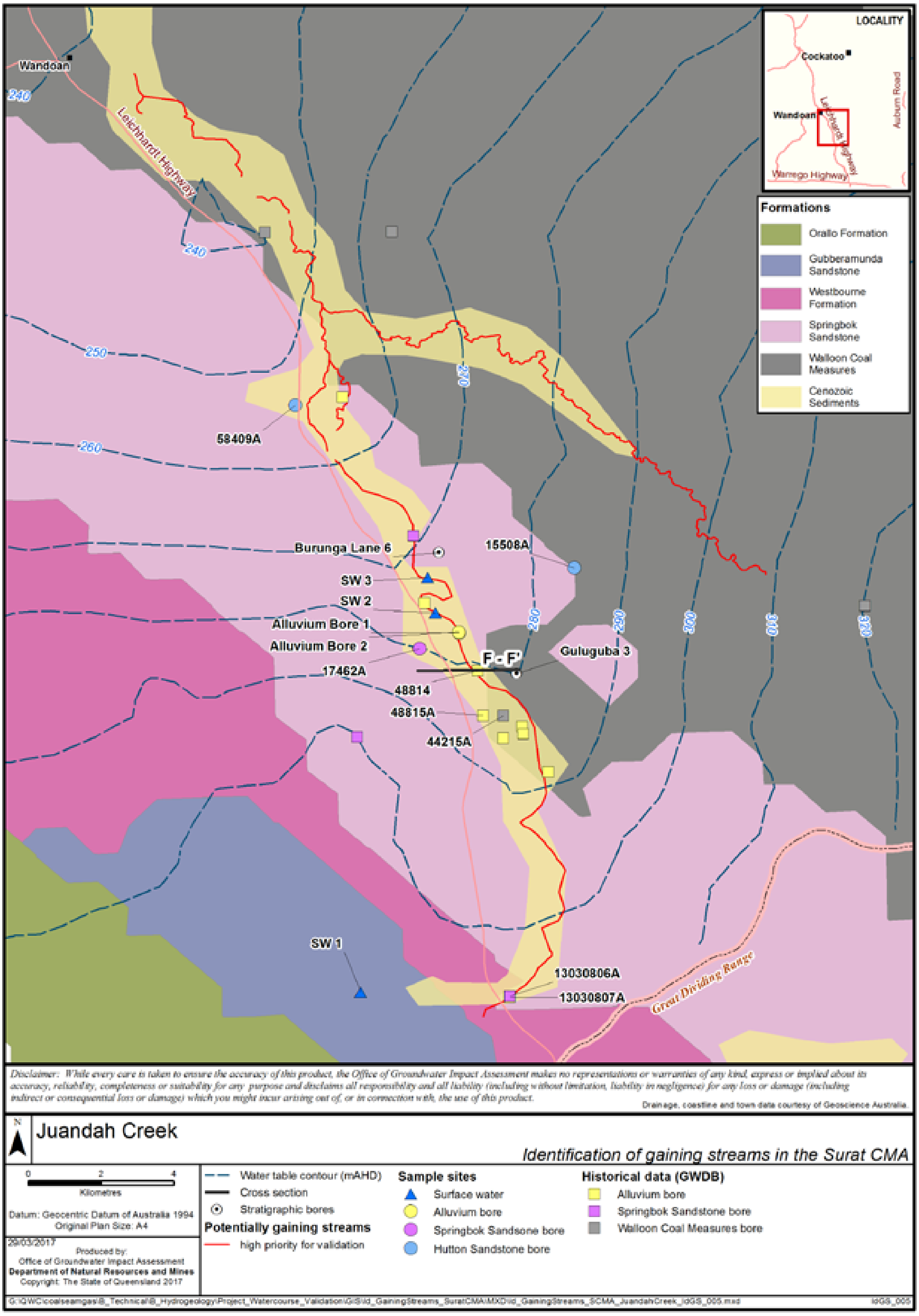

Figure 4-4 Surface water and groundwater sampling sites at Juandah Creek

4.1.3 Field observations

Juandah Creek is located within the Juandah land system (CSIRO, 1968). This section of the creek is dominated by wide sandy tributary drainage floors formed from the erosion of upgradient quartzose sandstone units (i.e. Springbok Sandstone, Mooga Sandstone) with moderately deep texture-contrast soils (CSIRO, 1968). The reach is located in the upper to mid-catchment and, as a consequence, is characterised by moderate energy and gradient surface water environments forming moderate alluvium dominated by light sandy clay loam on coarse sands (CSIRO, 1968).

Surface water sampling location SW1 was located in the upper sections of Juandah Creek within an abandoned sand and gravel mine. The creek was significantly modified for the extraction of these resources and multiple surface water pools remained within excavation pits (**Figure 4-5**). At this location, coarse sands, conglomerate and petrified wood were observed. This location adjoins the boundary of the Orallo Formation which commonly contains fossilised wood (Exon, 1976).

Aquatic vegetation assemblages observed at this site included *Typha sp.* which colonises swamps, margins of lakes and streams, irrigation channels and drains. The species is indicative of areas that are commonly wet (Mr Chris Pennay, Principal Botanist, Qld Herbarium, 2017, pers. comm., 20 March). These surface water pools were sampled for major ion and isotope analysis.

In the mid sections of this reach of Juandah Creek (SW2 and SW3), surface water was observed and sampled during field activities (**Figure 4-7**, **Figure 4-6** and **Figure 4-8**). In this area, the creek meanders significantly. This has resulted in both a broad and incised creek and the development of extensive fine-grained surficial and alluvial sediments.

At this location, the creek morphology forms a surface water catchment constriction and it is likely that shallow groundwater forms a mound in this area following high surface water flow and subsequent recharge to the colluvium. Correlating with this observation, there are numerous alluvial bores along the mid-watercourse sections, indicating a shallow and productive groundwater resource in this area. Landholders indicated bores screened in the alluvial sediments are operated year-round for domestic supply (Mr P. Erbacher, 2016, pers. comm., 5 December).

The surface water pools (SW2 and SW3) were located in areas where the bed sands had been incised by debris. The shallow water bodies contained aquatic invertebrates (as observed on 5 December 2016), suggesting that this is likely to be a more permanent feature. Landholder experiential knowledge supported that these surface water pools are sustained year-round (Mr P. Erbacher, 2016, pers. comm., 5 December).

Downstream of SW3, there are no observed areas of surface water. This was supported by the desktop analysis completed in this area (see Chapter 2).

Figure 4-5 Juandah Creek SW1

Figure 4-6 Juandah Creek SW3

Figure 4-7 Juandah Creek SW2

Figure 4-8 Juandah Creek SW3

4.1.4 Field data

Juandah Creek surface water and groundwater sampling sites are shown in **Figure 4-4**. Surface water sites were initially selected during the desktop assessment, using aerial imagery to identify areas of persistent surface water, and through landholder interviews. Groundwater bores screened in the outcropping geology were selected for sampling during the desktop assessment; actual bores sampled were ultimately determined by the availability of pumping infrastructure during the field campaign.

Surface water and groundwater was sampled and stored in accordance with the Queensland Monitoring and Sampling Manual, AS/NZS 5667:11 1998 Water Sampling Guidelines – Part 11 Guidance on sampling groundwater, and the Australian Government's Groundwater Sampling and Analysis – A Field Guide (2009:27 GeoCat #6890.1).

Field parameters collected – electrical conductivity (EC), pH, redox potential (ORP), temperature and dissolved oxygen (DO) – are detailed in **Table 4-1**. Additional water bore information was collected where possible, including standing water level (mBGL) using an electronic dip meter.

Radon (^{222}Rn) samples were collected using the method outlined by Leany & Herczeg (2006) and sent to CSIRO in Adelaide for laboratory analysis. Analysis of major ions and metals was undertaken by ALS Environmental laboratories in Brisbane.

