

# Surat Gas Project Updated CSG WMMP Annual Report

Reporting Period: 22 October 2020 to 21 October 2021

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## 1. Purpose

Arrow Energy's (Arrow) Surat Gas Project (SGP) was approved by the Australian Government under the *Environment and Protection and Biodiversity Conservation Act 1999* (EPBC Act) decision 2010/5344 on 19 December 2013. The conditions attached to approval EPBC 2010/5344 require a Stage 1 CSG Water Monitoring and Management Plan (WMMP) (as required under condition 13, and approved by the Australian Government on 18 December 2018) and an Updated CSG WMMP (as required under condition 17, and approved by the Australian Government on 22 November 2019) be prepared.

Section 8.2.4 of the SGP Updated WMMP requires Arrow to publish an annual report presenting a summary of progress towards Arrow's commitments and document Arrow's compliance against the approval conditions. This annual report is required to be prepared within three months of the anniversary date of the SGP commencement, which was 22 October 2020. This Report has been prepared to fulfil these obligations for the reporting period of 22 October 2020 to 21 October 2021 and provides:

- a summary of relevant monitoring results and analysis and interpretation of data, including:
  - groundwater levels (Section 3.1)
  - groundwater chemistry results (Section 3.2)
  - subsidence monitoring results (Section 3.3).
- documentation of corrective actions implemented to address any exceedances of trigger thresholds, limits, or non-compliance with approval conditions (Sections 3 and 7)
- details of any updates to the Field Development Plan (FDP) and implications for water monitoring and management (Section 4)
- reporting of any relevant ongoing studies and research projects, and includes any supporting technical studies as appendices to the annual report (Section 6)
- documentation of Arrow's compliance against the approval conditions over the preceding 12 months, including monitoring obligations and implementation of the early warning monitoring system (EWMS) (Section 7)
- reporting against the performance measure criteria detailed in Section 8.3 of the SGP Updated WMMP (Sections 3, 4.2 and 7).

## 2. SGP Status

The SGP commenced on 22 October 2020 and, in the first 12 months, Production had not started from any SGP production wells during the reporting period and, as such, no water was produced from these wells during the reporting period.

### 3. Monitoring and Management Programs

#### 3.1 Groundwater pressure/level

##### 3.1.1 Data collection

Groundwater pressure and level data were collected from all operational WMMP monitoring points throughout the reporting period where land access was in place except for RN42231553. Monitoring bore RN42231553 was not monitored in Q4 2021 and the pressure gauge was removed in Q2 2021. In accordance with Section 7.3 of the SGP Updated WMMP, the locations monitored and the frequency of monitoring were carried out throughout the reporting period in alignment with the most current Underground Water Impact Report (UWIR) of 2019. A summary of changes to the groundwater pressure/level monitoring program is provided in Section 3.4.

Throughout the reporting period there were instances where hourly data were unable to be collected due to monitoring equipment failure or access to the monitoring point was not in place. Nonetheless, of the 137 currently installed pressure/level monitoring points, all hourly data were collected from 103 (75 per cent) of them during the reporting period, nine (7 per cent) monitoring points were unable to be accessed either due to no land access agreement in place or weather restrictions, five (4 per cent) monitoring points were removed from the 2019 UWIR Water Monitoring Strategy (WMS) and subsequently were not monitored (as per Section 7.3 of the SGP CSG WMMP), and 20 (15 per cent) monitoring points experienced equipment failure at some point throughout the monitoring period and, subsequently, all hourly data were unable to be collected. It should be noted that although not all hourly data were collected from the monitoring points noted here, the majority of hourly data for the reporting period was collected from almost all of these monitoring points.

Individual hydrographs for each monitoring point are provided in Appendix A.

In accordance with Section 8.6 of the 2019 UWIR, Arrow provided to the Office of Groundwater Impact Assessment (OGIA) a WMS network implementation report and WMS water monitoring report by the required dates of 1 April and 1 October 2021.

##### 3.1.2 Data analysis

An analysis of data collected to date is provided in the following sections, noting that water production from SGP production wells had not started during the reporting period and, as a result, any changes in observed groundwater levels / pressure were not a result of the SGP.

##### **EWMS comparison**

Biannual comparison of the collected groundwater level/pressure data against the EWMS values was undertaken within 90 days of the end of each six-monthly monitoring period. No EWMS exceedances were identified during the reporting period and illustrations of these comparisons are provided in Appendix A.

##### **Condamine Alluvium trend analysis**

A hydrograph of the groundwater level data collected from the Condamine Alluvium monitoring bores is shown in Figure 3-1. The data show general

groundwater flow in the Condamine Alluvium, within the vicinity of Arrow’s monitoring network, is from south to north. The two bores (42231294 and 42231339) located to the east of Arrow’s tenure, and along the eastern margin of the Condamine Alluvium, show groundwater flow in this area is to the west/northwest.

A long-term slightly declining groundwater level trend is evident across most monitoring bores, with the majority of the bores located in the central Condamine Alluvium area (groundwater elevation between 305 and 325m AHD) displaying strong seasonal responses to non-CSG groundwater take (Figure 3-2) and thus the greatest observed drawdown (and generally subsequent recovery). Observed drawdown is greatest in Daandine-161 with 3.01m since 2013, and least in Macalister 7 which has risen 0.28m since August 2017.

Towards the end of the reporting period, increased rainfall across the region resulted in generally stable groundwater levels, with observed drawdown ranging from 0.65 m in Macalister 7 up to an observed groundwater level rise of 1.95 m in Carn Brea-17.

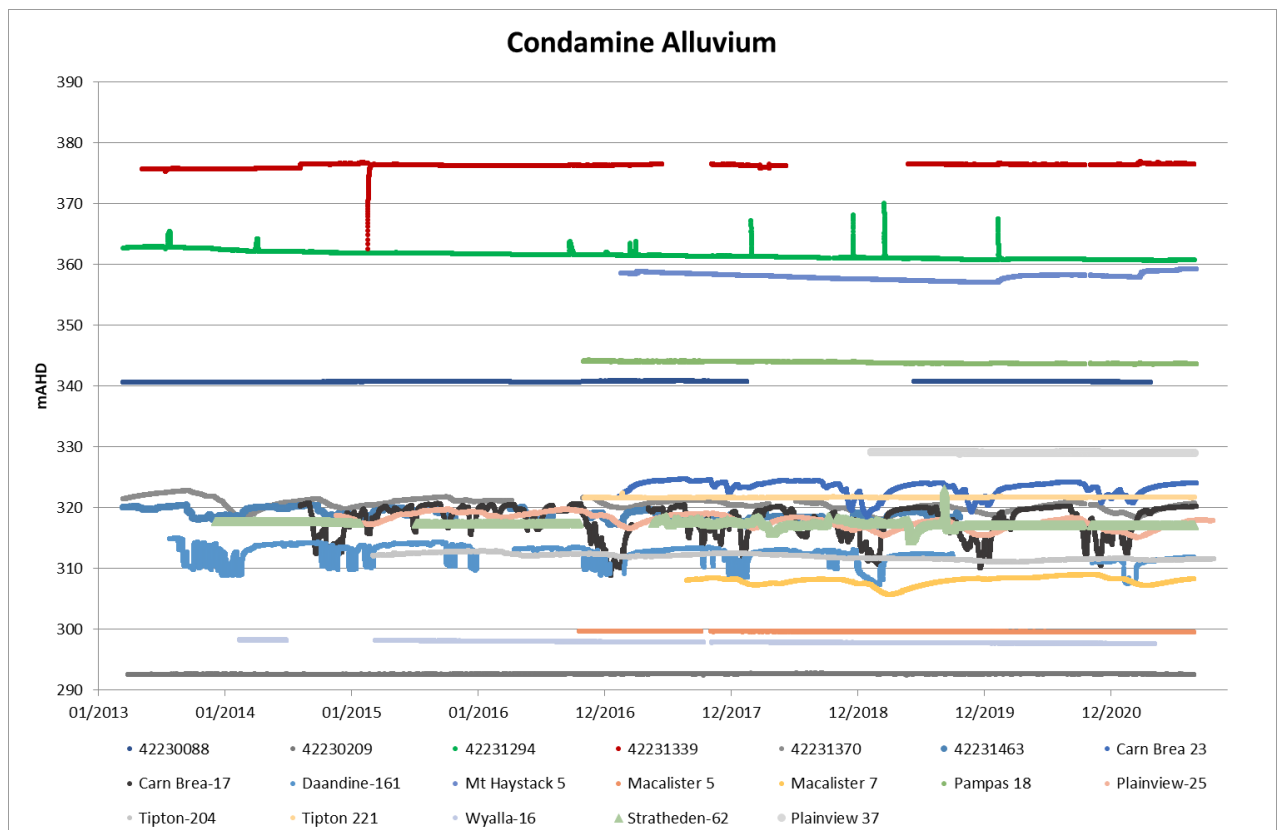


Figure 3-1: Condamine Alluvium monitoring bores hydrograph

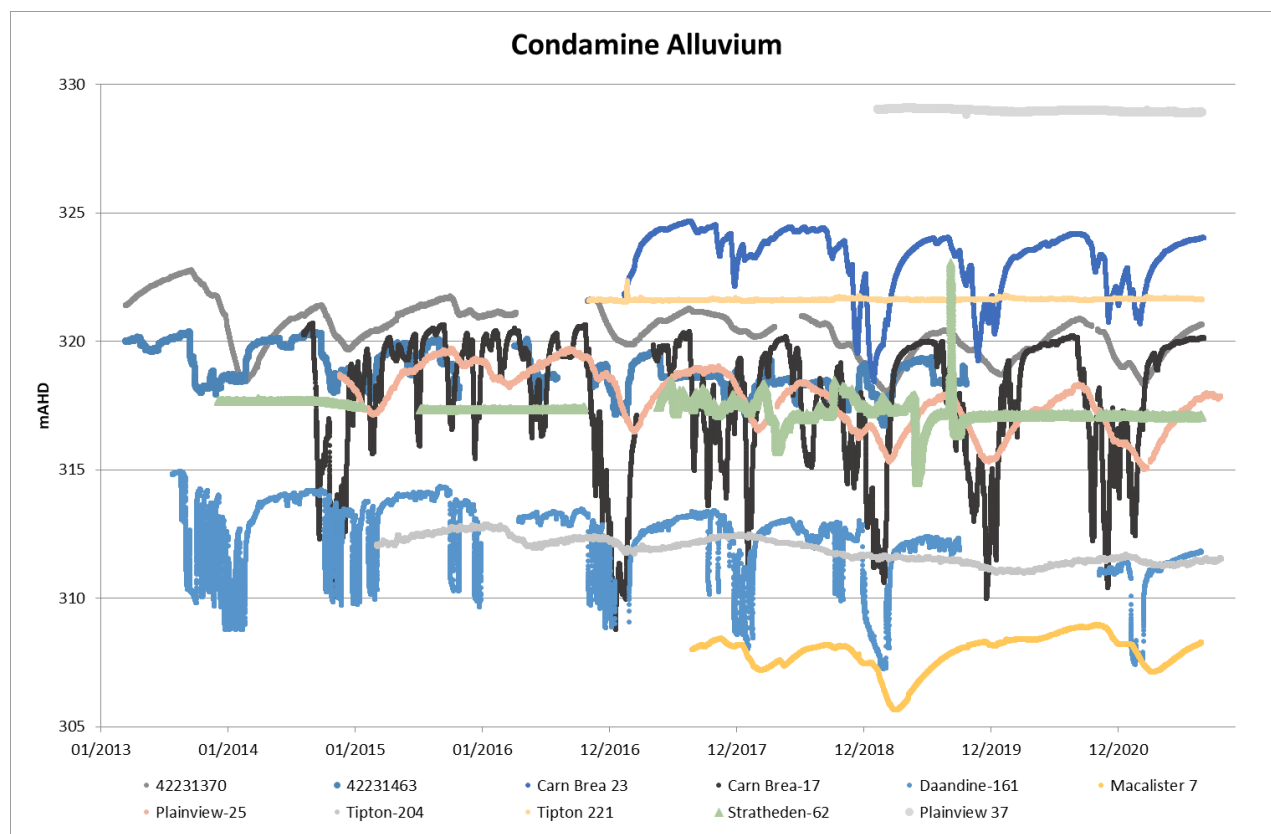


Figure 3-2: Central Condamine Alluvium area monitoring bores hydrograph

### Springbok Sandstone trend analysis

Groundwater levels/pressure in the Springbok Sandstone monitoring bores displayed varying trends; however, all monitoring points except for Glenburnie 20 (given its monitoring interval is a perched seepage zone and is not representative of the regional water table) displayed a groundwater elevation between 300 and 340 m AHD (Figure 3-3).

Daandine-123 displayed an overall rising trend in groundwater pressure while Stratheden-63, Meenawarra-21 and Glenburnie-18 (following a period of pressure equalisation succeeding bore installation), Glenburnie 20, Plainview 36, Longswamp 29 and Longswamp 33 displayed generally stable groundwater pressure trends. Hopeland-17 displayed variability in its groundwater pressure, most likely a result of nearby CSG production on neighbouring tenements (as noted in Section 5.4.2 of the 2019 UWIR [OGIA, 2019]), a workover in May 2020 to install a new pressure gauge (the gauge failed in November 2018) and swabbing of the bore in December 2020 to collect a groundwater sample (which the bore was still recovering from at the end of the reporting period as a result of low permeability of the formation). These trends in the Springbok Sandstone monitoring bores continued throughout the reporting year.

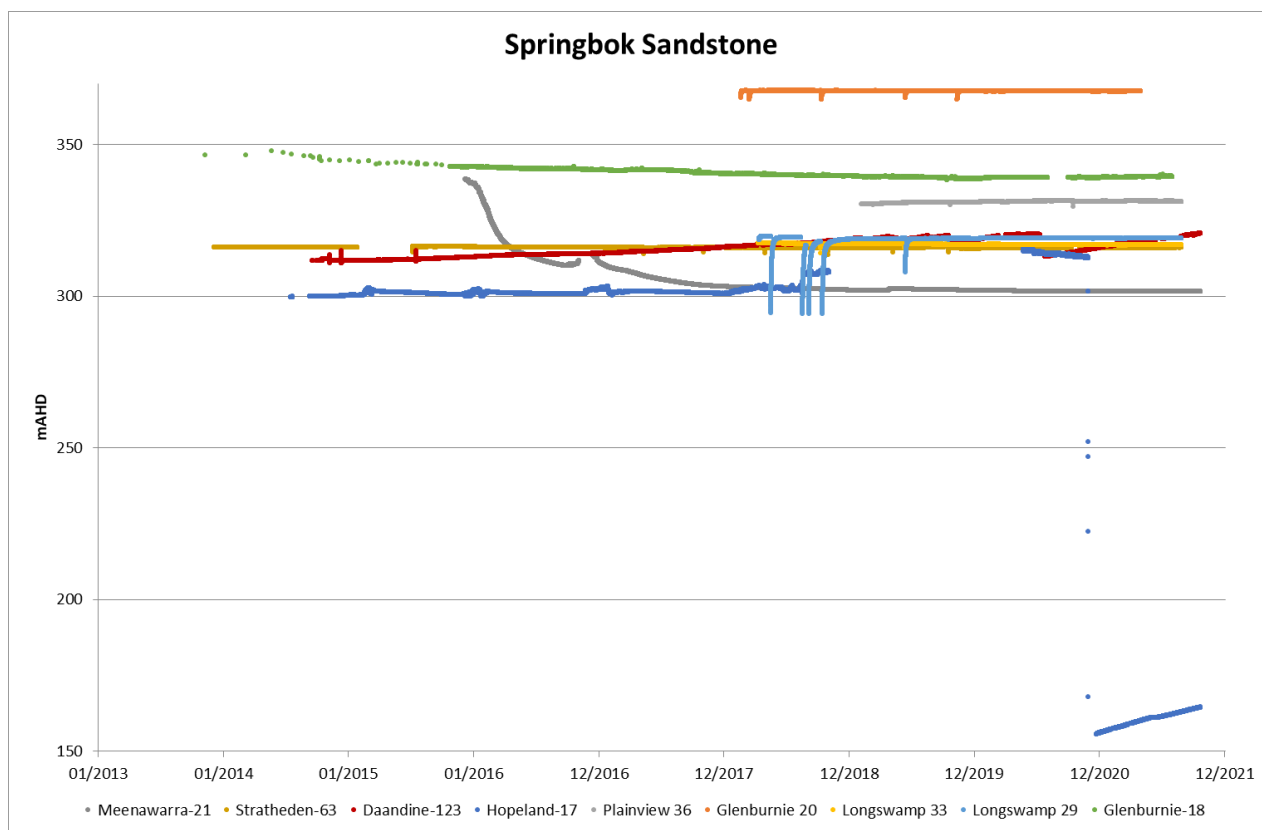


Figure 3-3: Springbok Sandstone monitoring bores hydrograph

### Hutton Sandstone trend analysis

All Hutton Sandstone monitoring bores showed a long-term declining trend (Figure 3-4) at rates that are consistent with Section 5.4.3 of the 2019 UWIR (OGIA, 2019), which is up to 2m per year. The largest observed drawdown has been in Daandine-121 with 10.69m since September 2014 (rate of 1.87m per year) with the least drawdown observed in Burunga Lane-176 of 0.46m between 2014 and 2018 (rate of 0.14m per year) and 42231553 of 0.1m between 2014 and 2021 (rate of 0.01m per year). This smaller observed drawdown rate in Burunga Lane-176 is also consistent with the 2019 UWIR (OGIA, 2019) which states that there is generally no groundwater level trends in the Hutton Sandstone north of the Great Dividing Range and the small drawdown rate in 42231553 is a result of this bore being located in the outcrop area of the Hutton Sandstone. Initial steeper drawdown curves were observed in Wyalla-17 and when a new pressure gauge was installed in Daandine-123 (July 2020), and are likely a result of pressure equalisation between the bore and the formation following workover of the bores to install the gauges.

These long-term trends have continued throughout the reporting period, noting that data have not been collected from Burunga Lane-176 since 2018 due to ongoing land access negotiations (Table 3-2).

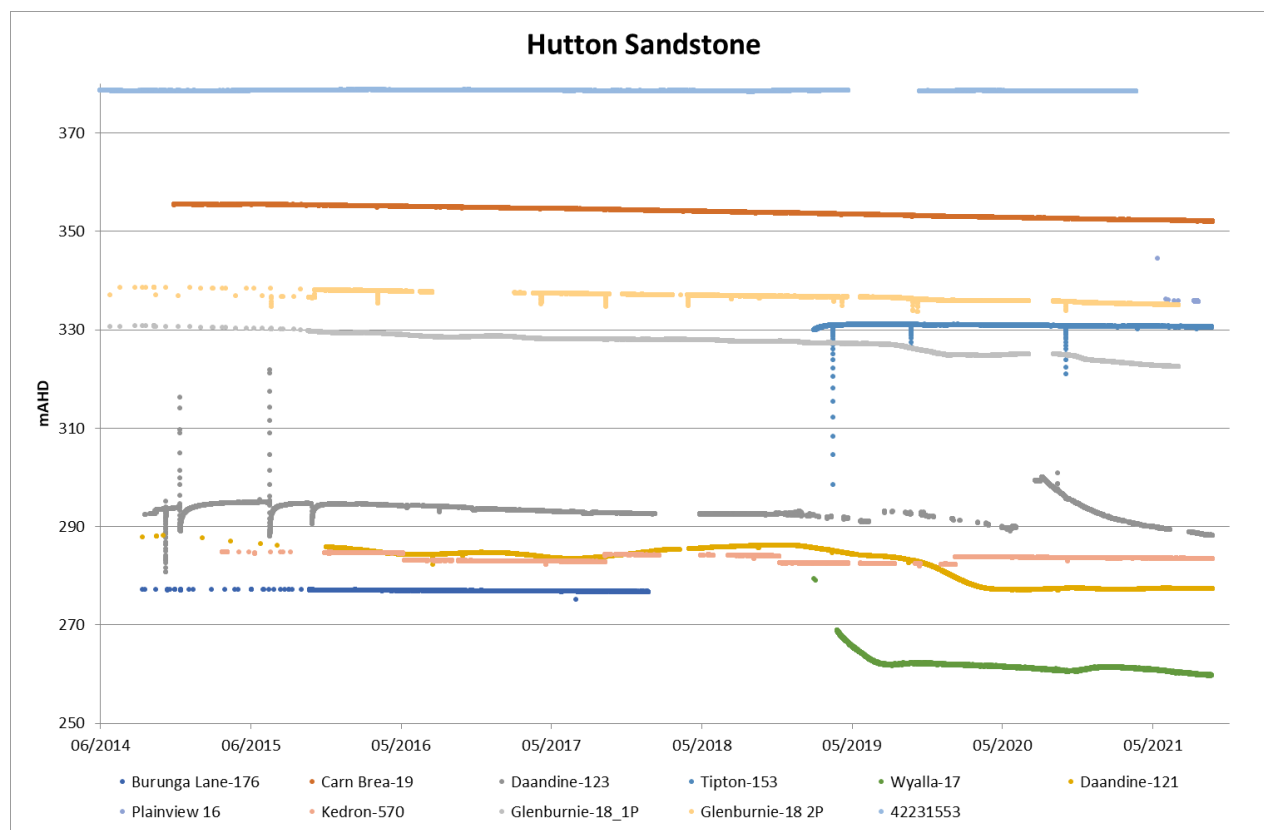


Figure 3-4: Hutton Sandstone monitoring bores hydrograph

### Precipice Sandstone trend analysis

Observed groundwater pressure trends in the Precipice Sandstone monitoring bores shows an increasing trend in Burunga Lane-174 (albeit until data collection paused in 2017 due to ongoing land access negotiations) and declining trend in the monitoring bores located further south within Arrow’s tenure (Figure 3-5). These trends are consistent with that described in Section 5.4.5 of the 2019 UWIR (OGIA, 2019) in that the rising pressure responses in the Precipice Sandstone as a result of the Reedy Creek reinjection facility is evident across Arrow’s northern tenements, and that further south there is extensive non-CSG development (in parallel with the Moonie oil field) which has resulted in regionally observed declines in groundwater pressure. The rate of drawdown is most notable in Tipton-194 (2.47m/year) and Carn Brea-20 (1.37m/year).

The groundwater pressure data collected throughout the reporting period are representative of the long-term trends stated above.

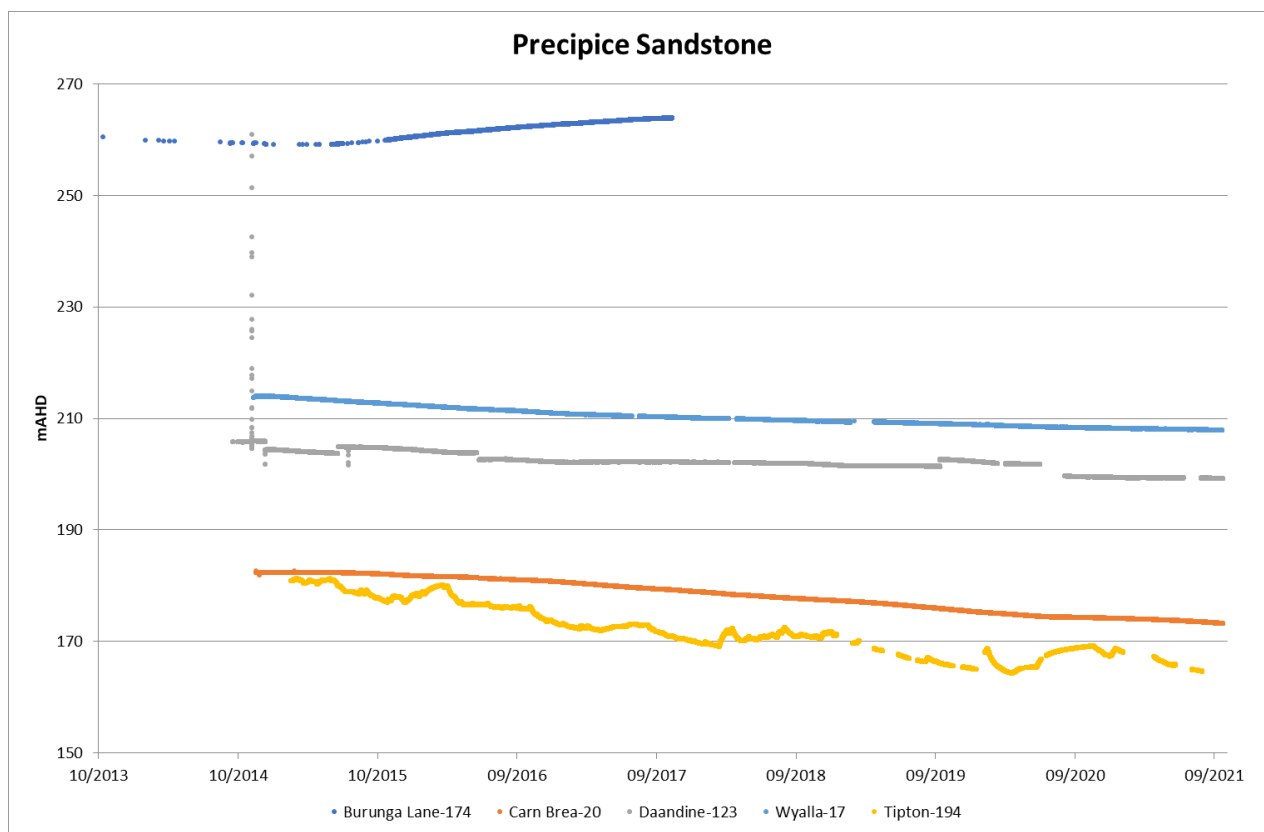


Figure 3-5: Precipice Sandstone monitoring bores hydrograph

### Walloon Coal Measures trend analysis

Hydrographs for the WCM observed groundwater pressures are provided in Figure 3-6 to Figure 3-9. The pressure data have been split into four hydrographs based on the large number of monitoring points and variation in observed pressure values. The hydrographs demonstrate, as predicted, the pressure responses at those locations close to CSG operations such as those monitoring points located at Daandine production field, Tipton production field and Hopeland area, while those monitoring bores further away from CSG operations display a more subdued (or no) pressure response.

As noted in Section 5, production from any SGP production wells did not start during the reporting period and any observed trends are from sources other than the SGP.

