5. Hydrogeology

5.1 Overview

The geological units and provinces that occur in the Project area and surrounds underpin the understanding of the hydrogeology in the assessment area. This section of the report:

- identifies and discusses New South Wales Office of Water (NOW) groundwater sources and the hydrogeological units (Figure 5.1) within these categories, and discusses the more detailed aspects of the hydrogeology within these broad categories
- details the methods for acquiring hydrogeological data and the results and analysis of the data
- provides an assemblage of the data and hydrogeological principles to present the conceptual hydrogeological model for the assessment area.

5.2 NOW – groundwater sources

NOW has categorised the groundwater sources in NSW based on a combination of large scale geological and hydrogeological mapping and geological descriptions. The water source boundary map is presented in Figure 5.1 for the assessment area. The water source boundaries are described in detail within three separate water sharing plans: Water Sharing Plan for the NSW MDB Porous Rock Groundwater Sources (NOW 2011b), the Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources (NOW 2008) and the Water Sharing Plan for the NSW MDB Fractured Rock Groundwater Sources (NOW 2011c).

Within the immediate vicinity of the Project area the groundwater source areas defined by NOW are:

- **Gunnedah-Oxley Basin MDB Groundwater Source**. This water source includes the Permian, Triassic, Jurassic, Cretaceous and Tertiary rocks within the boundary presented in Figure 5.1 as outlined in Part 1, clause 4, subclause 3 (a) in the Water Sharing Plan for the MDB Porous Rock Groundwater Source (NOW 2011b).
  The boundary illustrated in Figure 5. is indicative and all Permian, Triassic and outlier Jurassic rocks south of the Talbragar River are considered to be within the Gunnedah–Oxley Basin water source for the purpose of water management and licensing. It should be noted that the Gunnedah-Oxley Basin water source also includes the alluvium within the assessment area Part 1, clause 4, subclause 3 (b).
- **Talbragar Alluvial Groundwater Source**. The Talbragar River alluvium approximately 5 km upstream of the assessment area is managed as an independent groundwater source. The Talbragar Alluvial Groundwater Source is detailed in the Draft Water Sharing Plan for the Macquarie Bogan Unregulated and Alluvial Water Sources (NOW 2011a). The alluvium within this groundwater source is managed separately to the alluvium immediately adjacent to the Project area. NOW incorporates the alluvium associated with the Sandy Creek, Laheys Creek and the Talbragar River adjacent to the proposed mine site as part of the Gunnedah-Oxley Basin Groundwater Source (see dot point above).

- **Great Artesian Basin Groundwater Sources**. The NOW boundary for the GAB includes the significant areas of Jurassic rocks to the north of the Talbragar River. The isolated deposits of Jurassic rocks occurring south of the Talbragar River are included in the Gunnedah-Oxley Basin Groundwater Source (see first dot point).

- **Lachlan Fold Belt MDB Groundwater Source**. In the vicinity of the Project area the Lachlan Fold Belt Groundwater Sources include groundwater associated with the Devonian, Silurian and Ordovician rocks surrounding and underlying the Gunnedah-Oxley Basin.

It should be noted that the NOW groundwater source boundary map does not define the Lachlan Fold Belt and Gunnedah-Oxley Basin boundary at the same scale as the geological mapping, as can be seen by the underlying geological boundaries in Figure 5.1.
As discussed previously the Project site lies within the Gunnedah-Oxley Basin.

5.3 Hydrogeological units

The main hydrogeological units across the assessment area comprise of:

- quaternary alluvium aquifer associated with the unconsolidated sediments of the Talbragar River, Sandy Creek and Laheys Creek

- minor Tertiary fractured basalt caps occurring on some higher relief areas

- Jurassic sandstone porous rock occurs mainly to the north-west of the assessment area with some isolated areas of Jurassic sandstone also occurring to the west and south of the main Project area. To the north of the Talbragar River these Jurassic rocks form part of the Great Artesian Basin

- minor intrusions of Mesozoic igneous rock to the south of the Project area

- porous rocks of Permian and Triassic sandstone, coal and claystone associated with the Gunnedah Basin

- the fractured rocks of the Lachlan Fold Belt (Devonian, Silurian and Ordovician metasediments) which underlay and surround the porous Permo-Triassic rocks.

The hydrogeological units and water source boundaries are presented in Figure 5.1. Conceptual hydrogeological cross-sections are presented in Figure 5.2 to Figure 5.5, with cross-section lines shown on Figure 5.3.

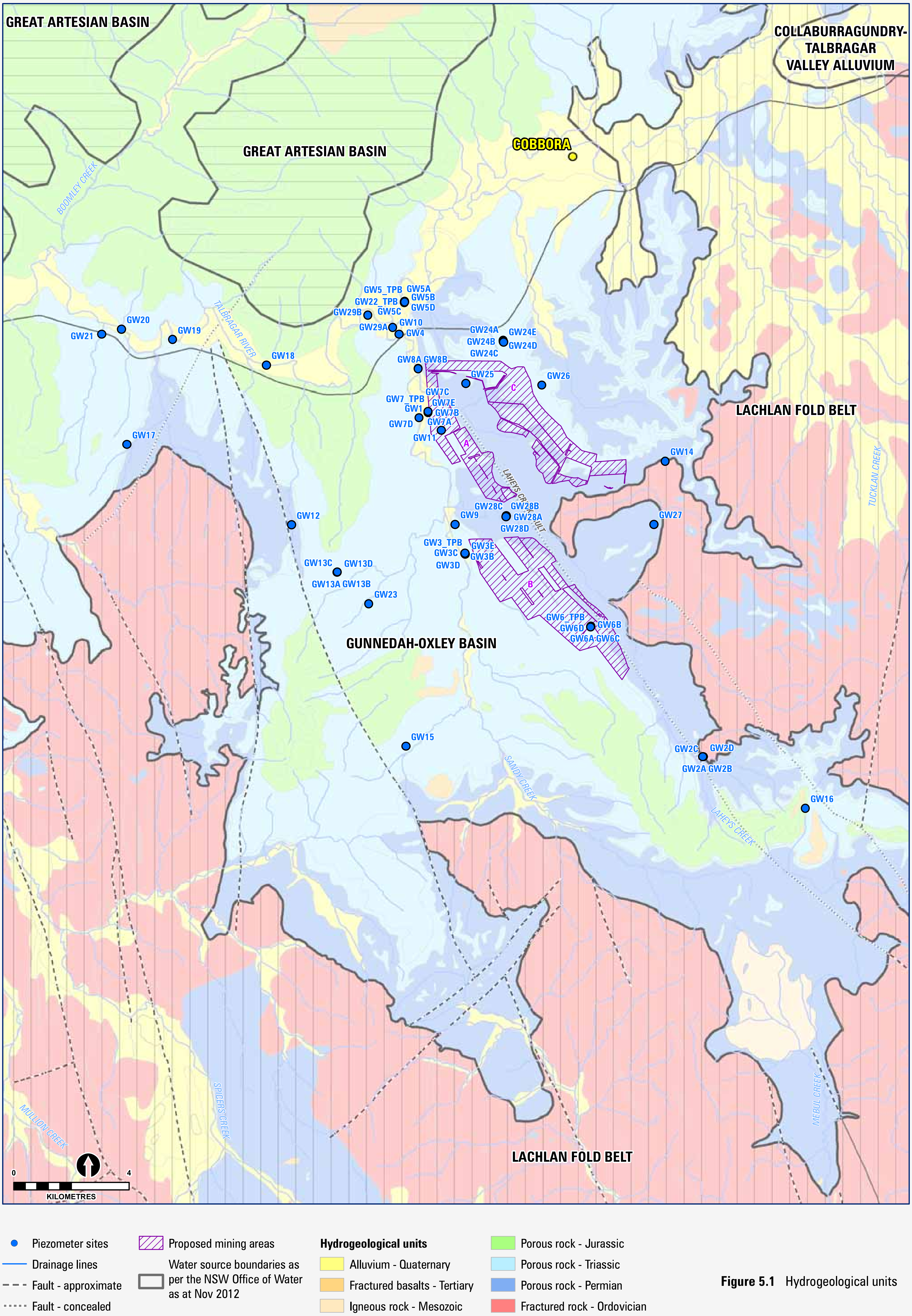
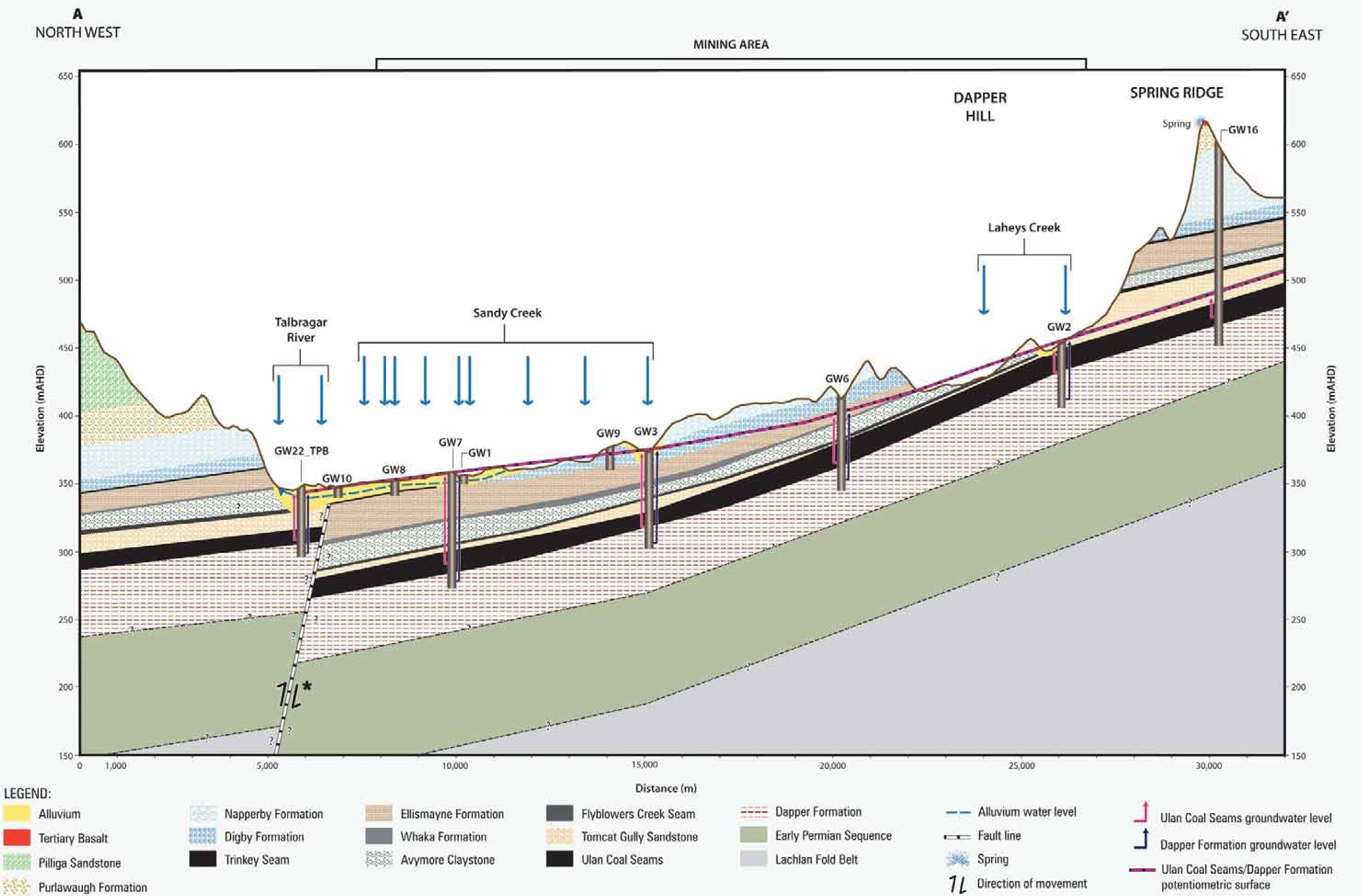


Figure 5.1 Hydrogeological units

Geologic map source: Geological Survey of New South Wales, 1999



Note: *Interpreted extension to Laheys Creek fault.

Figure 5.2 Conceptual hydrogeological cross-section A - A'

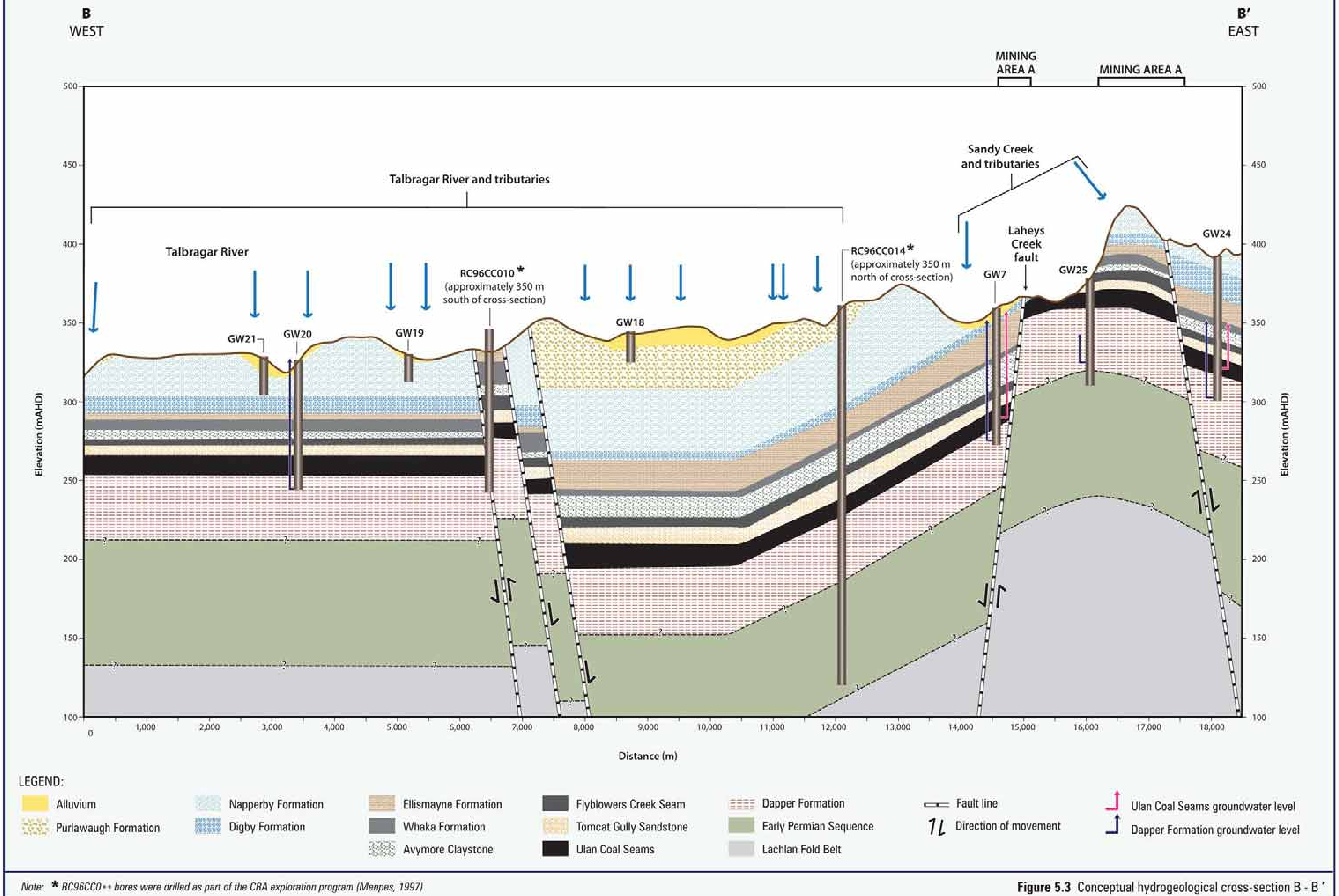
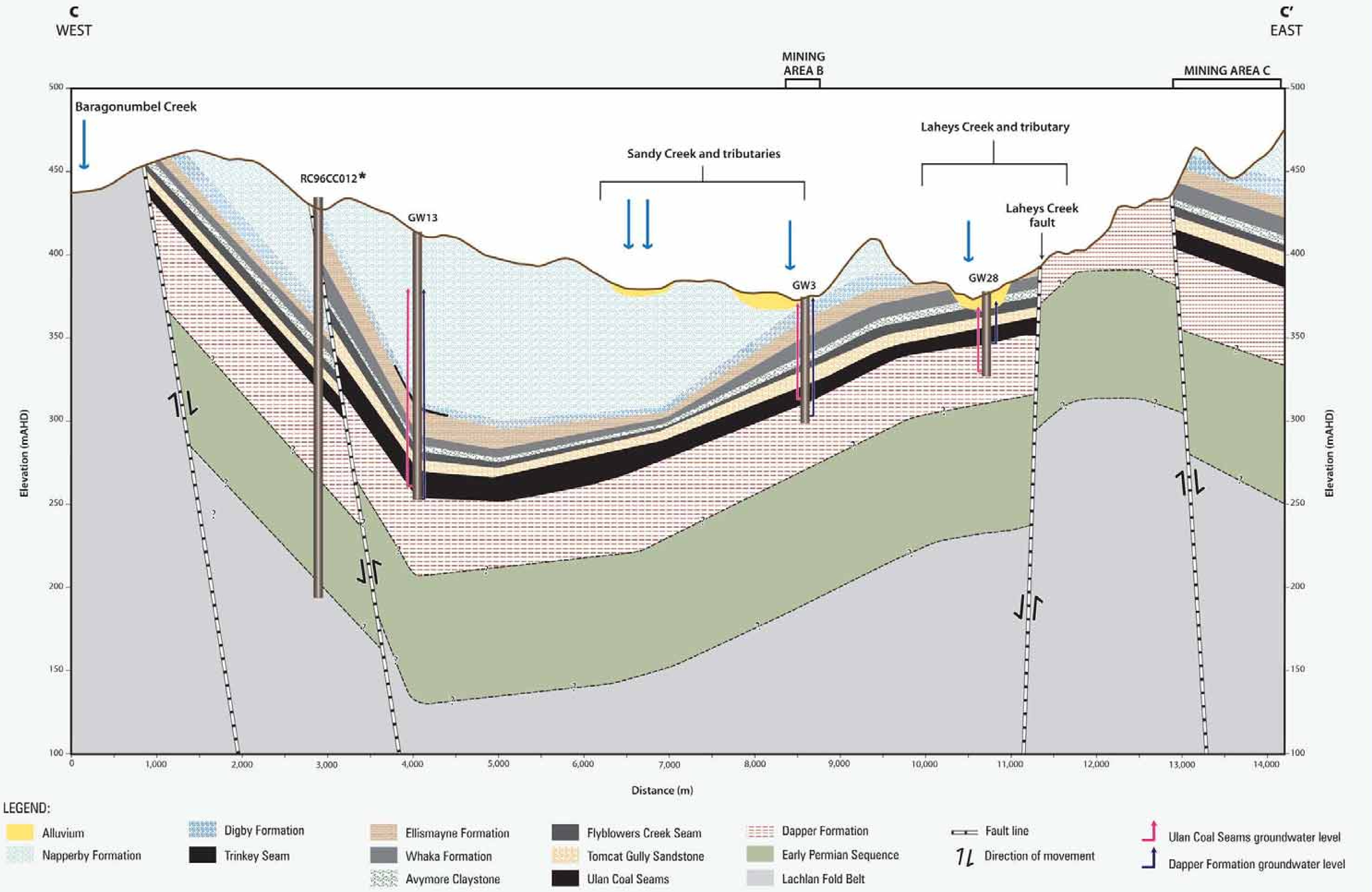