Table 4-1 Sample locations and field data - Juandah Creek

Site	Sample source	Water level	EC	pH	ORP	DO	Temp
		mBGL	*µS/cm*		mV	mg/L	ºC
SW3	Surface water	NA[1]	672	7.55	-76.10	1.70	25.29
SW2	Surface water	NA[1]	899	8.24	-46.00	6.05	34.00
SW1	Surface water	NA[1]	600	7.83	-40.50	4.36	32.85
Alluvium Bore 1	Alluvium	NA[1]	244	6.96	-47.70	1.12	23.77
Alluvium Bore 2	Alluvium	3.8	-	-	-	-	-
17462A	Springbok Sandstone	4.5	-	-	-	-	-
58409A	Hutton Sandstone	NA[2]	5044	7.98	-221.00	4.90	41.85
15508A	Hutton Sandstone	NA[2]	4703	8.08	-215.8	0.16	36.68

NA[1] – not applicable as the sample location is a surface water site.

NA[2] – standing water level unable to be measured due to pumping infrastructure.

4.2 Bungaban Creek

Bungaban Creek is an upper tributary of the Dawson River approximately 30 km north-east of Wandoan (**Figure 3-1**). The headwaters of this creek are further east along the Great Dividing Range. The creek flows west-north-west towards Taroom into the Dawson River. As shown in **Figure 4-12**, the surface geology along this section of the creek primarily includes the Hutton Sandstone. Surface water and bores sampled during the project are also shown. There are no existing or historical surface water gauging stations along this reach of Bungaban Creek.

4.2.1 Climate

The closest rainfall station to the site is Bungaban TM (035242). The closest weather station with total climate information is the Taroom Post Office (35070). **Figure 4-9** shows the average climate statistics from this station, based on daily climate measured over the period 1870 to 2017. Daily rainfall for the period July to December 2016 is shown in **Figure 4-10**.

As shown in **Figure 4-10**, 12.4 mm of rainfall was recorded at the Bungaban TM station in the month prior to the field activities. This rainfall was recorded over five separate events and is unlikely to have contributed significant surface water flows into Bungaban Creek during the collection of field data.

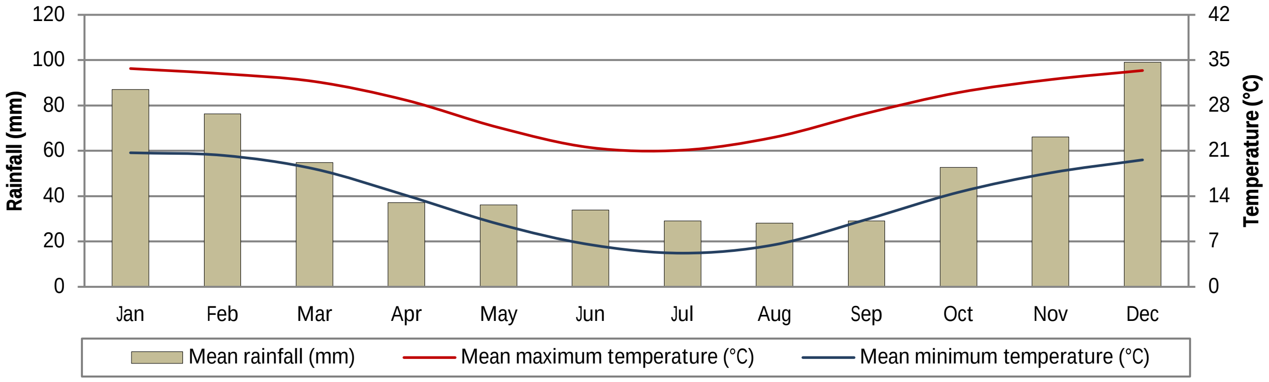

Figure 4-9 Average climate statistics at Taroom (35070) for the period 1870 to 2017

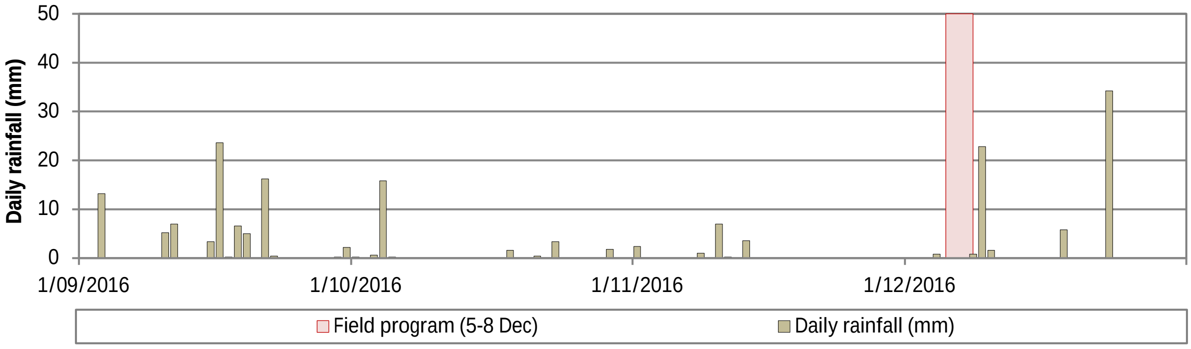

Figure 4-10 Bungaban TM (035242) rainfall statistics for the period July to December 2016

4.2.2 Hydrogeology

At this location, Bungaban Creek is eroded into the Hutton Sandstone and at some locations aligns with the geological contact with the Eurombah Formation of the Injune Creek Group. Cenozoic alluvial sediments are not significantly developed and occur in narrow deposits along the drainage line. As a result, only a limited number of groundwater bores are screened into the alluvial sediments along Bungaban Creek.

A cross-section of the creek and underlying geology is shown in **Figure 4-11**.

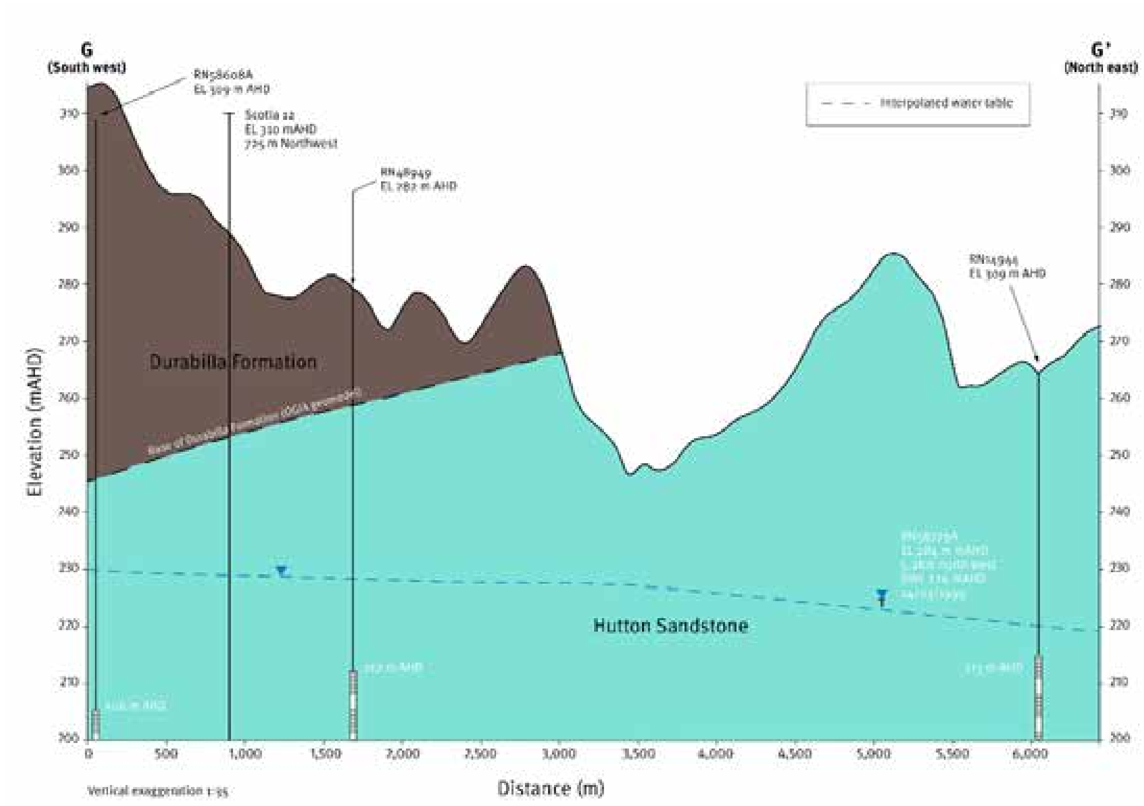

Figure 4-11 Cross-section of Bungaban Creek showing the underlying geology, stratigraphic water level controls. The depth to water table mapping (OGIA, 2017) is also included in the section.