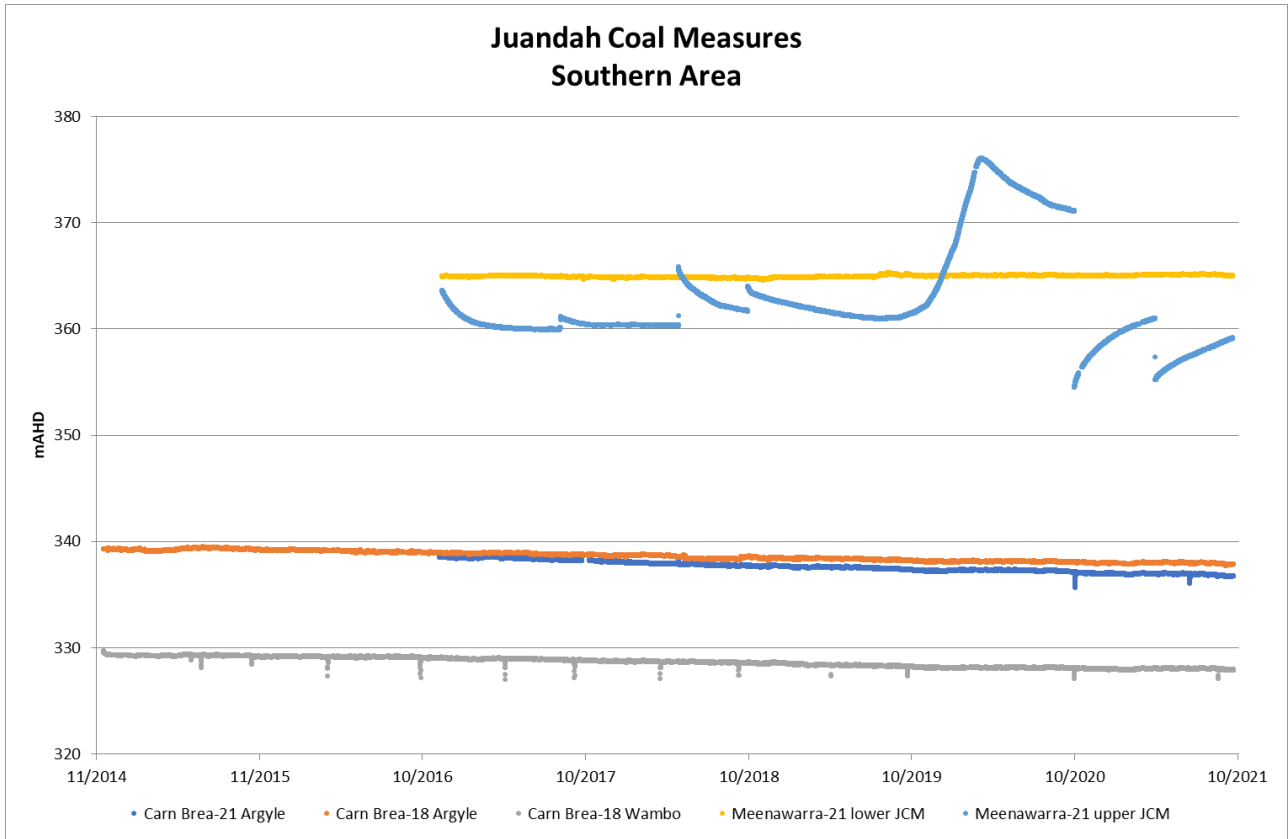


Figure 3-6: Juandah Coal Measures monitoring bores hydrograph – southern area

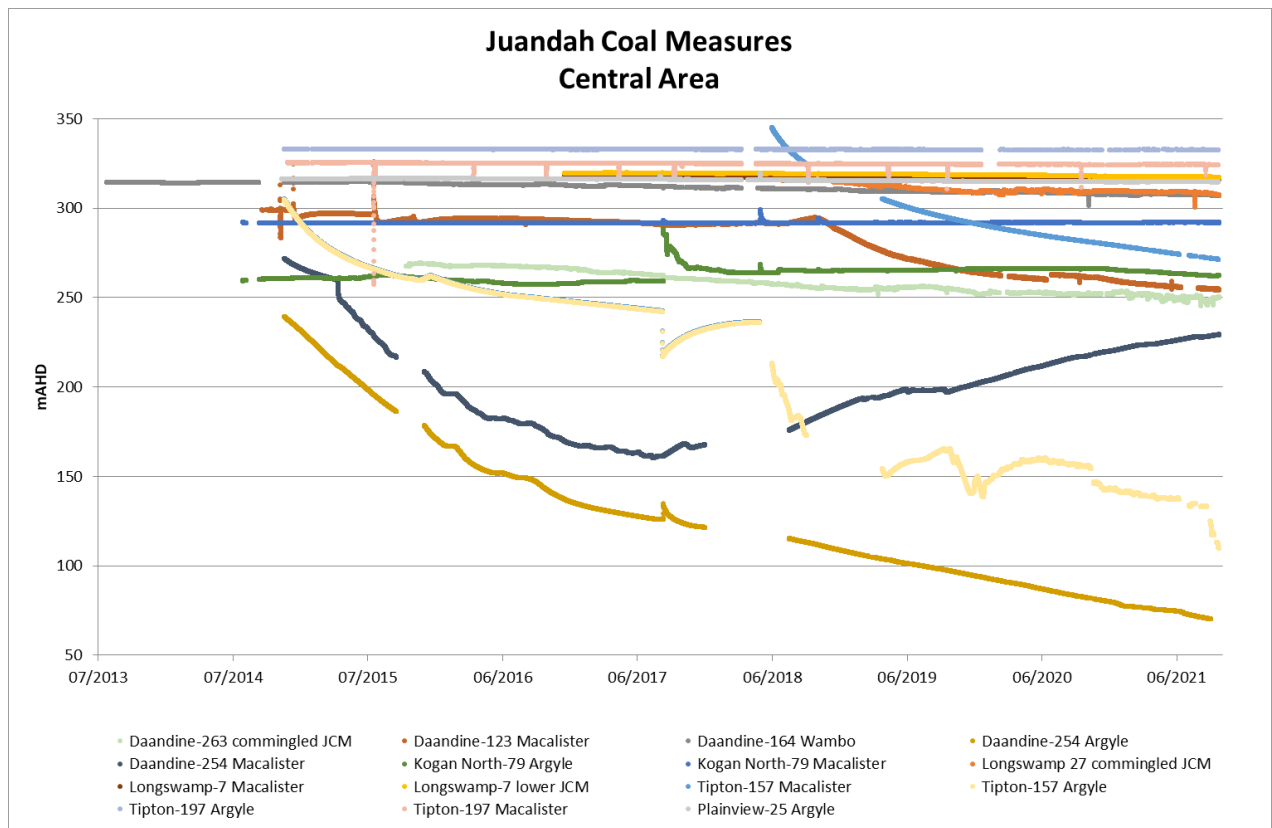


Figure 3-7: Juandah Coal Measures monitoring bores hydrograph – central area



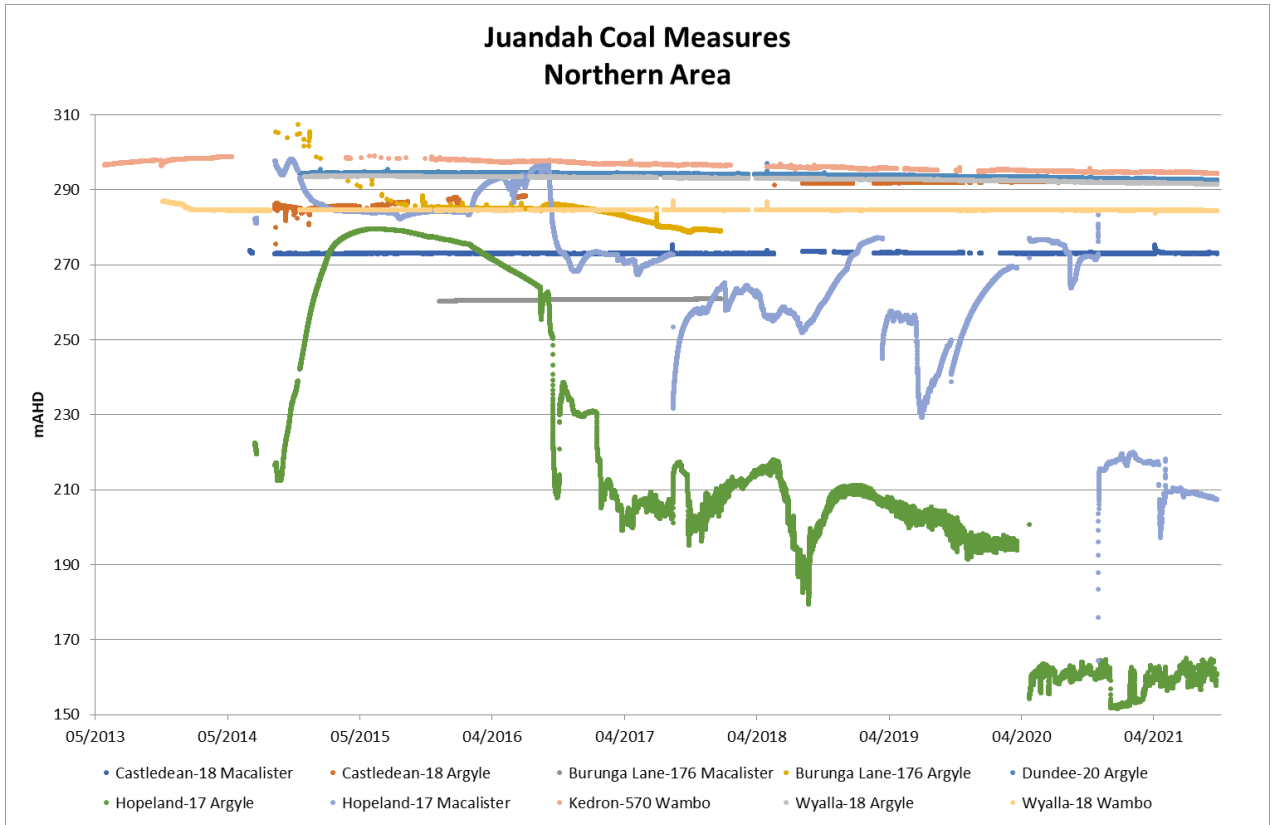


Figure 3-8: Juandah Coal Measures monitoring bores hydrograph – northern area

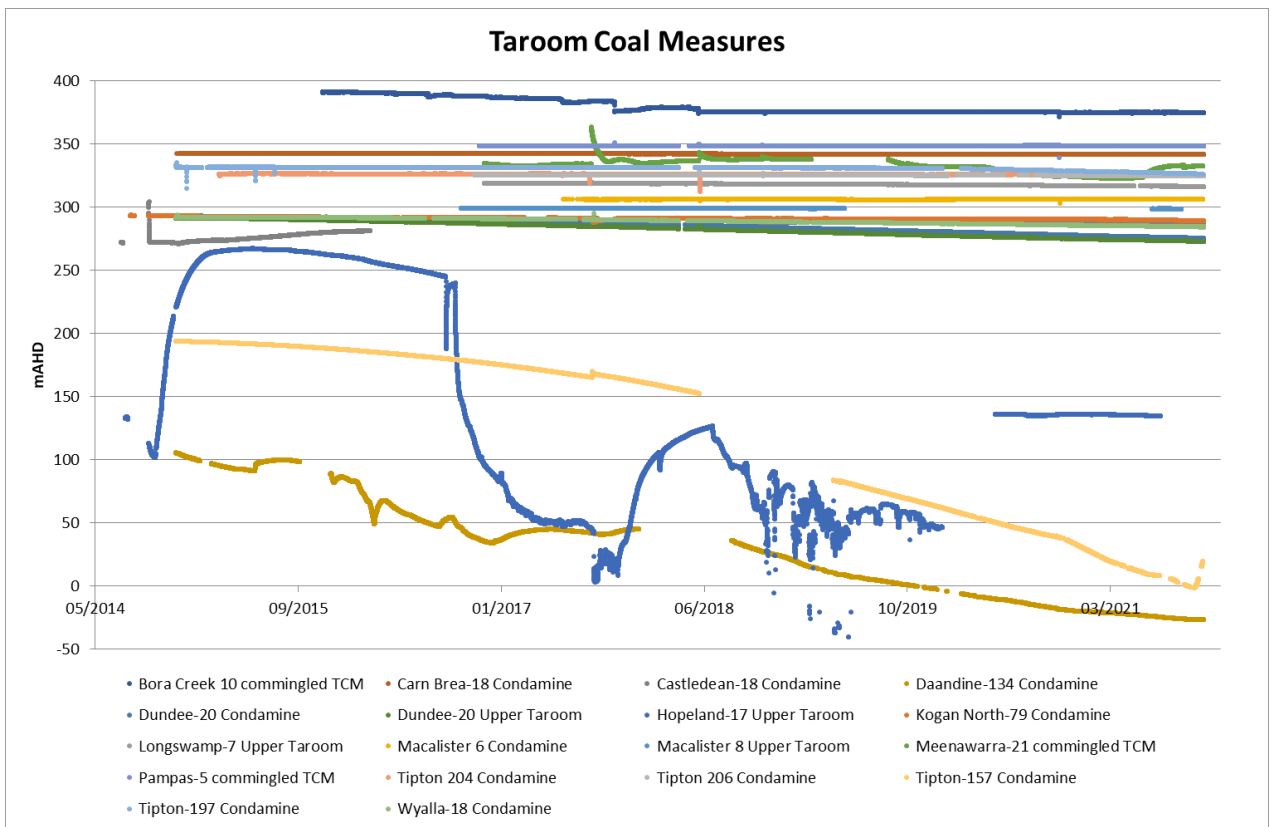


Figure 3-9: Taroom Coal Measures monitoring bores hydrograph

## 3.2 Groundwater quality

### 3.2.1 Data collection

Groundwater samples were collected from all operational WMMP monitoring points throughout the reporting period where land access arrangements were in place. In accordance with Section 7.3 of the SGP Updated WMMP, the locations monitored and frequency of monitoring throughout the reporting period were in alignment with the current UWIR, which was the 2019 version. A summary of changes to the groundwater quality monitoring program is provided in Section 3.4 and a list of monitoring bores sampled during the reporting period is provided in Table 3-1. It should be noted that the sampling frequency changed from previous UWIRs to the 2019 UWIR, including that sampling is no longer required from monitoring points where five samples have been collected (including one sample of dissolved strontium and strontium isotopes in Springbok Sandstone, Hutton Sandstone and Precipice Sandstone monitoring points).

A summary of groundwater sampling conducted during the reporting period is provided in Table 3-1. These groundwater samples were analysed for the 2019 UWIR suite which is provided in Table 3-4 and the results are provided in Appendix B.

**Table 3-1: 2019 UWIR groundwater chemistry monitoring points**

Bore Name	OGIA MP ID	WMS Status	Formation	Sampling completed during reporting period <sup>1</sup>
Burunga Lane-176	477	Replace	Hutton Sandstone	No sampling completed due to no land access
Carn Brea-17	39	Maintain	Condamine Alluvium	Sampled Q4 2020 and Q4 2021
Carn Brea-18	41	Maintain	WCM	Sampled Q4 2020 and Q4 2021
Carn Brea-19	45	Maintain	Hutton Sandstone	Sampled Q4 2020 and Q4 2021
Daandine-121	183	Maintain	Hutton Sandstone	Sampled Q4 2020
RN 42230209	282	Maintain	Condamine Alluvium	Sampled Q4 2020
Glenburnie-18	739	Integrate	Hutton Sandstone	Sampled Q4 2020
Plainview 36	790	Integrate	Springbok Sandstone	Sampled Q4 2020 and Q4 2021
Stratheden-63	623	Maintain	Springbok Sandstone	Sampled Q4 2020 and Q4 2021
Tipton-195	85	Maintain	Condamine Alluvium	Sampled Q4 2020 and Q4 2021
Tipton-197	89	Maintain	WCM	Sampled Q4 2020 and Q4 2021
Tipton 202	830	Proposed	Springbok Sandstone	Monitoring point not yet installed
Wyalla-16	248	Maintain	Condamine Alluvium	Sampled Q4 2020
RN 42231370	52	Maintain	Condamine Alluvium	Sampled Q4 2020

Notes:

1. Refer to Table 3-2 and Table 3-3 for sampling requirements

### 3.2.2 Data analysis

#### Physical parameters

#### Electrical conductivity (EC)

The distribution of EC data across the geological formations is presented in Figure 3-10. The data show the Precipice Sandstone has the greatest variability

(not including outliers) in EC, ranging from 432 to 10,990  $\mu\text{S}/\text{cm}$  and least variability in the Springbok Sandstone ranging from 3,456 to 4,984  $\mu\text{S}/\text{cm}$ .

EC data collected to date are graphically shown in Figure 3-11 to Figure 3-15. The data show EC levels in the monitoring bores are generally stable with a slight declining trend in RN42230209 (Figure 3-11), Daandine-124 (Figure 3-12) and Wyalla-17 (Figure 3-15).

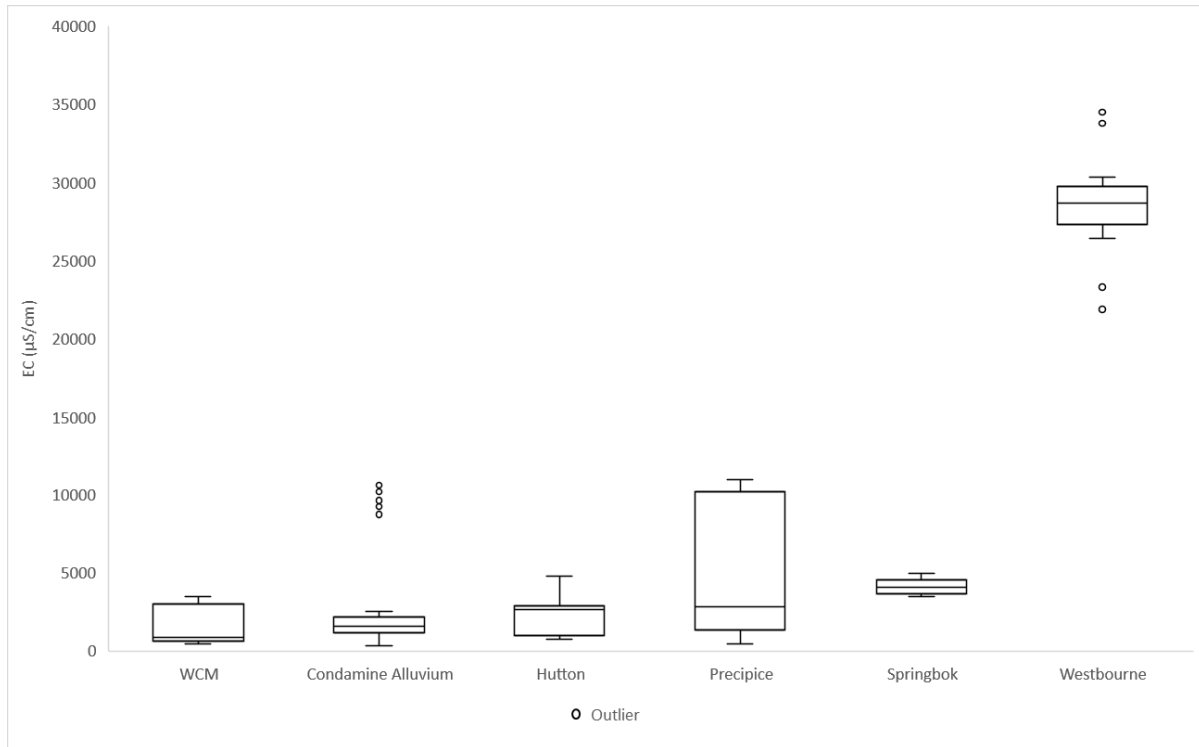


Figure 3-10: Chart of EC statistics

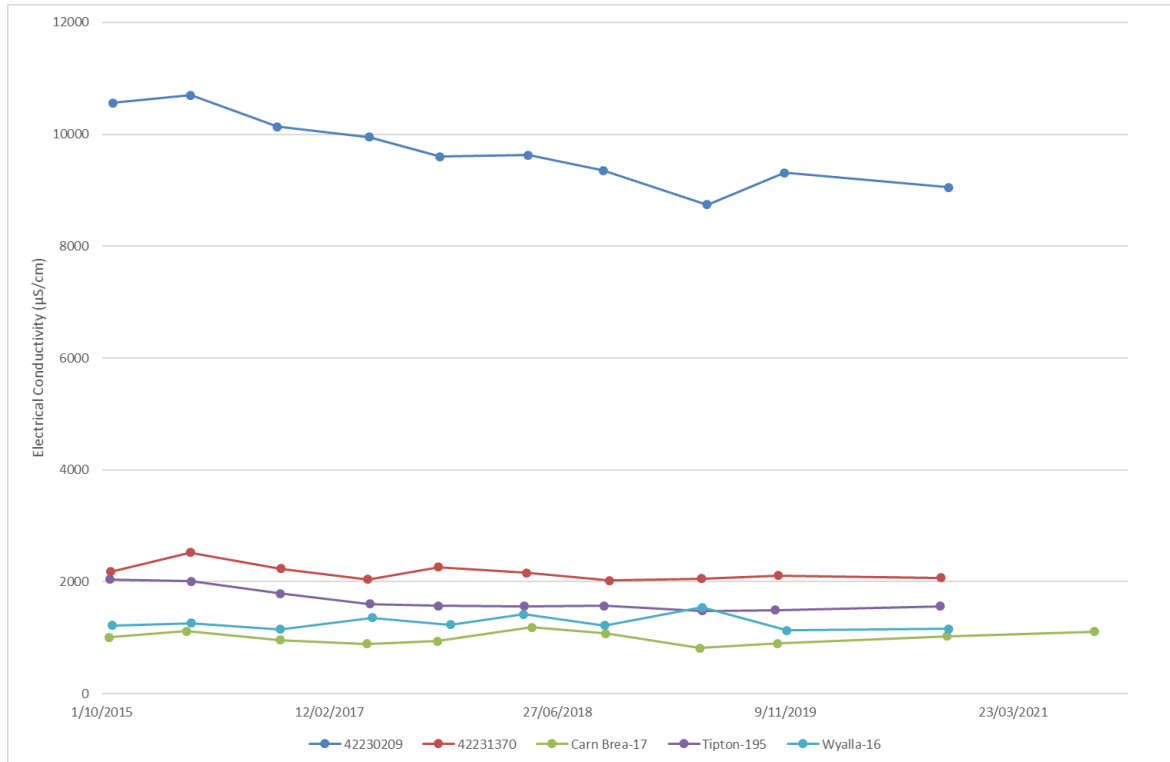


Figure 3-11: Condamine Alluvium electrical conductivity

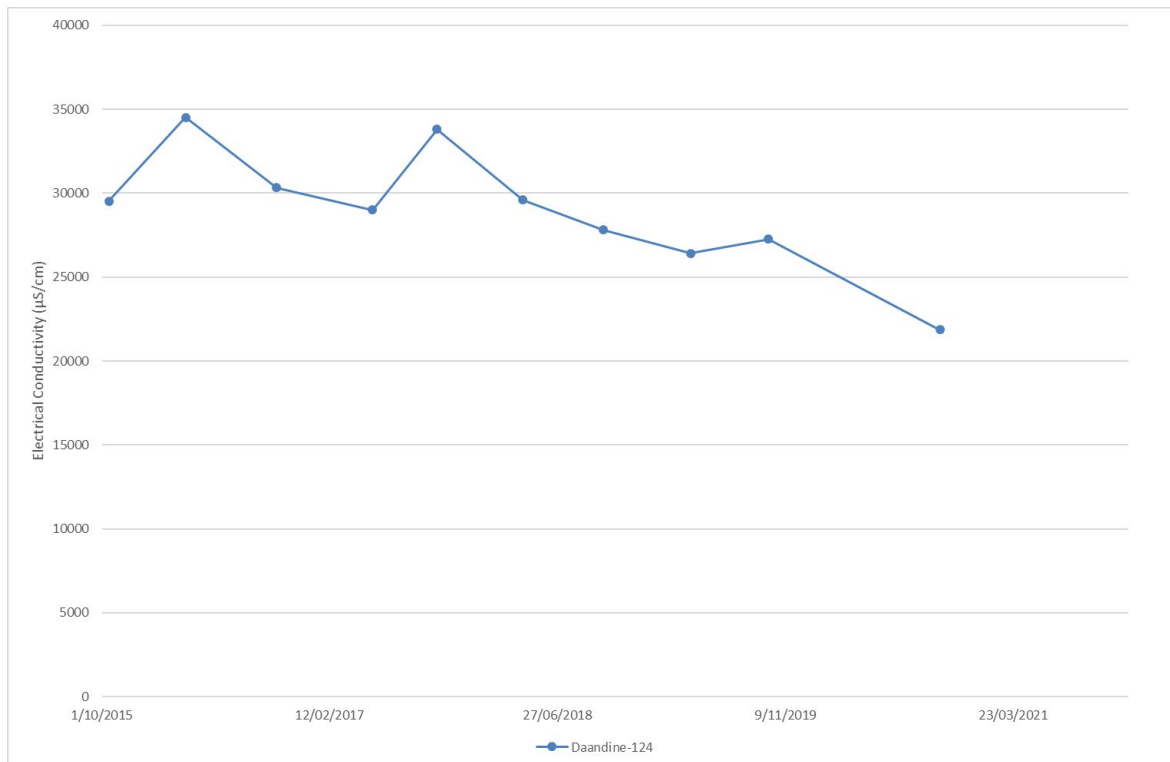


Figure 3-12: Westbourne Formation electrical conductivity

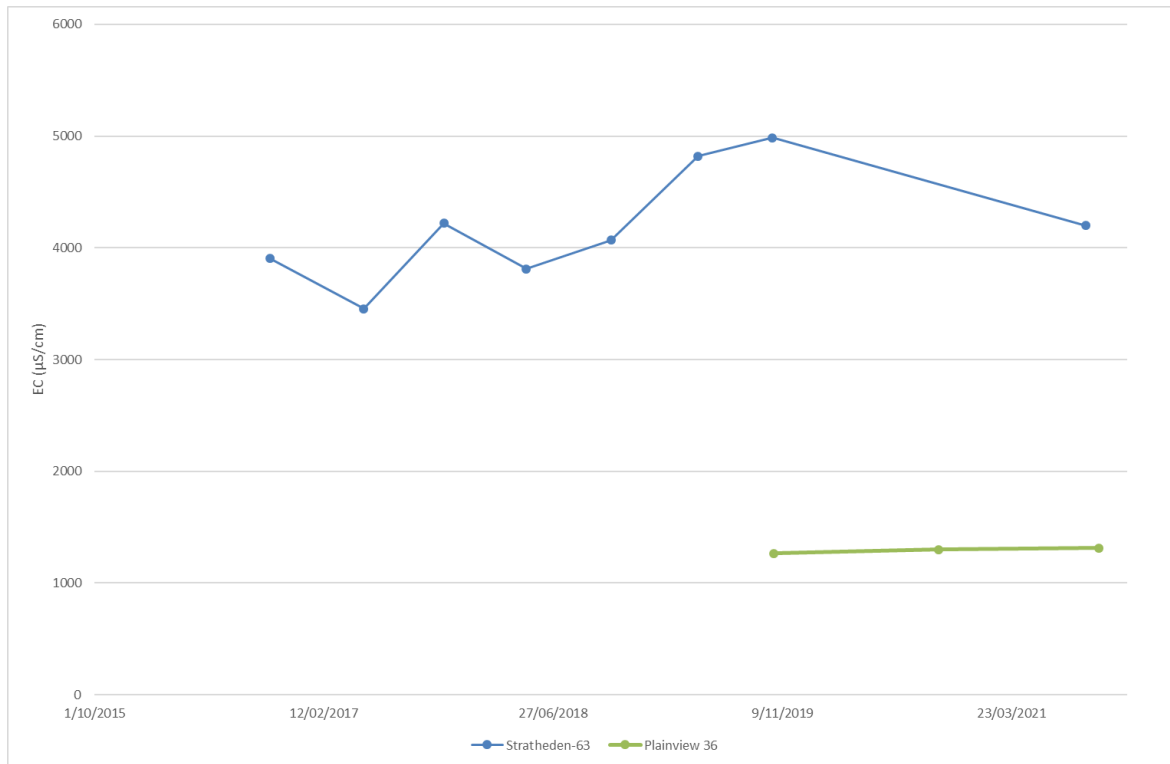


Figure 3-13: Springbok Sandstone electrical conductivity

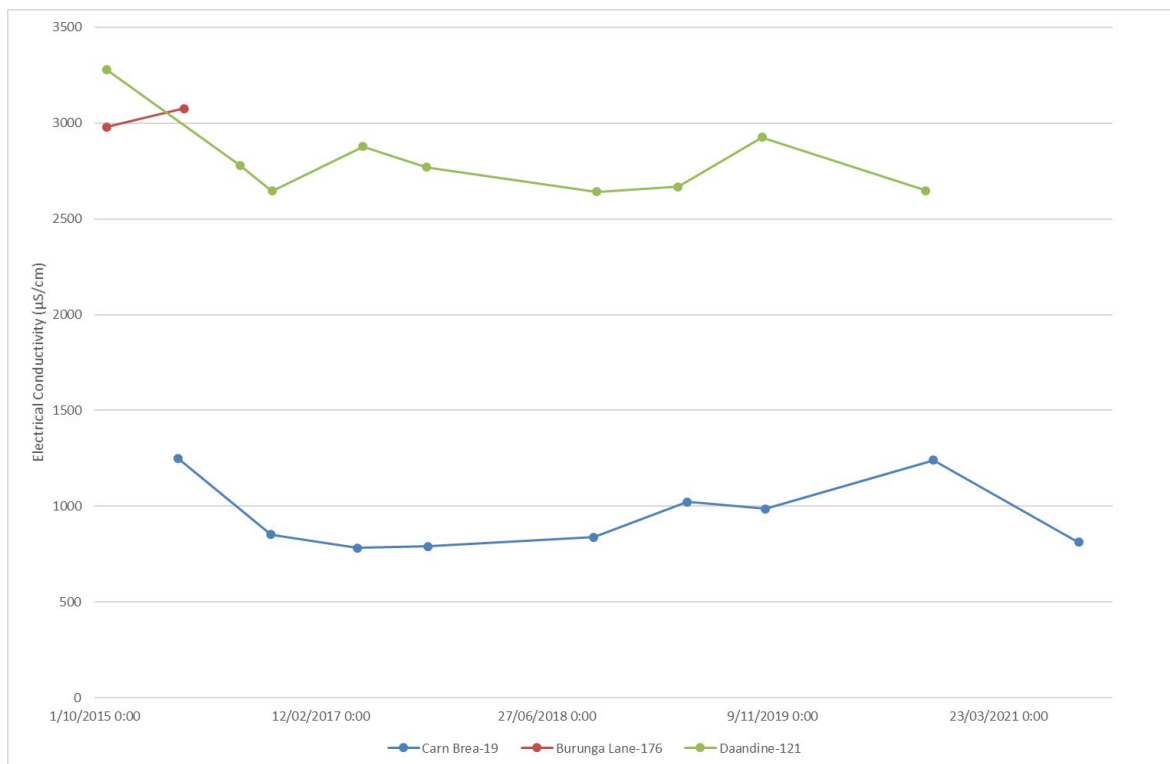


Figure 3-14: Hutton Sandstone electrical conductivity

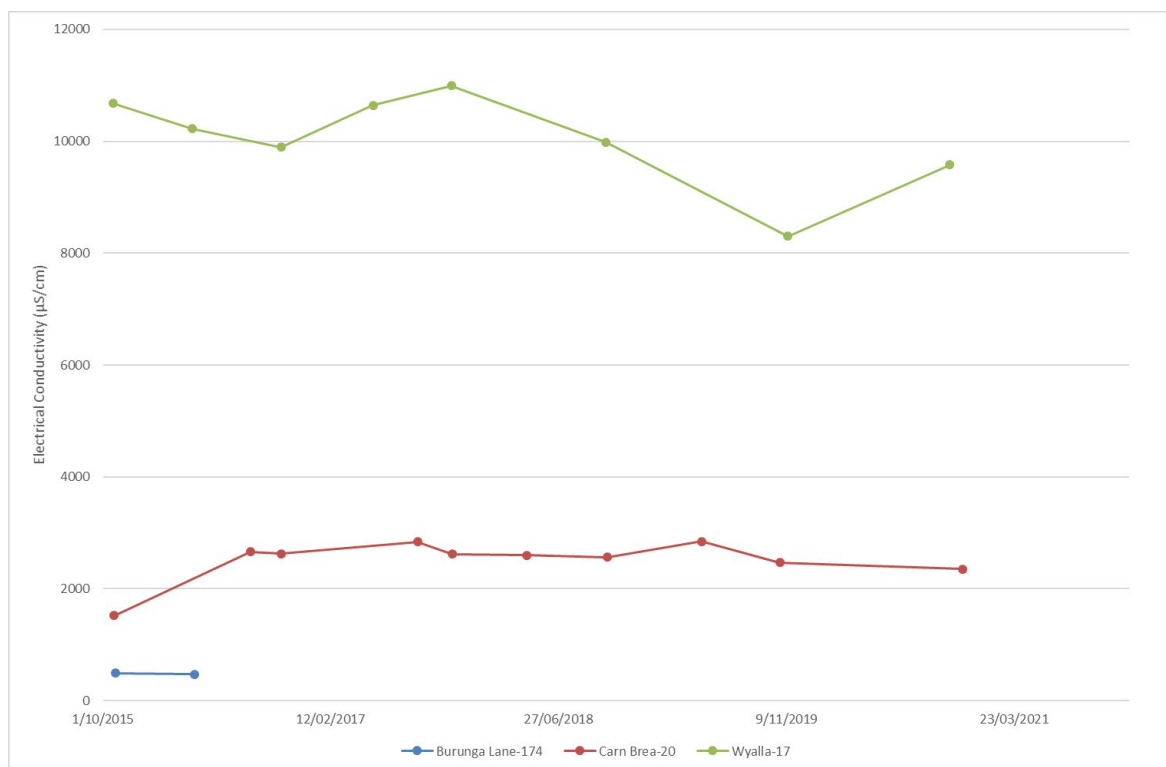


Figure 3-15: Precipice Sandstone electrical conductivity

**Field pH**

The distribution of pH data across the geological formations is presented in Figure 3-16. The data show the Springbok Sandstone has the greatest variability (not including outliers) in pH, ranging from 8.64 to 10.80 and least variability in the Precipice Sandstone ranging from 6.31 to 6.64.