Figure 5.3 Conceptual hydrogeological cross-section B - B′



Note: *RC96CC0** bores were drilled as part of the CRA exploration program (Menpes, 1997)

Figure 5.4 Conceptual hydrogeological cross-section C - C'

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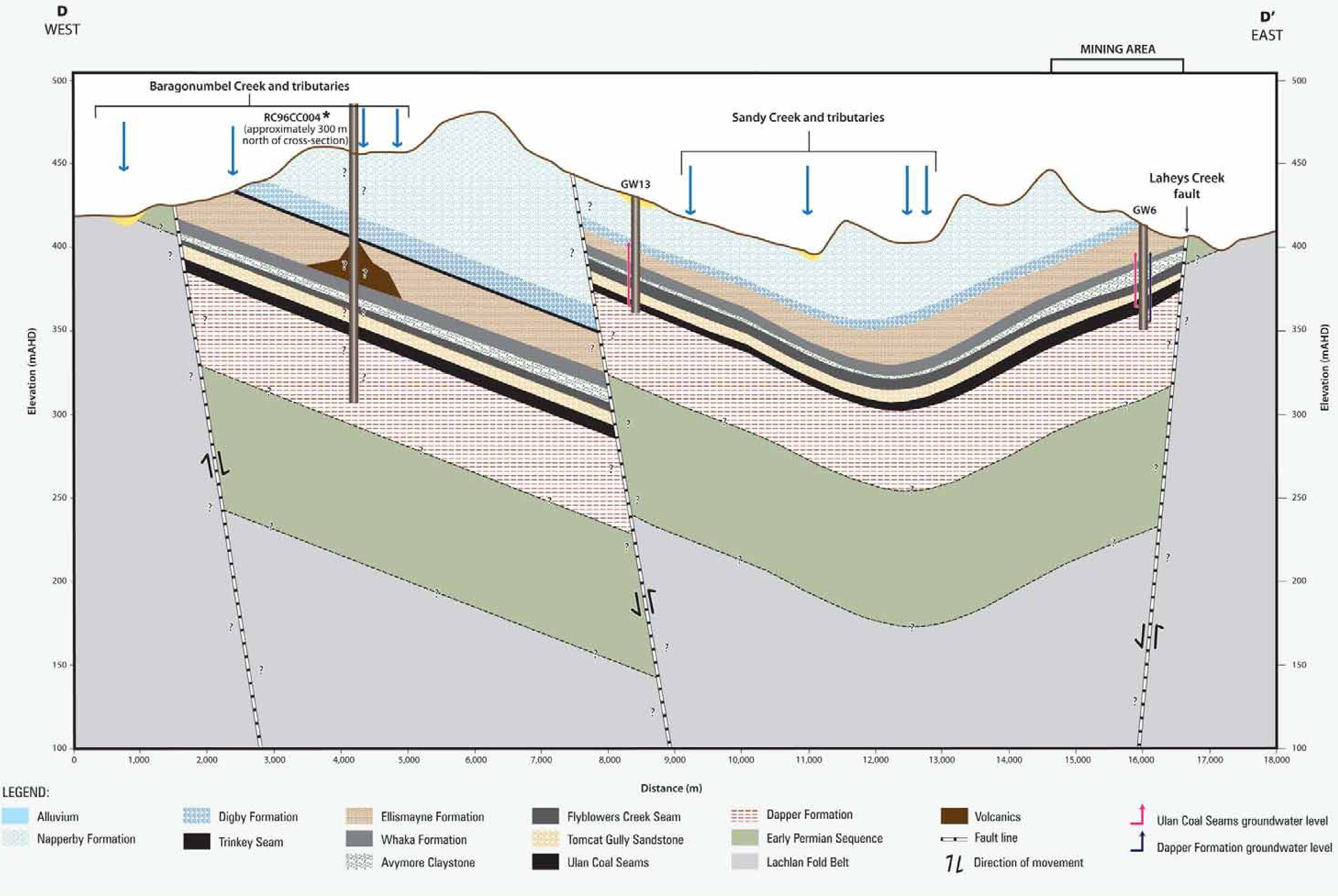

*Note: *RC96CC0** bores were drilled as part of the CRA exploration program (Menpes, 1997)*

Figure 5.5 Conceptual hydrogeological cross-section D - D′

5.3.1 Alluvium aquifers

The alluvium aquifer is present in the assessment area along the course of the Talbragar River, and Sandy Creek downstream of the Laheys Creek and Sandy Creek junction where it widens to become a broad flat channel and joins the Talbragar River. The alluvium aquifer is characterised by sandy gravel, interspersed with clay, and is of low permeability due to the high clay content.

Based on the geology intersected during drilling programs, the maximum depth of alluvium recorded was 23.5 m along the Talbragar River (GW5A). About 10 km upstream of the assessment area, the floodplain is much greater in extent both vertically and horizontally. As a result the alluvium aquifer in this upstream location is highly developed and used for primary production and town water supply (Dunedoo). This upstream area is managed as the Talbragar Alluvial Groundwater Source (NOW 2011).

Alluvial and colluvial sediments are also present in areas along Sandy Creek, Laheys Creek and Tucklan Creek. These are generally discontinuous and do not constitute a useful aquifer.

5.3.2 Tertiary fractured basalt

Tertiary basalt deposits are isolated outliers to the south and west of the assessment area. The deposits are of limited extent and form local hydrogeological systems overlying the broader regional systems. Rainfall provides direct recharge to the basalt, while groundwater within the basalt is likely to discharge in the form of seeps and springs at the contact with the underlying Jurassic, Triassic and Permian strata.

5.3.3 Porous rock – Jurassic sandstone

To the north-west of the assessment area lie the Jurassic Pilliga Sandstone and Purlawaugh Formation. These are the sandstone sediments of the Surat Basin. To the north of the Talbragar River these units form part of the larger Great Artesian Basin with the Pilliga sandstone forming part of the NSW southern recharge zone of the Great Artesian Basin.

The Purlawaugh Formation, which underlies the Pilliga Sandstone, comprises shales and interbedded sandstones, and forms a basal confining layer for the Pilliga Sandstone. The Jurassic units are therefore not considered to be hydraulically connected to the Permo-Triassic aquifers of the Gunnedah-Oxley Basin. Isolated deposits of the Purlawaugh Formation and Pilliga Sandstone are present within the assessment area; however, these outliers are considered part of the Oxley Basin (Australian Government 2009), and are managed and licensed as Gunnedah-Oxley Basin (NOW 2011b).

5.3.4 Porous rock – Permo-Triassic

The Triassic and Permian formations comprise a sequence of geological units, all of which have varying capacities to transmit water. Table 5.1 lists each unit within the sequence and their relative capacity to transmit water.

Table 5.1 Hydrogeological properties of porous rock units

Geological units		Hydrogeological properties
Triassic	Napperby Formation	water-bearing zone
	Digby Formation	water-bearing zone
Permian (Dunedoo formation)	Trinkey Seam	water-bearing zone
	Ellismayne Formation	water-bearing zone
	Whaka Formation	water-bearing zone
	Avymore Claystone	aquitard
	Flyblowers Creek Seam	water-bearing zone
	Tomcat Gully Sandstone	water-bearing zone
	Upper Ulan Seam	water-bearing zone
	C-Marker Claystone	aquitard
	Lower Ulan Seam	water-bearing zone
	Dapper Formation	water-bearing zone

The Dunedoo Formation consists of interbedded shales, claystones, coals, tuffaceous units and sandstones. The Dapper Formation and the Upper and Lower Ulan coal seams are recognised as the main water-bearing units, with low to moderate permeability. Anecdotally, the Tomcat Gully Sandstone can be locally quite transmissive and high yielding.

The Tomcat Gully Sandstone overlies the Ulan Upper seam and is separated from the Ulan Lower seam by a confining unit (aquitard), the C-Marker Claystone. Overlying the Tomcat Gully Sandstone is the Flyblowers Creek Seam, which is a minor water-bearing zone of higher clay content than the Ulan Coal Seams. The Dapper Formation underlies the Ulan Lower Seam.

Connectivity between the units is generally limited by confining or semi-confining units comprising shale, claystone, siltstone or other lower permeable materials. There is potential for leakage between confining layers, especially in highly fractured areas near faults and in areas where the confining layers have low clay content.

5.3.5 Fractured rocks of the Lachlan Fold Belt – Devonian, Silurian and Ordovician

Within the assessment area, the Lachlan Fold Belt fractured groundwater system underlies the porous rock aquifer of the Gunnedah-Oxley Basin. It comprises Devonian, Silurian and Ordovician aged rocks, which are characterised by metamorphosed sedimentary, volcanic and intrusive fractured rock of very low permeability. Outcropping basement rocks of the Lachlan Fold Belt occur to the west, east, south and south-east of the assessment area (Figure 5.1). As mining will not intersect the basement Lachlan Orogen units, this aquifer system will not be impacted by mining.

5.4 Recharge and discharge

Groundwater in the alluvium aquifer is unconfined. Recharge is via direct infiltration of rainfall and stream and riverbank recharge during flood events, with discharge affected by leakage to underlying aquifers or direct to springs and surface water.

Results of the TEM survey (Appendix G) indicate that adjacent to the Talbragar River and the lowest part of Sandy Creek are numerous conductive, near-surface, roughly meander-shaped features. It is likely that these are saline saturated (or at least moistened) alluvium. Flood events which occurred prior to the survey (2011), likely created a zone of resistive alluvium along the river itself.

The Permo-Triassic porous rock aquifers are primarily recharged by direct infiltration of rainfall into aquifer outcrop areas. Recharge may also occur to the porous rock aquifers by downward leakage from the overlying alluvium particularly in the upper sections of Sandy Creek and Laheys Creek. Discharges from the Permo-Triassic porous rocks may take place where aquifer units within the bedrock sediments outcrop, typically as springs on hillsides or baseflow to creeks and gullies. In the down gradient areas at nested groundwater monitoring sites where an alluvium bore is present (GW5 and GW7), the hydrographs (Appendix E) indicate groundwater pressures in the Permian deeper units are generally higher than those measured in the alluvium.

Based on groundwater elevations, the typical magnitude of head difference between the alluvium and Permian units was 0.5–1 m at site GW5 and 4–5 m at site GW7. This indicates an upward pressure gradient and potential groundwater flow from the Permo-Triassic units into the alluvium.

5.5 Groundwater levels and flow direction

Groundwater flow direction appears to mimic the topography with a flow direction for the alluvium down valley, consistent with surface water flows. Available groundwater level data in the unconfined alluvium aquifer indicates an inferred groundwater flow direction north towards the Talbragar River. Levels range from 353 m AHD up-gradient on Sandy Creek to around 341.5 m AHD at the Talbragar River.

Groundwater flow in the semi-confined to confined porous rock aquifer is influenced by stratigraphic dip and depth to aquifer, with influence also from geological structures. Groundwater level data indicates a high degree of connectivity between the Permian and Triassic units with groundwater levels measured at nested sites generally within 1 m in all porous rock aquifer bores.

The groundwater levels in the porous rock aquifer range from a high of approximately 452 m AHD in the elevated south east area (site GW2) of the assessment area, to a low of approximately 342 m AHD at the Talbragar River (site GW5). Groundwater flow is generally to the north, north-west. Groundwater level contours and flow direction are depicted in Figure 5.6.

Artesian pressures have been measured in the porous rock aquifers at sites GW3 and GW7 along Sandy Creek. The TEM survey (Appendix G) of this area strongly depicts various lithologies with a clear boundary extending approximately along the same line (i.e. Sandy Creek). The lithologies are deformed in some places, indicating evidence of faulting. Furthermore exploration drilling highlights a similar lineament along Sandy Creek, where the highest groundwater yields were encountered during drilling and artesian pressures observed (Figure 5.7).

Another interesting trend observed from the exploration drilling water-make data, is the depth of maximum water cut which increased westwards in the direction of dip and is consistent with the Dapper Formation hosting the main water bearing zone (Figure 5.8).
This demonstrates that, at least locally, groundwater flow may be influenced by the dip and faulting of strata.

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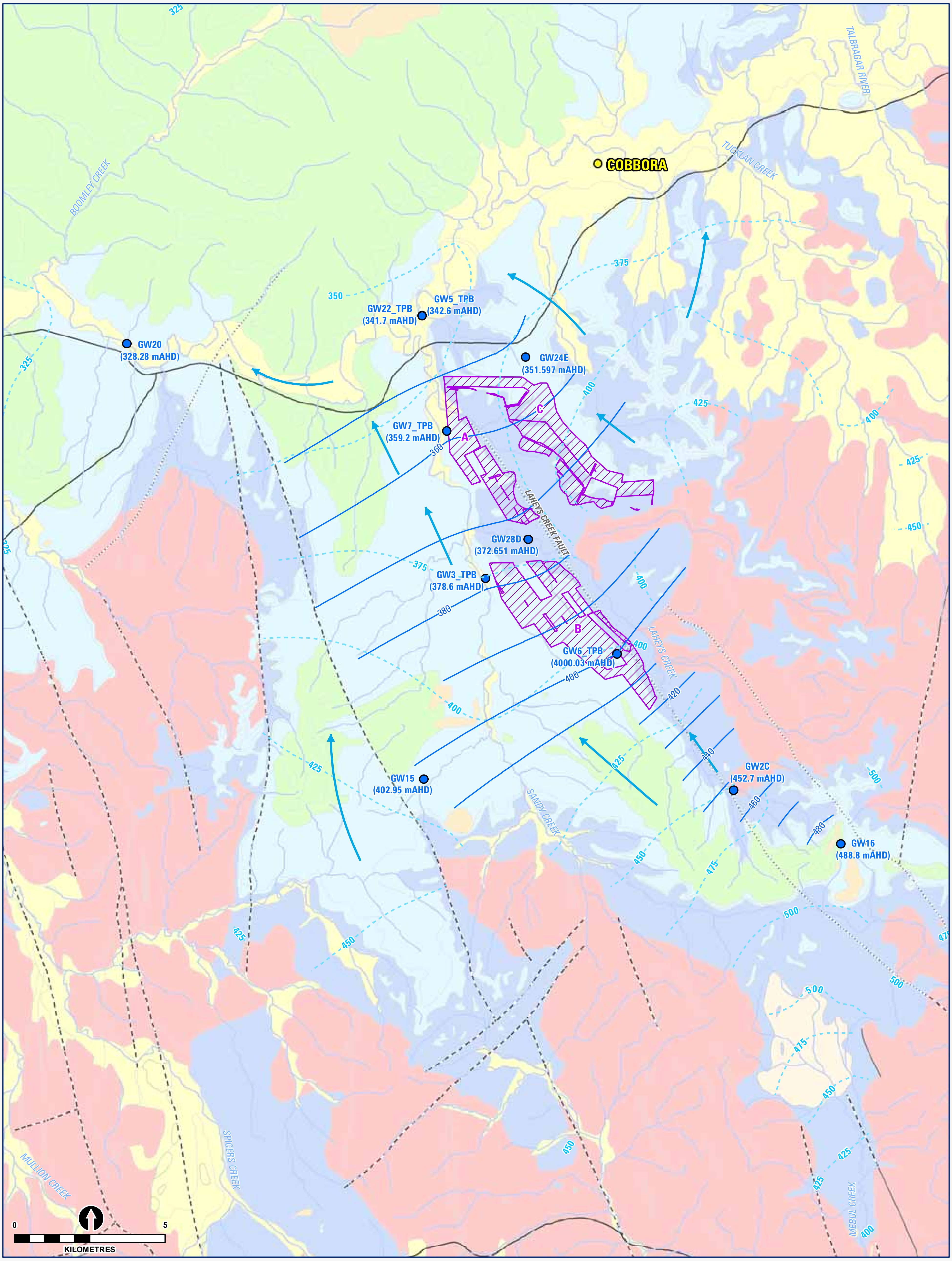