The locations of field-collected data and historical datasets are shown in **Figure 4-12**. The interpreted regional groundwater level indicates groundwater flow is away from the creek, suggesting the creek is under losing conditions. Groundwater bores along Bungaban Creek are predominantly screened in the Hutton Sandstone. Available water level data downstream (approximately 5 km) of the cross-section, RN 58779A (226 mAHD) and the nearest creek elevation (236 mAHD), also suggest this reach is likely to be under losing conditions.

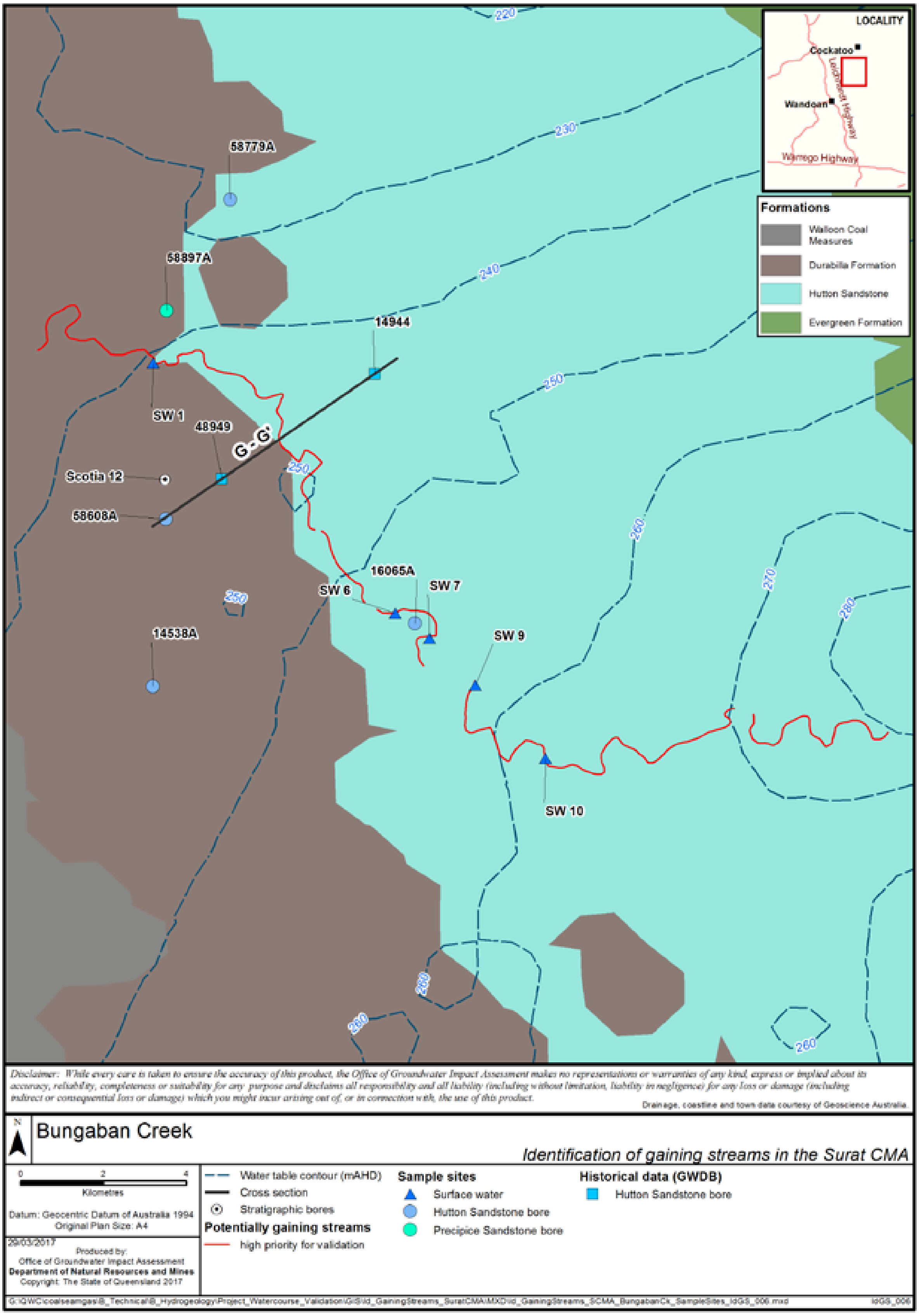

Figure 4-12 Surface water and groundwater sampling sites at Bungaban Creek

4.2.3 Field observations

Bungaban Creek is located within the Wandoan land system (CSIRO, 1968). At this location, the creek has been eroded into the Hutton Sandstone and generally conforms to the geological contact with the Eurombah Formation.

This section of the creek is higher in the catchment and, as a consequence, is characterised by high-gradient, narrow and high-energy surface water environments. As a result, the Hutton Sandstone is significantly incised with minor alluvial development, which is consistent with the surface geological mapping in this area (DNRM, 2017). Within these incised drainage lines, where alluvium exists, soils are dominated by shallow, light to medium clays (CSIRO, 1968), likely to be the result of erosion of the upstream Evergreen Formation and the adjacent Eurombah Formation.

While there was limited rainfall recorded in the month prior to the field activities (**Figure 4-10**), above-average rainfall occurred in September, with 83.2 mm recorded at the Bungaban TM station. This represents 48.8 mm above the long-term average rainfall for the month of September.

In the upstream sections of this location (SW6, SW7 and SW10), extensive sections of surface water were observed during the field activities (**Figure 4-14**, **Figure 4-15** and **Figure 4-17**). These sections were predominantly adjacent to the Mundell State Forest and are narrow, long and continuous waterhole sections. The water was visibly turbid, suggesting surface water runoff as a major process influencing water quality. Landholder experiential knowledge suggests that, at this location, some waterholes are near permanent features, contracting back during low-rainfall periods (Mr C. Hartwig, 2016, pers. comm., 6 December). These more permanent locations were observed to coincide with areas of minor alluvial development.

Further downstream from these sections, surface water sections were observed to be less extensive and less common than upstream reaches. A single site was sampled at SW1 (**Figure 4-13**). Landholder experiential knowledge indicated the downstream sections of Bungaban Creek in this area are relatively dry, with several minor waterholes which are not permanent (Mr S. Rathbone, 2016, pers. comm., 6 December). The pre-field desktop activities supported this observation with few persistent waterholes identified for field investigations.

Bullock Creek is a minor watercourse parallel to Bungaban Creek. A single site was sampled (SW2) following conversations with the local landholders (Mr S. Rathbone, 2016, pers. comm., 6 December) which suggested the location had sustained surface water over the past few years. This site is directly located at the contact of the Hutton Sandstone and the Eurombah Formation. The outcropping Hutton Sandstone is observed on the eastern bank (**Figure 4-18**).

Figure 4-13 Bungaban Creek SW1

Figure 4-14 Bungaban Creek SW6

Figure 4-15 Bungaban Creek SW7

Figure 4-16 Bungaban Creek SW9

Figure 4-17 Bungaban Creek SW10

Figure 4-18 Bullock Creek SW11

4.2.4 Field data

Bungaban Creek surface water and groundwater sampling sites are shown in **Figure 4-12.** The rationale for the selection of sampling sites is discussed in Section 4.1.4.