The collected pH data are graphically shown in Figure 3-17 to Figure 3-21. The data show pH levels in the monitoring bores are generally stable with a slight declining trend in Daandine-121 (Figure 3-20) and Carn Brea-20 (Figure 3-21).

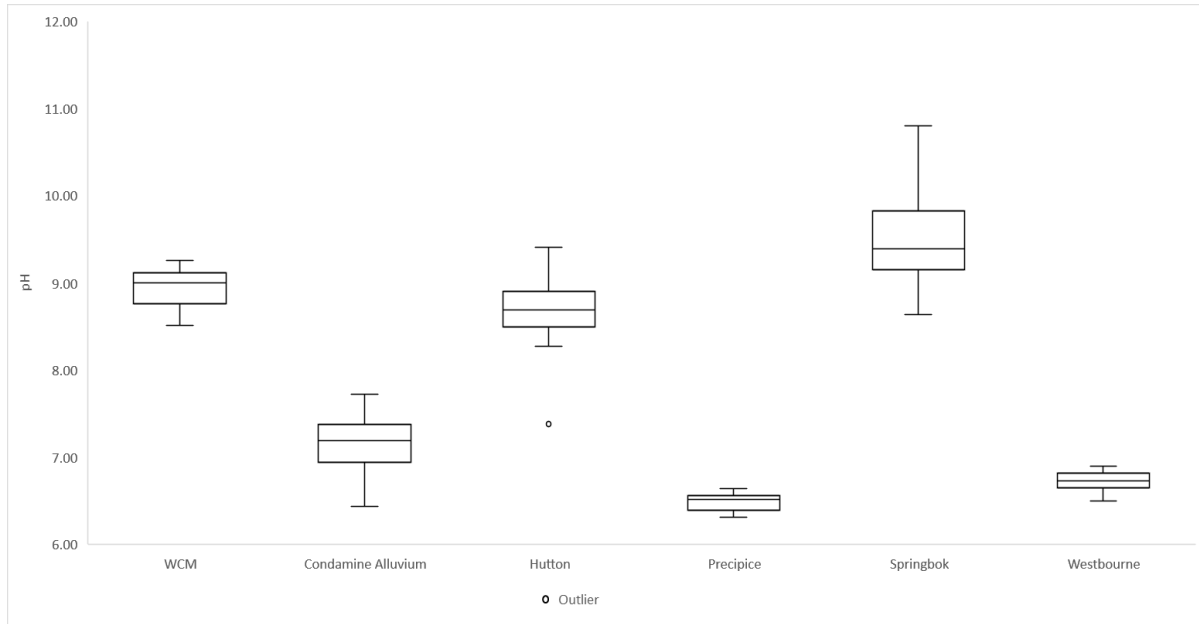


Figure 3-16: Chart of field pH statistics

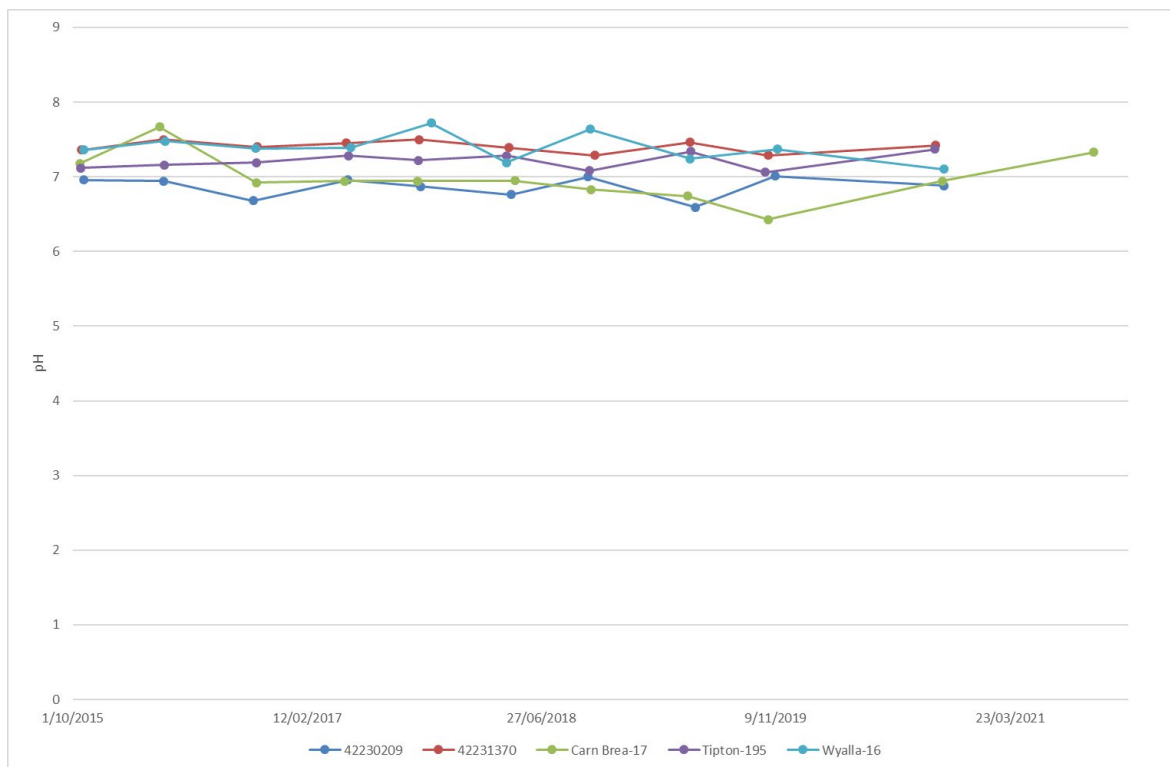


Figure 3-17: Condamine Alluvium pH

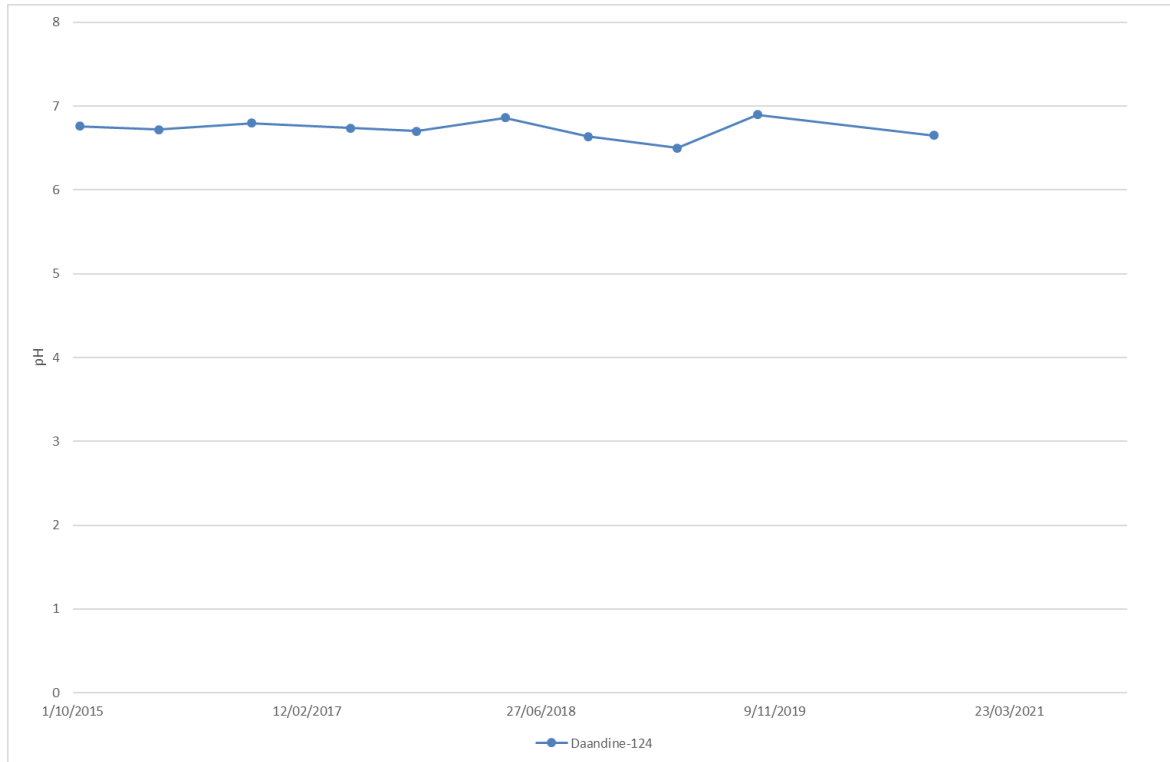


Figure 3-18: Westbourne Formation pH

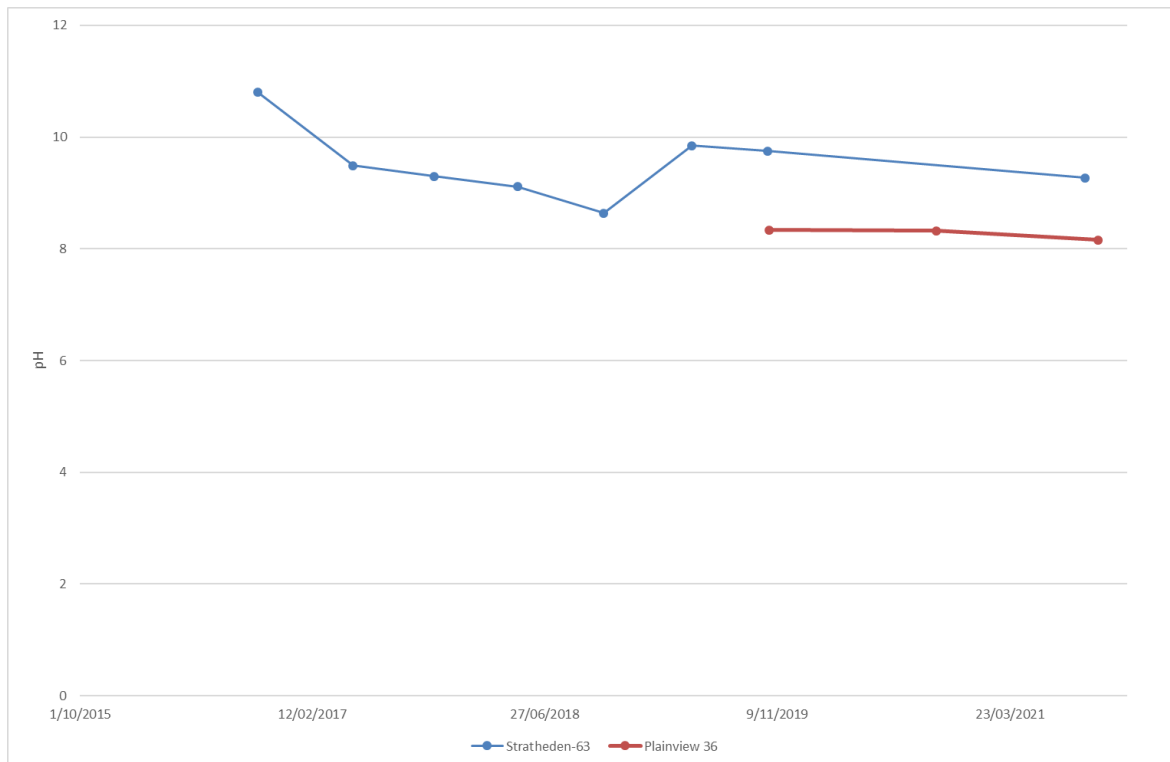


Figure 3-19: Springbok Sandstone pH



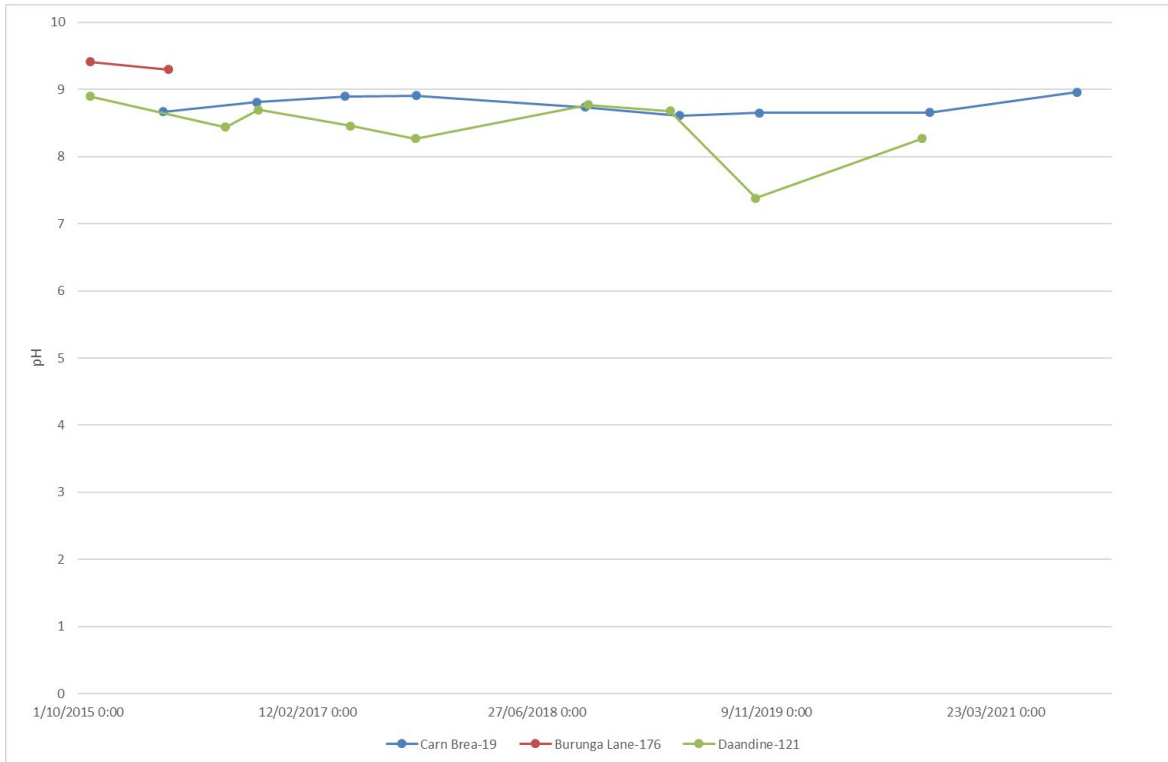


Figure 3-20: Hutton Sandstone pH

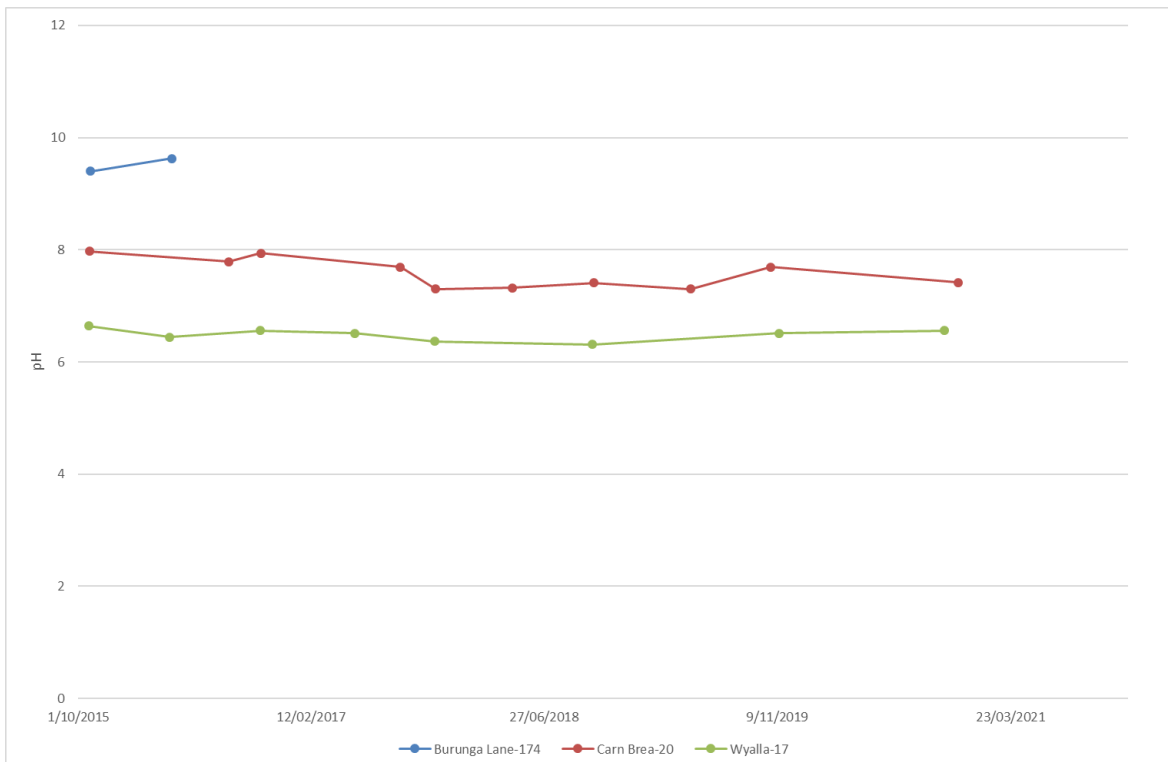


Figure 3-21: Precipice Sandstone pH

**Chemical composition**

The chemical composition of samples collected since 2017 from each of the geological formations is shown graphically in Figure 3-22 to Figure 3-25.

The Condamine Alluvium piper diagram (Figure 3-22) shows all bores except for Carn Brea-17 are predominantly sodium-chloride type water with carbonate-bicarbonate contributions and a magnesium and calcium contribution in Tipton-195. The chemical composition of samples collected from Carn Brea-17 indicate it is a magnesium-bicarbonate type water.

There is either no trend or a clustered recurring trend in chemical composition evident in all bores except for Wyalla-16 which shows a steady increasing carbonate-bicarbonate contribution.

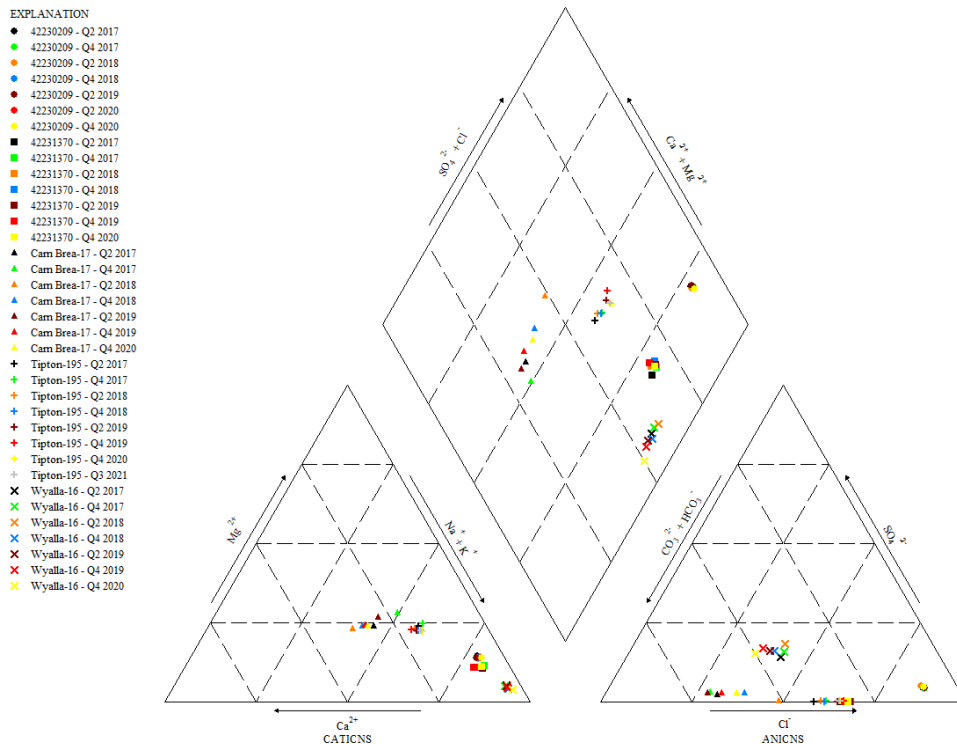


Figure 3-22: Condamine Alluvium Piper Diagram

The major ion data for the Westbourne Formation monitoring point (Daandine-124) (Figure 3-23) show it is sodium-chloride type water and there is no trend in chemical composition evident over time.

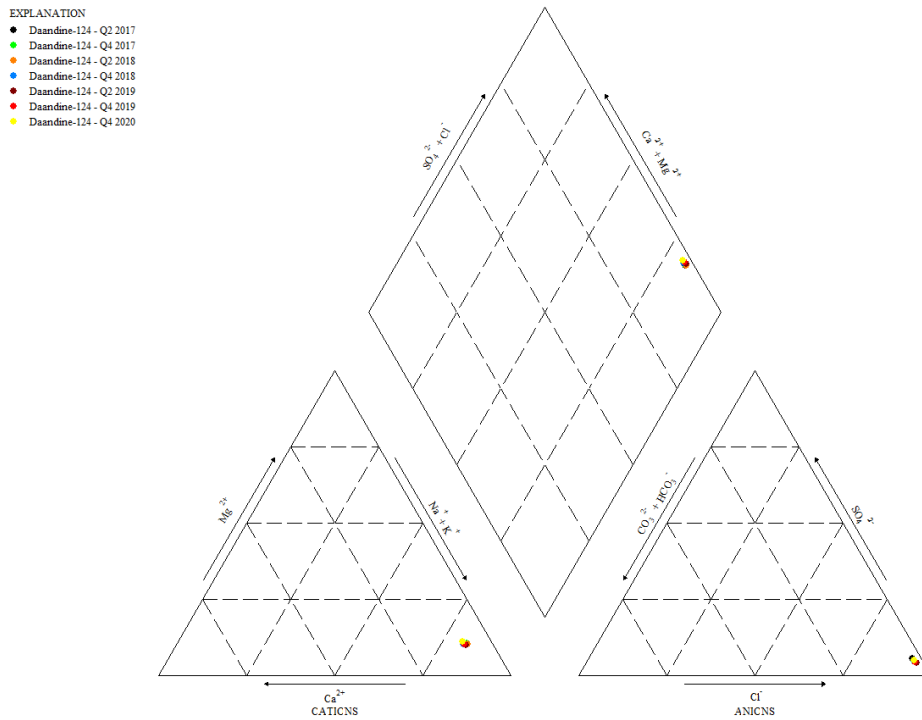
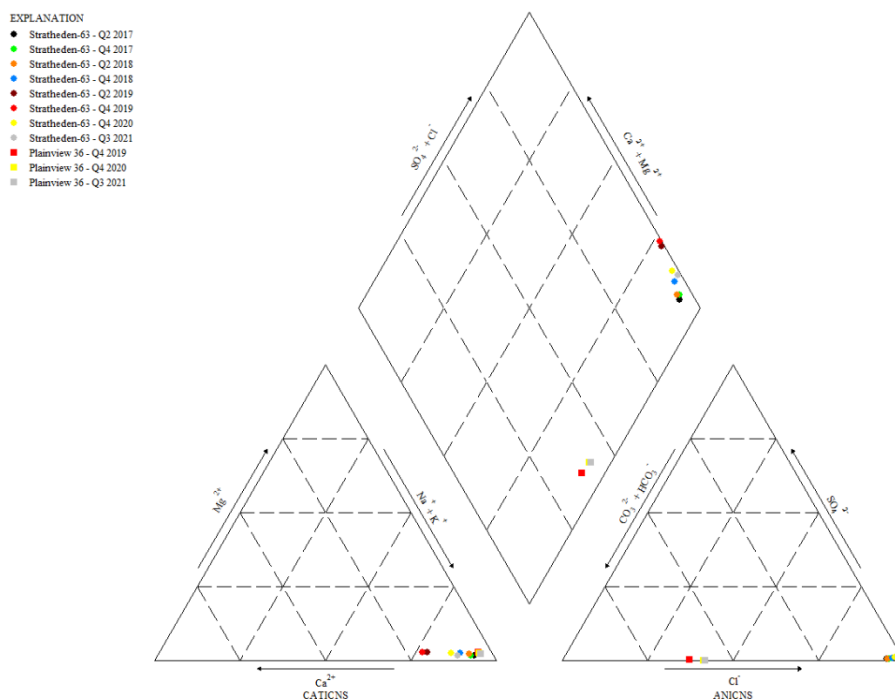


Figure 3-23: Westbourne Formation Piper Diagram

The major ion data for the Springbok Sandstone monitoring point Stratheden-63 (Figure 3-24) show it is sodium-chloride type water and there is a recurring trend in the calcium to sodium ratio evident over time. The chemical composition of Plainview 36 shows it is sodium-bicarbonate type water and there is no trend in the data, noting only three samples were collected during the reporting period.



**Figure 3-24: Springbok Sandstone Piper Diagram**

The major ion data for the WCM monitoring points (Figure 3-25) show Tipton-197 is sodium-chloride type water with a carbonate-bicarbonate contribution, and Carn Brea-18 is a sodium-bicarbonate type water. There is no trend evident in chemical composition in Tipton-197 while Carn Brea-18 is displaying a steady increasing carbonate-bicarbonate and decreasing chloride contributions over time.

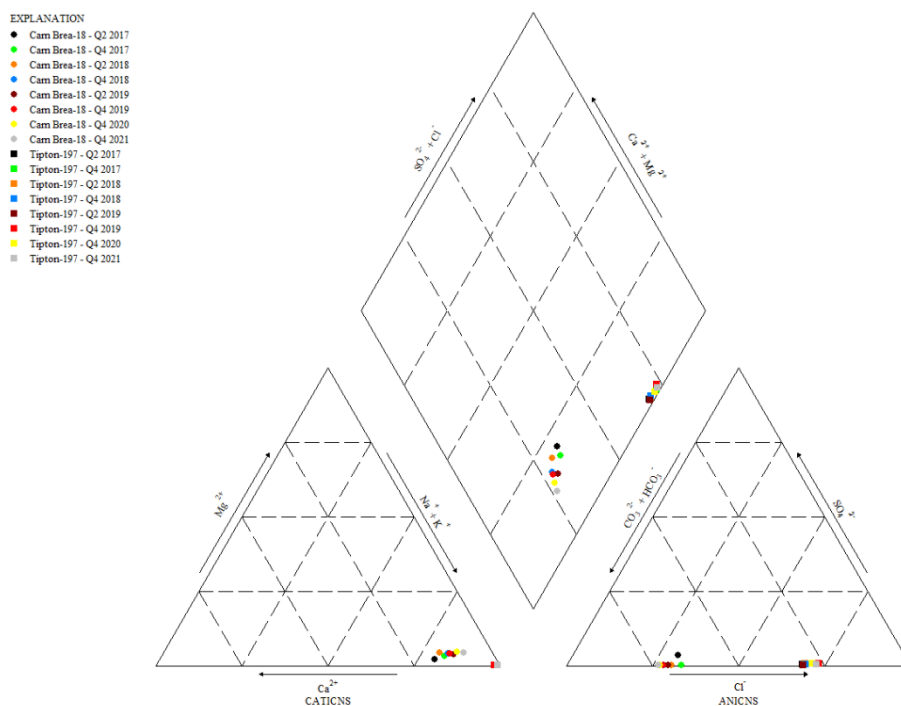


Figure 3-25: WCM Piper Diagram

The major ion data for the Hutton Sandstone monitoring points (Figure 3-26) show it is sodium-bicarbonate type water. There is a recurring trend in the calcium to sodium ratio evident over time in Carn Brea-19, and a recurring trend in the bicarbonate to chloride ratio evident over time in Daandine-121.

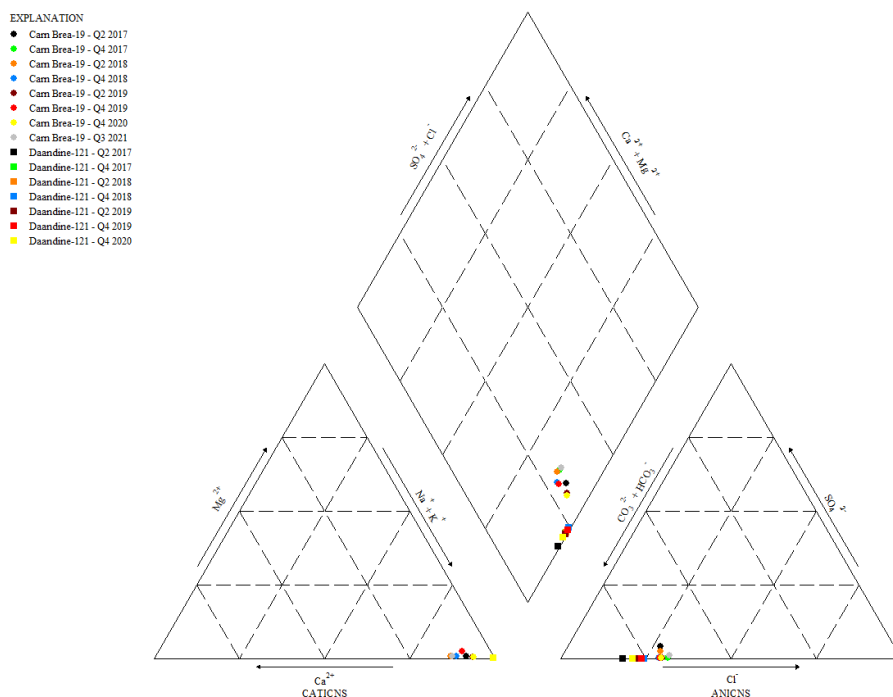


Figure 3-26: Hutton Sandstone Piper Diagram

The major ion data for the Precipice Sandstone monitoring points (Figure 3-27) show Wyalla-17 is sodium-chloride type water with a carbonate-bicarbonate contribution, and Carn Brea-20 is a sodium-bicarbonate type water. There is no trend evident in chemical composition in Wyalla-17 while Carn Brea-20 is displaying a slight but steady increasing chloride contribution over time.