- Piezometer sites
- Drainage lines
- Main roads
- Mine pit area
- Fault - approximate
- Fault - concealed
- Groundwater contours
- Potentiometric level in the deep Ulan Coal Seam (mAHD)
- Groundwater flow direction

Aquifer systems

- Alluvium
- Tertiary fractured basalts
- Great Artesian Basin
- Mesozoic igneous rocks
- Porous rock - Triassic
- Porous rock - Permian
- Lachlan Fold Belt

Figure 5.6 Groundwater level contours

Geologic map source: Geological Survey of New South Wales, 1999

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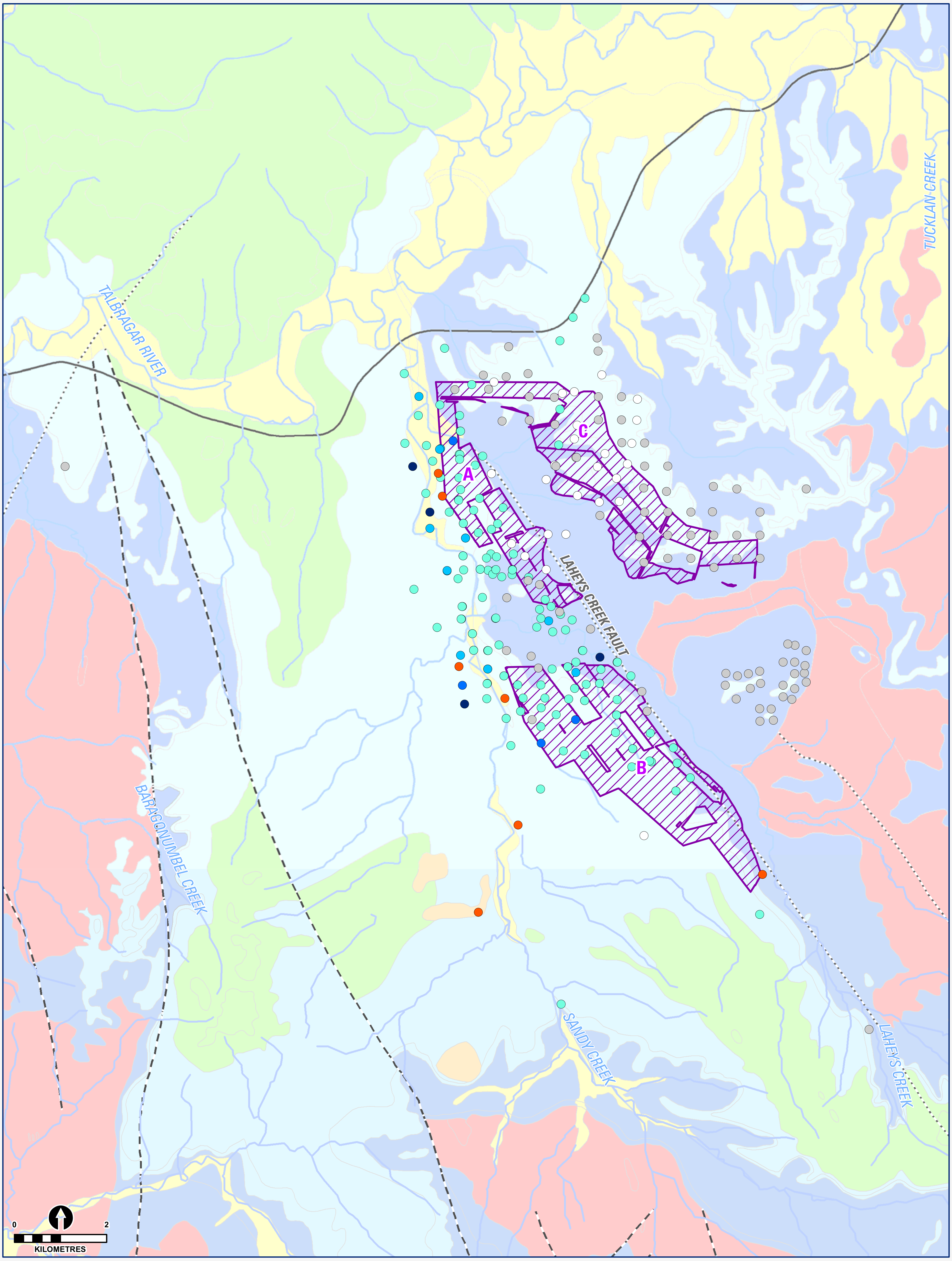

Maximum water rate (L/s)

- Negligible water and <0.1
- 0.1 – 2.5
- 2.5 – 5.0
- 5.0 – 7.5
- >10
- Artesian
- Dry

- Drainage lines
- Fault - approximate
- Fault - concealed
- Proposed mining areas

Hydrogeological units

- Alluvium - Quaternary
- Fractured basalts - Tertiary
- Igneous rocks - Mesozoic
- Porous rock - Jurassic
- Porous rock - Triassic
- Porous rock - Permian
- Fractured rock - Ordovician

Figure 5.7 Water make in exploration holes - maximum flow rate

Geologic map source: Geological Survey of New South Wales, 1999

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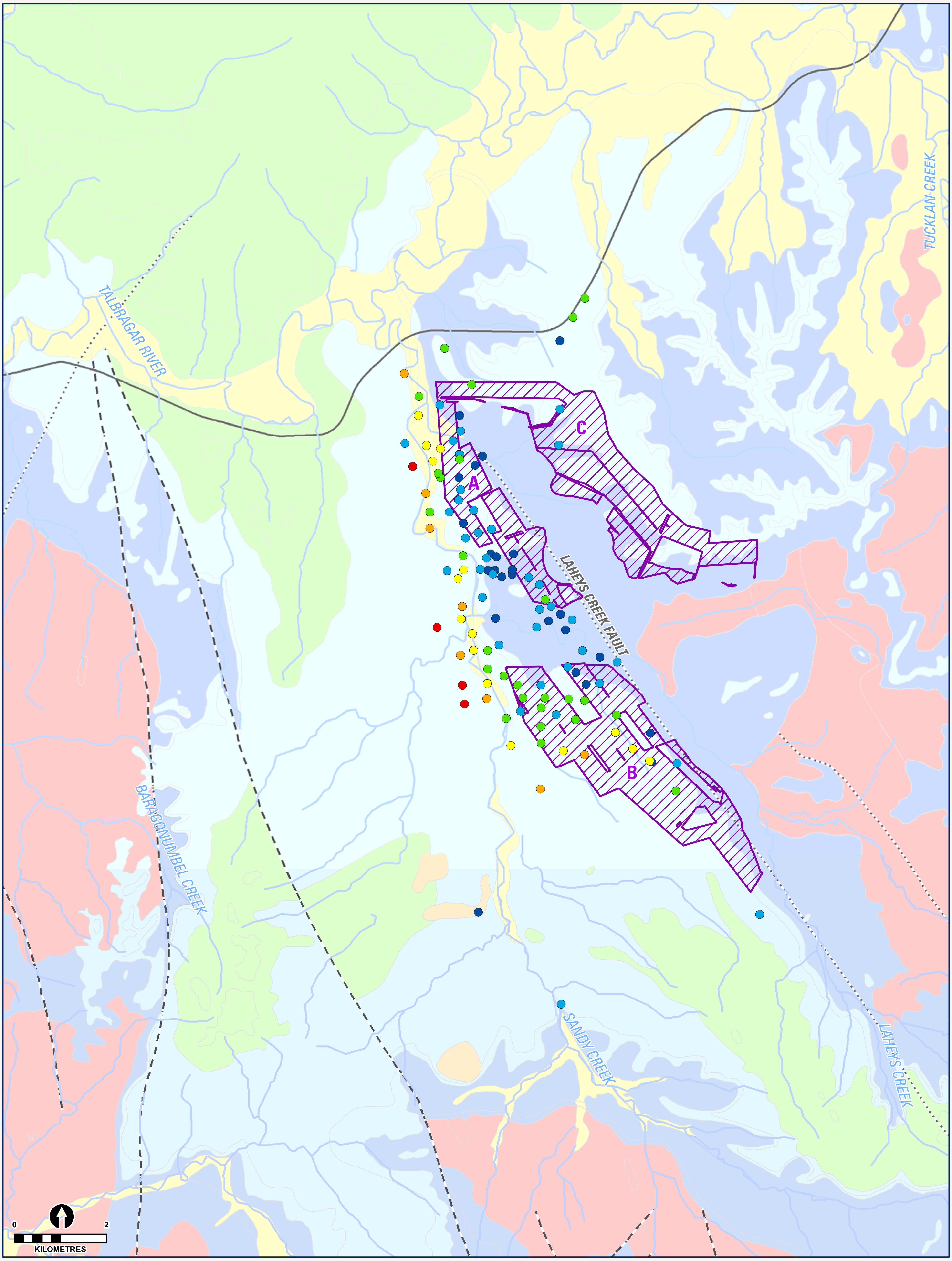

Figure 5.8 Water make in exploration holes - depth of maximum water cut

Geologic map source: Geological Survey of New South Wales, 1999

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5.5.1 Hydrographs

Available groundwater level data has been plotted as potentiometric pressure (m AHD) versus time (days), along with the long-term (1889–2011) cumulative deviation from mean rainfall (CDM) trend (Appendix E) to assess trends in recharge.

Analysis of the hydrographs indicates three primary trends:

1. There is an overall rising trend in water levels over the assessment area which corresponds to the CDM rainfall trend. Site GW7 is the exception; groundwater levels have continued to decline unlike at other sites which have plateaued despite the occurrence of high rainfall events at the end of 2010. This trend may indicate potential groundwater extraction from a nearby private bore.

2. Groundwater bores monitoring the alluvial and shallow weathered rock groundwater levels, located within close proximity to a creek or river, exhibit a rapid response to large and sustained rainfall events. Following the high rainfall events in December 2010, the following peak water level rises were recorded within 2 to 3 weeks; GW5A – 3 m, GW6A – 4 m, GW7A – 3 m, GW8A – 2.5 m, GW8B – 1 m, GW18 – 3.5 m and GW21 – 6 m. The most rapid groundwater level responses (rises) were generally identified in the bores nearest to a creek or river, indicating rapid flood recharge to these alluvial areas.

3. Groundwater bores monitoring the deeper confined units display a more muted response in water level changes. Rises observed over approximately 6 months were between 1 and 3 m. They were continual and sustained over a longer period (sites GW2A-D, GW3B-E, and GW6B-D), indicating slower leakage rates from the overlying units.

5.6 Hydraulic testing

5.6.1 Aquifer responses

Constant rate pumping tests were carried out to assess regional and local impacts of stressing the aquifer, and also the transmissivity and storage values of the aquifer.
Tests were for periods of 24 hours, 14 days or 21 days. Continuous monitoring of the water levels at the test production bore and nearby piezometers was undertaken.

Although aquifer hydraulic parameters can be (and were) derived from the tests, the main aim of the tests was to assess drawdown and rates of leakage between aquifers. It is noted later in this report that aquifer testing in multi-layered systems can yield erroneously high permeability values due to the violation of several assumptions in the Theis (1935) solution (Cook 2003).

5.6.1.1 Short-term tests

Short-term 24-hour pumping tests were undertaken to determine the most productive bore for a longer term test. Pumping tests were carried out as follows: GW3_TPB at 4.4 litres per second (L/s), GW5_TPB at 3.5 L/s and GW7_TPB at 4.4 L/s. Water level drawdown and recovery data was also used to assess hydraulic parameters.

Total drawdowns were measured in the test production bores at the completion of each test as follows:

- GW3_TPB at 42.7 m.
- GW5_TPB at 13.3 m.
- GW7_TPB at 36.9 m.

At the cessation of pumping the recovery of water levels was measured in each test production bore. At 10 minutes the following recoveries were observed:

- GW3_TPB at 95%.
- GW5_TPB at 90%.
- GW7_TPB at 65%.

For each test the porous rock aquifer piezometers showed a rapid and similar response to pumping in the associated test production bore. Where present at each site observation bores screened across the alluvium (GW5A and GW7B), and weathered rock (GW9), each showed minimal drawdown as a result of pumping at the associated test production bores.

5.6.1.2 Long-term tests

GW3_TPB 14-day test

GW3_TPB was pumped at 4.4 L/s for 14 days, with a total drawdown of 47 m.
Initial recovery in GW3_TPB was rapid, with 85% recovery after 10 minutes.

All piezometers showed a rapid response to pumping in the associated test production bore, with the exception of the observation bore screened across the weathered rock (GW9), which showed minimal drawdown as a result of pumping. This suggests poor hydraulic connection between the shallow weathered rock and the deeper porous rock aquifer.

Total drawdowns at each piezometer were GW3C: 5.7 m; GW3D: 7.4 m and GW3E: 13 m. The varying magnitudes of drawdown observed at each site indicate heterogeneity between the Permo-Triassic units.

Analysis of the recovery data during the 14-day test in the piezometers screening the Dapper Formation (GW3E) indicates that the cone of drawdown intersected a recharge boundary after approximately 800 minutes. The recharge boundary is likely to represent where the Dapper Formation is truncated as it outcrops at ground surface to the east, intersecting Laheys Creek (see Figure 5.4). Conversely, drawdown at GW3B, which screens a series of units in the Permian sequence, indicates a barrier boundary was intersected. This is likely due to the Permian sequence being truncated at ground level (see Figure 5.5). In this case the truncation provides a barrier because there is no recharge from surface water.

GW7_TPB 21-day test

GW7_TPB was pumped at 2.5 L/s for 21 days, with a total drawdown of 24.13 m. Similar to the 24-hour test, recovery was slower than experienced at the other sites with 85% reached after 810 mins (or 13.5 hours).

Drawdown trends in the porous rock aquifer piezometers GW7C, GW7D and GW7E each showed rapid responses to pumping, while the magnitude of drawdowns varied. Total drawdown recorded at each bore was GW7C: 9.4 m; GW7D: 9.5 m and GW7E: 11.3 m. While drawdown at GW7C and GW7D were comparable, the drawdown in GW7E was almost 2 m greater, which indicates heterogeneity between the Permo-Triassic units.

Drawdown in the alluvial bore (GW7A) was slight and estimated at between 0.1 m and 0.2 m after the effects of rainfall and barometric pressure variations were removed. It is noted that these effects almost overwhelmed the drawdown response.

GW22_TPB 21-day test

GW22_TPB was pumped at 2 L/s for 21 days, with a total drawdown of 22.2 m. Recovery of 85% was reached 6 minutes after pumping ceased.

Drawdown trends in the porous rock aquifer piezometers GW5B, GW5C, and GW5D showed a rapid and similar response to pumping. Total drawdowns recorded at each bore were GW5B: 2.3 m; GW5C: 2.5 m and GW5D: 2.7 m. The magnitude of drawdown in each monitoring bore was within 0.4 m of each other, indicating good hydraulic connection.

The groundwater level monitored at the alluvium aquifer bore GW5A showed an overall declining trend over the 21-day period. Interference due to rainfall events (105 mm total) and pump stoppages over the course of the test attributed to both positive and negative displacement of the water level; however, an estimated overall drawdown of between 0.1 and 0.15 m was observed.

The minimal drawdown observed suggests a poor hydraulic connection to the porous rock aquifer, and that rainfall and stream bank flood recharge is significant. Leakage rates were analysed further using a local-scale numerical groundwater model (see Section 5.6.2.1, below).

5.6.2 Aquifer hydraulic parameters

A summary of the results of the estimation of the hydraulic parameters for the alluvium and porous rock aquifers is provided in Table 5.2. It should be noted that while the reported values for hydraulic conductivity are a range, and the higher values are indicative of the presence of some localised higher permeability zones within the porous rock aquifer, that are not necessarily representative of the regional aquifer system. Table 5.5 details all parameter estimates from aquifer tests.

Table 5.2 Calculated aquifer hydraulic parameters

Aquifer	Test method	Hydraulic conductivity (m/d)	Storativity
Alluvium	Slug test	0.06–3.8	
Tomcat Gully Sandstone	Pumping test Slug test	3.7–19.4 0.012–0.7	7.1×10^{-4} – 3.1×10^{-2}
Ulan Coal Seam	Pumping test Slug test Packer test	2.3–10.2 0.3–0.8 8.5×10^{-3}–6.9×10^{-2}	2.2×10^{-5} – 2.9×10^{-3}
Dapper Formation	Pumping test Slug test	1.4–10.2 0.03–0.4	7.3×10^{-7} – 4.7×10^{-3}

5.6.2.1 Alluvium aquifer

Based on the rising head test results, the hydraulic conductivity of the alluvium aquifer is estimated to be within the range of 0.06 to 3.8 m/d.