Surface water and groundwater was sampled and stored in accordance with the Queensland Monitoring and Sampling Manual, AS/NZS 5667:11 1998 Water Sampling Guidelines – Part 11 Guidance on sampling groundwater, and the Australian Government's Groundwater Sampling and Analysis – A Field Guide (2009:27 GeoCat #6890.1).

Field parameters collected – electrical conductivity (EC), pH, redox potential (ORP), temperature and dissolved oxygen (DO) – are detailed in **Table 4-2**. Additional water bore information was collected where possible, including standing water level (mBGL) using an electronic dip meter.

Radon (^{222}Rn) samples were collected using the method outlined by Leany & Herczeg (2006) and sent to CSIRO in Adelaide for laboratory analysis. Analysis of major ions and metals was undertaken by ALS Environmental laboratories in Brisbane.

Table 4-2 Sample locations and field data - Bungaban Creek

Site	Sample source	Water level	EC	pH	ORP	DO	Temp
		mBGL	*µS/cm*		mV	mg/L	°C
SW1	Surface water	NA[1]	374	7.68	-44.20	4.48	27.29
SW2	Surface water	NA[1]	260	7.46	39.50	4.22	30.20
SW6	Surface water	NA[1]	395	7.98	12.90	4.95	31.27
SW7	Surface water	NA[1]	249	7.34	44.39	2.25	34.50
SW9	Surface water	NA[1]	261	7.46	54.60	4.53	32.50
SW10	Surface water	NA[1]	169	7.41	66.90	4.87	32.28
58779A	Hutton Sandstone	NA[2]	2909	7.54	-176.00	0.30	25.28
16065A	Hutton Sandstone	NA[2]	3262	7.55	-127.00	0.95	25.90
58608A	Hutton Sandstone	NA[2]	4070	7.46	-7.44	0.95	24.90
14538A	Hutton Sandstone	NA[2]	3485	7.70	-170.40	0.99	25.42
58897A	Precipice Sandstone	NA[2]	252	7.22	-84.10	2.28	32.45

NA[1] – not applicable as the sample location is a surface water site.

NA[2] – standing water level unable to be measured due to pumping infrastructure.

5 Results and analysis

The following sections provide analysis and results from the field observations and data collected for the Juandah and Bungaban creeks. The results are discussed in terms of groundwater flow, water chemistry and isotope analysis and incorporate both historical data and field data collected between 5 and 7 December 2016.

The assessment of likely groundwater flow directions to or from the study sites has been completed using two available datasets: interpolated depth to watertable mapping (OGIA, 2017) and a comparison between creek bed elevation and standing water level in nearby groundwater bores.

Water chemistry and isotopes are used to assess the relative contribution of rainfall and groundwater to riverine waterholes (see **Appendix A**). In this Chapter, major ion and isotope analysis (^{222}Radon) are discussed. Results from the samples collected from Juandah Creek and Bungaban Creek are provided in **Appendix 11.4**.

For comparison with major ion results, end members are required from potentially contributing water sources including rainfall and underlying aquifers. Rainfall data has been sourced from previous studies (Crosbie et al., 2012). Aquifer hydrochemistry data was collected during field activities. For some aquifers, nearby historical data (< 10 km) from the GWDB are also included to expand the available dataset.

At the conclusion of each section, the findings and field observations are integrated to provide a conclusion on the likely surface water and groundwater connectivity regime. It is important to note that the field data were collected during a single field campaign and additional data collection would increase confidence in the report's conclusions.

5.1 Juandah Creek

5.1.1 Groundwater flow directions and discharge

The depth to watertable mapping at the Juandah Creek site indicates the alluvium is potentially under gaining conditions. The horizontal hydraulic gradient is interpreted to be from the adjacent Springbok Sandstone and Walloon Coal Measures outcrop towards the alluvium (**Figure 4-4**). Groundwater flow directions generally conform with the surface water drainage pattern, from the south to the north.

Standing water level information collected during field activities and historical information from the GWDB indicate water levels within the outcrop are consistently within 5 metres of ground surface. This is observed in upstream sections (RN13030806A – Westbourne Formation, RN13030807A - Alluvium) and mid-stream sections (RN48815A – Alluvium, RN44215A – Alluvium and RN17462A – Springbok Sandstone) of the Juandah Creek (**Figure 4-4**). These data points support the observations from the depth to watertable mapping.

5.1.2 Water chemistry

Field water chemistry parameters measured at Juandah Creek are provided in **Table 4-1**. Laboratory results from these locations are provided in **Appendix A** and are presented with local rainfall data in **Figure 5-1**.

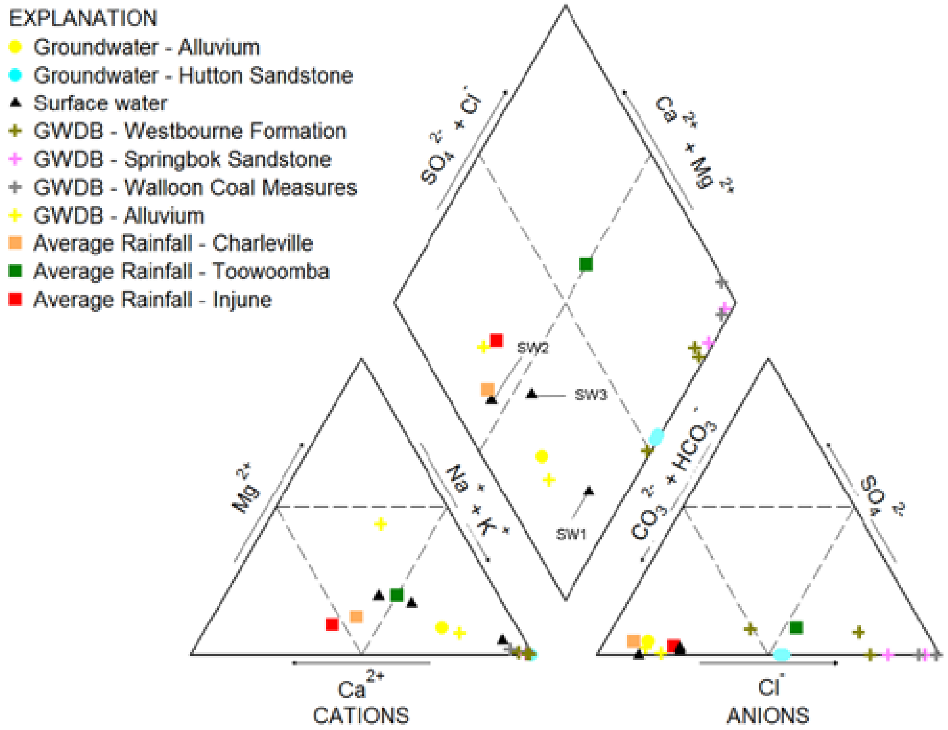

Figure 5-1 Piper diagram plot of water samples from Juandah Creek. Rainfall data derived from Crosbie et al. (2012).

As shown in **Table 4-1** and **Appendix B**, water at Juandah Creek is moderately fresh with total dissolved solids (TDS) ranging from 433 to 489 mg/L and electrical conductivity (EC) ranging from 600 to 899 μS/cm. These concentrations are significantly higher than available rainfall data which generally shows an EC of 10 to 100 μS/cm (Crosbie et al., 2012). The observed elevated concentrations may indicate the influence of evaporation on the sampled surface water, mixing with surface runoff and/or groundwater contribution to the surface water.

Groundwater from Alluvium Bore 1 screened in the alluvium is notably fresher (160 mg/L TDS), particularly when compared to the average groundwater salinity from bores screened in the Hutton Sandstone which are brackish (2470 mg/L). As shown in **Figure 5-1**, groundwater in the Hutton Sandstone, Springbok Sandstone and Walloon Coal Measures (Na-Cl type) is distinct from both the alluvium (Na-HCO_3 type) and rainwater. The consolidated formations show distinctly higher Chloride (Cl^-) and reduced Calcium (Ca^{2+}).