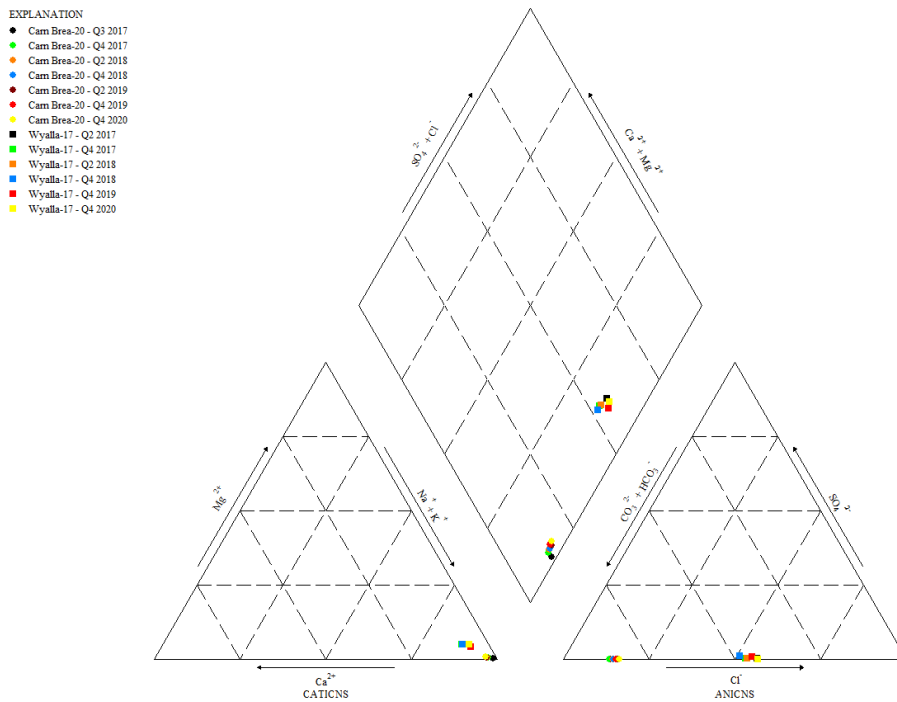


Figure 3-27: Precipice Sandstone Piper Diagram

### Trend analysis

Mann-Kendall trend analysis has been undertaken to evaluate increasing and decreasing trends in concentrations for monitored water quality parameters. Summaries of the results for each formation are provided in Figure 3-28 to Figure 3-33. The axis on the charts indicates the number of bores, within that formation, with an observed increasing (positive number) or decreasing (negative number) trend in the analyte concentration. A zero number represents no trend in the data.

The data show decreasing and increasing trends for a number of analytes including decreases in alkalinity, manganese and nickel, and increases in calcium, chloride, barium, iron, sodium and TDS. The magnitude of trends for individual monitoring points are presented in Appendix C.

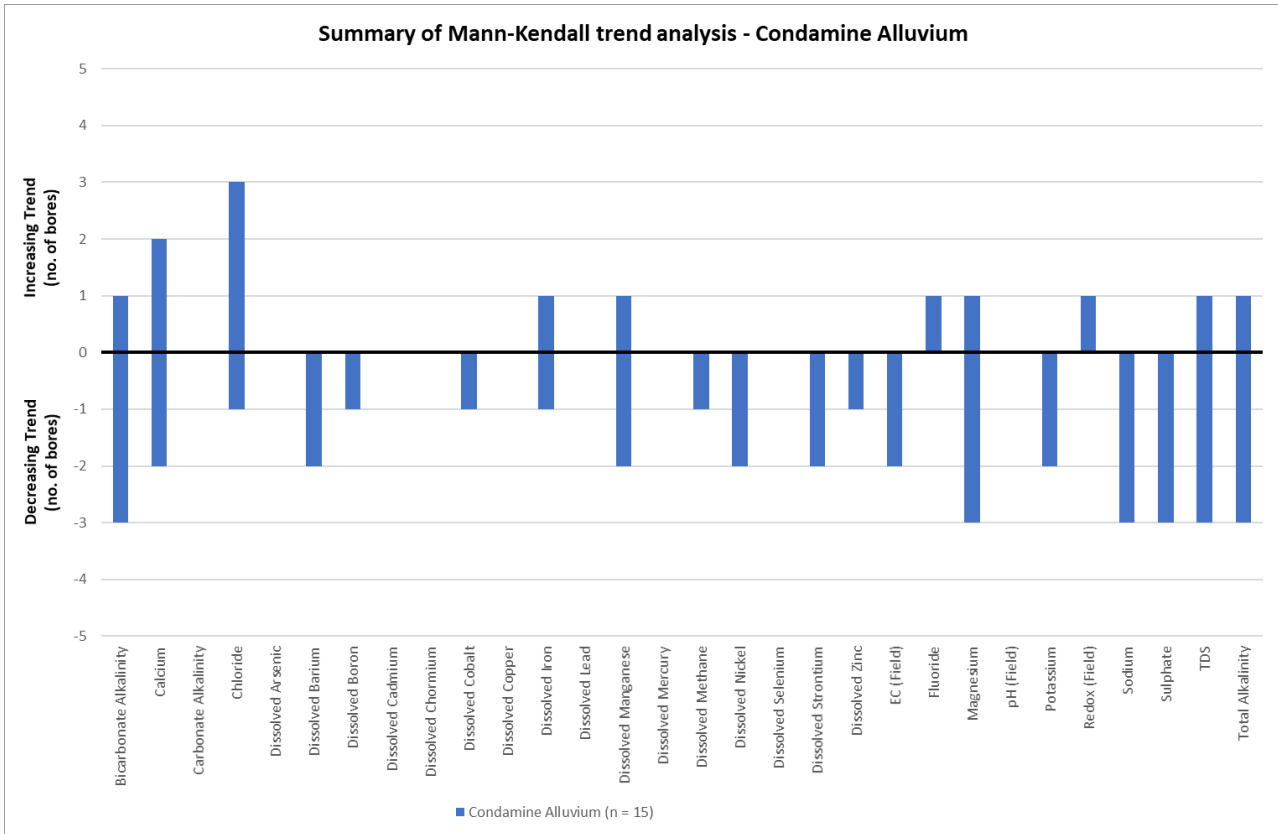


Figure 3-28: Summary of Mann-Kendall trend analysis for Condamine Alluvium monitoring bores

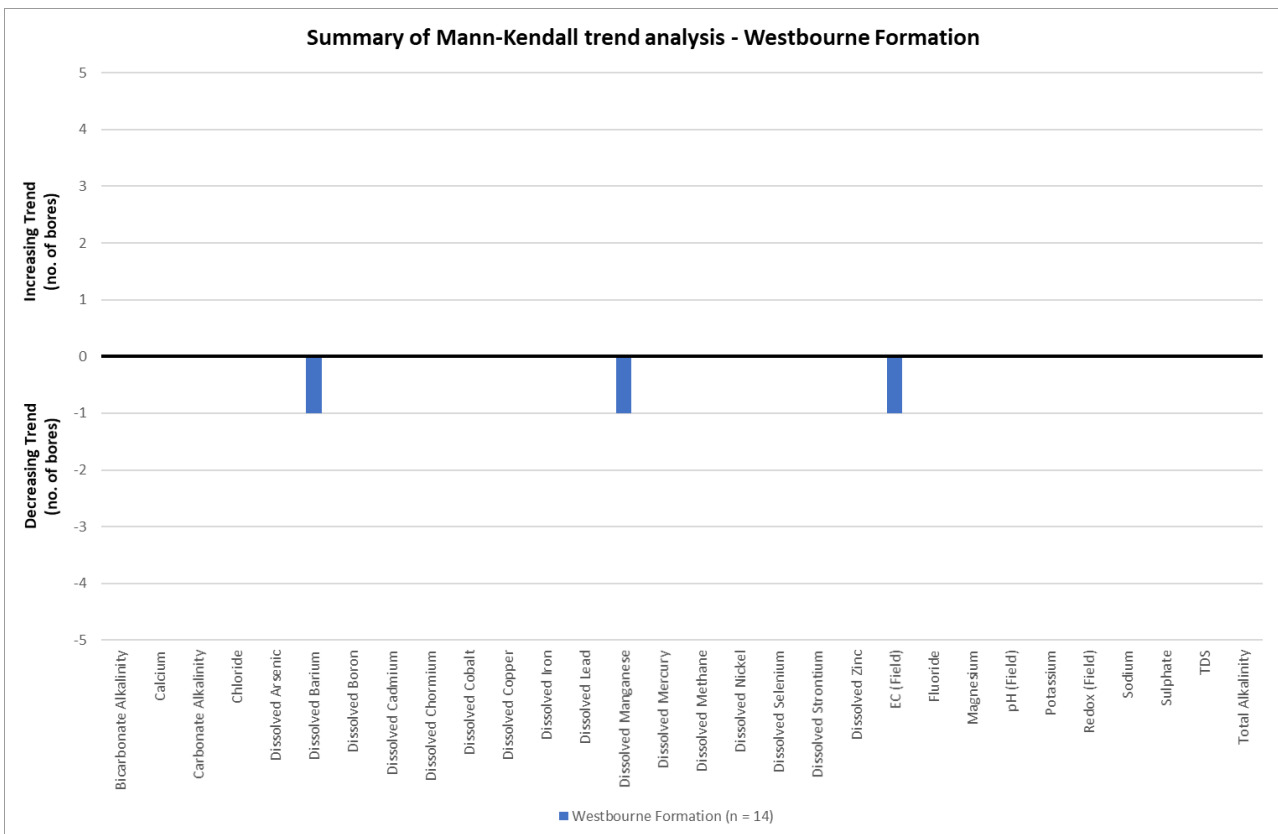


Figure 3-29: Summary of Mann-Kendall trend analysis for Westbourne Formation monitoring bores



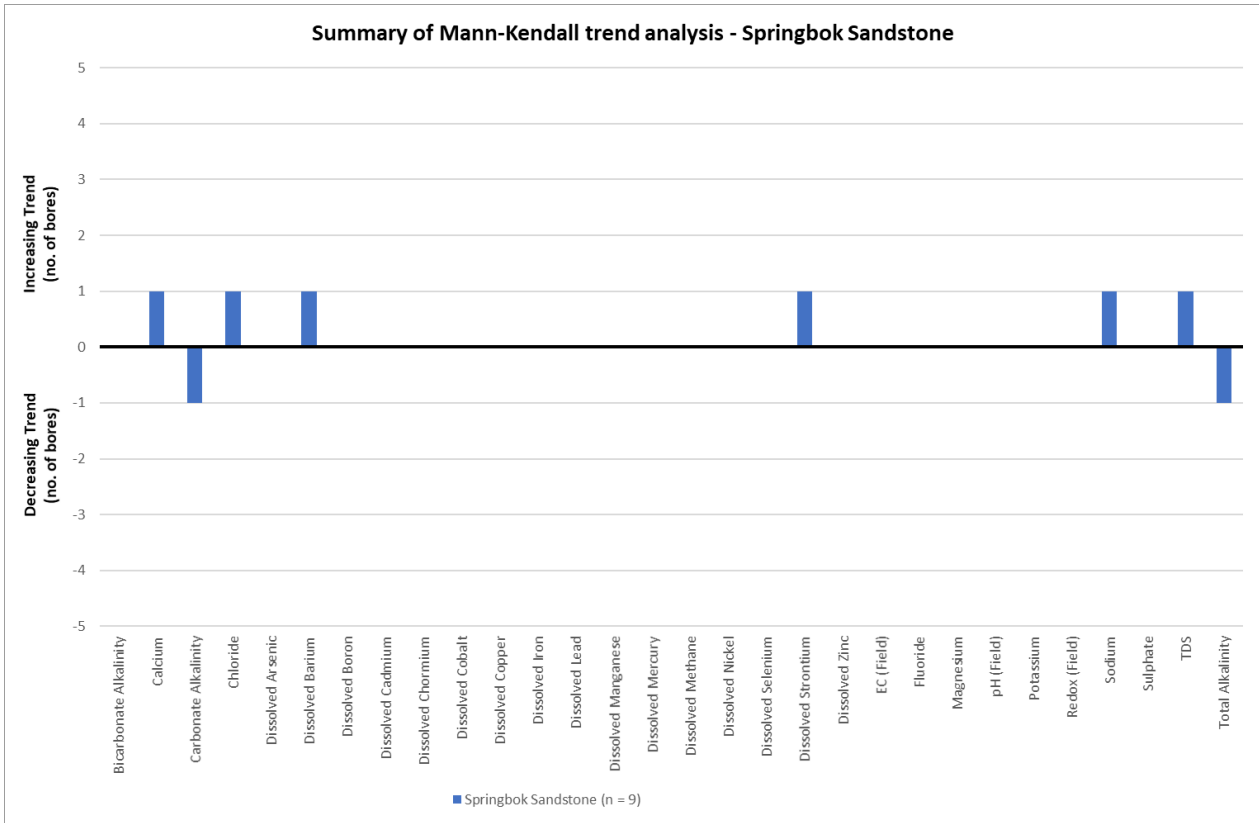


Figure 3-30: Summary of Mann-Kendall trend analysis for Springbok Sandstone monitoring bores

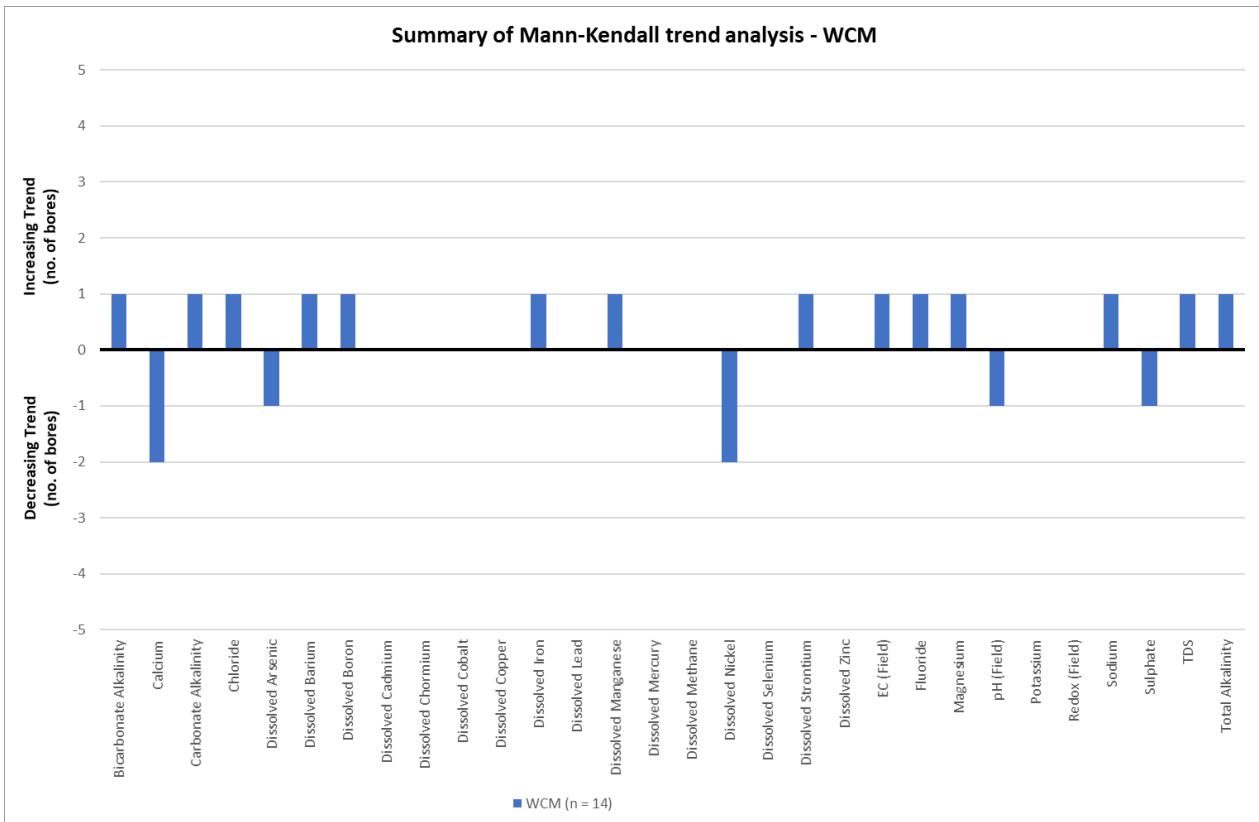


Figure 3-31: Summary of Mann-Kendall trend analysis for WCM monitoring bores

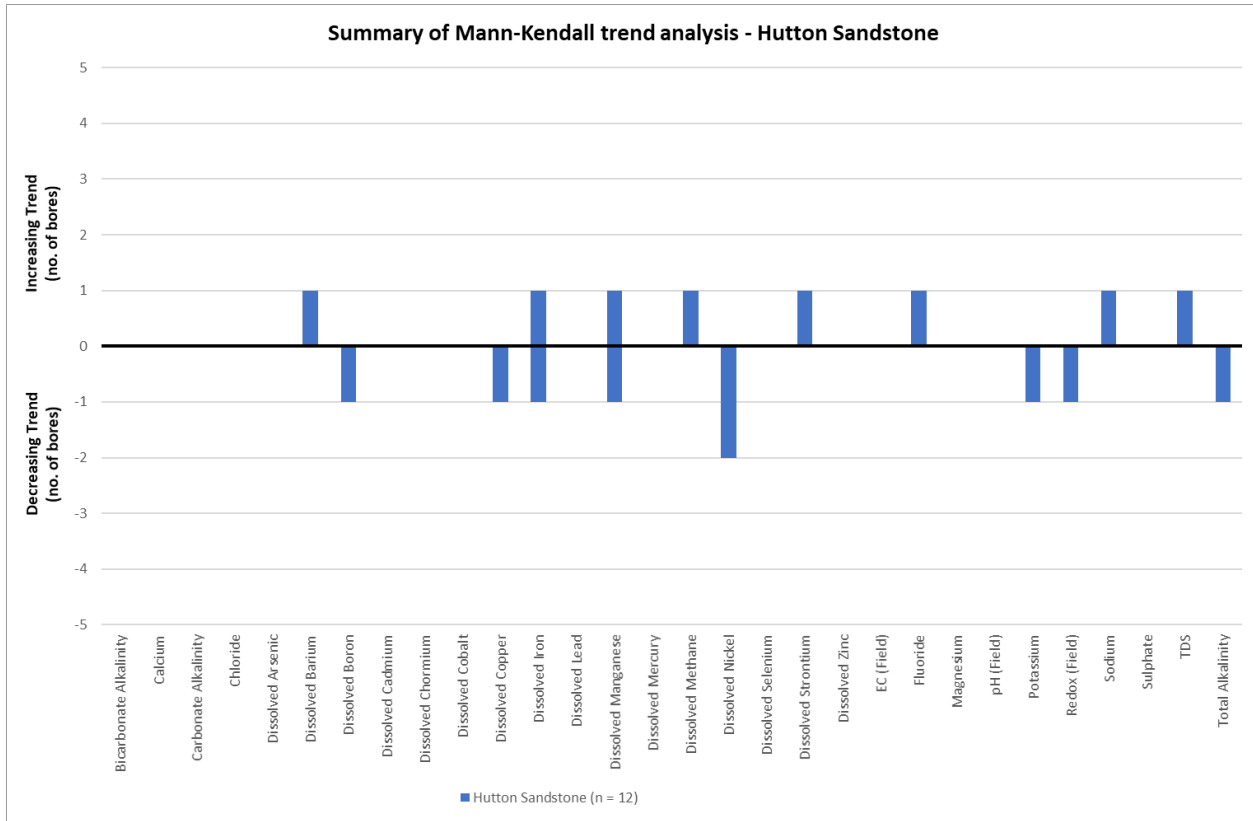


Figure 3-32: Summary of Mann-Kendall trend analysis for Hutton Sandstone monitoring bores

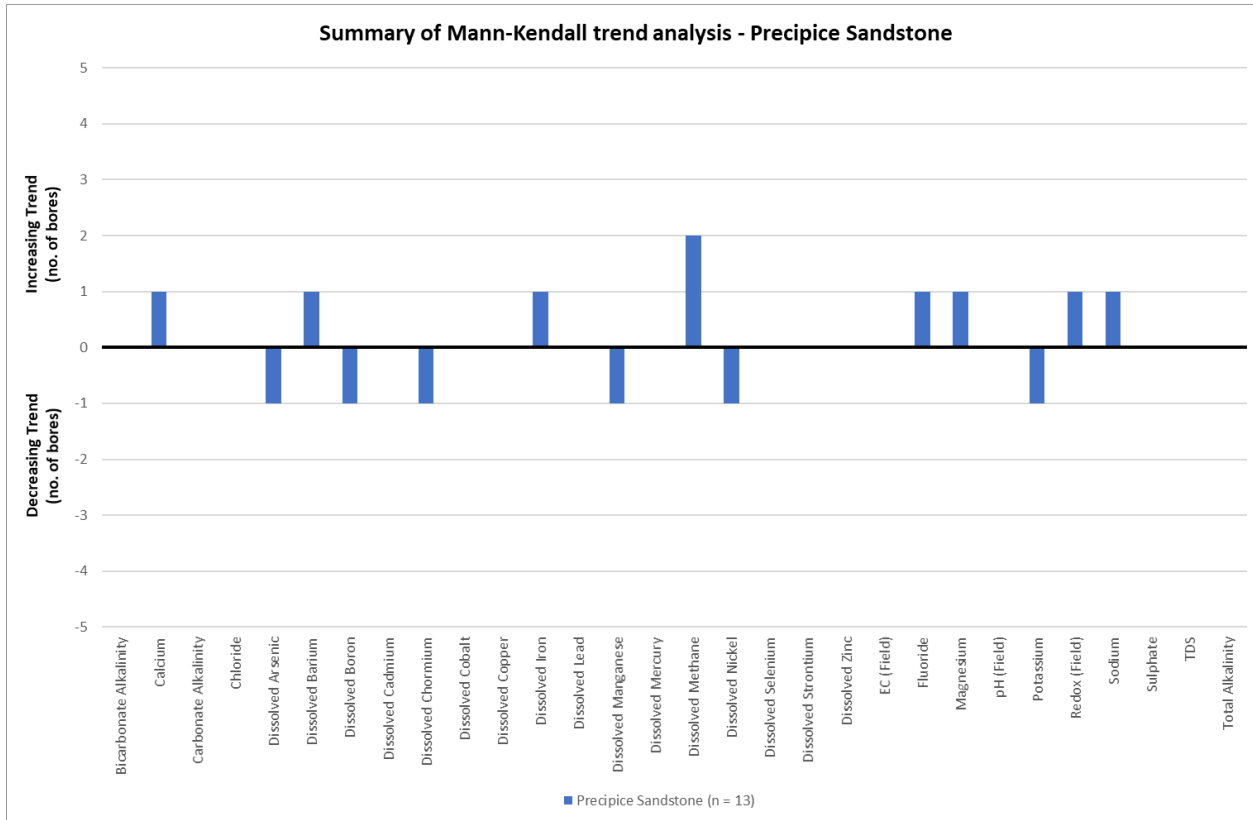


Figure 3-33: Summary of Mann-Kendall trend analysis for Precipice Sandstone monitoring bores

### 3.3 Subsidence monitoring

Coal seam gas occurs within coal formations through adsorption to the surface of the coal under hydrostatic pressure. Depressurisation of the coal seams below a threshold by groundwater extraction reduces hydrostatic pressure and liberates the gas from the formation. As the pressure falls, the gas migrates to the extraction wells. This process requires substantial lowering of groundwater pressure.

At any point below the ground surface, the weight of overlying strata is supported partly by water pressure and partly by the fabric of the rock mass. Any reduction in water pressure therefore results in an increased proportion of the load being carried by the rock mass, leading to compression of the rock. This is known as an increase in effective stress. The combined compression over the thickness of rock strata affected by reduced water pressure results in subsidence at the ground surface.

Any ground surface movement would normally be regionally consistent, and therefore unobtrusive in terms of environmental and land use impacts. However, monitoring systems have been established to distinguish any significant differential ground surface movement as a result of CSG operations from natural ground surface changes such as attrition and climatic induced soil swelling and depletion.

Regional scale monitoring extends across the full spatial extent of Arrow CSG tenements and is undertaken in partnership with the other CSG tenure holders across their leases to provide a comprehensive and seamless coverage.

#### 3.3.1 Data collection

Monitoring of subsidence was carried out by Altamira using satellite borne Interferometric Synthetic Aperture Radar technology (InSAR), a radar technique used in geodesy and remote sensing (Altamira, 2016), which provides change in ground elevation over time.

Arrow has acquired InSAR data since 2006, with the most recent satellite system (Sentinel) providing data since 2015. The Sentinel satellite system passes every 12 days (every 6 days since 2017) providing high frequency ground motion monitoring, with a vertical resolution to approximately 8mm/year.

The InSAR data provides a baseline from which future data can be assessed to determine changes in vertical ground elevation, and also provides a snapshot of current vertical ground movement.

Geotechnical ground movement monitoring points have also been installed to provide a ground-truthing check of the InSAR data. These points are instrumented with Global Navigation Satellite System (GNSS) Continually Operating Reference Stations (CORS), and provides mm accuracy of changes in vertical elevation.

#### 3.3.2 Data analysis

Following the baseline interferometric synthetic aperture radar (InSAR) survey for the period 2006 to 2015, and reported in the Stage 1 WMMP, Tre-Altamira was commissioned for ongoing surface deformation monitoring across the Arrow tenements, with the latest data available up to the end of June 2021.

Figure 3-34 shows a down-sampled data set, where the point cloud InSAR data was reduced to the median within a 1,000 m x 1,000 m grid. Stable has been classified as ground motion of less than 8 mm per year (subsidence or uplift) as related to the screening level identified in the Stage 1 WMMP.

Areas of subsidence are identified where the screening level of more than 50% of data points show downward movement of more than 8 mm/year in a 1,000 m grid cell, while areas of uplift are identified where more than 50% of data points show upward movement of more than 8 mm/year. As no production of water has been undertaken for the SGP (Section 2), any ground movement is unrelated to the SGP. Areas of subsidence and uplift are typically confined to cropping areas, particularly in areas with deep grey and black vertosols of the Condamine River floodplain, where farming operations and climatic induced soil swelling and depletion can result in ground movement.

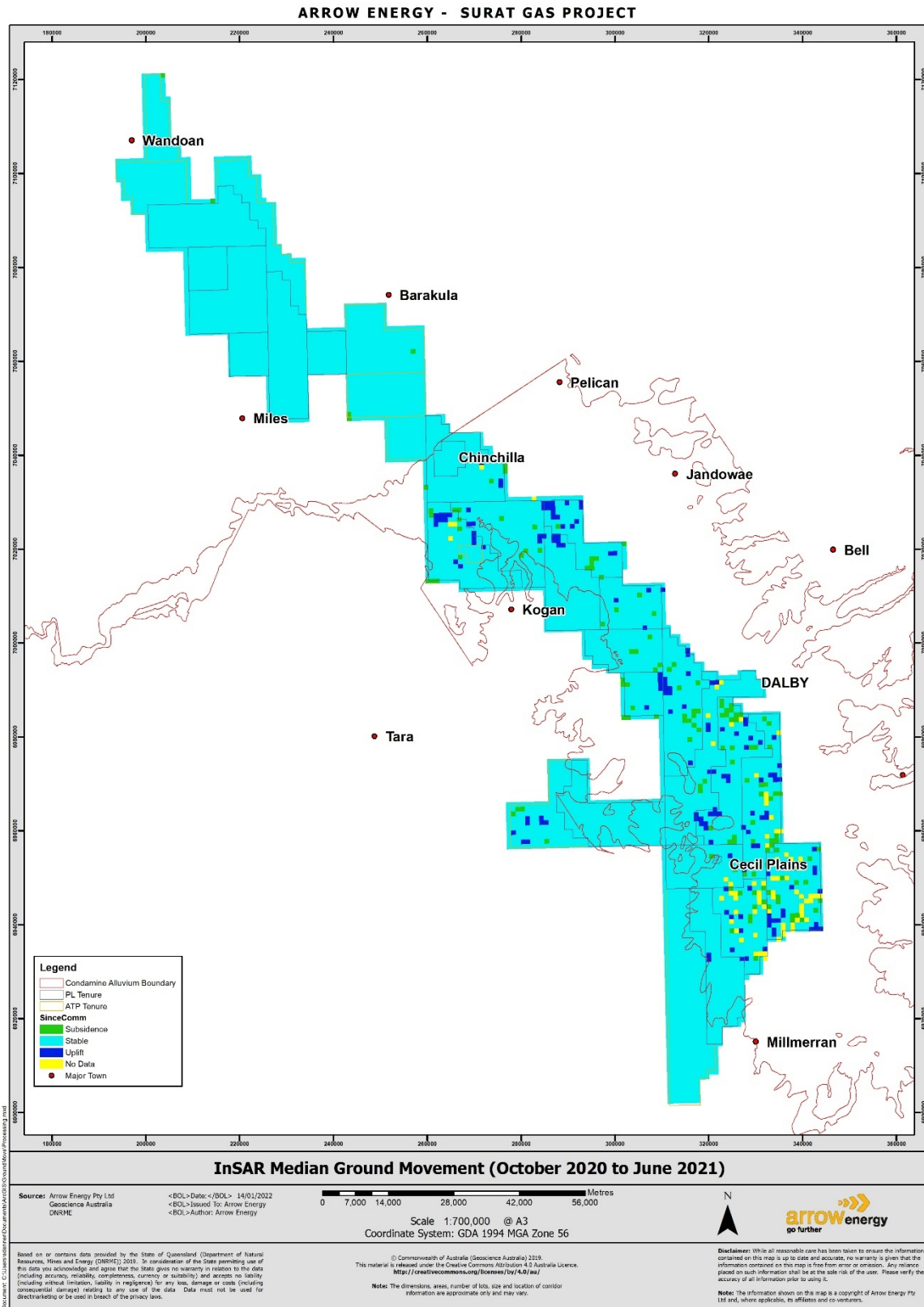


Figure 3-34: InSAR Median Ground Movement (October 2020 to June 2021 inclusive)

### 3.4 Update to monitoring networks

Groundwater monitoring locations and frequency of monitoring were revised upon the release of the 2019 UWIR in line with Section 7.3 of the SGP Updated WMMP. The monitoring network presented in Table 7-1 of the SGP Updated WMMP has been aligned with the 2019 UWIR water monitoring strategy (WMS) to ensure monitoring is undertaken proportionally to the predicted impacts presented in the 2019 UWIR. A summary of the changes to the monitoring network is provided in Table 3-2 and the updated list of monitoring points (and their purpose) is provided in Table 3-3 and illustrated in Figure 3-34 and Figure 3-35. In addition to the changes noted in Table 3-2, the groundwater chemistry suite and sampling frequency has been revised to align with that presented in the 2019 UWIR and is presented in Table 3-4.