More detailed analysis has been carried out to further assess the hydraulic conductivity of the alluvium aquifer using data obtained from the 21-day pumping test at GW22_TPB.

A local-scale numerical model was constructed using MODFLOW to estimate hydraulic parameters in each of the units at site GW5/GW22, in particular, the parameters that control leakage from the alluvium to the Permian aquifers when they are depressurised. To do this, the rainfall and barometric pressure corrected, drawdown data for the 21-day test was used with PEST to calibrate the modelled drawdown to the observed drawdown. Horizontal (K_h) and vertical (K_v) hydraulic conductivity and storage were allowed to vary. The results of the PEST run in which the best fit was obtained for the alluvium are listed below in Table 5.3.

K_h and K_v for the alluvium were estimated at approximately 1 m/d and 0.001 m/day respectively. The ratio of K_h to K_v is about 1000. The parameters for the other units, while valid for this location are not considered to reflect conditions for the regional aquifer system.

Table 5.3 Estimates of vertical and horizontal hydraulic conductivity at site GW5

Zone	Unit	K_h (m/d)	K_v (m/d)	K_v/K_h (m/d)	S_s	S_y
1	Alluvium	1.09	1.1×10^{-3}	1.0×10^{-3}	1.00×10^{-6}	3.37×10^{-2}
2	Tomcat	0.16	0.07	0.45	1.47×10^{-6}	
3	Ulan	3.87	0.22	0.06	2.00×10^{-6}	
4	Dapper	0.05	2.0×10^{-3}	0.05	5.48×10^{-5}	

K_h — horizontal hydraulic conductivity; K_v — vertical hydraulic conductivity; K_h/K_v — ratio of horizontal/vertical hydraulic conductivity; S_s — specific storage; S_y — Specific yield

5.6.2.2 Porous rock aquifer

The transmissivity, hydraulic conductivity and storativity of the porous rock aquifers have been estimated from data obtained during pumping tests, rising head 'slug' tests and packer tests. Hydraulic parameters discussed in this section include those for the Tomcat Gully Sandstone, Ulan Seams and the Dapper Formation. Hydraulic parameters have also been estimated for bores screened across several units, and are provided in Table 5.5.

Estimates of hydraulic conductivity in the porous rock aquifers ranged over five orders of magnitude, indicating significant heterogeneity within the porous rock. Table 5.4 shows hydraulic conductivity estimates from pumping tests to be significantly higher than those estimated through slug tests, packer tests or groundwater age dating.

Estimates of slug and packer testing for individual units are typically one or two orders of magnitude lower than estimates derived from test pumping. This is commonly observed and reflects the scale-dependent nature of permeability testing (especially in fractured or dual porosity aquifers), and also the inherent bias of each particular testing method (e.g. test pumping is not possible in formations of very low permeability). In addition, the standard Cooper-Jacob and This recovery approach were used to estimate hydraulic conductivity from piezometers screened in sub-units.

This approach is known to yield overestimates of permeability in monitored subunits when the pumping bore is screened across multiple units (Cook 2003). For these reasons, the hydraulic parameters estimated using data from the slug tests and packer tests are considered more representative of the formations, while the test pumping data is best used to determine leakage between units, and assess regional groundwater impacts.

The geometric means of slug test and packer test data are in the order of 10^{-1} and 10^{-2} m/d (see Table 5.4).

Groundwater age (^{14}C) provides an approximate upper limit to the subregional hydraulic conductivity; groundwater ages of approximately 40,000 years are observed at GW6 which, if we assume that groundwater recharged at the basin margin (t_0), implies a hydraulic conductivity of less than approximately 0.02 m/d (based on the observed hydraulic gradients).

There is little field test evidence for significant differences in hydraulic conductivity between the sandstone and siltstone units, although anecdotally the Ulan and the Tomcat can be locally quite transmissive and high yielding as noted during exploration drilling.

Table 5.4 Average horizontal hydraulic conductivity values from field testing (m/day)

Test	Geometric mean	Arithmetic mean	Notes
Slug tests	0.117	0.374	Bouwer-Rice method
Packer tests	0.012	0.017	
Slug + packer	0.049	0.235	
14C age	0.017	0.019	Seepage rate from Darcy's Law
Test pumping	3.6	5.6	Cooper-Jacob and Theis recovery analysis

Estimates of hydraulic conductivity (K) in coal seams and interburden from other studies (e.g. Bulli Seam Operations Groundwater Assessment (Merrick 2009); Hunter Valley Mackie 2009)) show similar large ranges, but typically average 10^{-1} to 10^{-2} m/d (partly weathered coal at shallow depths) and 10^{-2} to 10^{-4} m/d or less (weathered interburden).

Hydraulic conductivity also tends to decrease with depth, due to increasing lithostatic pressure and closing of joints and fractures, and so lower values of hydraulic conductivity may be more typical of deeper coal measures such as those in the Southern Coalfields. It is noted that within the assessment area the coal measures are relatively shallow (or outcropping) and are variably weathered and fractured which may justify slightly higher estimates of hydraulic conductivity.

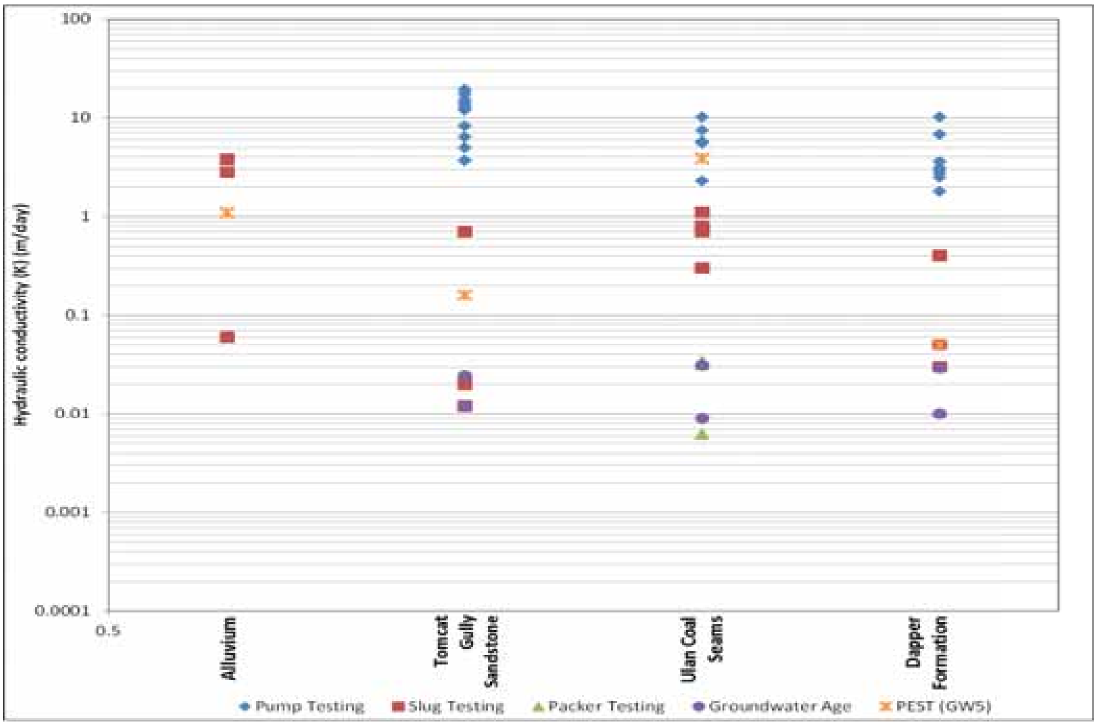


Figure 5.9 Estimated hydraulic conductivity

5.7 Groundwater quality

Groundwater quality for the alluvium and porous rock aquifers is discussed in the following sections. Groundwater quality results are compared to the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000). The ANZECC (2000) freshwater guidelines (95% level of protection) were selected as the area is moderately disturbed. The ANZECC (2000) guidelines for upland rivers in south-east Australia were also referred to because the site location is >150 m altitude and in NSW.

Major ion chemistry can be used to interpret the sources of natural waters. A Piper diagram can be used to graphically show the relative concentrations of major ions (Ca, Mg, Na, K, Cl, HCO_3 and SO_4). A Piper diagram for groundwater in the assessment area is presented in Figure 5.10**Error! Reference source not found.**. Evolution of groundwater chemistry along the direction of groundwater flow is shown on the north-south cross-section in Figure 5.11. The variability in groundwater salinity is shown on Figure 5.12.

Selected samples were analysed for stable isotopes of water (^{18}O and ^{2}H) and radiocarbon to assess origins of water and groundwater residence times. Stable isotopes for groundwater are compared to surface water, springs and the Global Meteoric Water Line ($\delta^2H = 8.\ \delta^{18}O + 10$ (Craig 1961)) and a Local Meteoric Water Line ($\delta^2H = 7.89\ \delta^{18}O + 14.18$ (Timms et al. 2009)) in Figure 5.13. The change in groundwater age along the direction of groundwater flow is shown on the north-south cross-section in Figure 5.14.

Table 5.5 Summary of hydraulic testing results

Bore	Screened unit	Estimation method	Transmissivity (T) (m^2/d)	Hydraulic conductivity (K) (m/d)	Storativity* (S)
GW5A	Alluvium	Rising head test (Bouwer-Rice 1976)		3.8	
GW28A	Alluvium	Rising head test (Bouwer-Rice 1976)		0.06	
GW28B	Alluvium	Rising head test (Bouwer-Rice 1976)		2.8	
GW29B	Digby Formation	Rising head test (Bouwer-Rice 1976)		0.05	
GW3C	Tomcat Gully Sandstone	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	49.7 DD 77.3 REC	8.3 DD 12.9 REC	4.7×10^{-3}
		14-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	30.3 DD 38.7 REC	5.0 DD 6.4 REC	7.4×10^{-3}
GW5B	Tomcat Gully Sandstone	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	52.7 DD 69.2 REC	17.6 DD 23.1 REC	3.1×10^{-2}
		3-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	55.8 DD	18.6 DD	2.7×10^{-3}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	39.6 DD	13.2 DD	1.6×10^{-3}
		Rising head test (Bouwer-Rice 1976)		0.7	
GW6B	Tomcat Gully Sandstone	Rising head test (Bouwer-Rice 1976)		0.02	
GW7C	Tomcat Gully Sandstone	24-hour pump test (Cooper-Jacob, 1946 (DD); Theis 1935 (REC))	11.2	3.7	1.8×10^{-4}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	12.2	4.0	9.5×10^{-5}
GW24C	Tomcat Gully Sandstone	Rising head test (Bouwer-Rice 1976)		0.012	
GW3D	Ulan Coal Seams	14-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	33.2 DD 31.6 REC	2.8 DD 2.6 REC	5.4×10^{-4}
GW5C	Ulan Coal Seams	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	34.6 DD 69.2 REC	5.8 DD 11.5 REC	2.9×10^{-3}
		3-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	60.6 DD 57.0 REC	10.1 DD 9.5 REC	1.6×10^{-3}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	39.6 DD	6.6 DD	3.2×10^{-4}
		Rising head test (Bouwer-Rice 1976)		0.8	

Bore	Screened unit	Estimation method	Transmissivity (T) (m^2/d)	Hydraulic conductivity (K) (m/d)	Storativity* (S)
GW6C	Ulan Coal Seams	Rising head test (Bouwer-Rice 1976)		0.3	
GW7D	Lower Ulan Seam	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	17.4	5.8	6.5×10^{-5}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	14.1	4.7	1.8×10^{-5}
GW24D	Ulan Seams	Rising head test (Bouwer-Rice 1976)		1.1	
GW28C	Ulan Seams	Rising head test (Bouwer-Rice 1976)		0.7	
GW3E	Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	18.3 DD 16.9 REC	3.1 DD 2.8 REC	6.6×10^{-3}
		14-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	16.6 DD 26.3 REC	2.8 DD 4.4 REC	6.0×10^{-4}
GW5D	Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	41.0 DD 55.4 REC	6.8 DD 9.2 REC	1.1×10^{-3}
		3-day pump test (Cooper-Jacob 1946 (DD)	51.7 DD	8.6 DD	1.4×10^{-3}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	45.2 DD	2.5 DD	6.6×10^{-4}
		Rising head test (Bouwer-Rice 1976)		44.7	
GW6D	Dapper Formation	Rising head test (Bouwer-Rice 1976)		0.4	
GW7E	Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	12.2	4.0	3.0 x 10-4
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	12.4 DD 8.9 REC	2.1DD 1.5 REC	3×10^{-5}
GW24E	Dapper Formation	Rising head test (Bouwer-Rice 1976)		0.03	
GW28D	Dapper Formation	Rising head test (Bouwer-Rice 1976)		0.05	
GW3_TPB	Whaka Formation, Avymore Claystone, Ulan Seams, Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	15.5 DD 27.8 REC	1.2 DD 2.2 REC	
		14-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	13.9 DD 36.6 REC	0.9 DD 2.9 REC	
GW3B	Whaka Formation, Avymore Claystone, Flyblowers Creek Seam, Tomcat Gully Sandstone	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	154.6 DD 131.4 REC	12.4 DD 10.5 REC	5.7×10^{-3}
		14-day pump test (Theis 1935 (REC))	43.5 REC	3.5 REC	

Bore	Screened unit	Estimation method	Transmissivity (T) (m^2/d)	Hydraulic conductivity (K) (m/d)	Storativity* (S)
GW22_TPB	Ulan Coal Seams, Dapper Formation	3-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	28.5 DD 31.6 REC	1.9 DD 2.1 REC	
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	14.1 DD	0.94 DD	
GW5_TPB	Tomcat Gully Sandstone, Ulan Coal Seams, Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	44.3 DD 85.2 REC	2.5 DD 4.7 REC	
		3-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	53.7 DD 76.9 REC	3.0 DD 4.3 REC	1.3×10^{-2}
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	28.7 DD	1.6 DD	6×10^{-3}
GW6_TPB	Whaka Formation	Packer test (Houlsby 1976)		7.52×10^{-3}	
	Whaka Formation, Avymore Claystone	Packer test (Houlsby 1976)		3.60×10^{-3}	
	Upper Ulan Seam	Packer test (Houlsby 1976)		6.30×10^{-3}	
	Lower Ulan Seam	Packer test (Houlsby 1976)		3.45×10^{-2}	
GW6A	Ellismayne and Whaka Formations, Avymore Claystone, Flyblowers Creek Seam	Rising head test (Bouwer-Rice 1976)		0.003	
GW7_TPB	Ellismayne and Whaka Formations, Avymore Claystone, Flyblowers Creek Seam, Tomcat Gully Sandstone, Ulan Coal Seams, Dapper Formation	24-hour pump test (Cooper-Jacob 1946 (DD); Theis, 1935 (REC))	8.5 DD 15.5 REC	0.2 DD 0.3 REC	
		21-day pump test (Cooper-Jacob 1946 (DD); Theis 1935 (REC))	27.9 DD 23.2 REC	0.5 DD 0.4 REC	
	Whaka Formation	Packer test (Houlsby 1976)		9.80×10^{-3}	
	Flyblowers Creek Seam	Packer test (Houlsby 1976)		2.60×10^{-2}	
	Upper Ulan Seam	Packer test (Houlsby 1976)		3.11×10^{-2}	

Note: DD = drawdown; REC = recovery; * Storativity is only calculated for drawdown

5.7.1 Alluvium aquifer

Groundwater quality is marginal to saline in the alluvium aquifer. The variable salinity may be associated with the depth of the piezometer and the clay content of the alluvium at each location. The highest salinities are found at monitoring piezometers screened across clayey gravels (GW1, GW10 and GW7A). Salinity in the alluvium aquifers is similar to surface water in the surrounding area (Section 5.6).

Groundwater in the alluvium aquifers is generally dominated by sodium and chloride, while in some locations magnesium and bicarbonate are dominant. Dissolved iron, copper and zinc concentrations are elevated in the alluvium aquifers. Total iron concentrations are higher than dissolved iron concentrations, indicating insoluble iron is naturally elevated in the alluvium aquifers. Elevated dissolved metal concentrations are considered to reflect natural background concentrations.

In 2009 and early 2010, concentrations of ammonia and nitrate were typically low in the alluvium aquifers, whereas total nitrogen and total phosphorus concentrations were elevated and generally exceeded the ANZECC (2000) guidelines. This may be reflective of natural processes or land practices in the area, with downward percolation of rainfall sourced water from overlying layers.

A summary of the water quality in the alluvium aquifers is presented in Table 5.6.