Surface water sampled from mid-section reaches (SW2 and SW3) shows a chemistry signature between the rainfall and alluvium end members, suggesting evolution of the surface water samples from rainwater and potential contributions from the alluvial groundwater resource.

Surface water sampled from the upstream section (SW1) is distinct from surface samples in the mid-reaches (SW2 and SW3). Enriched in Na^+ concentrations, this site shows some similarities in composition to the Westbourne Formation which forms the northern outcrop at the SW1 sampling location. The observed higher Na^+ is potentially the influence of surface runoff across the surrounding soils, which are highly sodic (CSIRO, 1968).

The available hydrochemistry data suggests the mid-stream (SW2 and SW3) and upstream reaches (SW1) appear similar to the alluvium and rainfall.

5.1.3 Isotope analysis

The measured ^{222}Rn activity in groundwater and surface water along Juandah Creek is shown in **Table 5-1**.

Table 5-1 Radon concentrations - Juandah Creek

Location	Site	Sample source	^{222}Rn
			Bq/L
Mid-stream	**SW3**	Surface water	1.02
	SW2	Surface water	0.76
Upstream	**SW1**	Surface water	0.14
Groundwater	**Paul's Alluvium Bore**	Alluvium	8.78
	15508A	Hutton Sandstone	5.70

The results indicate a distinction between the average activity levels in groundwater (5-10 Bq/L) and surface water (~0.10 Bq/L). The ranges of observed ^{222}Rn levels between groundwater and surface water are similar to those previously reported by Cartwright et al. (2011) and Martinez et al. (2015).

The activity of ^{222}Rn in surface water in the upstream section was measured at 0.14 Bq/L with ^{222}Rn activities notably higher (0.74 to 1.02 Bq/L) in the mid-stream sections. The ^{222}Rn activities in the mid-stream sections values are the highest measured values from surface waters values in this study. The lower ^{222}Rn activities measured in the upstream reaches may indicate shorter residence time in the groundwater system, or longer residence time in the surface water resulting in reduction or degassing in ^{222}Rn activity levels.

5.1.4 Conclusions

Analysis suggests the surface water sites in the mid-section of Juandah Creek (SW2 and SW3) were receiving groundwater discharge at the time of sampling. Similarly, upstream at SW1, groundwater is discharging to surface water, albeit to a lesser extent at this location. This conclusion is supported by the isotope analysis.

The depth to groundwater mapping and available standing water level data indicates there is potential for groundwater discharge from the Walloon Coal Measures and the Springbok Sandstone to the alluvium along Juandah Creek. Major ion analysis, however, indicates the hydrochemical composition of the alluvium is distinct from the adjacent Walloon Coal Measures and Springbok Sandstone. Although there is a hydraulic gradient between the consolidated formations and the alluvium, there appears to be limited connectivity between these units.

The hydrochemical composition of the sampled surface water indicates the most likely contributing water source is the alluvium and rainfall. This section of the creek is dominated by wide sandy tributary drainage floors, formed from the erosion of upgradient quartzose sandstone units with moderate levels of alluvium. Given the extensive level of groundwater development from the alluvium, there is a significant groundwater resource to support localised discharge to the surface.

Landholder experiential knowledge indicates there are areas of semi-permanent to permanent groundwater discharge in mid-section reaches of Juandah Creek. These sites were sampled in this project (SW2 and SW3).

The wetlands are in areas where the alluvium has been incised by debris or surface water flow processes. The location of groundwater discharge is likely to vary due to high flow surface water events and sedimentation of the creek bed. In addition, the unconfined alluvium is likely to respond to local rainfall events and therefore seasonal changes in groundwater discharge are anticipated.

The surface water sites along this section of the Juandah Creek are interpreted to be supported by the alluvium. Based on the hydrochemistry, there is limited connectivity between the alluvium and consolidated units.

Therefore, predicted impacts in the Walloon Coal Measures and Springbok Sandstone are unlikely to affect the identified gaining streams.

5.2 Bungaban Creek

5.2.1 Groundwater flow directions and discharge

The depth to watertable mapping at Bungaban Creek indicates the creek and minor alluvial development are likely to be under disconnected or losing conditions along this reach (**Figure 4-12**). This conclusion is supported by historical standing water level information. At this location, the nearest available groundwater measurements at the outcrop (RN 58779A, 226 mAHD) indicate a standing water level of 17 metres below ground (**Figure 4-12**).

5.2.2 Water chemistry

Field water chemistry parameters measured at Bungaban Creek are provided in **Table 4-2**. Laboratory results from these locations are provided in **Appendix B** and are presented with local rainfall data in **Figure 5-2**.

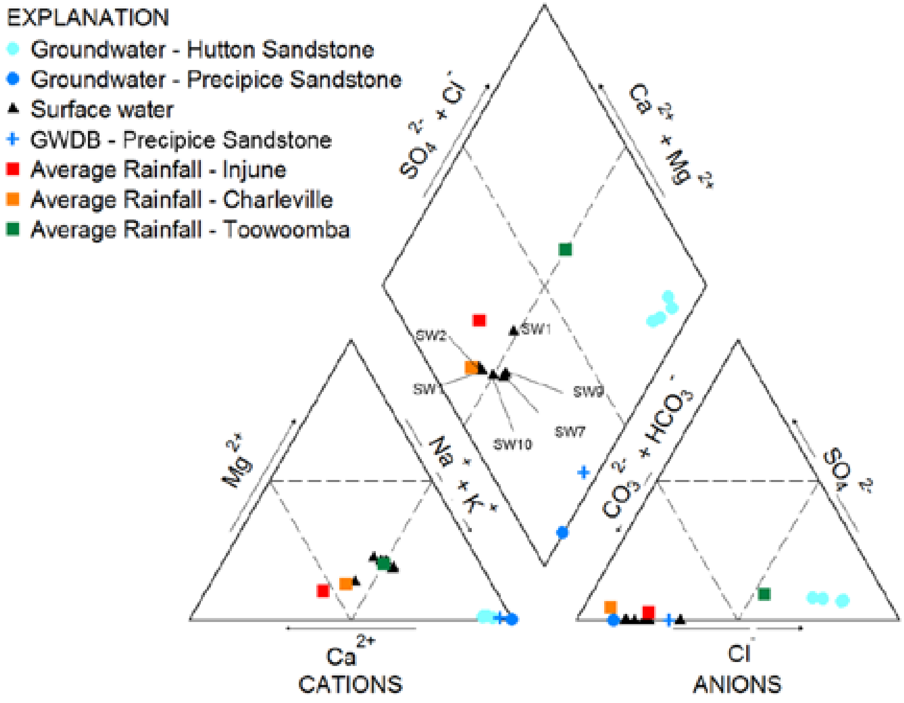

Figure 5-2 Piper diagram plot of water samples from Bungaban Creek. Rainfall data derived from Crosbie et al. (2012).

As shown in **Figure 5-2** and in **Appendix B**, water chemistry at Bungaban Creek is fresh, with results showing TDS ranging from 99 to 228 mg/L and EC from 152 to 350 μS/cm. These EC measurements are also higher than values recorded in rainfall (Crosbie et al., 2012), although it is fresher when compared to surface water in Juandah Creek.

Groundwater samples from bores screened in the Hutton Sandstone are brackish, with TDS ranging from 1900 to 2650 mg/L and EC from 2920 to 4080 μS/cm. Groundwater from the sampled bore screened in the Precipice Sandstone, underlying the Hutton Sandstone, is fresh with a TDS of 140 mg/L and an EC of 215 μS/cm. In terms of surface water samples, sites sampled on Bungaban Creek are fresh (< 250 mg/L TDS) compared to Juandah Creek.