Key changes to the monitoring programs are:

- the number of monitoring points has been increased from 120 in the SGP Updated WMMP to 169 to align with the 2019 UWIR
- the groundwater analysis suite has been expanded to include strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ )
- Table H-4 of the 2019 UWIR stipulates a groundwater sampling frequency of every six months until five samples have been obtained, with one of these samples analysed for dissolved strontium and strontium isotopes in Springbok Sandstone, Hutton Sandstone and Precipice Sandstone monitoring points.

Table 3-2: Summary of changes to the Updated CSG WMMP monitoring points to align with the 2019 UWIR monitoring requirements

Location ID	Target Aquifer	Original monitoring requirement as per Updated CSG WMMP			2019 UWIR Monitoring Requirement	Monitoring point status and current monitoring requirement based on 2019 UWIR
		Level / pressure	Water Quality	CA-WCM flux		
Bora Creek-10	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Burunga Lane-174	Evergreen	✓			No change. Still required to be monitored for the 2019 UWIR.	
Burunga Lane-174	Precipice	✓	✓		No change to the pressure monitoring requirement. Water quality monitoring requirement has been removed from the 2019 UWIR.	Access to the site was not possible during the reporting period due to ongoing negotiations with the landholder. The monitoring points are currently offline.
Burunga Lane-176	Hutton	✓	✓		No change. Still required to be monitored for the 2019 UWIR.	
Burunga Lane-176	WCM	✓				Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring in Burunga Lane-174 (removed from UWIR).
Carn Brea-17	Condamine Alluvium	✓	✓	✓	No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Carn Brea-18	WCM	✓	✓ (at UWIR MP 41 only)	✓	No change to the pressure monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Carn Brea-19	Evergreen	✓			No change to the pressure monitoring requirement.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Carn Brea-19	Hutton	✓	✓		No change to the pressure monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Carn Brea-20	Precipice	✓	✓		No change to the pressure monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Carn Brea-21	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Carn Brea-23	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Carn Brea-24	CA / WCM transition layer	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Castledean-18	Springbok	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point is operational but dry. Monitoring point operational. Monitoring as per Updated CSG WMMP.
Castledean-18	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-121	Hutton	✓	✓		No change to the pressure monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Daandine-123	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-124	Westbourne	✓	✓		No change to the level monitoring requirement. Water quality monitoring requirement has been removed from the 2019 UWIR	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (removed from UWIR).
Daandine-134	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-134	Eurombah	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-161	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-163	CA / WCM transition layer	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.



Location ID	Target Aquifer	Original monitoring requirement as per Updated CSG WMMP			2019 UWIR Monitoring Requirement	Monitoring point status and current monitoring requirement based on 2019 UWIR
		Level / pressure	Water Quality	CA-WCM flux		
Daandine-164	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-254	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-263	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Daandine-264	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Dundee-20	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Glenburnie-19	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Pressure gauge has failed. Access to the site to replace the failed pressure gauge was dependent on obtaining a land access agreement with the landholder. Monitoring as per Updated CSG WMMP.
Hopeland-17	Springbok	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Hopeland-17	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Upper Taroom Coal Measures pressure gauge temperature sensor failed on 6 July 2021. Planning of rectification work currently occurring. Other WCM monitoring points operational. Data validation ongoing to confirm observed pressure trends. Monitoring as per Updated CSG WMMP.
Kedron-570	Eurombah	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Kedron-570	Hutton	✓			No change. Still required to be monitored for the 2019 UWIR.	Pressure gauge temperature sensor failed on 8 May 2021. Planning of rectification work currently occurring. Monitoring as per Updated CSG WMMP.
Kedron-570	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Kedron-573	Springbok	✓			Springbok Sandstone monitoring point removed from the 2019 UWIR.	Monitoring point no longer monitored as per the 2019 UWIR
Kogan North-56	WCM	✓		✓	Monitoring point removed from the 2019 UWIR.	Monitoring point no longer monitored as per the 2019 UWIR. Monitoring point plugged and abandoned.
Kogan North-79	CA / WCM transition layer	✓		✓	Monitoring point removed from the 2019 UWIR.	Monitoring point no longer monitored as per the 2019 UWIR.
Kogan North-79	Condamine Alluvium	✓		✓	Monitoring point removed from the 2019 UWIR.	Monitoring point no longer monitored as per the 2019 UWIR.
Tipton-153	Hutton	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Long Swamp-1	WCM	✓			Monitoring point replaced by Longswamp 27 installed adjacent to Long Swamp-1.	Monitoring point (Longswamp 27) operational. Monitoring as per Updated CSG WMMP.
Longswamp-7	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Macalister-5	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Macalister-8	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Meenawarra-21	Springbok	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Meenawarra-21	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.



Location ID	Target Aquifer	Original monitoring requirement as per Updated CSG WMMP			2019 UWIR Monitoring Requirement	Monitoring point status and current monitoring requirement based on 2019 UWIR
		Level / pressure	Water Quality	CA-WCM flux		
Meenawarra-5	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Pampas-18	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Pampas-5	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Plainview-35	WCM	✓			No change. Monitoring point replaced previous UWIR monitoring point Plainview-1.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Plainview-25	CA / WCM transition layer	✓		✓		
Plainview-25	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring points operational. Monitoring as per Updated CSG WMMP.
Plainview-25	WCM	✓		✓		
RN 41620043	WCM (previously assessed by OGIA as Springbok Sandstone)	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
RN 42230088	Condamine Alluvium	✓		✓	Monitoring point removed from the 2019 UWIR.	Monitoring point no longer monitored as per the 2019 UWIR.
RN 42230209	Condamine Alluvium	✓	✓	✓	No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
RN 42231294	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
RN 42231295	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
RN 42231339	Condamine Alluvium	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
RN 42231370	Condamine Alluvium	✓	✓		No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
RN 42231463	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Stratheden-63	Springbok	✓	✓		No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020, and collection of samples for analysis of strontium isotopes completed in Q4 2021).
Tipton-157	WCM	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-195	Condamine Alluvium	✓	✓	✓	No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Tipton-196A	CA / WCM transition layer	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-197	WCM	✓	✓ (at UWIR MP 89 only)	✓	No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Tipton-204	CA / WCM transition layer	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-204	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.

Location ID	Target Aquifer	Original monitoring requirement as per Updated CSG WMMP			2019 UWIR Monitoring Requirement	Monitoring point status and current monitoring requirement based on 2019 UWIR
		Level / pressure	Water Quality	CA-WCM flux		
Tipton-204	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-206	Eurombah	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-206	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-221	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Tipton-222	CA / WCM transition layer	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Macalister 7	Condamine Alluvium	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Macalister 6	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Macalister 6	Eurombah	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
Wyalla-17	Hutton	✓			No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.
UWIR Site 94	Hutton	✓			Monitoring point not yet installed as 2016 UWIR timing requirement for installation (two years prior to production within 10km) was not triggered.  This monitoring point is no longer required under the 2019 UWIR.	Monitoring point no longer required.
UWIR Site 94	WCM	✓			Monitoring point not yet installed as 2016 UWIR timing requirement for installation (two years prior to production within 10km) was not triggered.  The 2019 UWIR requires this monitoring point to be installed in 2022.	Monitoring point is scheduled to be installed in 2022 as per the 2019 UWIR.
Wyalla-16	Condamine Alluvium	✓	✓	✓	No change to the level monitoring requirement. Water quality monitoring is no longer required as sufficient number of samples have been collected as per Table H-4 of Appendix H of the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Wyalla-17	Precipice	✓	✓		No change to the level monitoring requirement. Water quality monitoring requirement has been removed from the 2019 UWIR	Monitoring point operational. Monitoring as per Updated CSG WMMP except for the cessation of water quality monitoring (completion of collection of five samples in Q4 2020).
Wyalla-18	WCM	✓		✓	No change. Still required to be monitored for the 2019 UWIR.	Monitoring point operational. Monitoring as per Updated CSG WMMP.

Table 3-3: Revised Updated CSG WMMP Monitoring Network as per the 2019 UWIR WMS

Location ID	OGIA MP ID	Latitude	Longitude	Target Aquifer	UWIR Required Online Date	Monitoring point purpose			
						Level / pressure	Quality	CA-WCM flux	Early warning
41620043	578	-27.922222	151.121389	WCM	Complete	✓			✓
42230209	281	-26.7422	150.6799	Condamine Alluvium	Complete	✓	✓	✓	✓
42231294	75	-27.399278	151.548365	Condamine Alluvium	Complete	✓		✓	✓
42231295	76	-27.397504	151.561869	WCM	Complete	✓		✓	
42231339	49	-27.53057	151.503673	Condamine Alluvium	Complete	✓			✓
42231340	50	-27.531827	151.514789	WCM	Complete	✓			
42231370	51	-27.491498	151.393194	Condamine Alluvium	Complete	✓	✓		✓
42231463	37	-27.548794	151.313017	Condamine Alluvium	Complete	✓		✓	✓
42231548	165	-27.115339	151.497807	WCM	Complete	✓			
42231553	602	-26.921445	151.287057	Upper Hutton Sandstone	Complete	✓			
42231591	595	-27.591322	151.846677	Main Range Volcanics	Complete	✓			
42231597	597	-27.73082	151.76343	Main Range Volcanics	Complete	✓			
Baking Board 4	877	-26.567	150.653	WCM	2021 (delayed until 2022 in consultation with OGIA)	✓			
Baking Board 5	891	-26.48009491	150.5512695	Alluvium	Indicatively 2022. Year to be confirmed by OGIA	✓			
Barakula 2	869	-26.480094	150.551269	Hutton Sandstone	2022	✓			
Bora Creek 10	579	-27.924504	151.12492	WCM	Complete	✓			
Burunga Lane 186	494, 495, 496	-26.2301	149.9534	WCM	2022	✓			
Burunga Lane-174	478, 625	-26.242667	150.050176	Precipice, Evergreen	Monitoring points installed. Awaiting land access	✓			✓ (478)
Burunga Lane-176	473, 474, 475, 476, 477	-26.242897	150.049993	WCM, Hutton	Monitoring points installed. Awaiting land access	✓	✓ (477)		✓ (476)
Carn Brea 21	94	-27.437622	151.357504	WCM	Complete	✓		✓	
Carn Brea 22	882	-27.43779	151.357466	Hutton	Indicatively 2022. Year to be confirmed by OGIA	✓			
Carn Brea 23	92	-27.43762778	151.3576733	Condamine Alluvium	Complete	✓		✓	✓
Carn Brea 24	93	-27.437628	151.357707	Condamine Alluvium - Walloon Transition Layer	Complete	✓		✓	
Carn Brea-17	38	-27.533016	151.36648	Condamine Alluvium	Complete	✓	✓		✓
Carn Brea-18	40, 41, 42, 43	-27.532995	151.36633	WCM	Complete	✓	✓ (41)	✓	
Carn Brea-19	44, 45, 46	-27.532975	151.36618	Hutton, Evergreen	Complete	✓	✓ (45)	✓	✓ (44)
Carn Brea-20	47	-27.532954	151.36603	Precipice	Complete	✓	✓		✓
Castledean-18	375, 376, 377, 378	-26.552914	150.221984	WCM, Springbok	Complete	✓			✓ (375)
Daandine 263	181	-27.102426	150.961255	WCM	Complete	✓			
Daandine 264	148	-27.15307149	151.0442114	WCM	Complete	✓			
Daandine-121	182	-27.100415	150.955656	Hutton	Complete	✓	✓		✓
Daandine-123	159, 719, 720	-27.144075	150.948059	WCM, Precipice	Complete	✓			
Daandine-124	157	-27.144119	150.948001	Westbourne Formation	Complete	✓			
Daandine-134	162, 163, 164	-27.14401378	150.9485653	Tangalooma Sandstone, Eurombah, WCM	Complete	✓			
Daandine-161	166	-27.118534	151.075606	Condamine Alluvium	Complete	✓		✓	✓
Daandine-163	167	-27.119974	151.075875	Condamine Alluvium - Walloon Transition Layer	Complete	✓		✓	
Daandine-164	168	-27.120008	151.075969	WCM	Complete	✓		✓	
Daandine-254	160, 161	-27.144104	150.948239	WCM	Complete	✓			
Dundee-20	283, 284, 285	-26.743476	150.678351	WCM	Complete	✓		✓	
Glenburnie 19	23	-27.639218	151.167664	WCM	Complete	✓			

Location ID	OGIA MP ID	Latitude	Longitude	Target Aquifer	UWIR Required Online Date	Monitoring point purpose			
						Level / pressur e	Quality	CA- WCM flux	Early warning
Glenburnie 20	732	-27.83304667	151.0972642	Springbok	Complete	✓			
Glenburnie 21	733	-27.83242474	151.0980474	WCM	Complete	✓			
Glenburnie 22	734	-27.83252476	151.0981482	WCM	Complete	✓			
Glenburnie-18	735, 736, 737, 738, 739	-27.72017464	151.1565154	Hutton, WCM, Springbok	Complete	✓	✓ (739)		
Hopeland-17	615, 616, 617, 618	-26.973208	150.611817	Springbok, WCM	Complete	✓			✓ (615)
Kedron-570	626, 627, 628, 629	-26.413424	150.153717	WCM, Tangalooma Sandstone, Hutton	Complete	✓			✓ (629)
Kogan North-79	747, 748, 749	-26.99886636	150.9018044	WCM	Complete	✓			
Lone Pine-14	750	-27.55472483	151.3591434	WCM	Complete	✓			
Lone Pine-16	751	-27.55468423	151.3587845	WCM	Complete	✓			
Long Swamp 27	83	-27.343091	151.124186	WCM	Complete	✓			
Longswamp 28	752	-27.3415143	151.0917476	Westbourne Formation	Complete	✓			
Longswamp 29	753	-27.34150399	151.0915948	Springbok	Complete	✓			
Longswamp 30R	754	-27.34148851	151.0914061	WCM	Complete	✓			
Longswamp 31	755	-27.34347302	151.0957158	Condamine Alluvium	Complete	✓			
Longswamp 33	756	-27.26852415	151.0953309	Springbok	Complete	✓			
Longswamp 34	757	-27.26851019	151.0952109	WCM	Complete	✓			
Longswamp-7	145	-27.184333	151.127397	WCM	Complete	✓			
Macalister 5	244	-26.895087	150.954269	Condamine Alluvium	Complete	✓		✓	✓
Macalister 6	205, 206	-27.025681	151.133187	Eurombah Formation, WCM	Complete	✓		✓	
Macalister 7	203	-27.025639	151.133279	Condamine Alluvium	Complete	✓		✓	✓
Macalister 8	245	-26.895103	150.954439	WCM	Complete	✓		✓	
Meenawarra-21	34, 35, 36, 619	-27.57994613	151.1333987	WCM, Springbok	Complete	✓			✓ (619)
Meenawarra-5	33	-27.57794	151.133784	WCM	Complete	✓			
Mt Haystack 2	598	-27.727166	151.763337	WCM	Complete	✓			
Mt Haystack 4	600	-27.724061	151.276431	WCM	Complete	✓			
Mt Haystack 5	599	-27.723972	151.276483	Condamine Alluvium	Complete	✓			
Pampas 18	24	-27.61473529	151.2266555	Condamine Alluvium	Complete	✓		✓	✓
Pampas-5	25	-27.614646	151.226669	WCM	Complete	✓		✓	
Plainview 16	792	-27.385781	151.216533	Hutton	Complete	✓			
Plainview 36	789, 790	-27.3868	151.216	Springbok	Complete	✓	✓ (790)		
Plainview 37	791	-27.3868	151.216	Condamine Alluvium	Complete	✓			
Plainview-25	119, 120, 121	-27.25210762	151.2922186	Condamine Alluvium, Condamine Alluvium - Walloon Transition Layer, WCM	Complete	✓		✓	✓ (119)
Punch Bowl-15	796, 797	-26.55156345	150.3782458	WCM	Complete	✓			
Stratheden-62	822	-27.19895544	151.0267434	Condamine Alluvium	Complete	✓			
Stratheden-63	622, 623	-27.198933	151.026801	Springbok	Complete	✓	✓ (623)		✓ (622)
Tipton 153	620	-27.358607	151.153091	Hutton	Complete	✓			✓
Tipton 200	832, 834, 835, 836	-27.383	151.173	Hutton, WCM	2020 (delayed until 2022 in consultation with OGIA)	✓			
Tipton 202	830, 833	-27.383	151.173	Springbok	2020 (delayed until 2022 in consultation with OGIA)	✓	✓ (830)		
Tipton 203	831	-27.383	151.173	Condamine Alluvium	2020 (delayed until 2022 in consultation with OGIA)	✓			
Tipton 204	149, 150, 151	-27.149552	151.20938	Condamine Alluvium, Condamine Alluvium - Walloon Transition Layer, WCM	Complete	✓		✓	✓ (149)

Location ID	OGIA MP ID	Latitude	Longitude	Target Aquifer	UWIR Required Online Date	Monitoring point purpose			
						Level / pressure	Quality	CA-WCM flux	Early warning
Tipton 206	141, 142	-27.215683	151.348949	Eurombah, WCM	Complete	✓		✓	
Tipton 221	138	-27.215626	151.348869	Condamine Alluvium	Complete	✓		✓	✓
Tipton 222	139	-27.215589	151.348817	Condamine Alluvium - Walloon Transition Layer	Complete	✓		✓	
Tipton-157	72, 73, 74	-27.398089	151.088923	WCM	Complete	✓			
Tipton-194	861	-27.38748328	151.1181328	Precipice	Complete	✓			
Tipton-195	84, 85	-27.32054	151.20535	Condamine Alluvium	Complete	✓	✓ (85)	✓	✓ (84)
Tipton-196A	86	-27.320232	151.205042	Condamine Alluvium - Walloon Transition Layer	Complete	✓		✓	
Tipton-197	88, 89, 90, 91	-27.320228	151.205316	WCM	Complete	✓	✓ (89)	✓	
UWIR MP ID 842	842	-26.56916667	150.5822222	Hutton	Indicatively 2022. Year to be confirmed by OGIA	✓			
UWIR MP ID 843	843	-26.469	150.736	Hutton	Indicatively 2022. Year to be confirmed by OGIA	✓			
UWIR MP ID 868	868	-26.312681	150.377656	Hutton	Indicatively 2022. Year to be confirmed by OGIA	✓			
Wyalla-16	246, 248	-26.86619798	150.7550201	Condamine Alluvium	Complete	✓	✓ (248)	✓	✓
Wyalla-17	252, 624	-26.86632619	150.7549919	Precipice, Hutton	Complete	✓			✓ (252)
Wyalla-18	249, 250, 251	-26.8660577	150.7550667	WCM	Complete	✓		✓	

**Notes:**

(1) As noted in Revision 0 of the SGP Updated WMMP, the baseline monitoring assessment indicated Condamine Alluvium bores 42231370, Daandine-161 and Carn Brea-17 exhibited regular drawdown and recovery cycles of several metres because of nearby groundwater extraction for agricultural or other non-CSG uses. The magnitude of these groundwater fluctuations is such that these bores have limited use for early warning monitoring, and as such, have been excluded as early warning monitoring bores in the SGP Updated WMMP.



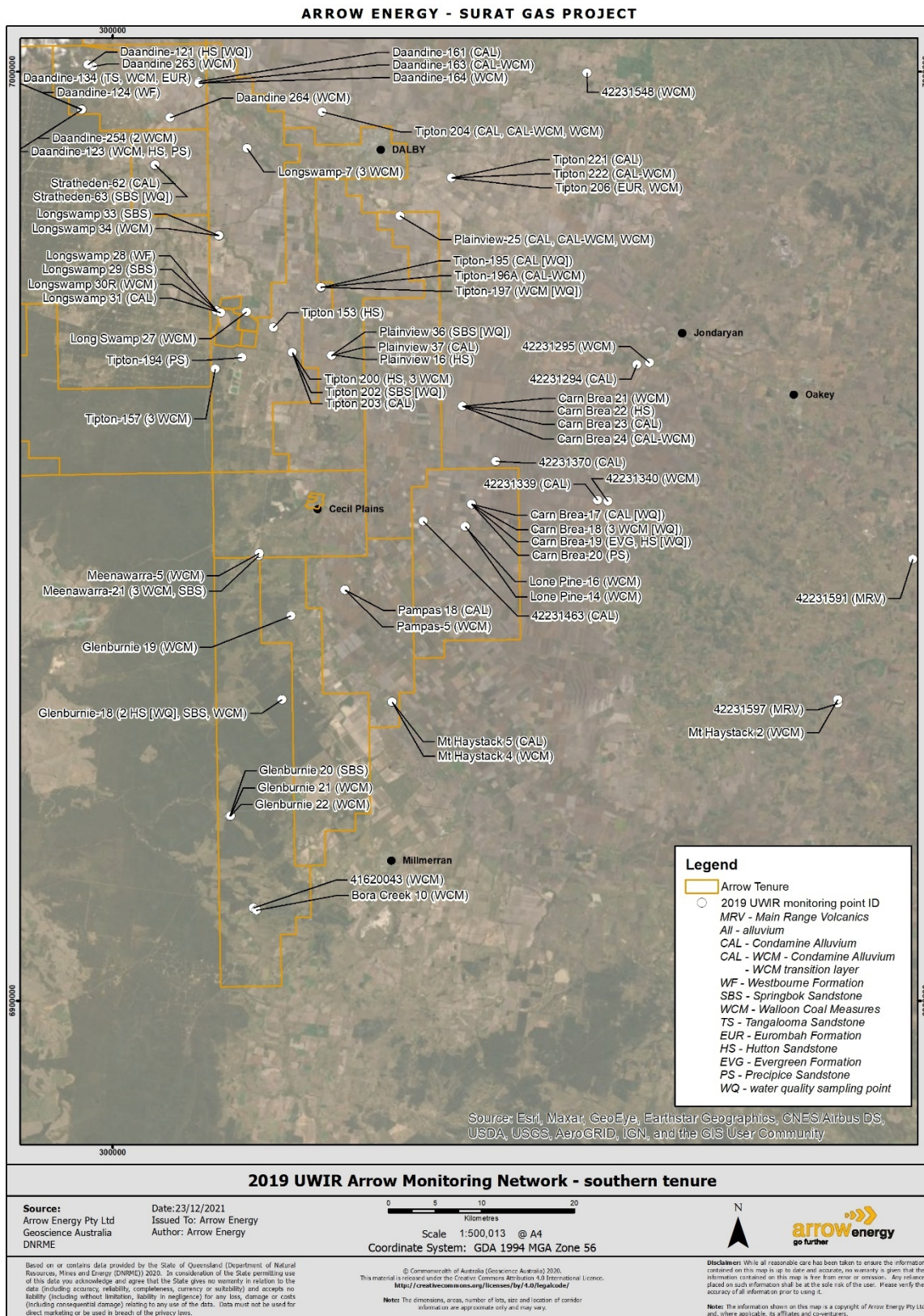
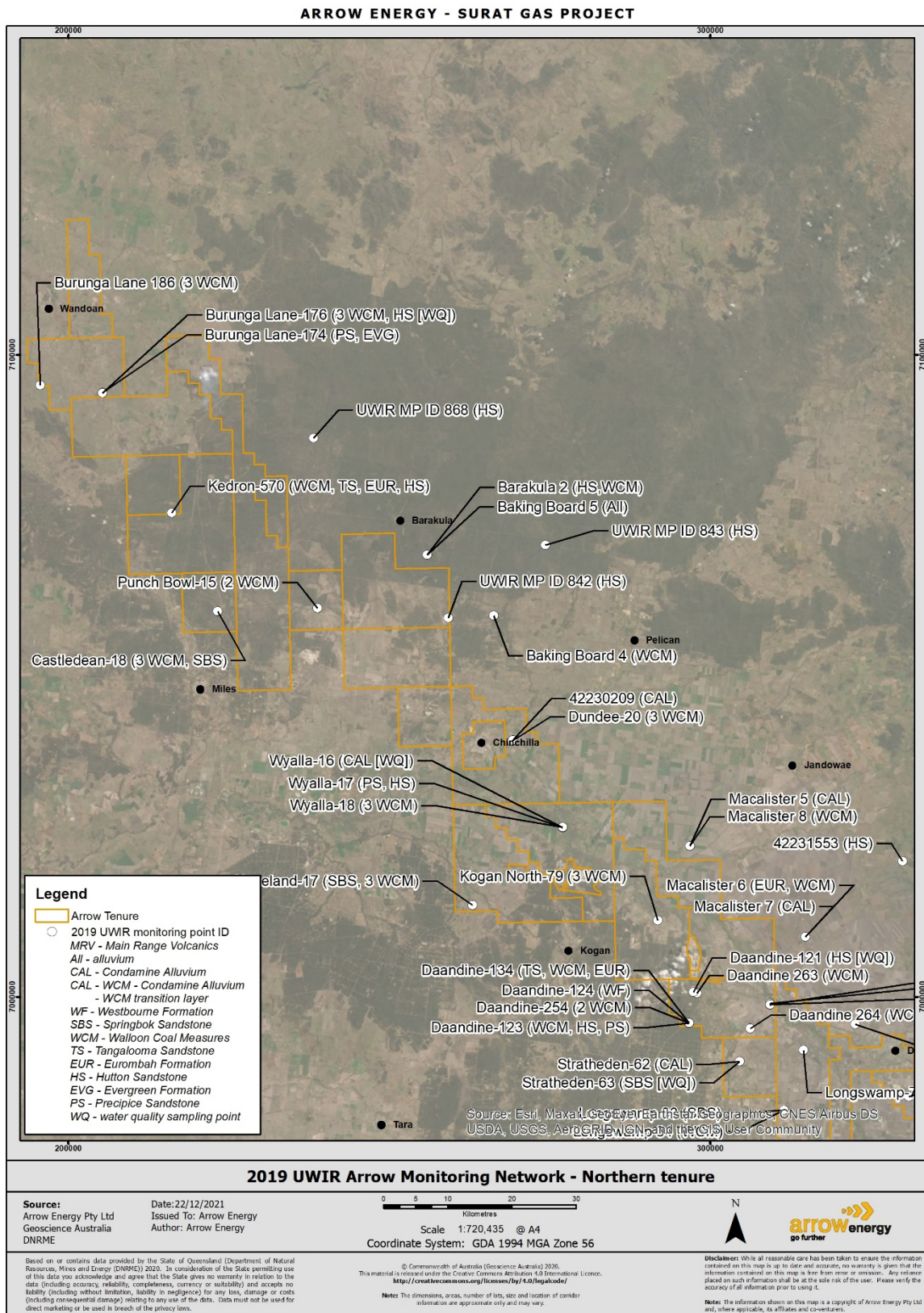


Figure 3-35: 2019 UWIR Arrow Monitoring Network – southern tenure





NOT FOR CONSTRUCTION

Figure 3-36: 2019 UWIR Arrow Monitoring Network – northern tenure

**Table 3-4: 2019 UWIR (OGIA, 2019) groundwater sampling parameters and frequency for groundwater monitoring points**

Suite	Type	Parameters to be measured as part of the suite	Frequency
Suite A	Field Parameters	Electrical Conductivity ( $\mu\text{S}/\text{cm}$ @ 25°C), pH, Redox Potential (Eh), Temperature ( $^{\circ}\text{C}$ ), Free gas at wellhead ( $\text{CH}_4$ )	Every six months until five samples obtained
	Laboratory analytes	Major cations and anions: Calcium ( $\text{Ca}^{2+}$ ), Magnesium ( $\text{Mg}^{2+}$ ), Potassium ( $\text{K}^+$ ), Sodium ( $\text{Na}^+$ ), Bicarbonate ( $\text{HCO}_3^-$ ), Carbonate ( $\text{CO}_3^-$ ), Chloride ( $\text{Cl}^-$ ), Sulphate ( $\text{SO}_4^{2-}$ ), Total Alkalinity	
		Metals (dissolved): Arsenic (As), Barium (Ba), Boron (B), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Mercury (Hg), Nickel (Ni), Selenium (Se), Strontium ( $\text{Sr}^{2+}$ ), Zinc (Zn)	
		Fluoride ( $\text{F}^-$ ), Total Dissolved Solids	
		Gas (dissolved): Methane ( $\text{CH}_4$ )	
Suite B	Laboratory analytes	Isotopes: Strontium ( $^{87}\text{Sr}/^{86}\text{Sr}$ )	Once only in: SBK, HUT, PCP
		Metals (dissolved): Strontium ( $\text{Sr}^{2+}$ )	

## 4. Updated Impact Predictions

### 4.1 Groundwater drawdown extent

Following the approval of the Updated CSG WMMP on 22 November 2019, the 2019 UWIR for the Surat CMA was approved by the Department of Environment and Science (DES) on 16 December 2019 and was the current UWIR at the time of writing this Report. Like that presented in the Updated CSG WMMP, the 2019 UWIR utilised Arrow's case 10a field development plan (FDP).

Although the FDP has not changed, changes have occurred in the predicted groundwater drawdown extent across the different iterations of the UWIR regional groundwater model (see Section 5.1 for more information on the differences between the UWIR models). Comparisons of the predicted Arrow-only groundwater drawdown between the Updated WMMP and 2019 UWIR are presented in Figure 4-1 to Figure 4-4 with the long-term affected area (5m) drawdown extents shown.

An assessment has been undertaken of the suitability of the Updated CSG WMMP and 2019 UWIR monitoring networks to monitor the predicted changes in groundwater pressure/level noting that the 2019 UWIR monitoring network supersedes the Updated CSG WMMP monitoring network in line with Section 7.3.1 of the Updated CSG WMMP.