Table 5.6 Water quality summary for alluvium aquifers

Parameter	Units	ANZECC (200)	No. samples	Min	Max	Mean [3]
EC	µ/S/cm	30-350[1]	48	**1850**	**6,949**	**3,648**
pH	pH units	6.5-7.5[1]	48	6.21	8.01	7.06
Al	mg/L	0.055[2]	48	<0.01	0.77	0.04
Ba	mg/L	na	48	0.03	0.48	0.14
Co	mg/L	ID	48	<0.001	0.056	0.007
Cu	mg/L	0.0014	15	<0.001	0.011	0.004
Fe	mg/L	ID	48	<0.05	3.20	0.43
Pb	mg/L	0,0034[2]	48	<0.001	0.003	<0.001
Mn	mg/L	1.9[2]	48	0.016	**5.70**	0.981
Ni	mg/L	0.011[2]	15	0.001	**0.012**	0.005
Zn	mg/L	0.008[2]	48	<0.005	**0.194**	**0.028**

Note: Metals are dissolved metal species.
1. trigger values for upland rivers in south-east Australia (ANZECC 2000)
2. 95% trigger values (ANZECC 2000)
3. mean calculated by halving values below detection limits
4. **Bold**[2] - value outside ANZECC guidelines
5. na – no trigger value available
6. ID – insufficient data to determine trigger value

Apparent groundwater ages in the alluvium aquifers, determined by radiocarbon dating, were modern (i.e. less than 100 years).

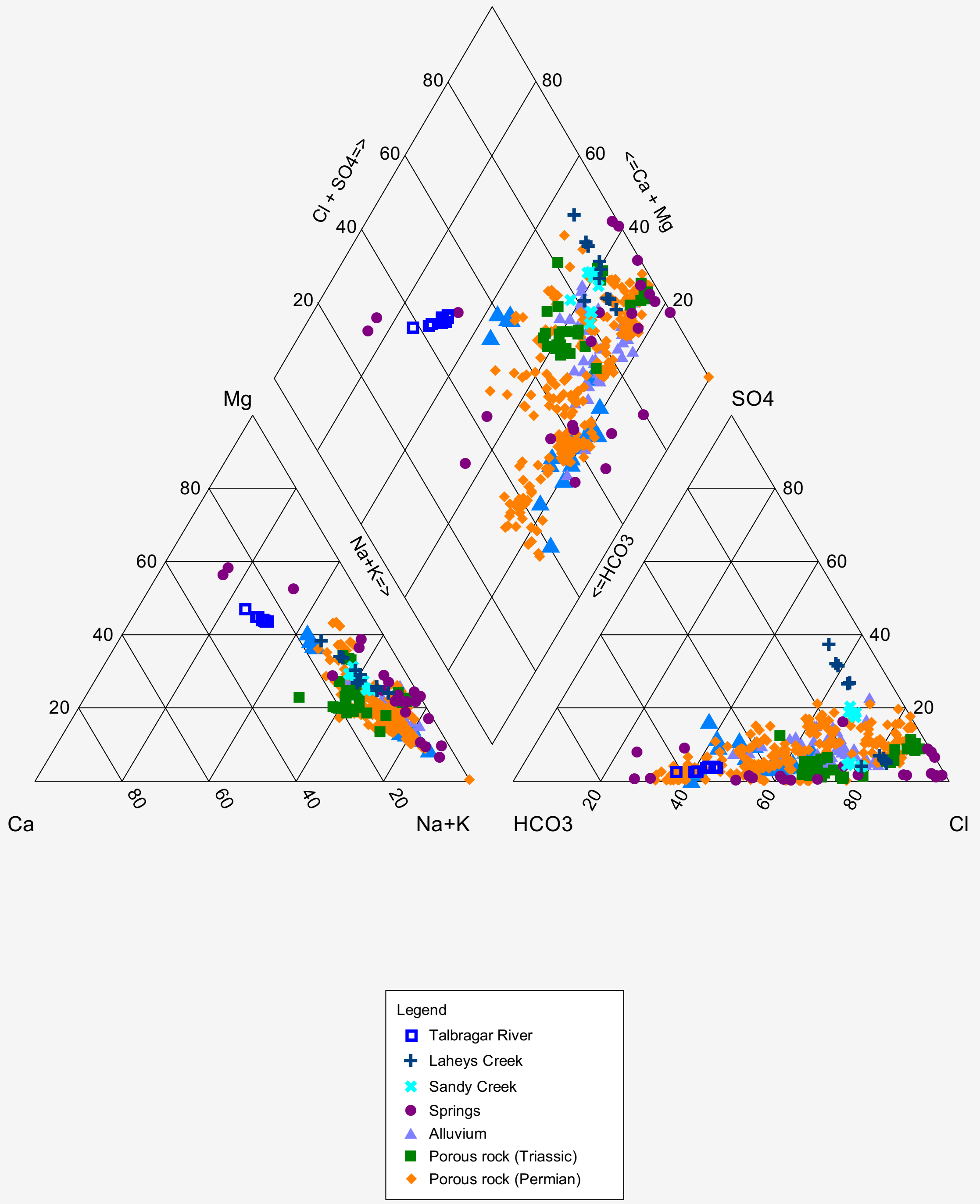
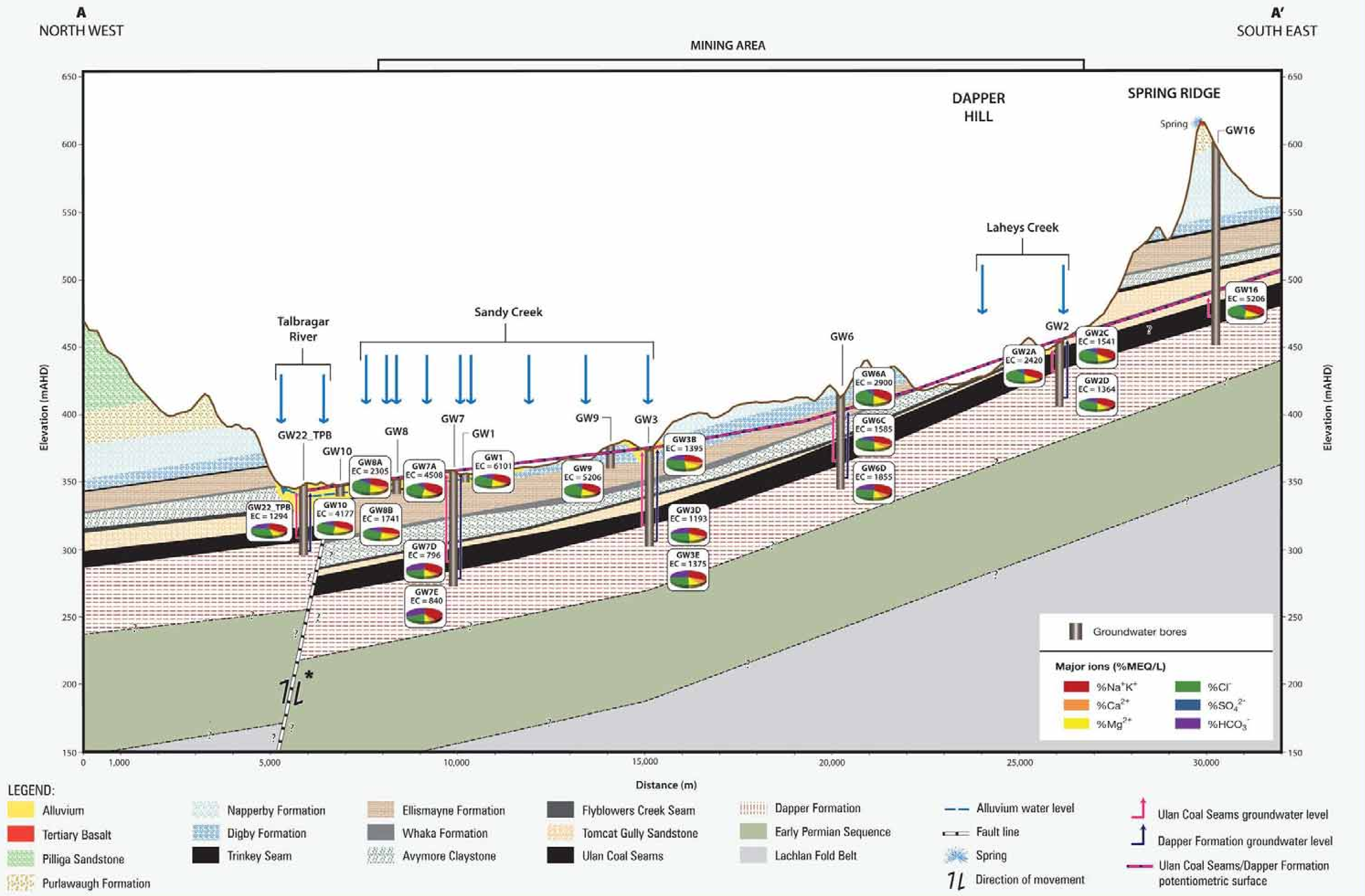


Figure 5.10 Piper diagram for groundwater, surface water and springs



Note: *Interpreted extension to Laheys Creek fault.

Figure 5.11 Cross-section (A - A') showing groundwater chemistry and salinity

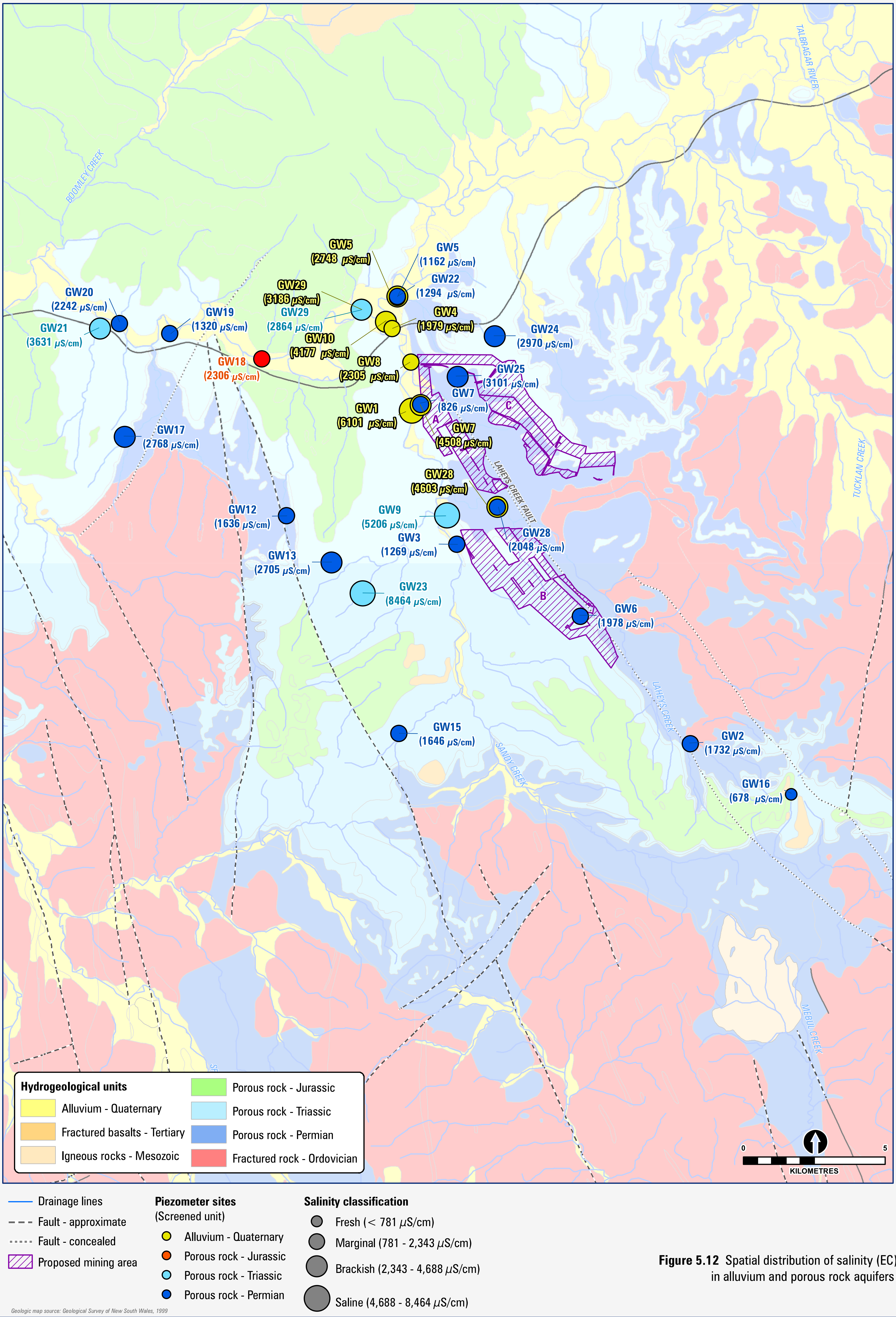


Figure 5.12 Spatial distribution of salinity (EC) in alluvium and porous rock aquifers

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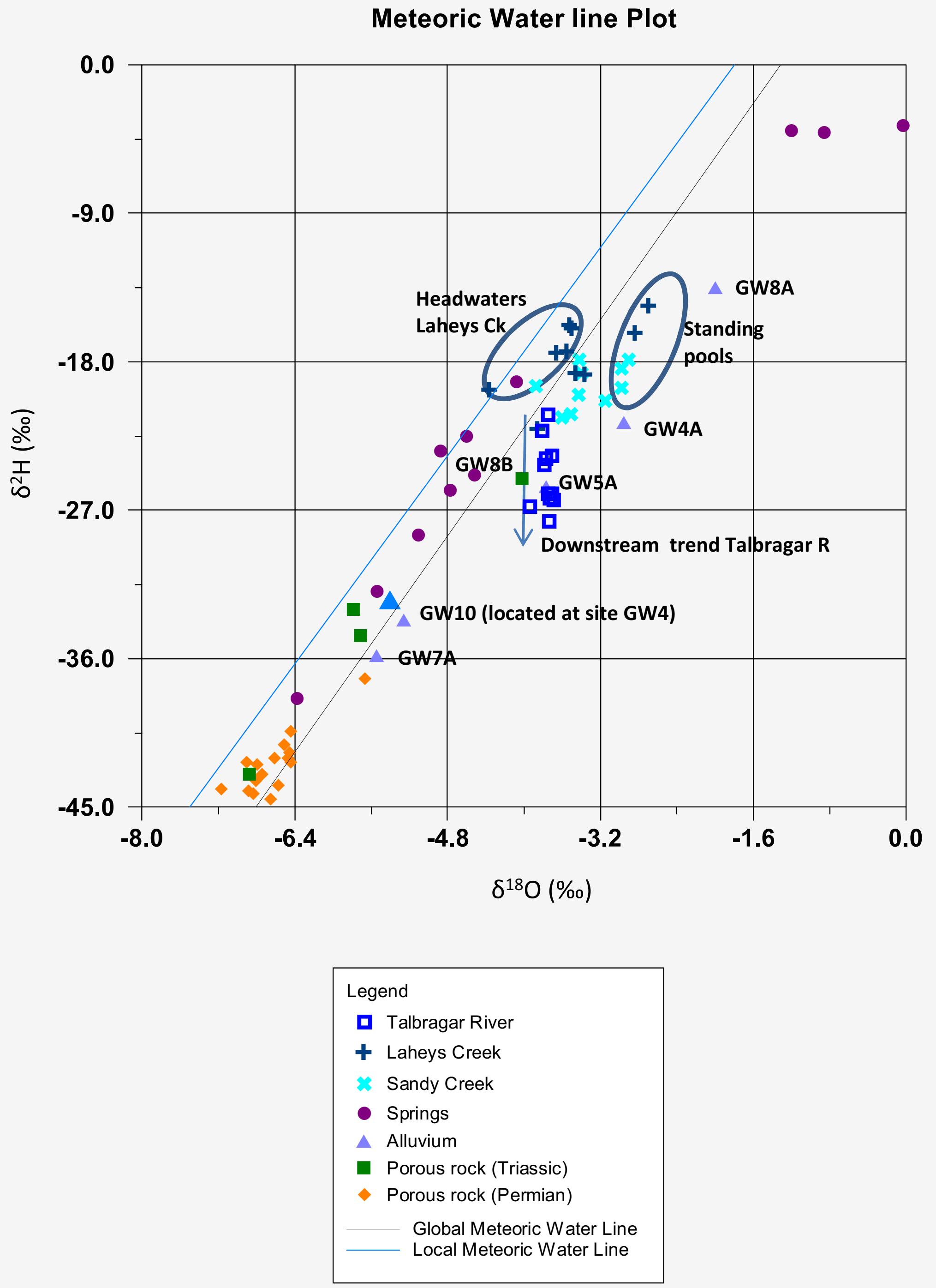

Figure 5.13 Bivariate plot of δ^2H v $\delta^{18}O$ results plotted against the GMWL