As shown in the piper plot (**Figure 5-2**), groundwater from bores screened in the Hutton Sandstone (Na-Cl type) is distinct from groundwater in the Precipice Sandstone ($Na\text{-}HCO_3$). Surface water chemistry are similar to rainfall and show variability across the sample sites.

The available hydrochemistry data suggest the surface water in Bungaban Creek is rainfall-derived, with minimal notable groundwater contribution.

5.2.3 Isotope analysis

The measured ^{222}Rn activity in groundwater and surface water along Bungaban Creek is shown in **Table 5-2**.

Table 5-2 Radon concentrations - Bungaban Creek

Location	Site	Sample source	^{222}Rn
			Bq/L
Downstream	**SW1**	Surface water	0.14
	SW11	Surface water	0.09
Mid-stream	**SW6**	Surface water	0.11
	SW7	Surface water	0.04
	SW9	Surface water	0.13
	SW10	Surface water	0.07
Groundwater	**58779A**	Hutton Sandstone	10.58
	16065A	Hutton Sandstone	12.53
	58608A	Hutton Sandstone	13.43
	14538A	Hutton Sandstone	11.89
	58897A	Precipice Sandstone	5.24

The results indicate a distinction between the average activity levels in groundwater (5-10 Bq/L) and surface water (~0.10 Bq/L). The ranges of observed ^{222}Rn levels between groundwater and surface water are similar to those previously reported by Cartwright et al. (2011) and Martinez et al. (2015).

Mean groundwater ^{222}Rn activity in Hutton Sandstone bores along Bungaban Creek was 12.11 Bq/L, with an observed range of 10.58 to 13.42 Bq/L. The exception to this is ^{222}Rn activity from the Precipice Sandstone bore (58897A), measured at 5.24 Bq/L. This apparent difference is also supported by observed distinctions in the recorded field parameters and the water types as shown in the Piper diagram (**Figure 5-2**).

Surface water ^{222}Rn activities are two orders of magnitude lower than those in nearby groundwater. Based on this data, the surface water sampled at Bungaban Creek is likely to be rainfall-derived, with minimal groundwater contributions.

5.2.4 Conclusions

From the analysis of available data, the surface water within Bungaban Creek is unlikely to be derived from a groundwater source and is interpreted to be supported by rainfall and overland flow. This conclusion is supported by the hydrochemistry results, groundwater flow analysis and field observations.

The depth to groundwater mapping and the limited available standing water level data indicate the creek is under losing conditions. In addition, major ion analysis indicates the hydrochemical composition of the surface water sites is distinct from the adjacent Hutton Sandstone and underlying Precipice Sandstone (**Figure 5-2**).

The continuous surface water sections along the mid-stream areas are most likely derived from rainfall. The surface water has very low measured salinity (139 to 395 *µS/cm*). The minor alluvium is dominated by sodic soils which have a very low saturated permeability and therefore are likely to maintain surface water pools over extended periods, with limited deep drainage to the underlying groundwater system.

6 Conclusions

Increasing confidence in the mapping of gaining streams in the Surat CMA is essential for improving the conceptual understanding of surface–groundwater interaction and for assessing impacts of CSG development on environmental values associated with those streams. At a desktop level, this project has mapped new and additional areas of potentially gaining streams using new datasets and information generated since the previous mapping by AGE (2005).

Field validation of gaining streams was necessary to improve confidence and further refine the mapping methodology. Given the large spatial extent of the study area, the magnitude of predicted impacts from P&G development (OGIA, 2016a) was used to prioritise areas for field validation. Two sites have been field validated as part of this project: Juandah Creek and Bungaban Creek.

At Juandah Creek, the available data indicates surface water is supported by groundwater from the alluvium and is unlikely to be fed by the underlying Walloon Coal Measures, Springbok Sandstone or Westbourne Formation. At Bungaban Creek, the available data indicate surface water is supported by rainfall and overland flow and is likely to be disconnected from or discharging to the underlying Hutton Sandstone. As a result of these findings, the risk of impact from P&G development on these sites has significantly reduced.

The Juandah Creek investigations provide an initial validation of the new methodology to identify gaining streams in the Surat CMA. Additionally, the findings from the field investigations have recognised the need to improve understanding of the connectivity between Cenozoic sediments within drainage and underlying bedrock (e.g. Walloon Coal Measures, Springbok Sandstone). Although the overlying Cenozoic sediments often contain only minor groundwater resources, more work is required to characterise their influence on groundwater flow from bedrock to streams.

The Bungaban Creek investigations indicate that the current methodology provides more confidence in the identification of gaining streams than previous assessments. Future refinements to the desktop methodology to identify gaining streams will continue to use the AGE (2015) assessment as a secondary line of evidence, rather than as a primary data for interpolation. The incorporation into the methodology of stream geomorphology and catchment position will also be evaluated as part of the next stage of the project.

There are 10 additional reaches identified as priorities for field validation over the next 12 months. The outcomes from this project will improve the conceptual understanding of surface water–groundwater connectivity in the Surat Basin and will provide a basis for the establishment of appropriate management strategies for gaining streams in the next iteration of the Surat UWIR.

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Streams – State of Queensland (Department of Natural Resources and Mines) 2016. Data from Commonwealth of Australia (Geoscience Australia) 2009 used in creating this dataset provided under Creative Commons Australia - Attribution licence. Updated data available at http://qldspatial.information.qld.gov.au/catalogue//

Streamflow data – State of Queensland (Department of Natural Resources and Mines) 2016. Updated data available at https://water-monitoring.information.qld.gov.au/

State geology – State of Queensland (Department of Natural Resources and Mines) 2017. Updated data available at http://qldspatial.information.qld.gov.au/catalogue//

Appendix A - Literature review: SW-GW analysis techniques

The main methods used in this study to investigate surface water and groundwater interactions will be focused on simple validation tools or measurements that are inexpensive and can be rapidly obtained to provide a first-pass assessment of groundwater–surface water connectivity. Where possible, the multiple investigation methods will also be considered for use as a 'multiple lines of evidence' approach.

Brodie et al. (2007) reviewed the available tools to assess connectivity between surface water and groundwater and trialled some of these tools in the Murray–Darling Basin. A summary report by SKM & CSIRO (2012) found five methods suitable for estimating groundwater discharge to streams.

Upon review of the studies, it was determined that the groundwater–surface water assessments using environmental tracers and hydraulic gradients are able to provide a rapid assessment of groundwater–surface water connectivity.

A.1 Head gradient analysis

The groundwater head difference (or gradient) between two or more points in the landscape or between the surface water and groundwater can be used to determine the flow direction and potential rate of groundwater flow. At the simplest level, groundwater flow directions can be determined by just comparing the groundwater heads to the river bed.

The quantity of groundwater flow between a watercourse and groundwater can also be estimated by solving for the components of the Darcy equation for fluid movement in a porous material (Darcy, 1856):

$$q = -K\,(\delta h/\delta l)$$

Where,

q is the specific discharge with units of L/T (Darcy velocity or Darcy flux)

K is the hydraulic conductivity

h is the difference between two hydraulic head measurements in metres

l is the distance between the two hydraulic head measurements in metres

Estimates of groundwater inflow would be resolved using depth to groundwater measurements or surface water levels to constraint the flow gradient, $\delta h/\delta l$, and a range of hydraulic conductivity (K) estimates. The volume of groundwater discharge Q (m^3/s) into the watercourse is then estimated using the calculated specific discharge, q (m/s), and a derived surface area of where groundwater exchange occurs in a cross-sectional area (m^2).

This method, while extremely simple to perform, provides only a snapshot of groundwater flux with the watercourse. Hydraulic conductivities are expressed in the vertical direction (K_v) and horizontal direction (K_h), but in reality this value is extremely complex to constrain even at the small-scale environment. Head gradients and groundwater saturation areas may continually change over time and will not be accurately represented using a single calculation. As a result, any inflows calculated should be only considered as estimates. Regardless, the estimate is a useful indicator of the degree of losing or gaining conditions of a watercourse.