The Springbok Sandstone 5m predicted drawdown extent has increased in the area south of Dalby (likely due to the modelling approach of the Horrane Fault) whilst it has contracted to the west of Dalby (Figure 4-1). The Hopeland area has seen an increased predicted drawdown extent and a contraction north of Miles. The distribution of the 2019 UWIR Springbok Sandstone monitoring points across the 2019 UWIR predicted drawdown extent is considered sufficient for the purposes of monitoring pressure/levels in the formation.



Previously, in the Updated CSG WMMP, the WCM 5m predicted drawdown extent was shown as two polygons surrounding the area of Chinchilla to Dalby to Cecil Plains, and around the Miles area (Figure 4-2). The 2019 UWIR WCM 5m predicted drawdown extent has increased to one larger polygon which largely covers Arrow's tenure and also extends east towards Toowoomba. While there are several reasons for this difference in predicted drawdown (Section 5.1), the 2019 UWIR regional groundwater model has incorporated increased lateral connectivity of the coal seams. As shown in Figure 4-2, the 2019 UWIR WCM monitoring network provides adequate spatial coverage across the predicted WCM drawdown extent and is therefore considered adequate.

The Hutton Sandstone 5m predicted drawdown extent has increased significantly from the Updated CSG WMMP to the 2019 UWIR (Figure 4-3). The location of both predicted 5m drawdown contours are associated with the Horrane Fault however it should be noted that Arrow's investigation of the fault indicates it is sealed and there is limited hydraulic connectivity between the WCM and the Hutton Sandstone. Nonetheless, the distribution of the 2019 UWIR Hutton Sandstone monitoring points is sufficiently spread across the predicted drawdown extent.

Consistent with the Updated CSG WMMP, the 2019 UWIR does not predict any Arrow-only drawdown greater than 5m in the Precipice Sandstone (Figure 4-4).

In regards to the Condamine Alluvium, as noted in Section 5.3, the 2016 UWIR predicted a change in flux in the base of the Condamine Alluvium of 1,160ML/yr due to the entire CSG industry. This has reduced by approximately 40 per cent in the 2019 UWIR to 735ML/yr. Arrow's contribution to the flux change is approximately 164ML/yr. This indicates a lower potential impact to the Condamine Alluvium.

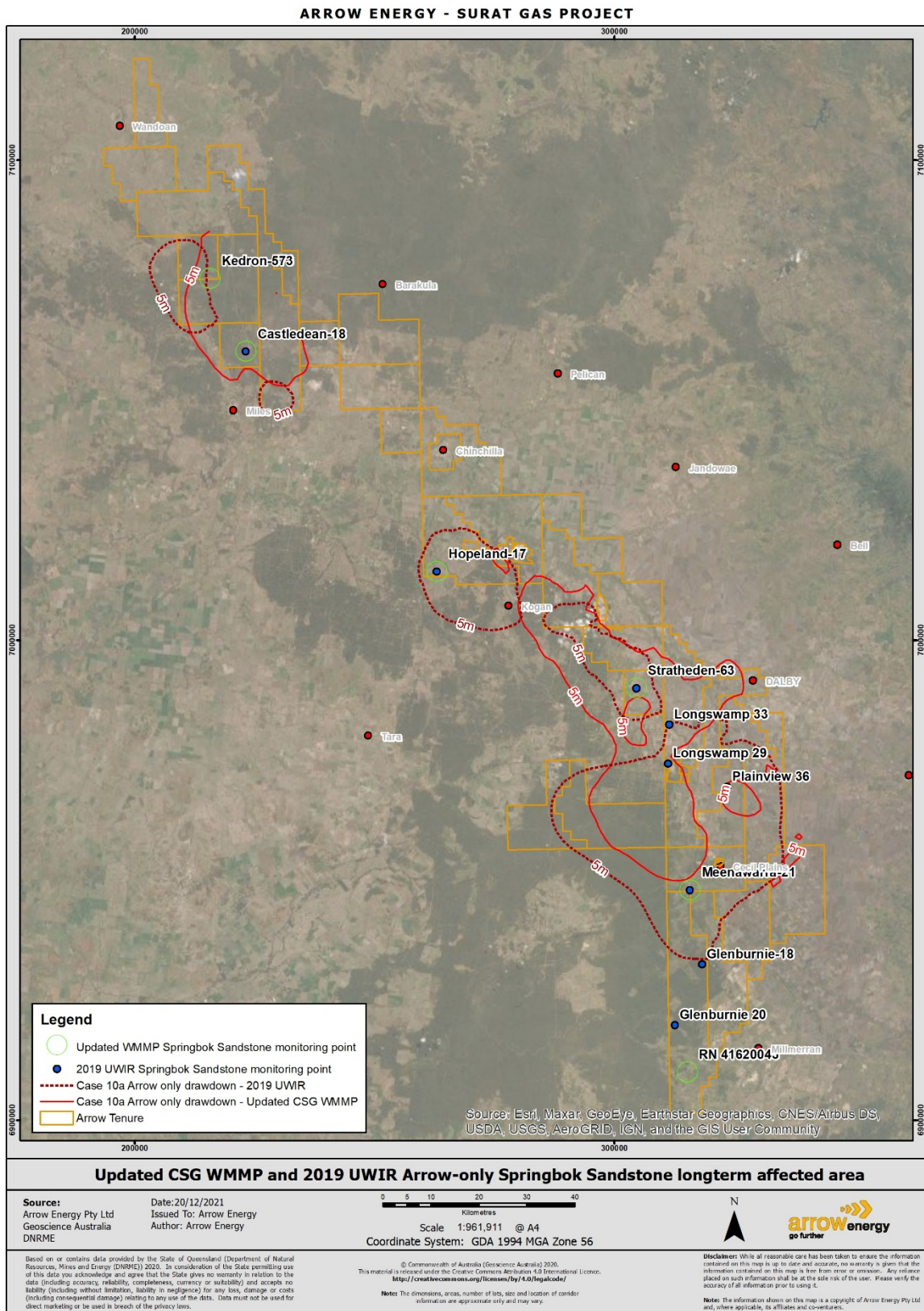


Figure 4-1: Updated CSG WMMP and 2019 UWIR Arrow-only Springbok Sandstone long-term affected area



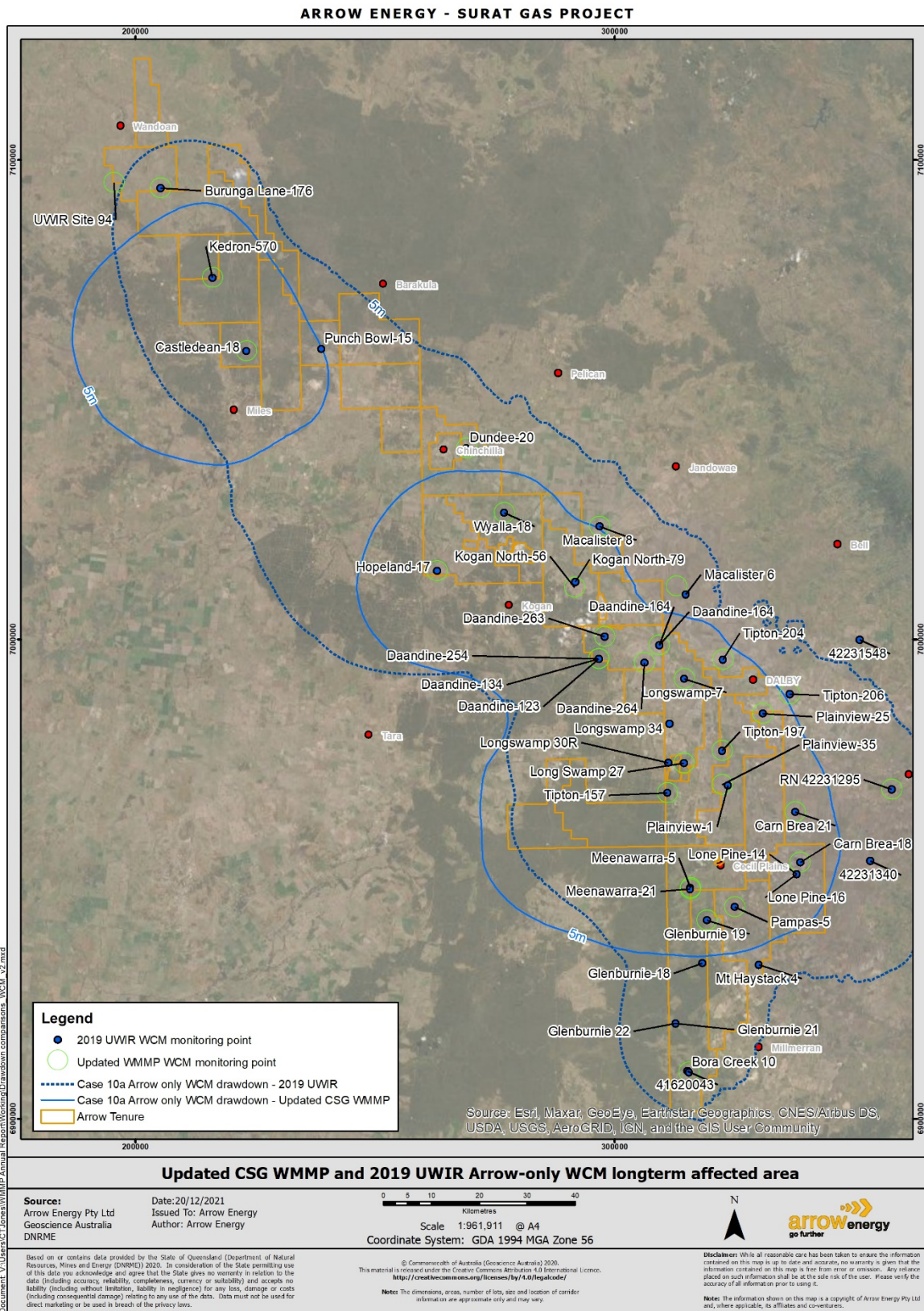


Figure 4-2: Updated CSG WMMP and 2019 UWIR Arrow-only WCM long-term affected area



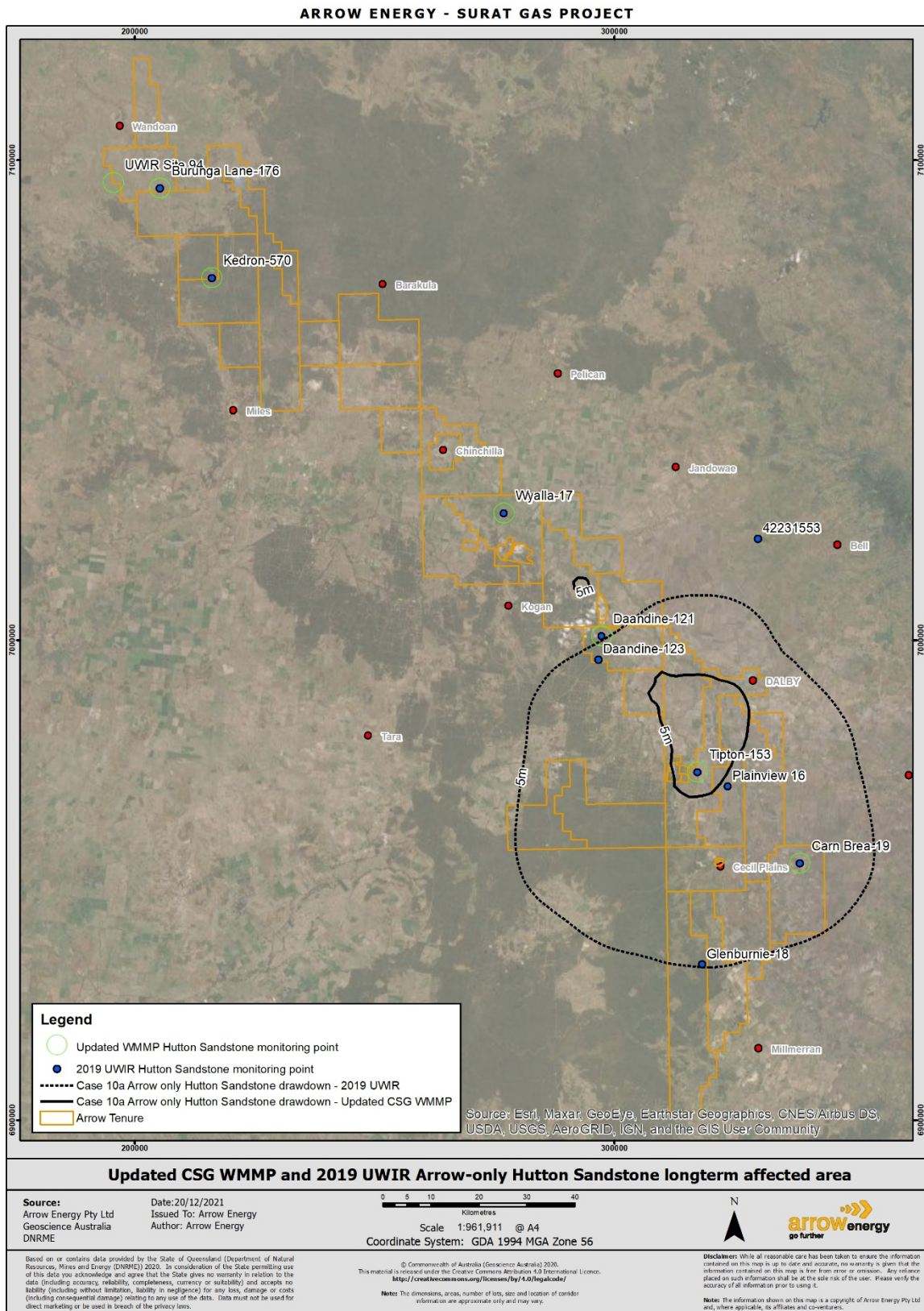


Figure 4-3: Updated CSG WMMP and 2019 UWIR Arrow-only Hutton Sandstone long-term affected area

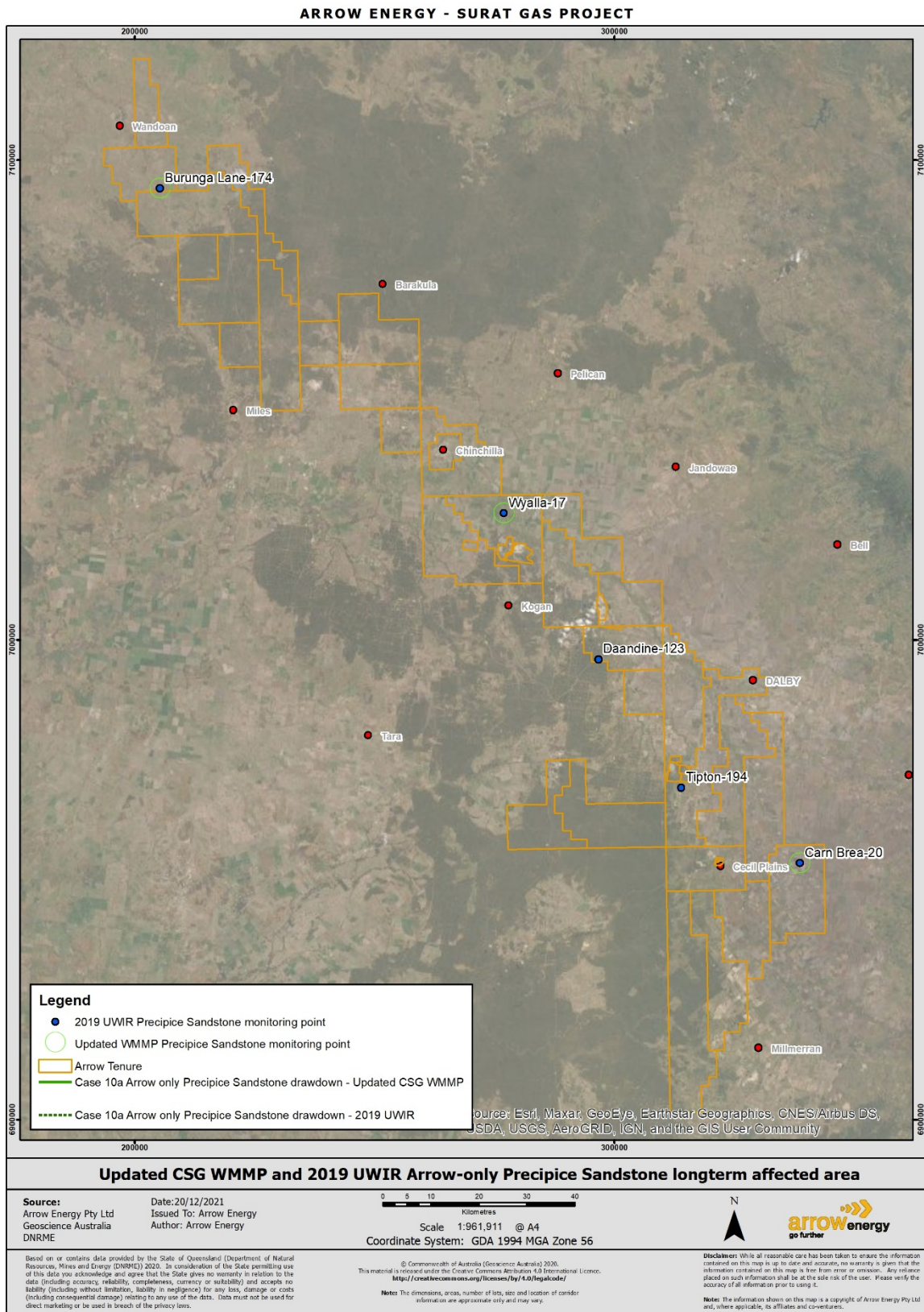


Figure 4-4: Updated CSG WMMP and 2019 UWIR Arrow-only Precipice Sandstone long-term affected area



## 4.2 Watercourse Springs

The 2019 UWIR lists potential watercourse springs within the Surat CMA. These potential watercourse springs were identified as a result of a research project completed by OGIA and detailed in their report Identification of Gaining Streams in the Surat Cumulative Management Area, Hydrogeology Investigation Report in 2017 (DNRME). The potential watercourse springs were identified through a desktop assessment, and a risk assessment of each of the sites was undertaken in the 2019 UWIR (Appendix I.2 of the UWIR) (OGIA, 2019) to identify any monitoring and mitigation plans for tenure holders. Field verification of identified potential watercourse springs was partially completed; however, some sites still required field verification.

Where an unverified watercourse spring was identified as high risk in the 2019 UWIR, OGIA assigned the requirement for field verification to tenure holders. Arrow was assigned two potential watercourse springs requiring field verification. Arrow completed the field verification of both sites and submitted the report to OGIA on 30 August 2021.

Multiple lines of evidence including analysis of isotopes, hydrogeochemistry, biophysical assessment, and desktop assessment of potentiometric surfaces and elevation data were applied to assess the ecohydrological function of two potential gaining watercourse reaches on L Tree and Dogwood Creeks within Arrow's tenure. The field verification concluded that while limited to a single dry-season assessment event, there was no evidence of GAB aquifer discharge to the assessed watercourse reaches.

## 5. WMMP Revision

In accordance with Section 8.6 of the SGP Updated WMMP, assessments were undertaken during the reporting period as a result of both the commencement of the SGP and the release of the 2019 UWIR. These assessments were:

- revision of the Early Warning Monitoring System
- risk assessment of potential terrestrial groundwater dependent ecosystems
- potential changes to stream connectivity.

### 5.1 Early Warning Monitoring System

Section 7.5.3 of the SGP Updated WMMP requires the early warning indicators, trigger thresholds and limits to be reviewed according to any new OGIA model output, within 90 days of the approved UWIR being issued and upon receiving technical files from OGIA for that UWIR.

If an early warning indicator, trigger level or limit for the next three year period is greater than 10 per cent of the values reported in the latest version of the WMMP for any of the aquifers, a revised WMMP will be submitted for Ministerial approval, reflecting the revised drawdown predictions from the new UWIR. Arrow is to submit the revised WMMP for Ministerial approval within 90 days, following the initial 90-day review period of the early warning indicators, trigger thresholds and limits.

In line with the above process, the EWMS levels were revised based on the 2019 UWIR (OGIA, 2019) and was completed on 20 January 2021 (90 days after the SGP commencement date of 22 October 2020). The 2019 UWIR groundwater model was used to derive the revised EWMS levels for the Hutton Sandstone and Precipice Sandstone using the framework outlined in Section 7.5.2 of the SGP Updated WMMP. The revised EWMS levels for the Hutton Sandstone and Precipice Sandstone varied by greater than 10 per cent from the levels in the latest version of the WMMP. This triggered the requirement for the SGP Updated WMMP to be revised to include the updated EWMS levels (in accordance with Section 8.6 of the SGP Updated WMMP) and was submitted to DAWE on 20 April 2021 (90 days after the completion of the EWMS assessment).

These revised EWMS levels have not yet been approved by the Federal Department of Agriculture and the Environment (DAWE) and, as such, are not yet being applied.

The revised EWMS levels are presented in Table 5-1 noting no change is proposed to the Condamine Alluvium or Springbok Sandstone.

**Table 5-1: EWMS for the Condamine Alluvium and consolidated aquifers**

Aquifer	Maximum model-predicted P95 cumulative drawdown level <sup>(1)</sup> (over 100 years, at any point on Arrow tenure)	Drawdown factor	Limit <sup>(1)</sup>	Early warning indicator (EWI) (Commencing Jan-2021 to Dec2023) <sup>(1)</sup>	Trigger threshold (Commencing Jan-2021 to Dec- 2023) <sup>(1)</sup>
Condamine Alluvium	16 m	2 m	18 m	7 m	12.5 m
Springbok Sandstone	72 m	5 m	77 m	31 m	54 m
Hutton Sandstone	95 m	5 m	100 m	46 m	73 m
Precipice Sandstone	47 m	5 m	52 m	33 m	43 m

**Notes:**

(1) The EWMS reported in the table applies until the end of 2023, three years after the commencement of the Action. The model predictions and corresponding limits, early warning indicators and trigger thresholds will be reviewed whenever a new or revised OGIA model simulation in a UWIR has been developed and approved to take effect.

(2) The early warning indicator, trigger threshold and limit will be reviewed upon release of each new UWIR. The next UWIR is expected to be released in 2022.

The reasons for this variance between the original and revised EWMS levels are predominantly due to model structure and parameter changes between the 2012 (the 2012 model was used in the SGP Updated WMMP because this model included uncertainty analysis from 200 realisations, while the 2016 version of this model did not include uncertainty analysis and therefore could not be used as a source of data for the WMMP) and 2019 UWIR groundwater models. The major differences that are likely to have affected the model outputs include:

- model code
- model structure
- model parameterisation.

The influence of these factors is discussed in further detail below.

### Model code

The 2012 UWIR groundwater model used the Modflow 2005 code. This is a single phase or water flow model and does not account for effects of gas on relative permeability. The local, small-scale effects of gas on water flow are important in the rate of flow of water to CSG wells. In a dual phase system, there is an exponential decline in water yield as coal seams are depressurised and gas is desorbed from the coal. This was understood and discussed by OGIA (then Queensland Water Commission) in the 2012 UWIR (QWC, 2012). The 2019 UWIR groundwater model addressed this issue by modifying how layers desaturate. This is discussed in detail in the 2019 UWIR Groundwater Modelling Report (OGIA, 2019b) and summarised below.

Desaturation in the dual phase context is different from single phase in that more water is derived from pore spaces than elastic storage and the amount of formation permeability (relative permeability) available to water is reduced as more gas is freed to occupy the pore spaces.

In single phase models, air saturation in the vadose zone can be simulated using the van Genuchten equation where desaturation occurs at the air-water interface. In the 2019 UWIR groundwater model this is modified such that it allows desaturation to start at the saturation pressure of the Langmuir isotherm that governs gas desorption or the groundwater pressure, whichever is the lower pressure. This results in a solution for dual phase pressures that has less uncertainty than the upscaling in the large regional model.

### Model structure

The 2012 UWIR groundwater model simulated the WCM with three layers comprising upscaled interburden layers above and below a nominal coal layer. For the 2019 UWIR groundwater model, six layers are used to represent the WCM. In addition, the Springbok and Hutton sandstones are represented with two layers each in the latter model. This change in structure results in different parameterisation and different boundary conditions for these layers.

In addition to the model's layer structure, the 2019 UWIR groundwater model included dual porosity in the WCM. The necessary upscaling for the large regional model could have distorted the relative water permeability curve. This problem was overcome to a large extent through adoption of a dual porosity formulation whereby a permeable, porous medium is assumed to possess mobile and immobile domains which are separate in function but not in space (DNRME, 2019b).

### Model parameterisation

The changes in model code and model structure together with more calibration data available in the 2019 UWIR groundwater model led to changes in model parameterisation that affected the model predictions. The calibrated parameters for horizontal hydraulic conductivity for each model are presented in both the 2012 (QWC, 2012) and 2019 UWIRs (OGIA, 2019).



## 5.2 Potential terrestrial groundwater dependent ecosystems

The 2019 UWIR included an assessment of terrestrial groundwater dependent ecosystems (GDE) which was further revised in OGIA's 2019 UWIR Approval Condition 3 Response (OGIA, 2020) released on 16 December 2020. This document was submitted to the DES by OGIA as part of the conditions of approval of the 2019 UWIR<sup>1</sup>. The document is available from OGIA upon request. The associated technical data were provided to Arrow on 10 February 2021 in response to Arrow's request in November 2020 following the SGP commencement on 22 October 2020.

Arrow was obliged to revise the GDE risk assessment in accordance with Section 8.6 of the SGP Updated WMMP. Arrow completed the revised desktop risk assessment on 11 May 2021 (90 days from 10 February 2021) i.e. within 90 days of a new approved UWIR being issued (and upon receiving technical files from OGIA). Arrow's revised risk assessment is provided in Appendix D.

The risk assessment identified two potential terrestrial GDEs predicted to be at risk of being impacted from the Action or the cumulative CSG operation. A summary of the desktop risk assessment is provided in Section 5.2.1, with further detail provided in Appendix D. As a result, further work is required to be undertaken to gather supporting data to confirm the ecosystems' reliance on groundwater and validate the findings of the desktop assessment. An outline of this proposed further work is provided in Section 5.2.2. In the instance a high-risk site was identified in the risk assessment, section 8.6 of the SGP Updated WMMP also requires a revised Updated WMMP be submitted to DAWE within 90 days of completing the risk assessment. A revised Updated WMMP was therefore submitted to DAWE on 9 August 2021 detailing the risk assessment and proposed further work. This revised Updated WMMP has not yet been approved by DAWE.

### 5.2.1 Risk assessment

OGIA's terrestrial GDE desktop assessment method (OGIA, 2020), detailed in the document Attachment 1 Condition 3 Response (attached as Appendix A to Appendix D of this Report), integrates:

- GIS mapping of potential terrestrial GDEs
- areas of predicted drawdown in the 2019 UWIR groundwater model within outcropping aquifers
- regional ecosystem (RE) mapping
- biodiversity status.

Eight potential terrestrial GDE areas were identified by OGIA as potentially at risk of impact. Arrow assessed these eight sites against available data such as

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<sup>1</sup> The Chief Executive of the Department of Environment and Science approved the 2019 Surat CMA UWIR on 16 December 2019 with conditions including Condition 3 which required submission of an environmental values assessment with the first annual review that updates the assessment of impacts presented in the approved UWIR on the following environment values: a. terrestrial groundwater dependent ecosystems; b. changes in water quality of each aquifer; and c. irrigation land.

depth to groundwater, landscape setting, field survey vegetation mapping, and previous assessments conducted in the Stage 1 CSG WMMP and Revision 0 of the Updated CSG WMMP (Appendix D – Stream Connectivity and GDE Impact Assessment memo). Arrow's review identified that all but two of the eight areas are considered to either not be at risk of impact or unlikely to represent a terrestrial GDE.

OGIA (2020) note that the priority knowledge gaps for further investigation of medium or high-risk sites are:

- validation and confirmation of the GDE mapping and associated REs
- conceptualisation of the identified terrestrial GDEs in terms of:
  - quantification of their ecological water requirements – the temporal nature, quantity and quality of groundwater use
  - their likely ecological response to changes in groundwater regime.

### 5.2.2 Field investigations

In line with the above, Arrow has commenced further investigations to gather multiple lines of evidence at the two areas identified as potential GDEs at risk of impact. The investigations started in October 2021 and will be completed by 30 June 2022. A report summarising the outcomes of the investigations will be prepared 90 days from 30 June 2022 for inclusion in the next Updated WMMP annual report. The investigations will include:

1. Further development of conceptualisation of the ecohydrological relationships and recognition of stressors for the identified potential terrestrial GDEs. This assessment will identify comparative sites located outside of the terrestrial GDE investigation areas to be included in step 2 below. Adequate comparative sites may not be present for the purposes of this assessment, given the unique site setting of these sites (i.e. vegetation type in conjunction with specific geological setting).
2. Conducting a dry season field survey in the second half of 2021 to gather multiple lines of evidence, comprising:
  - a. walking the area to visually assess landscape setting, soil types, vegetation (including current health), geology, hydrology, geomorphology, stressors (i.e. cattle, anthropogenic), water input sources and their relative contributions
  - b. mapping the vegetation to confirm RE mapping.
  - c. assessing water sources of target vegetation by measuring groundwater levels (if possible), collecting representative leaf water potential samples, collecting stable isotope samples from plant xylem, surface water pools (if present), groundwater (if possible) and soil moisture.
3. Reviewing the collected data and comparison with the desktop conceptualisation. If required, conducting a wet season field survey in the first half of 2022 to assess water sources of target vegetation by:

- a. measuring groundwater levels (if possible)
- b. collecting representative leaf water potential samples and
- c. collecting stable isotope samples from plant xylem, surface water pools (if present), groundwater (if possible) and soil moisture.

If the multiple lines of evidence collected from the investigation identifies that the site is a terrestrial GDE and is at risk of being impacted by the action, a monitoring program will be established within 90 days of the completion of the investigation report, and an EWMS will be developed in accordance with Section 7.5.4 of the SGP Updated WMMP. Within a further 90 days thereafter, findings from this work, and assignment of an EWMS (if required), will be documented in a revised Updated WMMP Annual Report.