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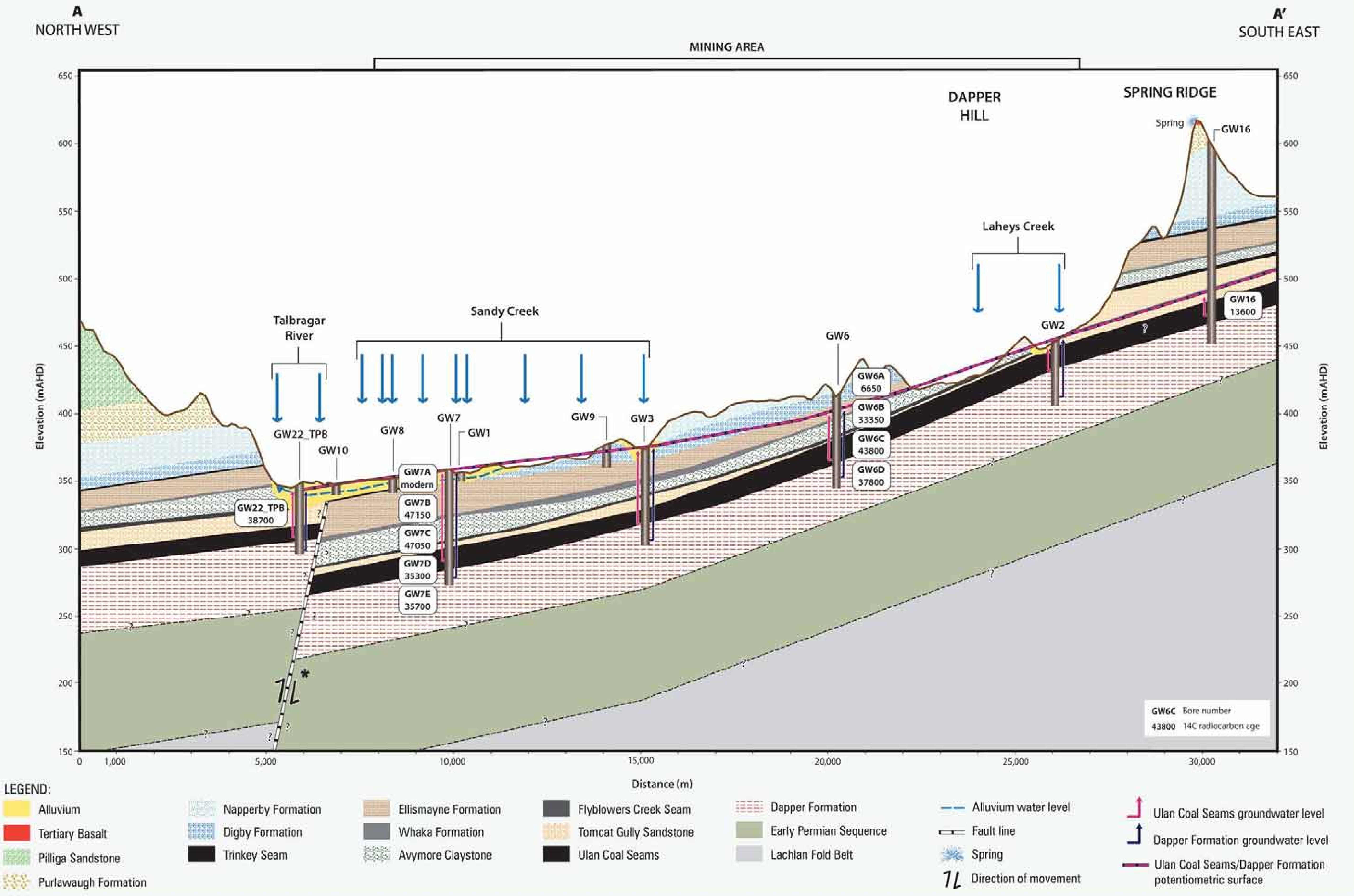
CHC PTY LTD



Note: * *Interpreted extension to Laheys Creek fault.*

Figure 5.14 Cross-section (A - A') showing groundwater age

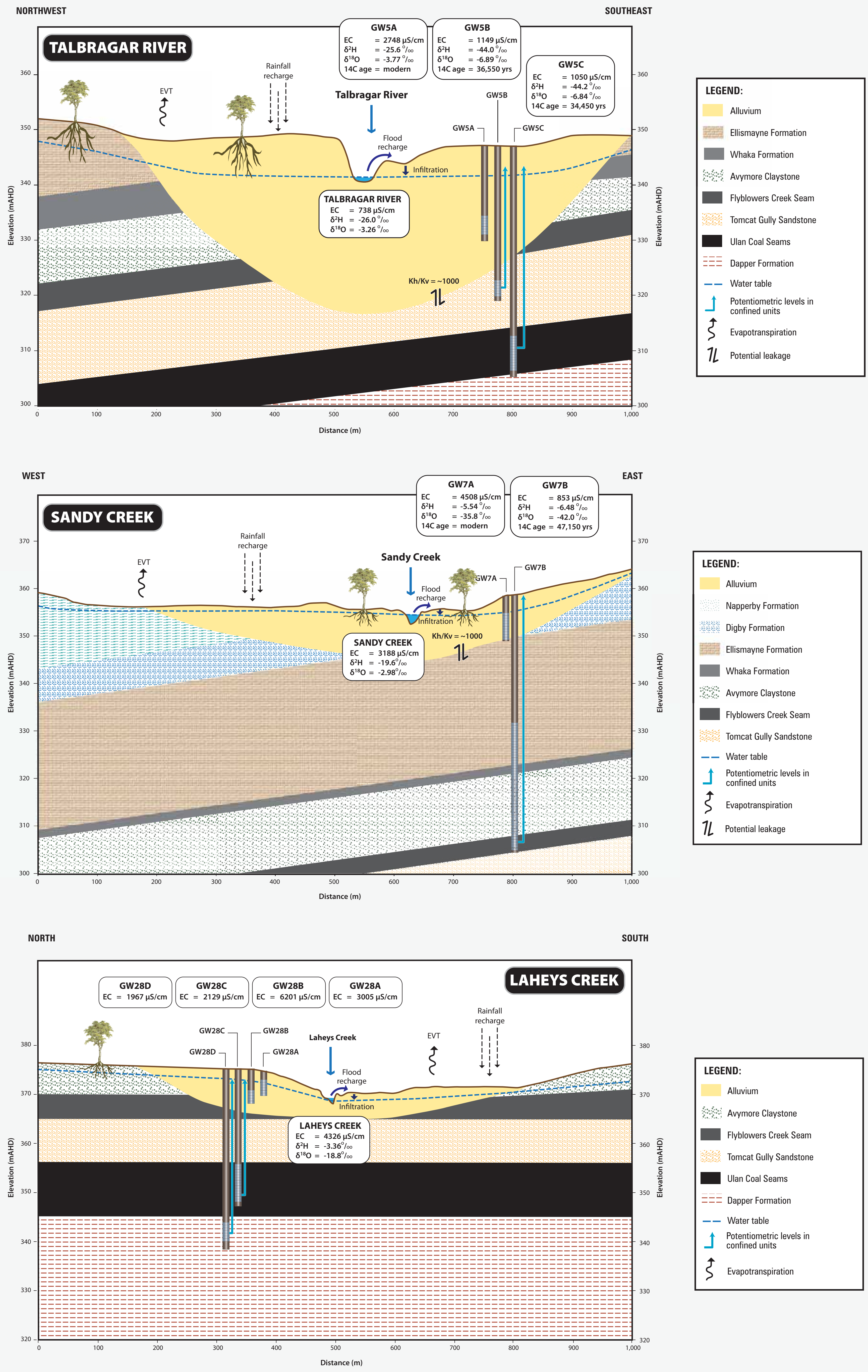


Figure 5.15 Conceptual hydrogeological cross-sections for Talbragar River, Sandy Creek and Laheys Creek

5.7.2 Porous rock — Permo-Triassic

The Permo-Triassic porous rock aquifers typically contains brackish, slightly acidic and sodium-chloride type waters. Although some differences in water quality occur between the Triassic and Permian aquifers, they are characteristically similar.

5.7.2.1 Triassic aquifers

The Triassic aquifers are marginal to saline with a higher average salinity than other units in the assessment area. The pH is slightly acidic to slightly alkaline and was often within the ANZECC (2000) guideline range of pH 6.5 to pH 7.5.

The Triassic aquifers are dominated by chloride and sodium ions, and at some locations bicarbonate and magnesium ions. Dissolved copper, zinc and manganese concentrations often exceeded the ANZECC (2000) guidelines; however, this is likely to be representative of natural background concentrations within the Triassic aquifers.

In 2009 and early 2010, concentrations of ammonia and nitrate were low in the Triassic aquifers, whereas, total nitrogen and total phosphorus concentrations were elevated and generally exceeded the ANZECC (2000) guidelines. Elevated total phosphorus and total nitrogen concentrations can be attributed to land practices or natural processes.

A summary of the water quality in the Triassic aquifers is presented in Table 5.7.

Table 5.7 Water quality summary for Triassic aquifers

Parameter	Units	ANZECC (2000)	No. samples	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	31	**827**	**9,060**	**3,993**
pH	pH units	6.5–7.5[1]	31	**5.83**	**7.67**	6.51
Al	mg/L	0.055[2]	31	<0.01	**0.09**	0.015
Ba	mg/L	na	31	<0.001	0.8	0.257
Be	mg/L	ID	31	<0.001	0.094	0.004
Co	mg/L	ID	31	<0.001	0.044	0.009
Cu	mg/L	0.0014	5	<0.001	0.011	0.003
Fe	mg/L	ID	31	<0.05	7.16	2.02
Pb	mg/L	0.0034[2]	31	<0.001	**0.008**	<0.001
Mn	mg/L	1.9[2]	31	0.05	**6.27**	1.00
Ni	mg/L	0.011[2]	5	<0.001	**0.031**	**0.014**
Zn	mg/L	0.008[2]	31	<0.005	**0.126**	**0.033**

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

5.7.2.2 Permian aquifers

The Permian aquifers are fresh to saline. The Whaka Formation and Flyblowers Creek Seam have the highest salinities. The Dapper Formation and the Lower Ulan Coal Seam have the lowest salinities in the Permian aquifers.

The pH of the Permian aquifers range from acidic to alkaline and are generally below the ANZECC (2000) guideline range of pH 6.5 to pH 7.5.

The Permian aquifers are dominated by sodium, magnesium, chloride and bicarbonate ions, with the exception of monitoring bore GW24C. The groundwater measured at GW24C was found to be sodium and potassium dominated. Water types varied with location in the assessment area. Different Permian formation aquifers are often found to be more similar at nested monitoring sites, than within the same Permian units at separate sites. This may indicate vertical connection between the Permian units.

Dissolved metal concentrations are generally below ANZECC (2000) guideline values in the Permian units, with the exception of dissolved nickel and zinc. Concentrations of dissolved iron were elevated and total iron concentrations were higher, indicating insoluble iron is in higher concentrations in the Permian aquifers. The elevated metal concentrations are considered representative of natural background conditions.

In 2009 and early 2010, concentrations of ammonia and nitrate were typically below the ANZECC (2000) guidelines in the Permian aquifers. Total nitrogen and total phosphorus concentrations typically exceeded the ANZECC (2000) guidelines. This can be attributed to land practices or natural processes.

A summary of the water quality in the Permian aquifers is presented in Table 5.8.

Table 5.8 Water quality summary for Permian aquifers

Parameter	Units	ANZECC (2000)	No. samples	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	222	**556**	**9,030**	**1,618**
pH	pH units	6.5–7.5[1]	222	**5.27**	**12.24**	**6.46**
Al	mg/L	0.055[2]	222	<0.01	**7.92**	**0.08**
Ba	mg/L	na	222	0.029	0.949	0.157
Be	mg/L	ID	222	<0.001	0.002	<0.001
Co	mg/L	ID	222	<0.001	0.126	0.006
Cu	mg/L	0.0014	57	<0.001	0.011	0.001
Fe	mg/L	ID	222	<0.05	91.1	14.50
Pb	mg/L	0.0034[2]	222	<0.001	**0.093**	0.001
Mn	mg/L	1.9[2]	222	0.009	**3.56**	0.56
Ni	mg/L	0.011[2]	57	<0.001	**0.156**	**0.011**
Zn	mg/L	0.008[2]	222	<0.005	**1.08**	**0.05**

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

Apparent groundwater ages in the Permian aquifers, determined by radiocarbon dating, range from 6,650 to 47,150 years.

5.8 Surface water – groundwater connectivity

Surface water and groundwater connectivity exists across the assessment area in a variety of forms, including springs/seeps (discussed in Section 5.8.5.3), baseflow and semi-permanent pools within the Talbragar River and tributaries, and flood flow recharge to groundwater. Conceptual cross sections through alluvium in Talbragar River, Sandy Creek and Laheys Creek are shown in Figure 5.15 to illustrate the following discussion.

5.8.1 Talbragar River

5.8.1.1 Hydraulic gradient

Groundwater levels at the alluvium piezometers GW4, GW10 and GW5A were compared with the river stage elevations in the Talbragar River at each location (Table 5.9). The higher groundwater levels compared to the Talbragar River stages confirms that the Talbragar River, in that location, at that time was potentially a gaining stream. Photos 5.1 and 5.2 show the Talbragar River at the time of the survey near GW4 and GW5A.

The longer-term monitoring at these sites indicates the groundwater levels used for the comparison are not temporarily high as a result of recent rainfall but instead are close to average conditions (see Appendix E). The groundwater flow direction at these sites is established to be towards the Talbragar River.

Table 5.9 Comparison of Talbragar River and alluvium groundwater levels

Piezometer	Talbragar River level (mAHD) 29 April 2010	Groundwater level (mAHD) 29 April 2010
GW4	339.3	342.7
GW10	339.3	339.8
GW5A	339.7	341.1

(Photos by Boardman and Peasley (2010))

Photo 5.1 Talbragar River near GW4

Photo 5.2 Talbragar River near GW5A

In August 2011, Parsons Brinckerhoff completed a survey of the Talbragar River in the assessment area to identify potential locations of groundwater baseflow discharge. Samples were collected at 10 locations for chemical and isotopic analysis (Table 5.10). At the time of the survey, there was continuous flow the entire length of the survey area and there were no obvious visual signs of groundwater discharge.

During the survey of the Talbragar River salinity and pH increased along the flow path. Major ion chemistry was dominated by Mg-Na-Ca-HCO_3-Cl and was distinctly different from surface water from Laheys and Sandy creeks, and groundwater from the alluvium or porous rock aquifers (Table 5.10). Dissolved metals concentrations were generally low and did not exceed the ANZECC (2000) guidelines.

Based on hydrogeochemical evidence, the contribution of groundwater baseflow within the study area must be low and this is further investigated in Section 5.8.4.

Table 5.10 Water quality summary for Talbragar River (10 samples)

Parameter	Units	ANZECC (2000)	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	**732**	**1,146**	**941**
pH	pH units	6.5–7.5[1]	7.4	**8.65**	**8.43**
Al	mg/L	0.055[2]	<0.01	**0.24**	0.03
Ba	mg/L	na	0.049	0.061	0.057
Fe	mg/L	ID	<0.05	0.30	0.05
Mn	mg/L	1.9[2]	0.021	0.100	0.037
Zn	mg/L	0.008[2]	<0.005	**0.047**	**0.013**

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

5.8.2 Sandy Creek

In August 2011, Parsons Brinckerhoff completed a survey of Sandy Creek in the assessment area to identify potential locations of groundwater baseflow discharge. Samples were collected at 10 locations for chemical and isotopic analysis (Table 5.11). At the time of the survey, surface water was present in a series of disconnected semi-permanent pools.

Table 5.11 Water quality summary for Sandy Creek (10 samples)

Parameter	Units	ANZECC (2000)	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	**1903**	**3280**	**2690**
pH	pH units	6.5–7.5[1]	6.88	**8.46**	**8.06**
Al	mg/L	0.055[2]	<0.01	0.03	0.01
Ba	mg/L	na	0.156	0.27	0.23
Co	mg/L	ID	<0.001	0.001	<0.001
Fe	mg/L	ID	<0.05	0.26	0.06
Mn	mg/L	1.9[2]	0.213	0.734	0.478
Zn	mg/L	0.008[2]	<0.005	0.007	<0.005

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

The survey at Sandy Creek found salinity increased along the flow path. pH ranged from near-neutral to alkaline, however, there was no correlation between pH and distance along flow path. The major ion chemistry of Sandy Creek was generally dominated by Na-Mg-Cl (Figure 5.10**Error! Reference source not found.**), with the exception of samples collected at the headwaters and the confluence with the Talbragar River, which were dominated by Na-Mg-Cl-HCO_3. Dissolved metals concentrations were generally low and did not exceed the ANZECC (2000) guidelines.

Major ion chemistry of Sandy Creek is similar to the alluvium in the vicinity of the confluence with the Talbragar River (GW8A, GW10 and GW7A), although there are some differences in salinity between groundwater from the alluvium and surface water.

5.8.3 Laheys Creek

In August 2011, Parsons Brinckerhoff undertook a survey of Laheys Creek within the assessment area to identify potential locations of groundwater baseflow discharge. Samples were collected at 10 locations for chemical and isotopic analysis (Table 5.12). At the time of the survey, surface water was present in a series of disconnected semi-permanent pools.

The survey at Laheys Creek found salinity typically increased from the headwaters in the south-east of the assessment area along the flow path to the confluence with Sandy Creek. The pH was neutral to alkaline, however, there was no correlation between pH and distance along flow path. Surface water evolved from Na-Mg-Cl in the headwaters to Na-Mg-Cl-SO_4 type water in the lower reaches.

Table 5.12 Water quality summary for Laheys Creek (10 samples)

Parameter	Units	ANZECC (2000)	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	**853**	**4676**	**2742**
pH	pH units	6.5–7.5[1]	7.03	**8.50**	**7.92**
Al	mg/L	0.055[2]	<0.01	**0.18**	0.04
Ba	mg/L	na	0.049	0.196	0.110
Co	mg/L	ID	<0.001	0.002	0.001
Fe	mg/L	ID	<0.05	1.83	0.28
Mn	mg/L	1.9[2]	0.031	1.16	0.49
Zn	mg/L	0.008[2]	<0.005	**0.032**	**0.009**

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

5.8.4 Environmental isotopes

A meteoric water line plot presents the stable isotope results for groundwater, surface water and springs in the assessment area in Figure 5.13. Isotope results for alluvium, porous rock aquifers and surface water are summarised in Table 5.13. Stable isotopes were analysed to assist with assessing:

- connection between the alluvium groundwater and surface water
- connection between porous rock aquifers and alluvium groundwater and/or surface water.