A.2 Major ion chemistry

Major cations (magnesium, calcium, sodium, and potassium) and anions (chloride, bicarbonate, sulphate) are naturally occurring dissolved constituents in water and can be used as a natural tracer to identify groundwater and surface water interactions within a watercourse (Brodie et al., 2007). The major ionic composition of water is mainly determined by rainfall composition (surface water) or acquisition from water-rock interaction over time (groundwater).

Major ion data can be presented in graphical format using Piper diagrams (trilinear diagrams) to plot the percentage of major ions on triangular and diamond-shaped boxes for visual evaluation and determination of hydro-geochemical type of water samples. The objective of the plots is to enable a visual analysis to identify distinct hydro-geochemical compositions (e.g. Na-Cl, Ca-HCO_3 type) to characterise 'surface water' and 'groundwater' end members. The diagram may also indicate intermediate compositions and trends along flow paths or mixing of water end members. Although Piper diagrams are widely used, visualisation of large amounts of data may become challenging. Piper diagrams also do not consider minor ions which may be important to characterise certain hydro-geochemical water types.

A.3 Radon

A naturally occurring noble gas, ^{222}Rn is a product of radioactive decay chains originating from rocks such as igneous and metamorphic rocks that contain high uranium-238 content. Radon produced from radioactive decay within the rocks is dissolved in groundwater. Groundwater that discharges to the surface will rapidly lose its radon content due to degassing into the atmosphere. Radon is therefore a natural tracer that shows relatively high concentrations in groundwater and in the immediate vicinity of groundwater discharge locations. Radon concentrations are also typically two to three orders of magnitude lower in surface waters compared to groundwater (Cartwright et al., 2011 and Martinez et al., 2015), making it a particularly sensitive indicator of groundwater inflow.

Results from analysis of ^{222}Rn concentrations can be used to identify the groundwater end member where it is relatively high and surface water end member where it is close to zero due to degassing process. A quantitative estimate of groundwater inflow into a watercourse can be calculated using the following equation (Atkinson et al., 2015 and Martinez et al., 2015):

$$I = (Q.(\ \delta C_r/\delta x) - w.E.C_r + k.d.w.C_r + \lambda.d.w.C_r) \,/\, (C_i - C_r)$$

Where,

I = groundwater inflow (m3/m/day)

C_i = dissolved ^{222}Rn activity of groundwater (Bq/m^3)

C_r = dissolved ^{222}Rn activity of surface water (Bq/m^3)

Q = stream discharge, in m^3/day

w = stream width (m)

d = stream depth (m)

λ = radioactive decay rate (1/day)

E = evaporation rate (m/day)

K = reaeration coefficient, in 1/day (range is from 0.5 to 5 (Atkinson et al., 2015))

Radon activities in the surface water and groundwater end members (C_i, C_r) can be obtained from the analysis of water samples. The stream dimensions can be estimated from a DEM or a surveyed cross-section of the watercourse, while estimates of stream discharge and evaporation rates can be obtained from stream gauging and meteorological stations. Similarly, stream discharge data can be obtained from stream gauging sites.

The radon method may overestimate the proportion of groundwater input into watercourses, if input from short-term water storage in creek banks and the hyporheic zone is comparatively significant compared to regional groundwater input (Cook et al., 2006). It is anticipated that limiting sampling activities to dry periods will reduce these influences.

Appendix B - Laboratory results

Table B-1 Laboratory results - ^{222}Rn (CSIRO)

Sample ID	Sample ID	Date / Time	Water type	Longitude (zone 56)	Latitude (zone 56)	^{222}Rn in water, Bq/l	^{222}Rn in water, Bq/l Uncertainty
58409A	58409A	2016-12-05 08:40:00	Groundwater	201850	7097881	NA	NA
SW 2	Downfall Creek Road	2016-12-05 11:00:00	Surface water	205441	7092265	0.763674426	0.043730702
SW3	Dead Cow Bend SW	2016-12-05 13:30:00	Surface Water	205232	7093228	1.021878182	0.057446891
Alluvium Bore 1	Paul's Alluvium Bore	2016-12-05 16:10:00	Groundwater	206042	7091731	8.783821663	0.478409923
15508A	15508A	2016-12-05 18:00:00	Groundwater	208851	7093568	5.696405576	0.311190863
SW 1	Bungaban Creek SW1	2016-12-06 09:30:00	Surface Water	206831	7138484	0.139202647	0.015803894
SW 2	Bullock Creek SW	2016-12-06 10:00:00	Surface Water	203545	7133389	0.090724651	0.007968393
SW 7	Bungaban Creek SW7	2016-12-06 11:00:00	Surface Water	213005	7131974	0.037902162	0.005608659
58608A	58608A	2016-12-06 12:30:00	Groundwater	207197	7134728	13.42895638	0.729894783
14538A	14538A	2016-12-06 13:30:00	Groundwater	207002	7130680	11.89339559	0.646686318
SW10	Bungaban Creek SW10	2016-12-06 15:20:00	Surface Water	215596	7129132	0.070755073	0.007352605
SW 9	Bungaban Creek SW9	2016-12-06 16:00:00	Surface Water	214031	7130868	0.130880621	0.010247959
58897A	58897A	2016-12-07 09:00:00	Groundwater	207097	7139758	5.238773933	0.28608517
58779A	58779A	2016-12-07 10:00:00	Groundwater	208423	7142468	10.57584887	0.575241345
16065A	16065A	2016-12-07 12:05:00	Groundwater	212681	7132325	12.52905524	0.681274432
SW 6	Bungaban Creek SW6	2016-12-07 13:15:00	Surface Water	212245	7132560	0.109127685	0.009131282
SW 1	Juandah Creek SW1	2016-12-07 15:15:00	Surface Water	203840	7081818	0.136292989	0.010333113

Table B-2 Laboratory results - major ion chemistry (ALS)

Date	Sample ID	pH	Electrical Conductivity @ 25°C	Total Dissolved Solids (Calc.)	Total Hardness as $CaCO_3$	Hydroxide Alkalinity as $CaCO_3$	Carbonate Alkalinity as $CaCO_3$	Bicarbonate Alkalinity as $CaCO_3$	Total Alkalinity as $CaCO_3$	Sulfate as SO_4^{-} Turbidi-metric
		pH Unit	*µS*/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
05/12/2016	**58409A**	8.31	3730	2420	12	<1	9	1000	1010	<1
05/12/2016	**SW 2 (Juandah Creek)**	8.08	666	433	204	<1	<1	338	338	<1
05/12/2016	**SW 3 (Juandah Creek)**	8.31	752	489	177	<1	4	317	321	5
05/12/2016	**Alluvium Bore 1**	7.49	246	160	42	<1	<1	112	112	5
05/12/2016	**15508A**	8.36	3870	2520	10	<1	21	964	984	<1
06/12/2016	**SW 1 (Bungaban Creek)**	7.81	350	228	89	<1	<1	123	123	<1
06/12/2016	**SW 2 (Bungaban Creek)**	7.80	233	151	66	<1	<1	107	107	<1
06/12/2016	**SW 7 (Bungaban Creek)**	7.59	222	144	50	<1	<1	91	91	<1
06/12/2016	**58608A**	7.92	4080	2650	186	<1	<1	303	303	121
06/12/2016	**14538A**	8.07	3470	2260	102	<1	<1	277	277	102
06/12/2016	**SW 10 (Bungaban Creek)**	7.71	152	99	39	<1	<1	70	70	<1
06/12/2016	**SW 9 (Bungaban Creek)**	7.77	225	146	60	<1	<1	103	103	<1
07/12/2016	**58897A**	8.29	215	140	<1	<1	<1	106	106	<1
07/12/2016	**58779A**	8.54	2920	1900	131	<1	34	302	336	99
07/12/2016	**16065A**	8.48	3320	2160	128	<1	27	307	334	107
07/12/2016	**SW 6 (Bungaban Creek)**	8.24	346	225	83	<1	<1	144	144	<1
07/12/2016	**SW 1 (Juandah Creek)**	8.39	672	437	39	<1	9	266	276	7