### 5.3 Potential changes to stream connectivity

Section 5.2 of the SGP Updated WMMP requires Arrow to reassess potential changes to stream connectivity within 90 days of an approved UWIR being issued and upon receiving technical files from OGIA for that UWIR. If triggered, Arrow will submit a revised WMMP within 90 days (following the initial 90 days for the reassessment) for Ministerial approval. This reassessment was completed on 20 January 2021 (90 days after the SGP commencement date of 22 October 2020).

The SGP Updated WMMP assessment of impacts to stream connectivity used the flux through the base of the Condamine Alluvium applied to the base of the Central Condamine Alluvium Model (CCAM).

Potential changes to stream connectivity are reassessed by comparison of the predicted magnitude of the groundwater flux changes provided in the SGP Updated WMMP and that determined using the latest UWIR.

The 2016 UWIR predicted a change in flux in the base of the Condamine Alluvium of 1,160ML/yr due to the entire CSG industry. This has reduced by approximately 40 per cent in the 2019 UWIR to 735ML/yr. Arrow's contribution to the flux change is approximately 164ML/yr.

This indicates a lower potential impact to the Condamine Alluvium and lower potential for subsequent impact to stream connectivity than previously estimated. In light of this, no revision of the SGP Updated WMMP was required for this assessment.

## 6. Arrow's Contribution to Industry and Government Knowledge Base

One groundwater-related research project was completed during the reporting period. The project was the use of helium isotopes to assess flux rates under the Condamine Alluvium. Arrow worked with CSIRO to test a new method of mapping the vertical movement of the Surat Basin's groundwater using noble gas isotopes.

The project investigated whether the difference in helium between the alluvium and Walloon Coal Measures (WCM) was large enough to be meaningfully detected. The study area was much shallower than other areas around the world where these isotopes had been used. The results of the initial testing indicated that proof of concept was achieved and that the vertical advective groundwater velocities are less than 1mm/year. Future changes in helium concentration and its isotopes can now be used to indicate if flux is occurring and to calculate the flux rate between the alluvium and the WCM. This provides direct evidence of flux and an independent measure for comparison to predictive models.

A copy of the report is provided in Appendix E.

## 7. Compliance with the WMMP

The approved SGP Updated WMMP was developed based on an adaptive management framework which meets the water-related approval conditions. Compliance, therefore, with the SGP Updated WMMP demonstrates compliance with the approval conditions.

Throughout the reporting period, Arrow maintained compliance with the WMMP with the exception of one occurrence where a shallow monitoring bore was not monitored for groundwater level in Q4 2021 (Section 6). Compliance with the WMMP is demonstrated through:

- publication of the approved Updated CSG WMMP on Arrow's website
- publication of this annual report on Arrow's website within three months of the anniversary of the start of the SGP
- providing raw data to OGIA as required in Section 8.6 of the 2019 UWIR for potential inclusion (at the discretion of Department of Regional Development, Manufacturing and Water [DRDMW]) on the Queensland Globe database
- met performance measure criteria for assessment of the protection of matters of national environmental significance (MNES), namely:
  - adequacy of the groundwater monitoring network was reviewed according to the predicted drawdown from a new OGIA model (2019 UWIR) (Section 4)
  - the EWMS was reviewed according to a new OGIA model output (2019 UWIR) (Section 5.1)
  - the desktop terrestrial GDE risk assessment was reviewed following the release of a new UWIR (2019 UWIR) (Section 5.2)
  - potential changes to stream connectivity were reviewed according to a new OGIA model output (2019 UWIR) (Section 5.3)
  - monitoring obligations (groundwater and subsidence) were carried out in accordance with the 2019 UWIR except for occurrences where equipment failure occurred, access to a site was not

possible and failing to monitor monitoring bore RN42231553 in Q4 2021 (Section 3)

- assessment of potential watercourse springs nominated by OGIA in the 2019 UWIR (Section 4.2).
- the EWMS was implemented noting that there were no exceedances of early warning indicators, trigger thresholds or limits during the reporting period.

In addition to the above, Arrow's compliance with all EPBC Approval 2010/5344 conditions is documented in the report Surat – EPBC Approval 2010/5344 Annual Compliance Report 2020/2021 (B00-ARW-ENV-REP-00042) available on Arrow's website.

## 8. Document Administration

This document has been created using ORG-ARW-IMT-TEM-00005 v4.0

### Revision history

Revision	Revision Date	Revision Summary	Author
1.0	17/01/2022	Issued for Use	Chris Jones

### Related documents

Document Number	Document title

### Acceptance and release

#### Author

Position	Incumbent	Release Date
Team Lead Hydrogeology	Chris Jones	17/01/2022

#### Stakeholders and reviewers

Position	Incumbent	Review Date
Communications and Social Impact Manager	Liz Edwards	14/01/2022
Principal Community (Acting)	David Kiefer	14/01/2022
Senior Environment Biodiversity Offsets Advisor	Daniel Potter	14/01/2022
Media & Content Specialist	Simon Radich	14/01/2022
Groundwater Manager	Stephen Denner	14/01/2022

#### Approver(s)

Position	Incumbent	Approval Date
Groundwater Manager	Stephen Denner	17/01/2022

## 9. References

Department of Natural Resources, Mines and Energy, 2017. *Identification of Gaining Streams in the Surat Cumulative Management Area, Hydrogeology Investigation Report*, March 2017, Office of Groundwater Impact Assessment

Office of Groundwater Impact Assessment, 2019. *Underground Water Impact Report for the Surat Cumulative Management Area, July 2019*. Queensland Government

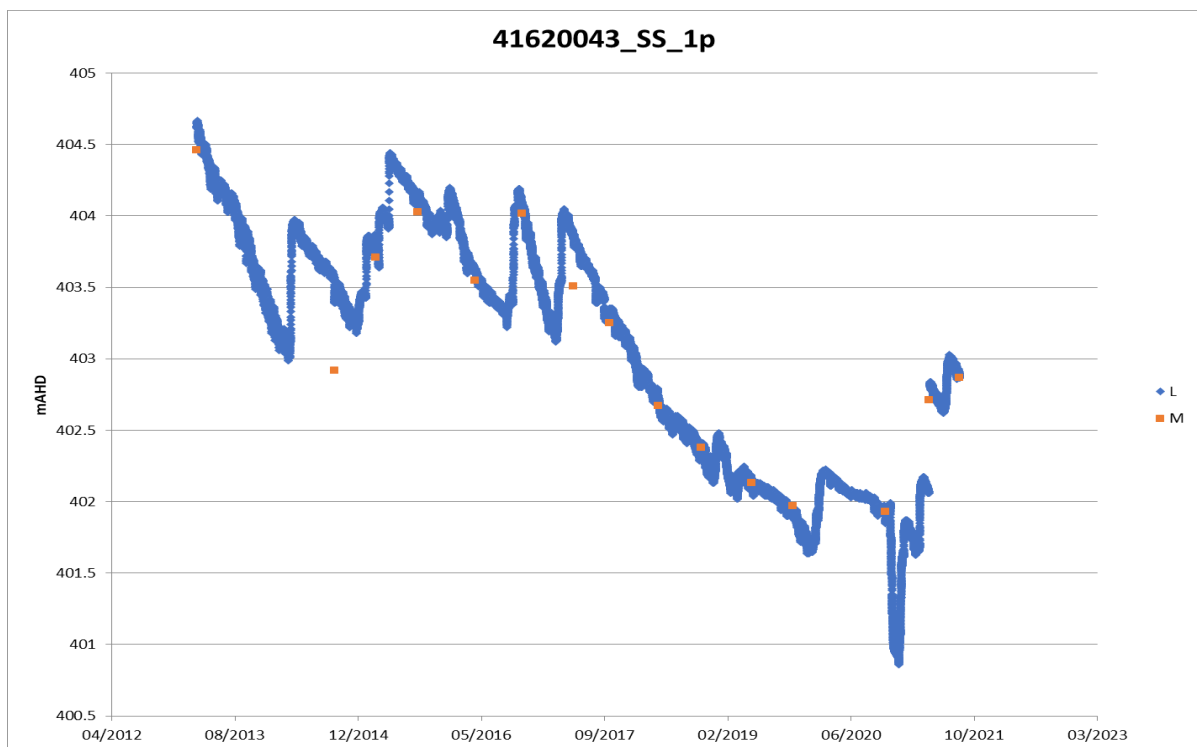
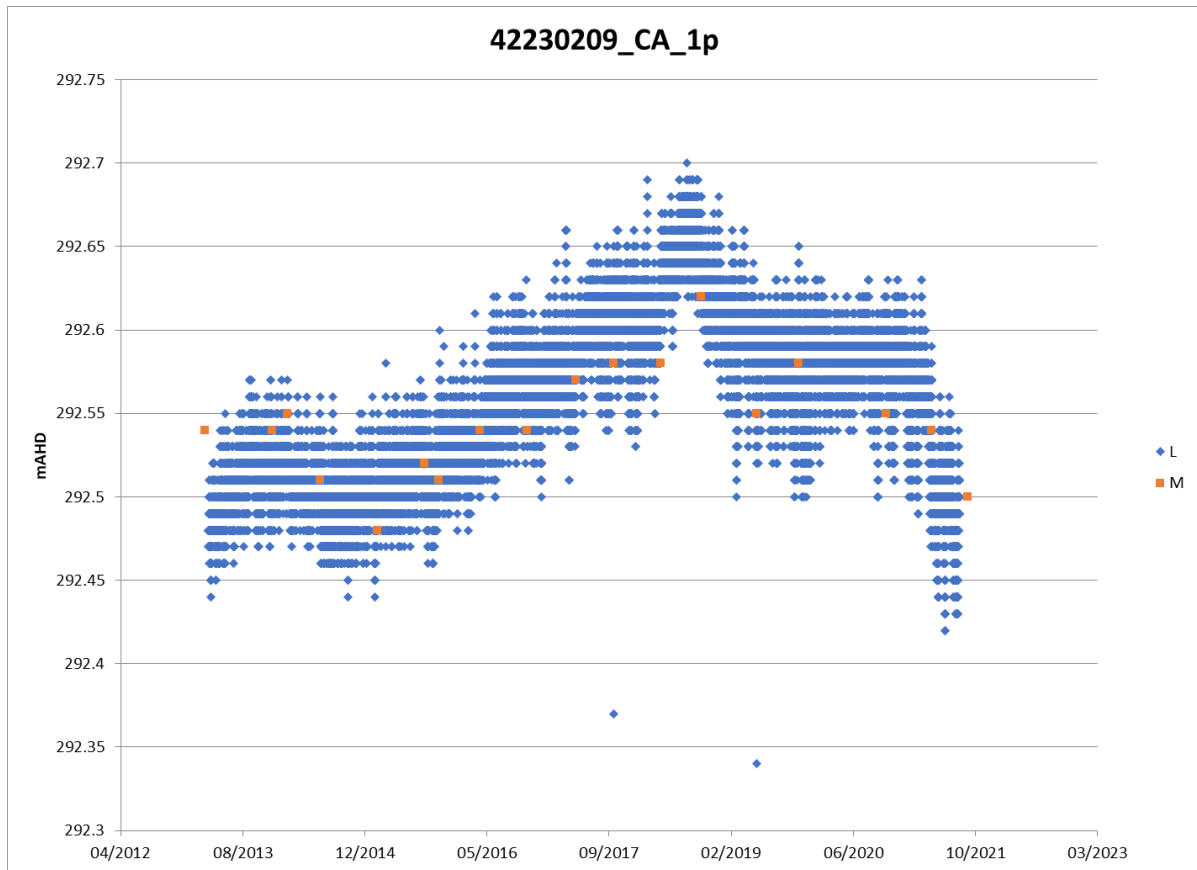
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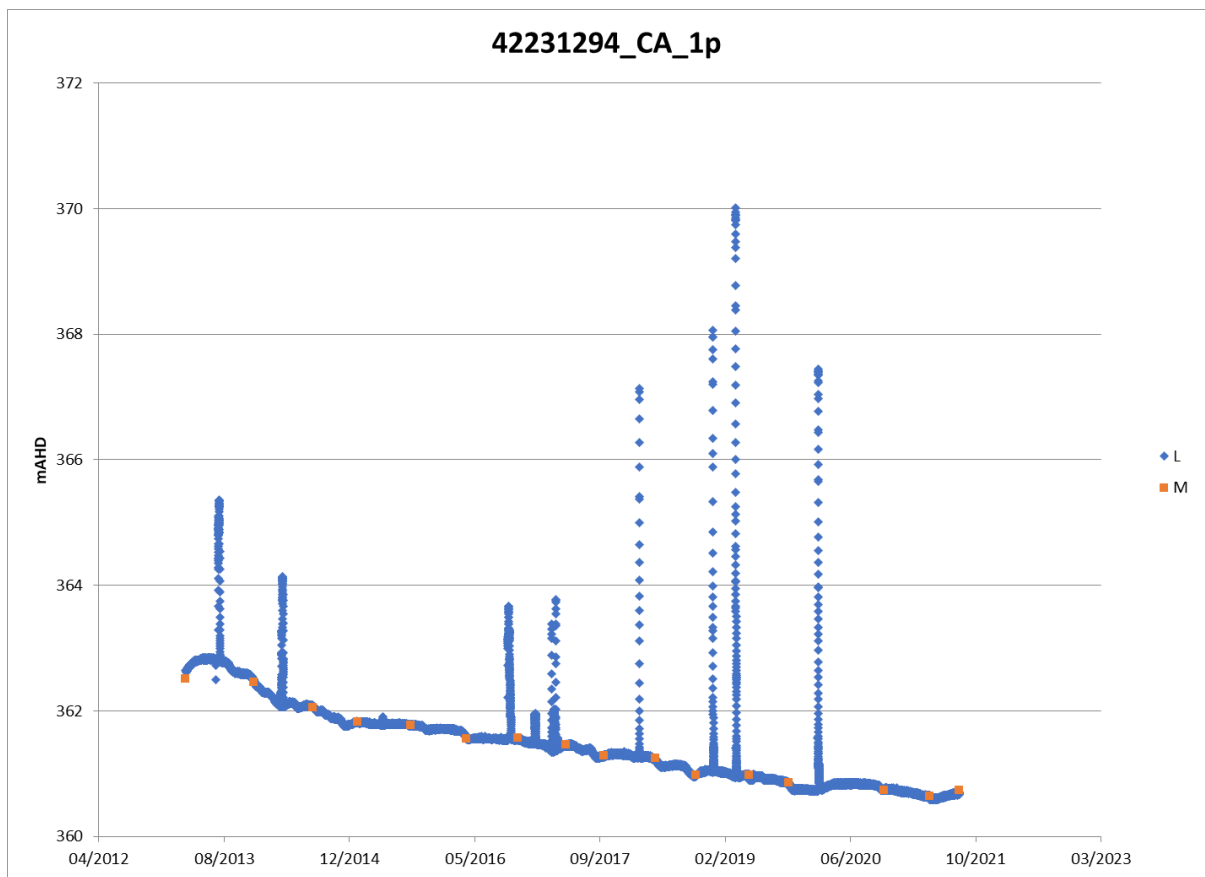
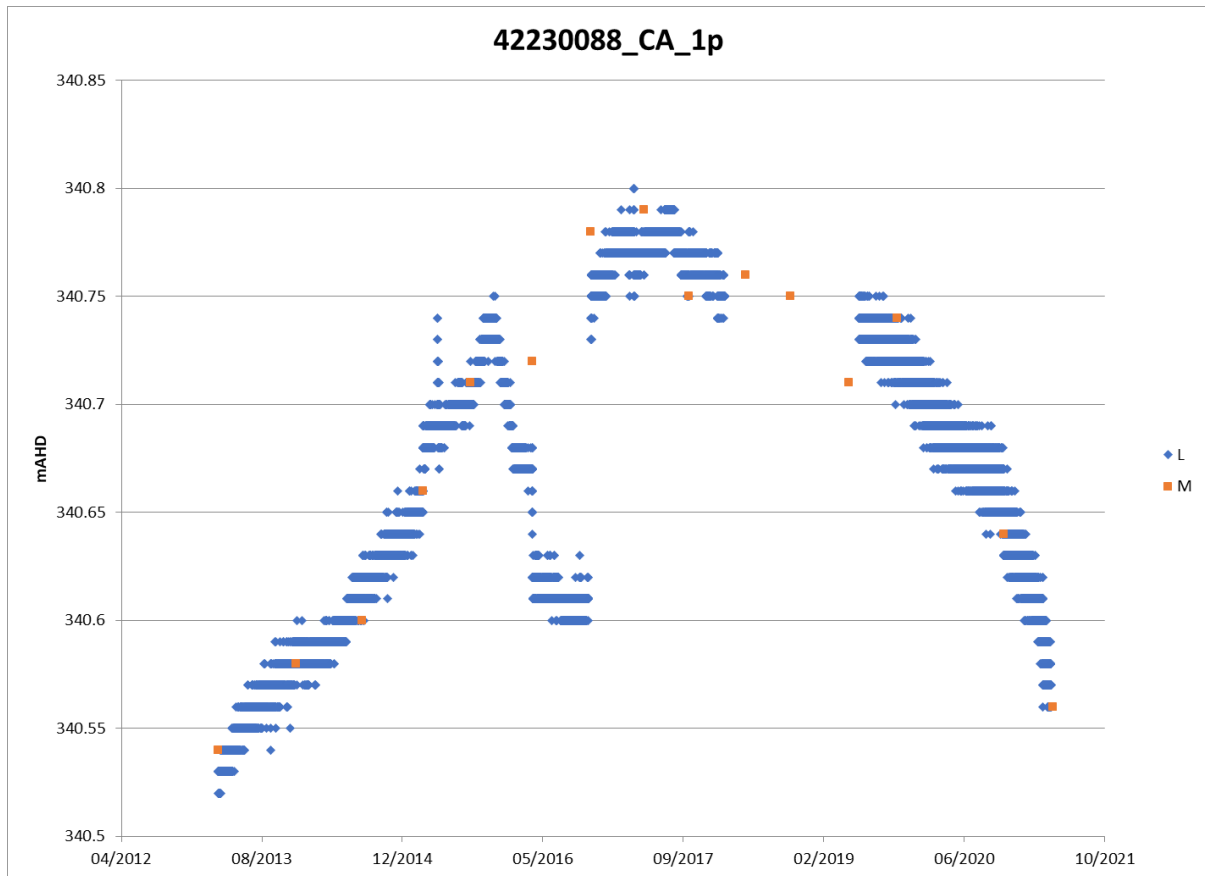
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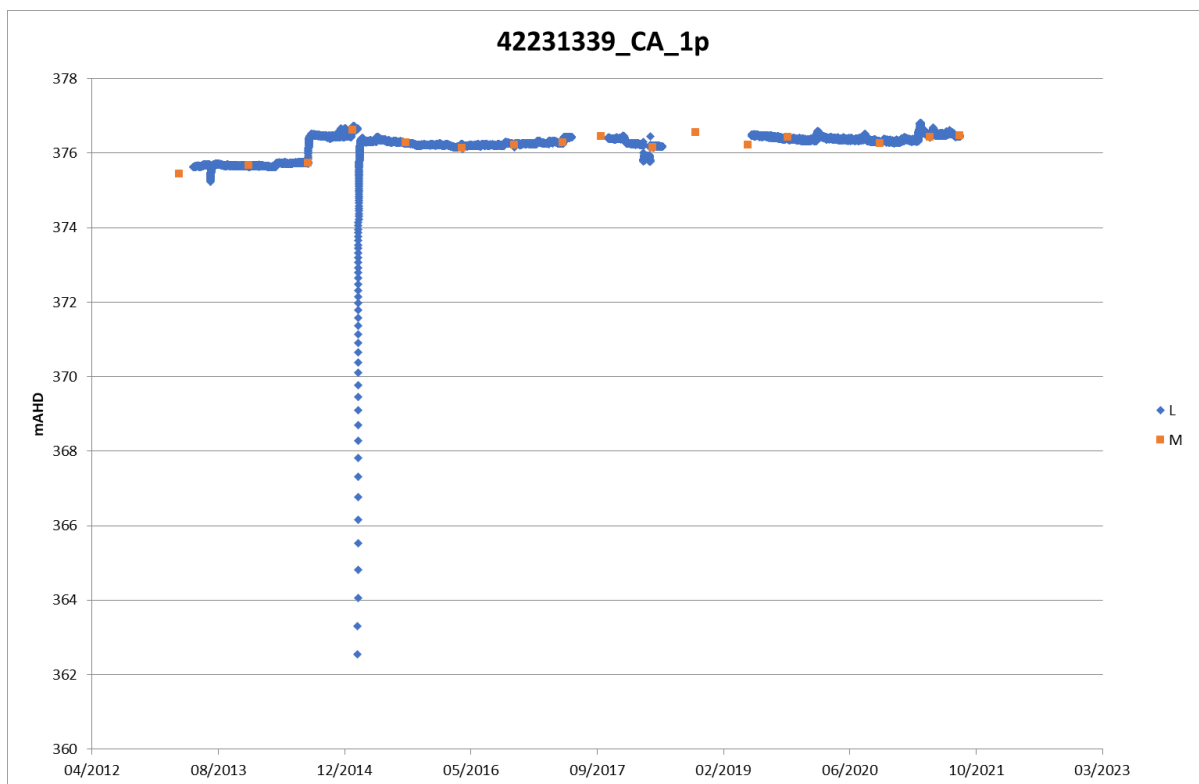
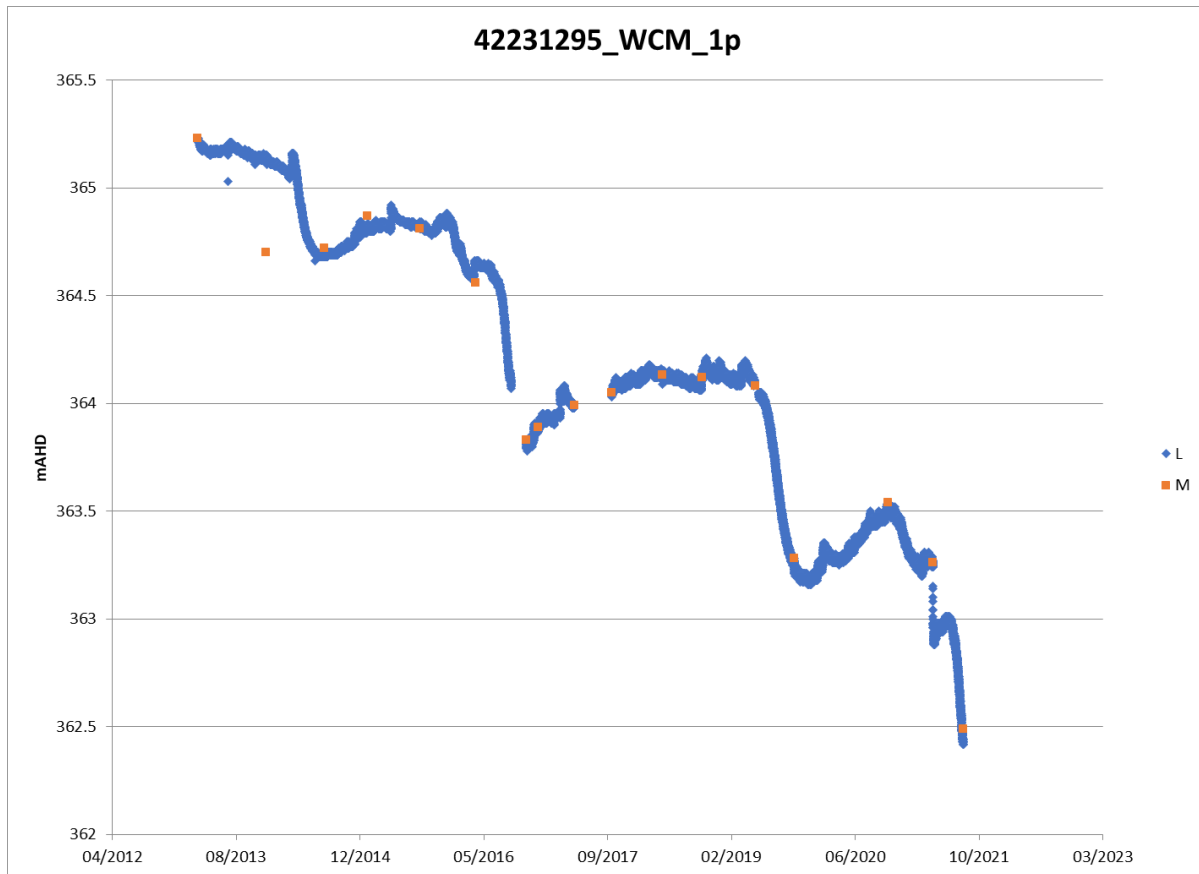
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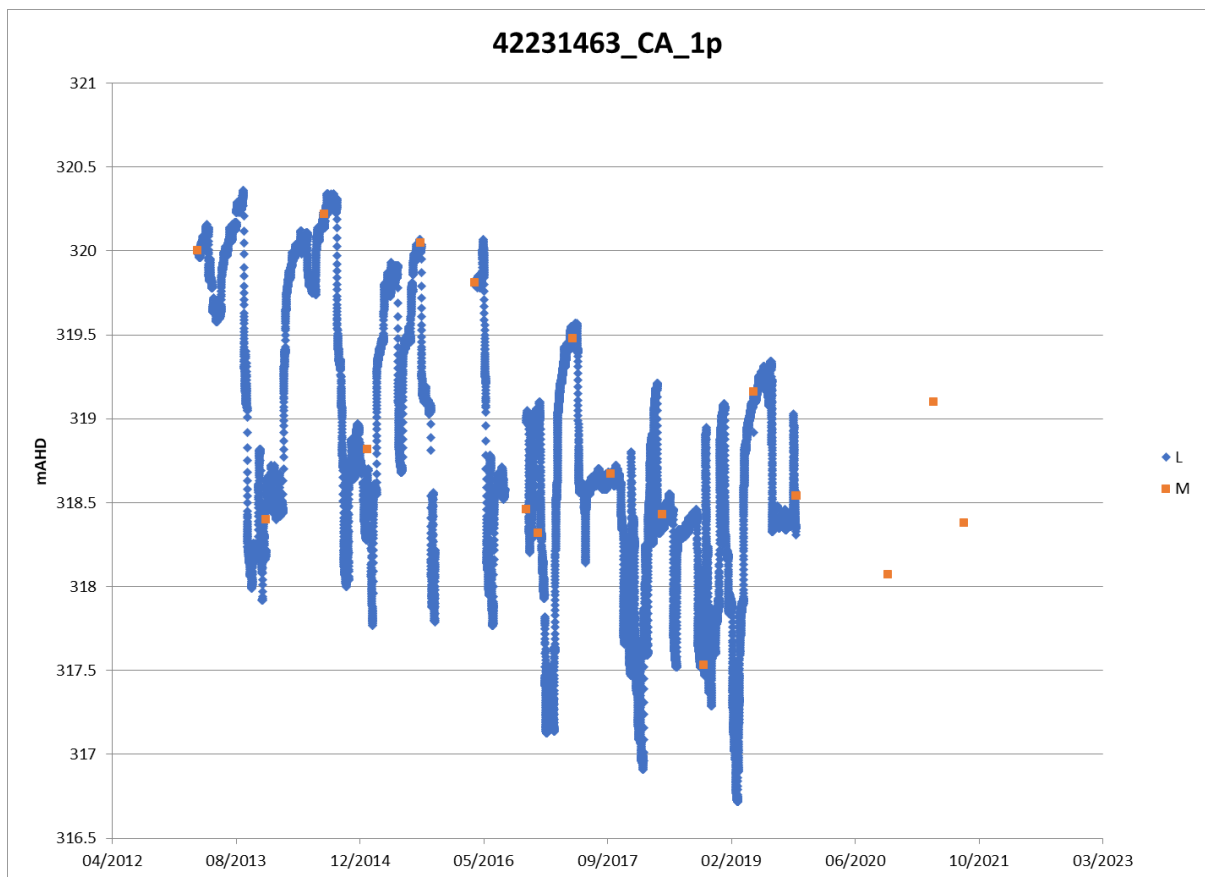
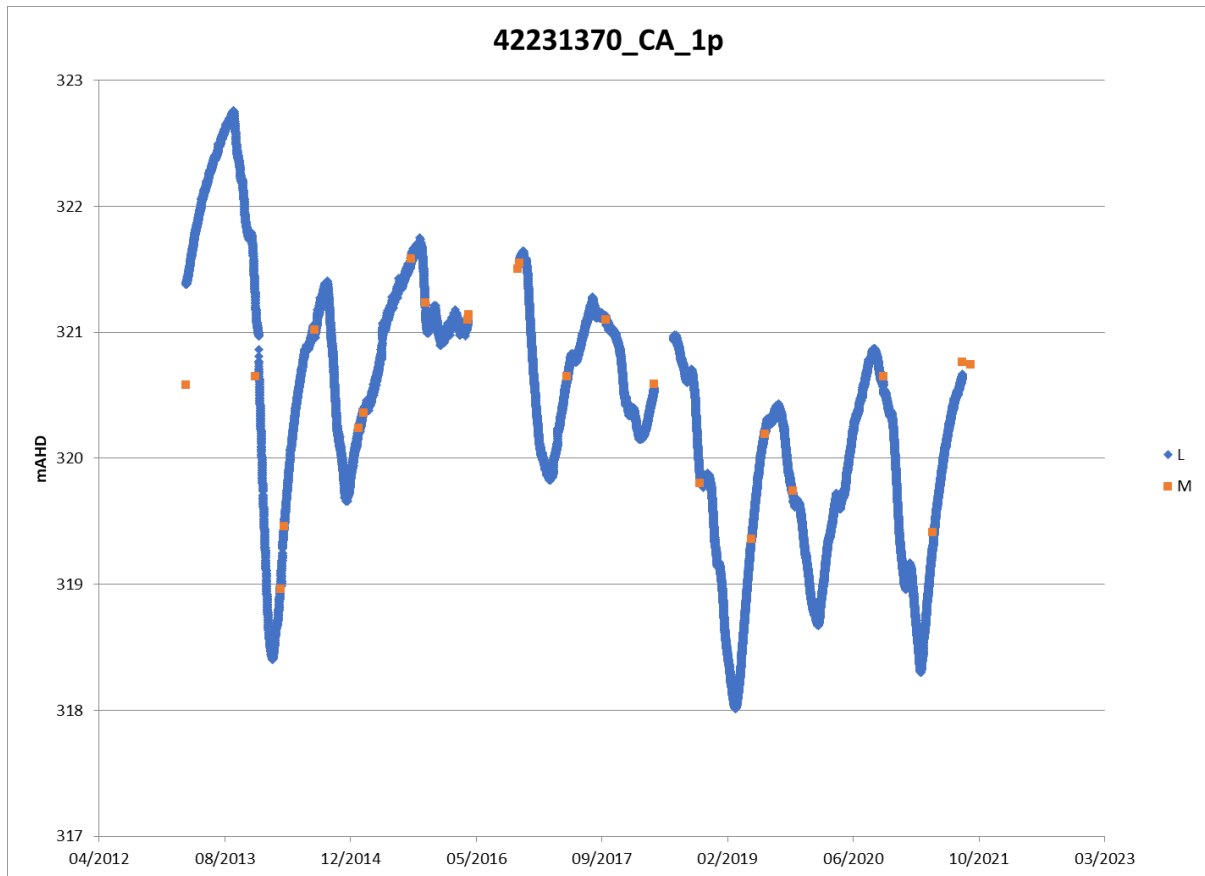
**Appendix A – Hydrographs**