Table 5.13 Stable isotope summary for alluvium, porous rock and surface water

Unit	$\delta^{18}O$ (‰)			$\delta^{2}H$ (‰)		
	Min	**Max**	**Mean***	**Min**	**Max**	**Mean**
Alluvium Aquifer	-5.5	-2.0	**-3.9**	-35.8	-13.5	**-26.1**
Porous rock (Triassic)	-6.9	-4.0	**-5.6**	-43.0	-25.1	**-33.9**
Porous rock (Permian)	-7.2	-5.7	**-6.5**	-44.5	-37.2	**-42.2**
Talbragar River	-3.8	-3.7	**-3.8**	-27.7	-21.2	**-24.8**
Sandy Creek	-3.9	-2.9	**-3.3**	-21.4	-17.9	**-19.5**
Laheys Creek	-4.4	-0.9	**-3.3**	-22.1	-4.1	**-16.5**

The major findings from stable isotopes are:

- The isotopic values of surface water from the Talbragar River plot near the GMWL at the western boundary of the assessment area, and show a general trend of ^{2}H depletion along the flow path, with isotopic values merging towards those of the alluvium in the vicinity of GW5. The isotopic signatures suggest that there is some connection between alluvium groundwater and surface water along the Talbragar River in the vicinity of its confluence with Sandy Creek. These results support the hydrograph data for GW5A, which shows sharp rises in level in response to rainfall and relatively steep recession curves which is indicative of direct riverbank recharge by flood waters.
- Stable isotope values from Sandy Creek plot to the right of the GMWL, indicating surface water has undergone evaporative enrichment. This is consistent with the condition of surface water at time of sampling (standing water in a series of disconnected semi-permanent pools).
- The isotopic signatures of Sandy Creek are distinctly different from the isotopic signature of the Permian aquifers, suggesting that even in those locations where Permian rocks outcrop, the connection between groundwater and surface water is limited.
- The isotopic signatures of Laheys Creek headwaters plot close to GMWL, and are distinctly different to the isotopic signature of the Permian aquifers. These results are consistent with the headwaters of Laheys Creek being located in a groundwater recharge zone.
- Surface water samples collected from shallow standing pools in mid-reaches of Laheys Creek show an evaporative signature (plot right to the GMWL). These isotopic signatures appear to be similar to those of the Laheys Creek headwaters, but with an isotopic enrichment in 18O by evaporation.

- The isotopic signatures of the alluvium at GW4A and GW8A are isotopically enriched (plotting to the right of the GMWL), and appear to represent an evaporated surface water signature. The channel of Sandy Creek in the vicinity of these monitoring bores is less confined than further upstream and the U-shaped geometry of the channel indicates that overbank flooding occurs. These isotopic findings are consistent with recharge of evaporated floodwaters.

- There are distinct isotopic differences between GW8A (shallow alluvium) and GW8B (deep alluvium/top of the Triassic) indicating very limited connection between Triassic aquifers and deep alluvium.

- There are distinct isotopic differences between GW4 (shallow alluvium) and GW10 (deep alluvium/top of the Triassic) (bores are located at the same site located adjacent to Sandy Creek), indicating very limited connection between Triassic aquifers and deep alluvium.

- The isotopic signature of groundwater in the alluvium at GW7A is isotopically similar to those of groundwater samples from Triassic aquifers indicating a limited hydraulic connection between the Triassic aquifers and alluvium at this location. The isotopic data supports the hydraulic data, which indicates a strong upward gradient (but weak hydraulic connection (low conductivity) across the alluvium interface).

5.8.5 Potential groundwater availability to ecosystems

Groundwater is potentially available to ecosystems in the following environments:

- shallow groundwater in alluvium

- semi-permanent pools (non-flowing) within the creeks

- springs/seeps (including Naran Springs).

5.8.5.1 Shallow groundwater in the alluvium

Figure 5.17 indicates areas where groundwater is inferred from monitoring and modelling to occur within 3 m of the ground surface (the assumed maximum rooting depth for trees). The 3 metres represents an appropriate depth for the limit of evapotranspiration across the area due to the likely maximum depth of the capillary fringe, and the prevalence of shallow rooted vegetation. These alluvial areas tend to be restricted to a narrow zone close to the creek and river channels. Where groundwater is inferred to be shallow, there is potential for groundwater to discharge to semi-permanent pools.

5.8.5.2 Semi-permanent pools

The Project ecologist has identified six semi-permanent pools that potentially provide a refuge function to aquatic ecology. These are shown in Figure 5.17. Water quality at these aquatic ecology sites and in the shallow alluvium is discussed in the preceding sections. A more detailed discussion on semi-permanent pools is provided in the Cobbora Coal Project - Surface Water Assessment (Parsons Brinckerhoff 2012).

5.8.5.3 Springs

Seventeen springs were identified in this study, a number of which were dammed and could therefore not be conclusively shown to be spring-fed. The springs identified generally occurred at the contact between permeable Jurassic sandstone and underlying Triassic shales or between the Tertiary basalts and underlying strata. These are located in upland areas to the south and south-east of the mining area, or on the northern side of the Talbragar River (Figure 5.16). The two springs located north of the Talbragar River are associated with discharges from Jurassic strata and one of these springs contributes to baseflow of a nearby creek (a tributary of Boomley Creek).

Naran Springs is designated a high-priority groundwater dependent ecosystem (GDE) identified in the Water Sharing Plan for the MDB Porous Rock Groundwater Source (NOW 2011b). It is located approximately 5.25 km to the west of the proposed mining area A (Figure 5.17). The location of Naran Springs was identified in the field during a site visit in March 2012. The 'spring' was found to be dammed and was not in a natural condition.

A water sample was collected from the spring and was analysed. The stable isotope result indicated an evaporated rainfall signature, similar to other spring water samples collected in the area.

Identified springs generally ranged from fresh to brackish, with the exception of the springs associated with the Jurassic strata, which were saline. The lower salinity springs to the south and south-east of the mining area are rainfall-fed, while the brackish springs were either rainfall-fed springs (or seeps) affected by evaporation, or springs associated with shallow groundwater systems.

The pH was generally slightly acidic and was often below the ANZECC (2000) guideline range of pH 6.5 to pH 7.5. Higher pH values were found to the west of the mining area.

Springs are generally Na-Mg-Cl dominant (Figure 5.10), with increasing HCO_3^- in springs associated with Tertiary basalts in the south-east of the assessment area.

Dissolved metals were detected at most spring locations but were below the ANZECC (2000) guideline range, except for aluminium.

In 2009, concentrations of ammonia and nitrate were low and typically below the ANZECC (2000) guidelines. Reactive phosphorus concentrations occasionally exceeded the ANZECC (2000) guidelines.

A summary of the water quality in the identified springs is presented in Table 5.14.

Table 5.14 Water quality summary for private springs

Parameter	Units	ANZECC (2000)	No. samples	Min	Max	Mean[3]
EC	µS/cm	30–350[1]	23	48	**8,830**	**1,362**
pH	pH units	6.5–7.5[1]	23	**4.53**	**8.98**	**6.20**
Al	mg/L	0.055[2]	17	<0.01	**4.43**	**0.55**
Ba	mg/L	na	17	0.009	0.446	0.116
Co	mg/L	ID	17	<0.001	0.063	0.006
Fe	mg/L	ID	17	<0.05	10.80	1.29
Pb	mg/L	0.0034[2]	17	<0.001	**0.006**	<0.001
Mn	mg/L	1.9[2]	16	0.014	0.643	0.230
Zn	mg/L	0.008[2]	17	0.006	**0.126**	**0.030**

Note: Metals are dissolved metal species.
1 trigger values for upland rivers in south-east Australia (ANZECC 2000)
2 95% trigger values (ANZECC 2000)
3 mean calculated by halving values below detection limits
4 **Bold** — value outside ANZECC guidelines
5 na — no trigger value available
6 ID — insufficient data to determine trigger value

Stable isotopic ratios for spring samples generally plot on the GMWL indicating springs are of meteoric origin (rainfall recharge (Figure 5.13)). A number of samples plot to the right of the GMWL; it is important to note these samples were collected from shallow pools/dams and isotopic signatures are the result of isotopic fractionation by evaporation.

One spring located south-west of the mining area (LS41) had an isotopic signature similar to older, more isotopically depleted signatures of groundwater. The groundwater level within the Permo-Triassic rocks at this location is estimated at approximately 50 m below the surface.

Therefore, the water supplying this spring is likely to be associated with slow groundwater flow through the low hydraulically conductive units of the Purlawaugh Formation, which consist of sandstones, siltstones and mudstones. This spring has anecdotally being flowing continuously since agricultural development commenced in the area and is located on the contact between the Jurassic and Permo-Triassic units.

Apparent spring water ages, determined by radiocarbon dating, were modern to less than 400 years.

Based on the geochemical and isotopic evidence, springs are rainfall recharge fed, and occur due to the relatively short flow paths within the basalt system and limited connectivity between the basalt and underlying formation. Springs appear to be typically associated with isolated (local) hydrogeological systems overlying the more regional systems.

5.9 Conceptual model

A hydrogeological conceptual model is a summary, accompanied by a graphical representation, of the key processes considered to control groundwater levels and flow within a groundwater system. The conceptual model describes how water enters, exits, is stored, and moves within a hydrogeological system and how groundwater interacts with surface water systems and potentially dependent ecosystems. Ultimately the conceptual model informs the development of a numerical predictive groundwater model which is used to assess impacts on hydrologic systems from activities such as mining and groundwater extraction.

The conceptual model for groundwater systems in the assessment area is based on the cumulative results from an extensive groundwater investigation program carried out over three years. While our conceptual understanding is always evolving as new data comes to light, there is now a strong scientific basis for the following conceptual framework.
The current conceptual understanding of the groundwater system in the assessment area is depicted on the hydrogeological cross sections in Figure 5.15.

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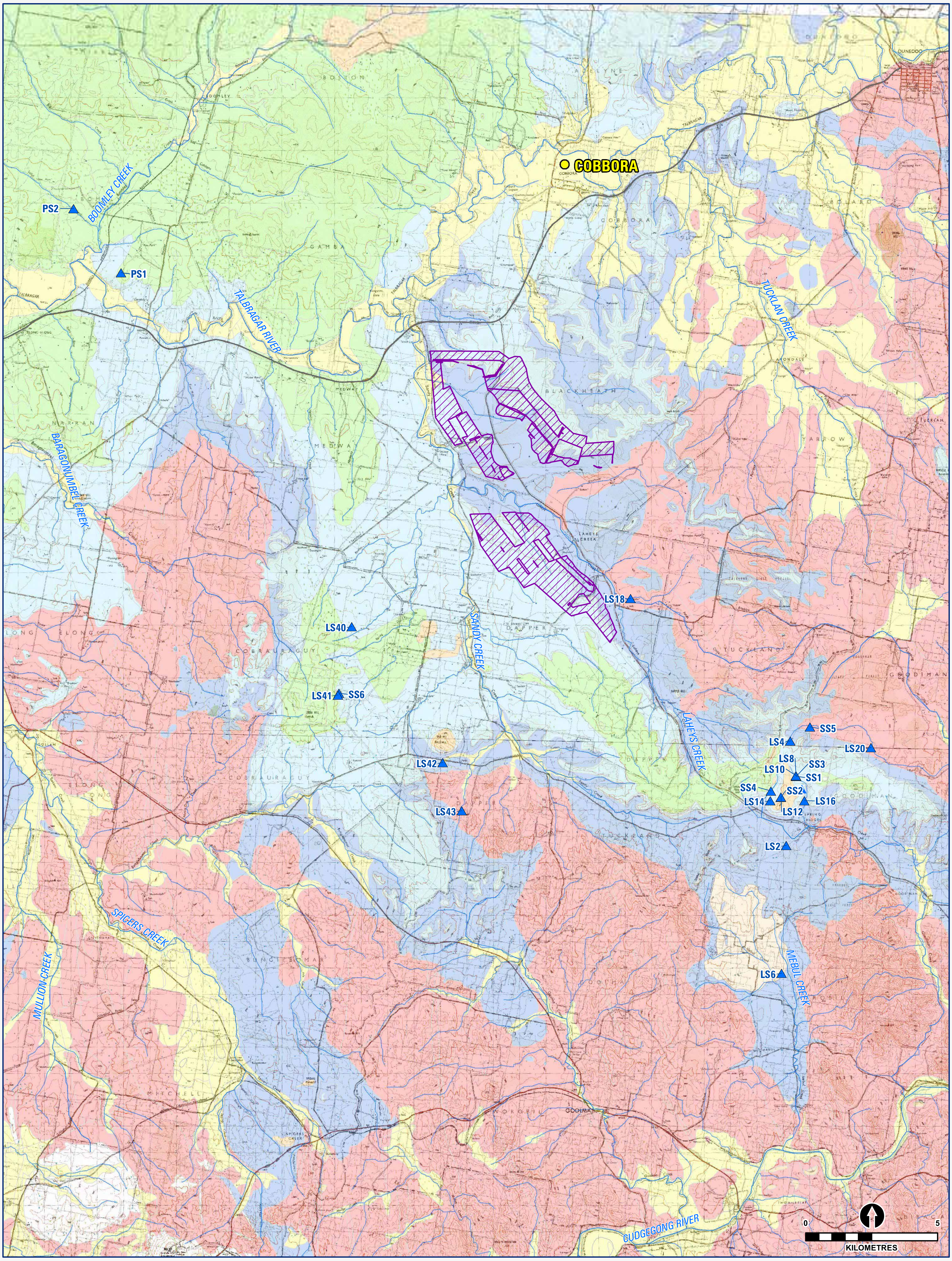

▲ Springs

Proposed mining areas

Hydrogeological units

- Alluvium - Quaternary
- Fractured basalts - Tertiary
- Igneous rocks - Mesozoic
- Porous rock - Jurassic
- Porous rock - Triassic
- Porous rock - Permian
- Fractured rock - Ordovician

Figure 5.16 Spring survey

Geologic map source: Geological Survey of New South Wales, 1999

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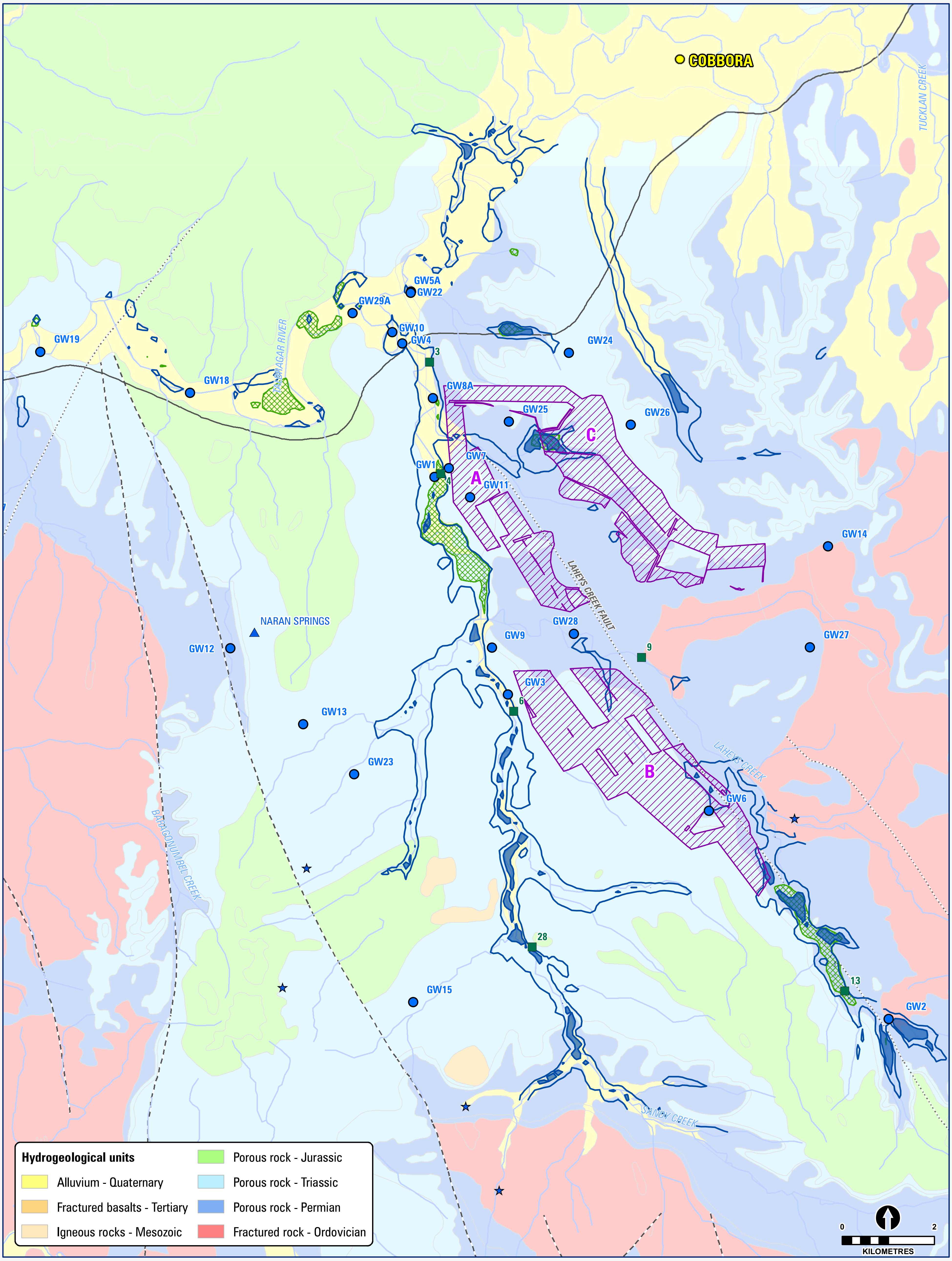

- Piezometer sites
- Drainage lines
- Fault - approximate
- Fault - concealed
- Proposed mining areas

Potential GDE

- Springs (identified in spring survey)
- High priority GDE*
- Aquatic ecology sites

Potential groundwater available to ecosystems
(Based on model)

- 0 - 3 m below ground level in alluvium
- 3 - 5 m below ground level in alluvium
- Artesian heads in Dapper Formation

Figure 5.17 Modelled potential groundwater availability to ecosystems

*Water Sharing Plan for the NSW Murray Darling Basin Porous Rock Groundwater Sources 2011, NSW Office of Water 2011

5.9.1 The groundwater systems

Within the assessment area and immediate surrounds groundwater occurs within four regionally significant aquifer systems:

1. the alluvium aquifer associated with unconsolidated sediments of the Talbragar River, and also minor alluvium associated with the tributaries to the Talbragar River (Sandy Creek and Laheys Creek)

2. the porous rock aquifer within the Permo-Triassic sediments of the Gunnedah-Oxley Basin

3. porous rock aquifers of Jurassic age

4. fractured rock aquifers within the metamorphic basement rocks of the Lachlan Fold Belt.