Date	**Sample ID**	**Chloride**	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Mercury**	**Fluoride**	**Total Anions**	**Total Cations**	**Ionic Balance**
		mg/L	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**meq/L**	**meq/L**	**%**
05/12/2016	**58409A**	671	5	<1	854	5	<0.0001	4.8	39.1	37.5	2.07
05/12/2016	**SW 2 (Juandah Creek)**	27	52	18	68	15	<0.0001	0.1	7.51	7.42	0.65
05/12/2016	**SW 3 (Juandah Creek)**	59	43	17	91	19	<0.0001	0.1	8.18	7.99	1.19
05/12/2016	**Alluvium Bore 1**	10	12	3	41	4	<0.0001	0.2	2.62	2.73	----
05/12/2016	**15508A**	712	4	<1	906	4	<0.0001	4.4	39.7	39.7	0.04
06/12/2016	**SW 1 (Bungaban Creek)**	34	21	9	32	12	<0.0001	0.4	3.42	3.49	1.02
06/12/2016	**SW 2 (Bungaban Creek)**	11	20	4	16	14	<0.0001	0.1	2.45	2.38	----
06/12/2016	**SW 7 (Bungaban Creek)**	14	12	5	21	10	<0.0001	0.3	2.21	2.18	----
06/12/2016	**58608A**	1010	63	7	793	4	<0.0001	<0.1	37.1	38.3	1.66
06/12/2016	**14538A**	855	36	3	682	3	<0.0001	<0.1	31.8	31.8	0.01
06/12/2016	**SW 10 (Bungaban Creek)**	9	9	4	15	5	<0.0001	0.3	1.65	1.56	----
06/12/2016	**SW 9 (Bungaban Creek)**	11	14	6	18	9	<0.0001	0.4	2.37	2.20	----
07/12/2016	**58897A**	8	<1	<1	48	2	<0.0001	0.3	2.34	2.14	----
07/12/2016	**58779A**	651	46	4	551	5	<0.0001	0.1	27.1	26.7	0.78
07/12/2016	**16065A**	761	43	5	633	5	<0.0001	0.2	30.4	30.2	0.25
07/12/2016	**SW 6 (Bungaban Creek)**	24	20	8	38	11	<0.0001	0.4	3.55	3.59	0.51
07/12/2016	**SW 1 (Juandah Creek)**	50	9	4	136	5	<0.0001	0.5	7.07	6.82	1.79

Date	Sample ID	Arsenic	Beryllium	Barium	Cadmium	Chromium	Cobalt	Copper	Lead	Lithium
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
05/12/2016	**58409A**	<0.001	<0.001	0.163	<0.0001	<0.001	<0.001	<0.001	<0.001	0.044
05/12/2016	**SW 2 (Juandah Creek)**	0.002	<0.001	0.233	<0.0001	<0.001	0.002	<0.001	<0.001	0.003
05/12/2016	**SW 3 (Juandah Creek)**	0.003	<0.001	0.210	<0.0001	<0.001	0.001	<0.001	<0.001	0.003
05/12/2016	**Alluvium Bore 1**	0.001	<0.001	0.060	<0.0001	<0.001	<0.001	0.001	<0.001	0.002
05/12/2016	**15508A**	<0.001	<0.001	0.140	<0.0001	<0.001	<0.001	<0.001	<0.001	0.047
06/12/2016	**SW 1 (Bungaban Creek)**	0.002	<0.001	0.102	<0.0001	<0.001	0.002	0.002	<0.001	0.002
06/12/2016	**SW 2 (Bungaban Creek)**	0.002	<0.001	0.085	<0.0001	<0.001	0.002	0.001	<0.001	0.002
06/12/2016	**SW 7 (Bungaban Creek)**	0.002	<0.001	0.076	<0.0001	<0.001	0.002	0.002	0.001	0.003
06/12/2016	**58608A**	<0.001	<0.001	0.051	<0.0001	<0.001	<0.001	<0.001	<0.001	0.059
06/12/2016	**14538A**	<0.001	<0.001	0.049	<0.0001	<0.001	<0.001	<0.001	<0.001	0.046
06/12/2016	**SW 10 (Bungaban Creek)**	0.001	<0.001	0.054	<0.0001	<0.001	<0.001	0.003	<0.001	0.002
06/12/2016	**SW 9 (Bungaban Creek)**	0.001	<0.001	0.071	<0.0001	<0.001	0.002	0.003	<0.001	0.002
07/12/2016	**58897A**	<0.001	<0.001	0.012	<0.0001	<0.001	<0.001	0.003	<0.001	0.008
07/12/2016	**58779A**	<0.001	<0.001	0.054	<0.0001	<0.001	<0.001	<0.001	<0.001	0.086
07/12/2016	**16065A**	<0.001	<0.001	0.056	<0.0001	<0.001	<0.001	<0.001	<0.001	0.072
07/12/2016	**SW 6 (Bungaban Creek)**	0.002	<0.001	0.096	<0.0001	<0.001	<0.001	0.001	<0.001	0.002
07/12/2016	**SW 1 (Juandah Creek)**	0.006	<0.001	0.054	<0.0001	<0.001	0.002	0.006	<0.001	0.008

Date	Sample ID	Lead	Lithium	Manganese	Nickel	Selenium	Strontium	Vanadium	Zinc	Boron
		mg/L	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
05/12/2016	**58409A**	<0.001	0.044	0.006	<0.001	<0.01	0.367	<0.01	<0.005	0.38
05/12/2016	**SW 2 (Juandah Creek)**	<0.001	0.003	0.990	0.003	<0.01	0.839	<0.01	<0.005	0.07
05/12/2016	**SW 3 (Juandah Creek)**	<0.001	0.003	0.485	0.003	<0.01	0.761	<0.01	<0.005	<0.05
05/12/2016	**Alluvium Bore 1**	<0.001	0.002	0.003	<0.001	<0.01	0.173	<0.01	<0.005	<0.05
05/12/2016	**15508A**	<0.001	0.047	0.003	<0.001	<0.01	0.345	<0.01	<0.005	0.36
06/12/2016	**SW 1 (Bungaban Creek)**	<0.001	0.002	0.758	0.002	<0.01	0.316	<0.01	<0.005	0.07
06/12/2016	**SW 2 (Bungaban Creek)**	<0.001	0.002	0.238	0.002	<0.01	0.340	<0.01	<0.005	<0.05
06/12/2016	**SW 7 (Bungaban Creek)**	0.001	0.003	0.171	0.003	<0.01	0.192	<0.01	<0.005	0.06
06/12/2016	**58608A**	<0.001	0.059	0.167	<0.001	<0.01	2.77	<0.01	<0.005	0.16
06/12/2016	**14538A**	<0.001	0.046	0.163	<0.001	<0.01	1.48	<0.01	<0.005	0.12
06/12/2016	**SW 10 (Bungaban Creek)**	<0.001	0.002	0.046	0.002	<0.01	0.134	<0.01	<0.005	<0.05
06/12/2016	**SW 9 (Bungaban Creek)**	<0.001	0.002	0.412	0.003	<0.01	0.204	<0.01	<0.005	<0.05
07/12/2016	**58897A**	<0.001	0.008	0.025	<0.001	<0.01	0.018	<0.01	0.009	<0.05
07/12/2016	**58779A**	<0.001	0.086	0.044	<0.001	<0.01	1.46	<0.01	0.141	0.18
07/12/2016	**16065A**	<0.001	0.072	0.047	<0.001	<0.01	1.85	<0.01	<0.005	0.18
07/12/2016	**SW 6 (Bungaban Creek)**	<0.001	0.002	0.341	0.002	<0.01	0.315	<0.01	<0.005	0.06
07/12/2016	**SW 1 (Juandah Creek)**	<0.001	0.008	0.254	0.004	<0.01	0.150	<0.01	<0.005	0.11

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