Of these, the first two aquifer systems are by far the most important in the assessment area with regard to groundwater and surface water impacts.

The Lachlan Fold Belt fractured aquifer is of very low permeability, does not host a significant groundwater resource and will not be intersected by mining. Jurassic rocks associated with the GAB occur to the north of the Talbragar River. However, much of the Jurassic rocks in the assessment area are disconnected outliers and are considered part of the Gunnedah-Oxley basin for water management purposes.

The basal unit of the Jurassic rocks (Purlawaugh Formation) comprises shales and interbedded sandstones and therefore the aquifer units of the Jurassic formations are considered not to be hydraulically connected to the underlying Permo-Triassic aquifers. Groundwater modelling carried out as part of this investigation supports the conclusion that the porous Jurassic aquifers will experience negligible impact from the proposed operations.

The Permo-Triassic coal measures and sandstone units form an open folded and faulted sequence of porous rocks that unconformably overlie the low permeability basement rocks of the Lachlan Fold Belt. Groundwater monitoring indicates that the Permo-Triassic rocks act essentially as a single (but heterogeneous) porous aquifer unit of low to moderate permeability. Within the major river and stream valleys, alluvial deposits comprising mostly sandy and gravelly clays form minor aquifers.

Although the alluvium directly overlies the Permo-Triassic rocks, the alluvium aquifers are distinct systems that are locally recharged and hydraulically poorly connected to the regional Permo-Triassic aquifer.

The dominant surface water features in the assessment area are the Talbragar River and its main tributary streams, along which groundwater discharges via evapotranspiration and, locally, by minor direct seepage. For the most part the stream and river channels are within Quaternary alluvial deposits of low permeability, but at several locations, Permo-Triassic rocks are exposed in the stream bed and banks.

The Talbragar River and its tributaries are ephemeral systems in the assessment area, i.e. there is no sustained baseflow during dry periods, despite artesian groundwater pressures in adjacent and underlying rocks.

Within this aquifer framework, groundwater storage and flow is largely driven by the following key processes:

- Rainfall recharge (inflow).
- Evapotranspiration (outflow).
- Baseflow discharge to streams and the Talbragar River (outflow).
- Inter-aquifer connectivity (inflow/outflow).
- Regional through flow (inflow/outflow).

A more detailed discussion of the current understanding of these processes along with supporting rationale is provided in the following subsections.

5.9.2 Groundwater flow

Groundwater levels and flow direction are mainly influenced by geology and topography with the latter mainly controlling the location of major hydraulic boundaries: areas of recharge at outcrop along ridges and interfluves, and areas of discharge along major streams and rivers. Groundwater flow is also controlled locally by geology, stratigraphic dip, faulting and episodic flooding.

Interpreted groundwater level contour plots are shown in Figure 5.6 based on observed groundwater elevations and output from the calibrated numerical model.
Groundwater elevations define a piezometric surface which is a subdued reflection of the topography; groundwater movement is perpendicular to groundwater contours such that groundwater flow in the assessment area is generally in a northerly direction (towards the Talbragar River) in all units.

In detail, groundwater levels in each unit are slightly different reflecting the local hydraulic controls and aquifer heterogeneity. In addition observations from exploration drilling and transient electromagnetic (TEM) imaging indicate that dipping strata and faulting can influence groundwater flow and yield on a local scale.

It should be noted that actual groundwater flow velocities are limited by the generally low permeability of the Permo-Triassic aquifer and are likely to be in the order of 10 to 20 cm per year under natural conditions (assuming an average hydraulic conductivity of 10^{-1} to 10^{-2} m/d). Such velocities are consistent with radiocarbon dating that indicates groundwater residence times of 40,000 to 50,000 years in Permo-Triassic rocks in the lower Sandy Creek catchment.

Groundwater within the alluvium flows in a downstream direction and is convergent on the river channel. Groundwater within the Permo-Triassic aquifer flows in a generally northerly direction, but also converges on major drainages where discharge occurs mainly via evapotranspiration.

Nested piezometers show that there is a strong downward hydraulic gradient along ridges and interfluves (indicating a recharge area (e.g. GW24A-E)), whereas there is typically an upward hydraulic gradient along the major creeks and the Talbragar River (e.g. GW7A-E), suggestive of discharge zones. The piezometer nest near Laheys Creek (GW28A-D) indicates a slight downward gradient suggesting that streams are recharge features (losing streams) in their upper reaches.

Depth to the water table varies with topography. Along the ridges and upper slopes, groundwater is encountered typically 25 m to 35 m below the ground surface. Near the stream and river channels, groundwater is encountered at shallow depths — typically less than 3 m below the surface.

Artesian pressures (where groundwater levels in the aquifer are higher than the ground surface) have been noted at two locations along Sandy Creek (GW3B-E and GW7B-E) within the Permo-Triassic units indicating that those aquifer units become confined below the Quaternary alluvium. Groundwater levels within the alluvium at the same locations (GW3A, GW7A) are several metres lower, indicating both a strong upward gradient and a very weak hydraulic connection (low conductivity) across the alluvium interface.

On a regional scale the Surat Basin sedimentary units dip into the basin to the north and north-west. The underlying Lachlan Orogen units are trending to the north. Structurally the graben block within the valley has been tilted in a northerly direction and groundwater flow is likely to follow this regional structural fabric.

5.9.3 Recharge

Groundwater recharge is defined as the component of rainfall or surface water that infiltrates to the water table and therefore contributes to groundwater storage. In arid and semi-arid parts of Australia recharge to the groundwater systems is typically low as a proportion of total rainfall (<5%) with most rainfall lost to surface runoff and evapotranspiration.

Within the assessment area, groundwater recharge occurs through the following main mechanisms:

- Direct rainfall infiltration in areas of sedimentary and fractured rock outcrop (along the ridges and mid-slopes); fractures provide preferential paths for infiltration in these areas.
- Infiltration of surface runoff from headwater creeks, gullies and ponds that incise sedimentary or fractured rocks.
- Direct rainfall recharge of unconsolidated alluvium and weathered rock in the lower slope and valley floor areas.
- Stream and riverbank recharge during flood events.

Recharge from direct rainfall over the entire assessment area, but particularly areas of sandstone outcrop is supported by monitoring bore hydrographs. Almost all hydrographs show a trend of increasing groundwater levels that correlate well with the cumulative deviation from mean monthly rainfall (CDM) trend.

As noted elsewhere, this investigation has shown that the most significant recharge occurs during large and sustained rainfall events (e.g. December 2010) when evaporative losses are low relative to precipitation and streams and rivers are in flood.

By contrast, low intensity rainfall events during dry spells typically do not lead to significant groundwater recharge due to high evaporative losses and resaturation of the shallow soil profile.

During the period of high rainfall in late 2010, groundwater levels rose between 1 m and 3 m and remained elevated (relative to early 2010) for more than 6 months after the wet period. The rate of recharge can be very high in mid-slope areas where water gathers in hollows or creek beds (e.g. GW6A-D — up to 5 m rise in groundwater level).

Groundwater level rise in deeper units of the Permo-Triassic sequence (e.g. Dapper Formation) tend to be more subdued indicating that recharge to those units is by somewhat delayed leakage from overlying units.

Hydrographs for monitoring bores installed adjacent to stream channels tend to show sharp rises in groundwater level and relatively steep recession curves, indicative of direct riverbank recharge by flood waters. This phenomenon is noted both in the alluvium aquifers (GW8A; GW5A) and in Permo-Triassic sandstones adjacent to the river channels (e.g. GW18; GW21). Infiltration during flood events is therefore an important recharge mechanism, despite the typical (long-term average) hydraulic gradient towards the creek and river channels.

Isotopic data and radiocarbon dating provide the most compelling evidence for sources of recharge and groundwater residence times. Corrected radiocarbon ages for groundwater within the Permo-Triassic sequence tend to increase in age from the groundwater basin margin (approximately 14,000 years at GW16) down-gradient towards the major discharge areas (e.g. 38,000 to 40,000 years at GW6). The groundwater contains distinctly lighter isotopic ratios of hydrogen and oxygen (lower $\delta^{2}H$ and $\delta^{18}O$ values) suggesting recharge during a cooler climate, consistent with the inferred age and travel times.

By contrast, groundwater in the alluvium aquifers tends to be modern (<100 years — GW5A, GW7A) and has typically higher values of $\delta^{2}H$ and $\delta^{18}O$, similar to surface water samples. The radiocarbon and stable isotope data are therefore consistent with relatively recent recharge of water to the alluvial system via rainfall and/or surface water infiltration. Upward leakage and mixing of older groundwater from the Permo-Triassic rocks appears to be minor where the alluvium is well developed.

Results of the TEM survey indicate that around the Talbragar River and the lowest part of Sandy Creek, there are numerous conductive, near-surface, roughly meander-shaped features (Appendix G). It is likely that these are sinuous abandoned channels that are saturated with saline groundwater derived from evaporated rainwater and flood waters. A zone of slightly more resistive material along the river itself is likely due to riverbank recharge from recent flood events.

5.9.4 Discharge

Groundwater discharge refers to any net loss from the aquifer system. Typically discharge from aquifers occurs via seepage into streams (providing baseflow), springs, evaporative losses where groundwater is shallow, transpiration of plants and abstraction for human activities. Evapotranspiration is a term used to describe the sum of evaporation and plant transpiration from the earth's land surface to atmosphere.

Within the assessment area, groundwater discharge from springs and stream baseflow is considered to be a relatively minor component of the overall water budget. Baseflow in the Talbragar River and Sandy Creek is essentially zero during periods of low rainfall. It is assumed that many of the non-flowing semi-permanent pools along the creeks and rivers are sustained in part by some seepage from the alluvium and also the Permo-Triassic aquifer where exposed in the stream bed.

However, groundwater contours and vertical hydraulic gradients near streams indicate that significant discharge must be occurring along the valley axes. Groundwater levels in the alluvium are typically several metres lower than the underlying sedimentary aquifer implying discharge from the alluvium aquifer but relatively limited leakage into the alluvium from the underlying formations.

It is assumed that the discharge is mainly via evapotranspiration, both as direct evaporation from the soil profile where groundwater is shallow, and transpiration by vegetation.

Evapotranspiration only occurs within a certain depth below the ground surface and the rate decreases with depth to until an 'extinction depth' is reached, where essentially no loss to evapotranspiration occurs. The actual depth of influence for evapotranspiration depends on numerous factors including plant type and root zone depth, soil compaction, and soil or rock type. On a local scale it is assumed that evapotranspiration could occur to depths of up to 5 m but may be up to 10 m where deep-rooted trees grow. However, over the study area 3 metres would represent an appropriate depth for the limit of evapotranspiration due to the likely maximum depth of the capillary fringe, and the prevalence of shallow rooted vegetation. Given that evapotranspiration rates are greater than average annual rainfall rates, and groundwater is relatively shallow in low-lying areas, evapotranspiration is considered a major process by which water is removed from the groundwater system on a catchment-wide scale.

5.9.5 Surface water – groundwater connectivity

Interaction between surface water and groundwater systems occurs though a variety of mechanisms, including:

- baseflow to streams and semi-permanent pools
- flood flow recharge to groundwater
- discharge at springs/seeps.

A large component of the groundwater investigation was aimed at gaining an understanding of surface water – groundwater connectivity. It is clear that surface water – groundwater interactions are complex, variable over time, and also variable across the assessment area depending on the nature of the stream bed, alluvium and underlying aquifer. The following general conclusions are drawn from the investigations.

5.9.5.1 Baseflow to streams and semi-permanent pools, and flood flow

- Surveys of stream bed elevations and groundwater levels show that over lower stretches of the Sandy Creek, Laheys Creek and the Talbragar River, hydraulic gradients are towards the channel, indicating a potential for groundwater discharge to streams. In contrast, upper reaches of creeks are likely to be disconnected losing systems.
- Semi-permanent pools along Sandy Creek, Laheys Creek and the Talbragar River appear to be sustained by some seepage from the alluvium aquifers, and potentially also the Permo-Triassic aquifer where they outcrop in the stream beds. However, surface water samples from these pools tend to have stable isotopic signatures that are distinct from groundwater derived from the Permo-Triassic units.
- All surface water channels cease to flow (including the Talbragar River) for periods of time when rainfall is low (there is no significant baseflow component).
  Baseflow recession curves for the tributary creeks are steep (typically days) while recession curves for the Talbragar are longer (weeks), but ultimately reduce to zero baseflow over time. This indicates that groundwater discharge from the main regional aquifer (Permo-Triassic units) is not a major contributor to surface water flows and the rapid recessions may instead indicate temporary storage in alluvium proximal to the channel.

- Where alluvial deposits are developed along the stream and river courses, the connection between the Permo-Triassic aquifer and the alluvium aquifer is weak and the alluvium aquifers form distinct local aquifer systems. This is evidenced by the strong vertical hydraulic gradients across the alluvium interface and distinct isotopic composition and radiocarbon ages, as discussed in the recharge subsection (5.8.3).

- Long-term (21-day) pumping tests were carried out at two locations (GW5 and GW7) in an attempt to induce leakage across the alluvium interface and assess the vertical conductivity of the alluvium. In both cases, drawdown in the order of 10–20 cm was noted towards the end of the tests, implying very low leakage rates and a horizontal to vertical permeability ratio in the order of 1,000 or more. Moderate rainfall that fell during both tests generated enough recharge to almost negate the induced drawdown. This is consistent with other lines of evidence that suggest that induced leakage rates due to depressurisation of the coal measures would be very low and probably less than the long-term rate of recharge to the alluvial systems via rainfall and floods.

- Hydrographs from monitoring bores adjacent to creek and river channels show sharp ‘flashy’ responses to high rainfall and flood events indicative of direct recharge from flood waters. The surface water recharge signatures are noted mainly in the alluvium, but also the Permo-Triassic aquifer where the alluvium deposits are thin or absent.

- Groundwater levels in the alluvium appear to take approximately 6 to 8 months after a major flood event to approach the pre-flood groundwater levels. This suggests that semi-permanent pools may be sustained for a similar length of time between high flow events.

In summary, groundwater elevations indicate that lower stretches of stream and river reaches are potentially gaining systems. Groundwater discharge to the creeks is sufficient to sustain the semi-permanent pools throughout most of the year (although some are known to dry out), but insufficient to produce permanent flow. In addition the alluvial systems are poorly connected such that depressurisation of the coal measures due to mining is likely to induce only minimal leakage from alluvium aquifers and surface water where alluvium occurs. Rainfall and flood recharge will likely be sufficient to sustain the local alluvium aquifers and semi-permanent pools where they are poorly connected to the Permo-Triassic aquifer. However there is potential for leakage to be induced from surface water where alluvium is thin or absent.

5.9.5.2 Discharge at springs and seeps

A number of springs occur at the contact between permeable Jurassic sandstone and underlying Triassic shales or between the Tertiary basalts and underlying strata. These are located in upland areas to the south and south-east of the mining area, or on the northern side of the Talbragar River. Two springs located north of the Talbragar River are associated with discharges from Jurassic strata and one of these springs contributes to baseflow of a nearby creek (a tributary of Boomley Creek).

Hydrogeochemical and isotopic evidence indicates that most of the springs are derived from recent (<400 years) recharge waters and are associated with isolated (local) hydrogeological systems overlying regional systems (i.e. perched or interflow systems). They are also in areas where the groundwater levels for the Permo-Triassic units are generally deep below the surface (in many places > 50 m below ground). Therefore, springs and seeps in the area are considered to be independent of the regional Permo-Triassic groundwater system.