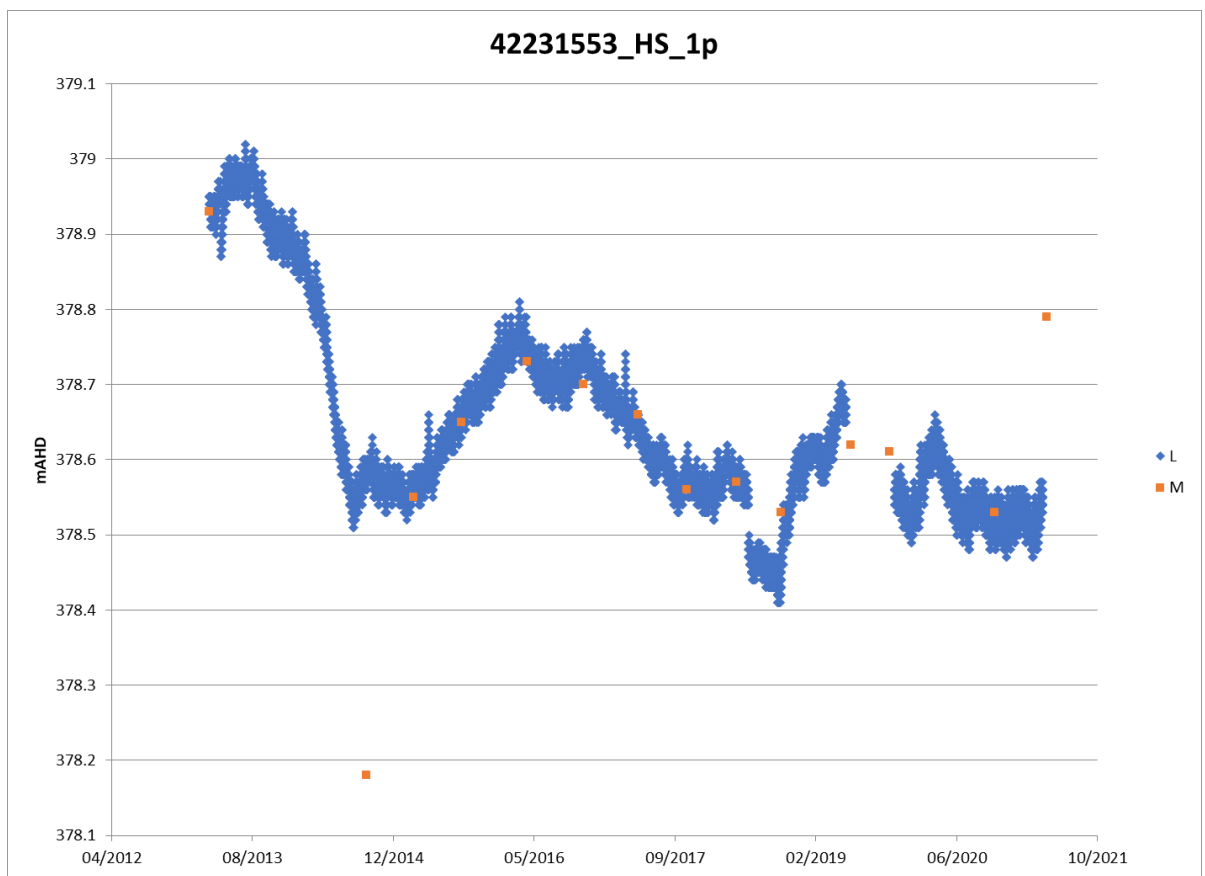
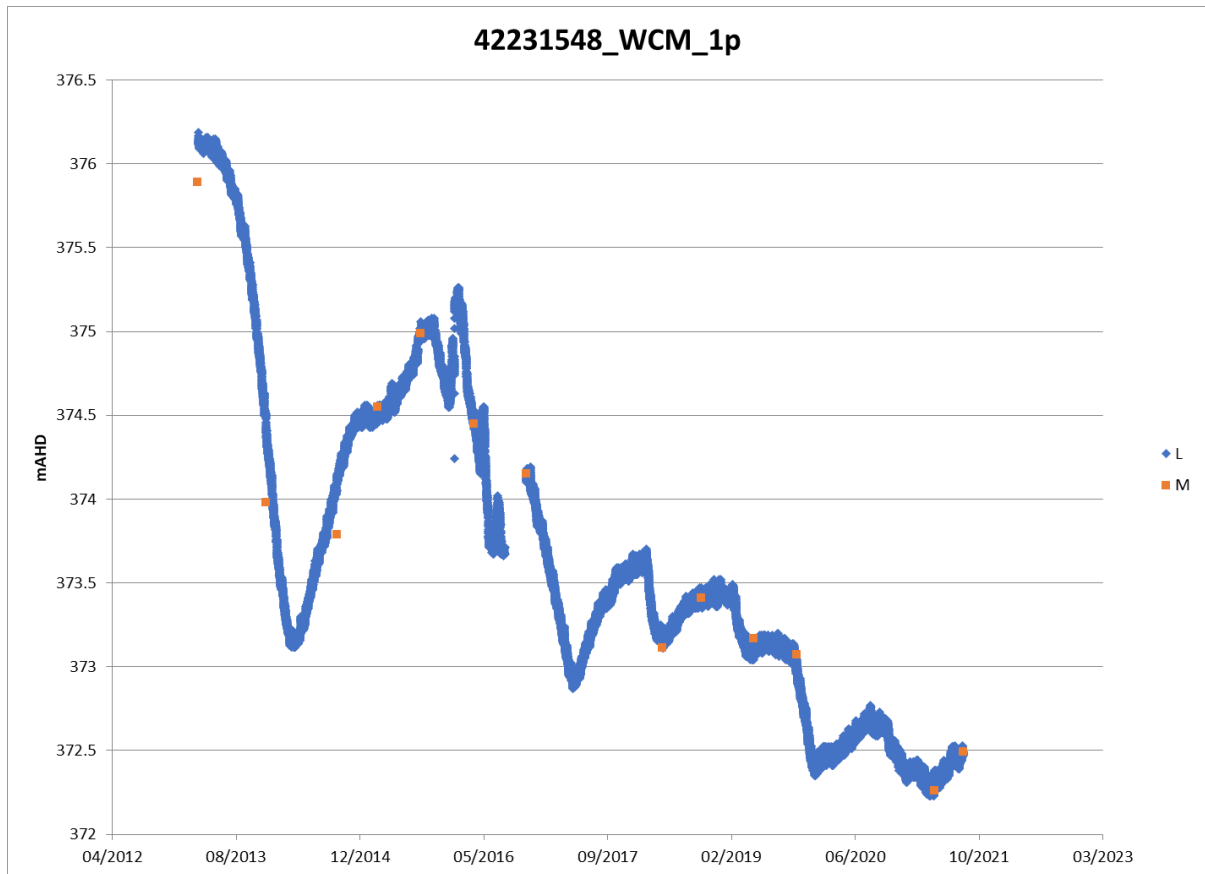


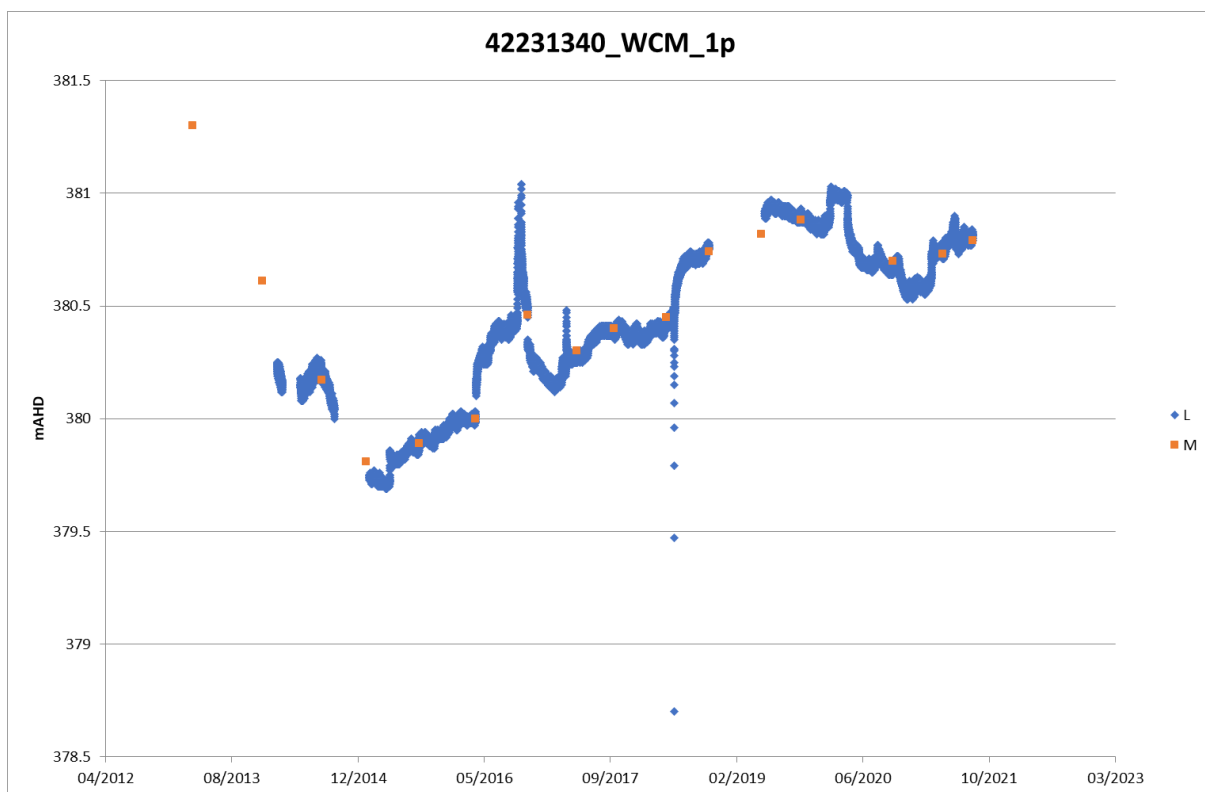
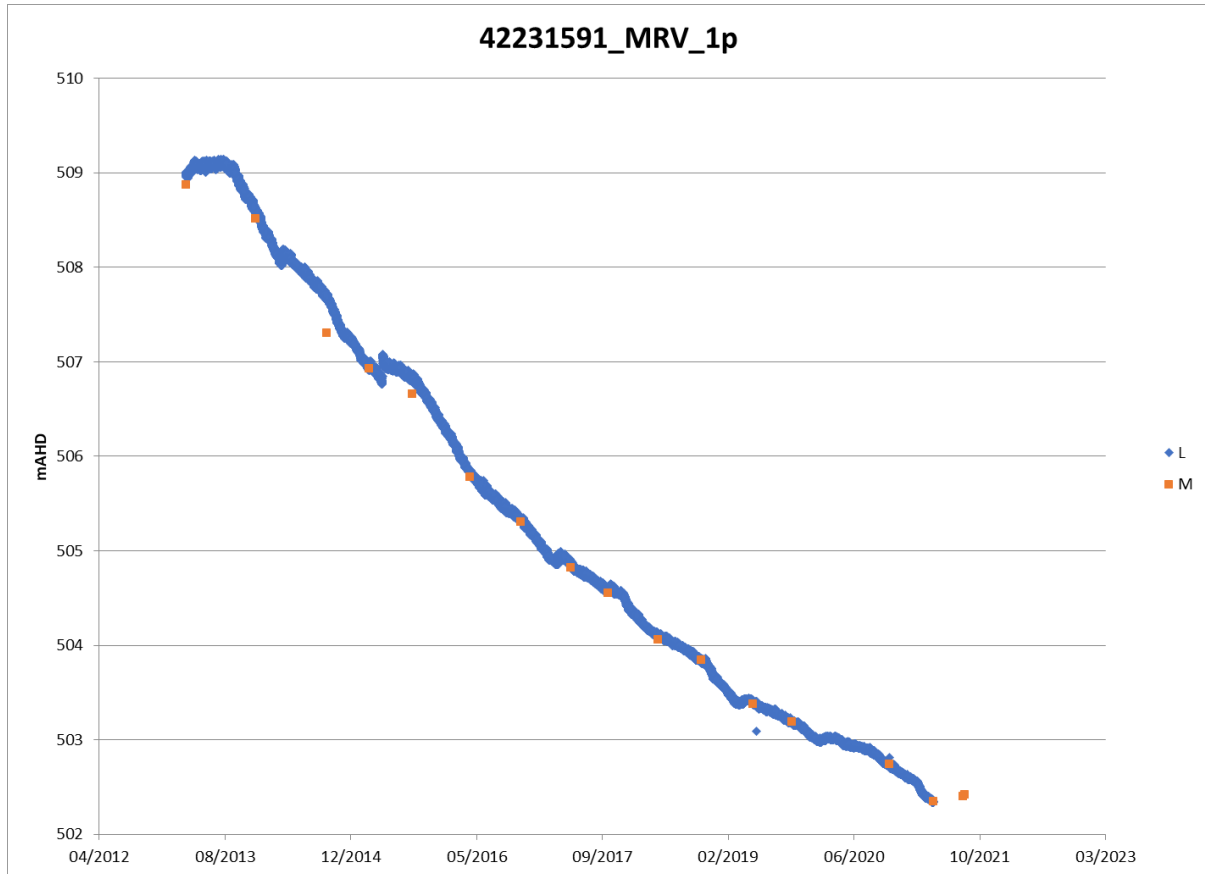


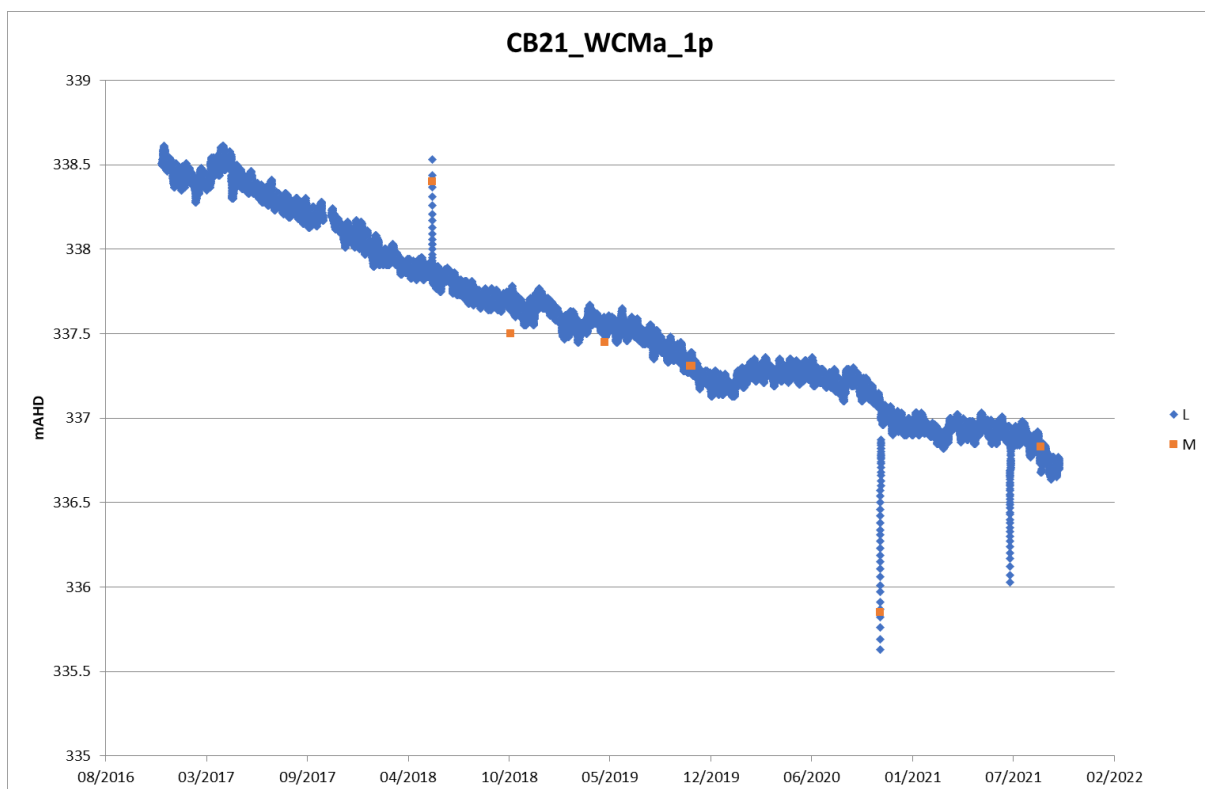
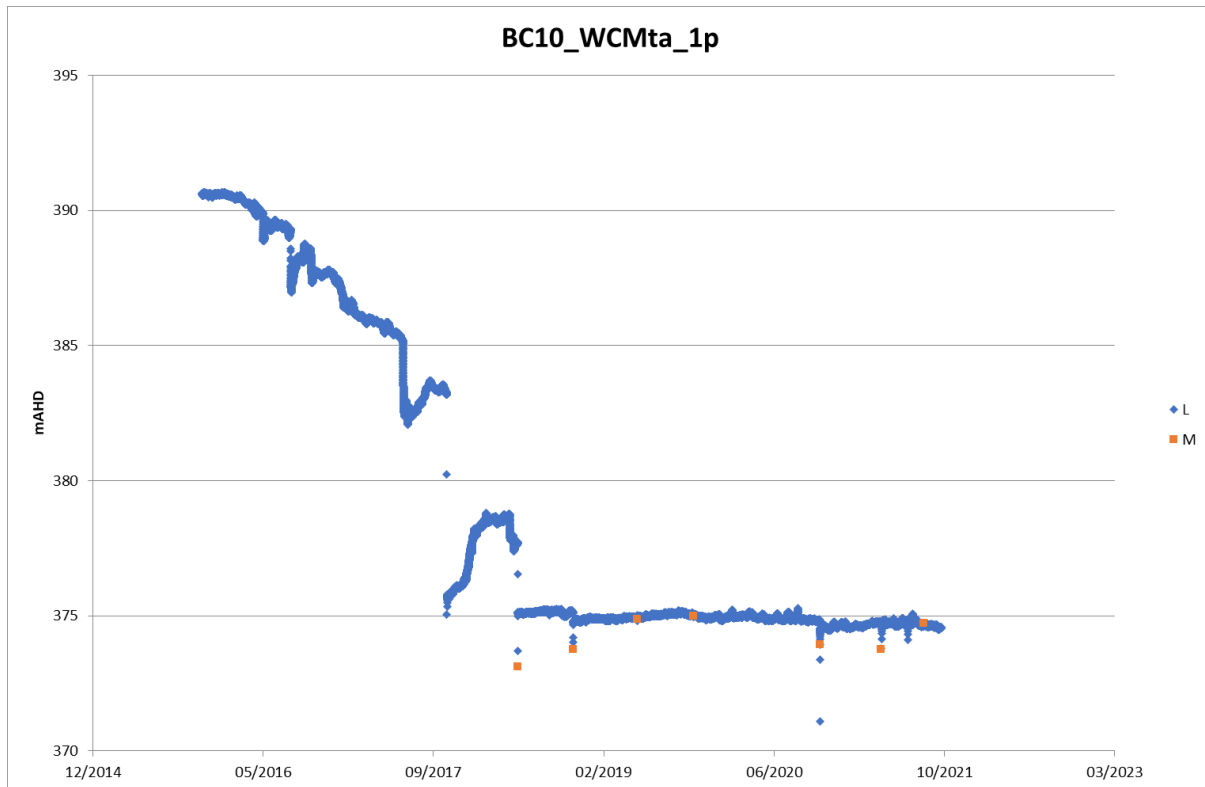


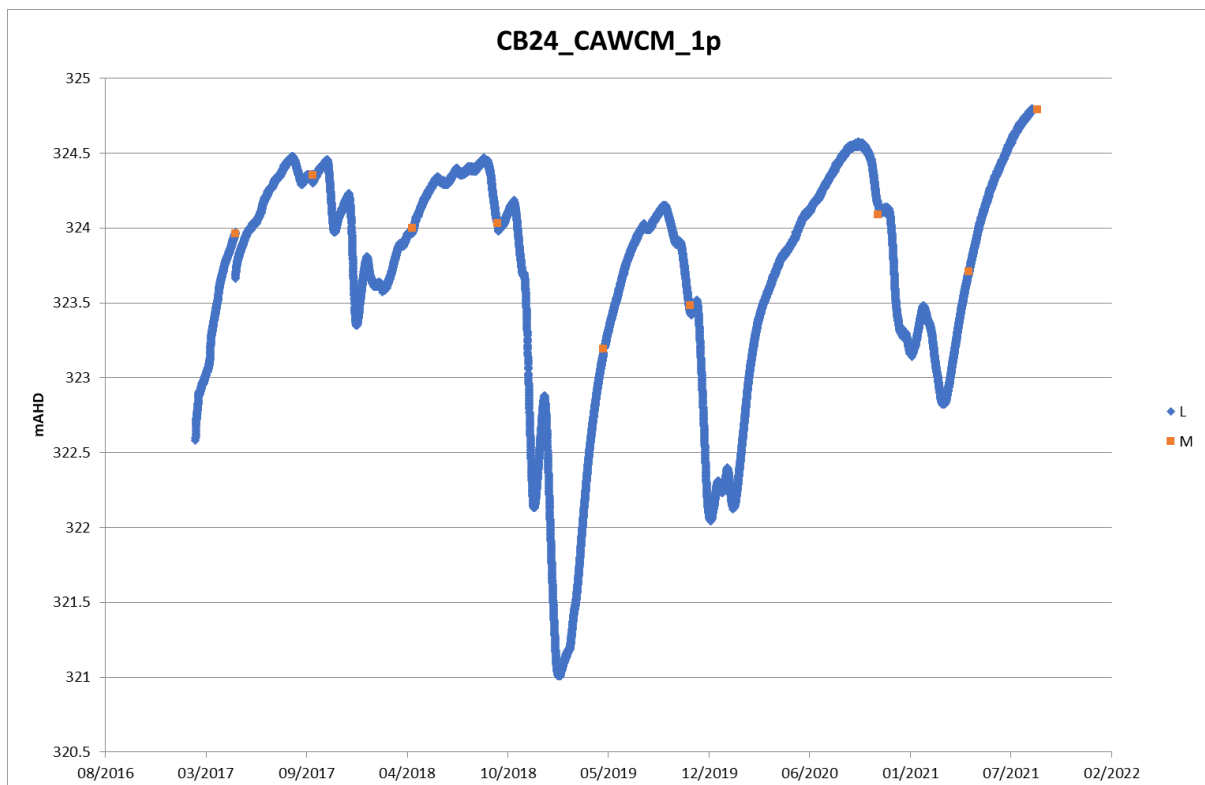
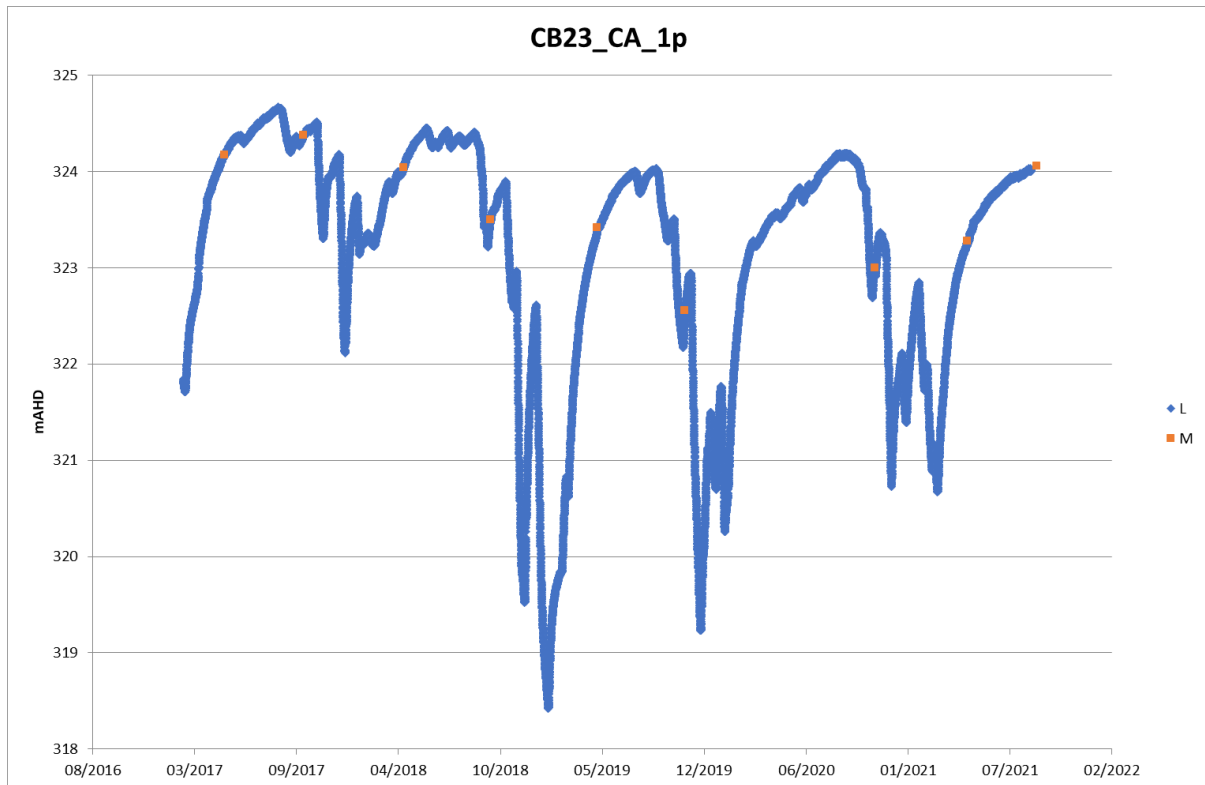




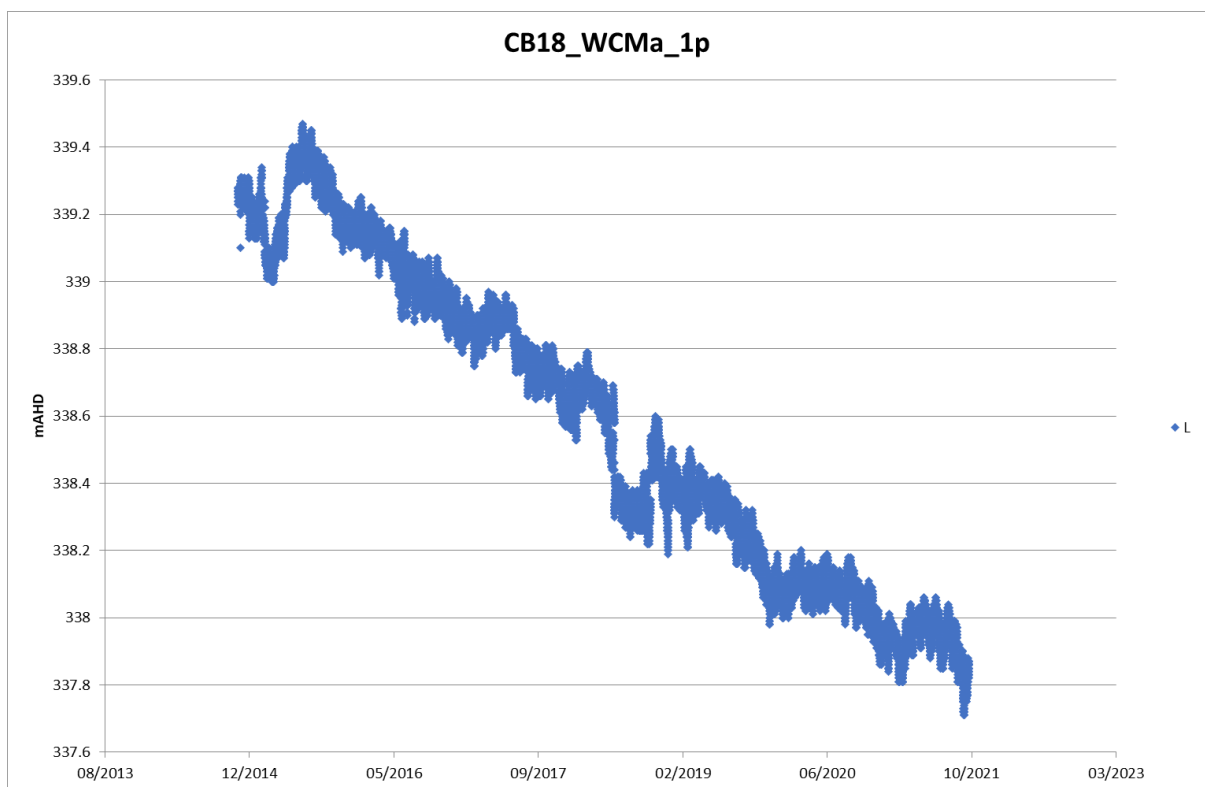
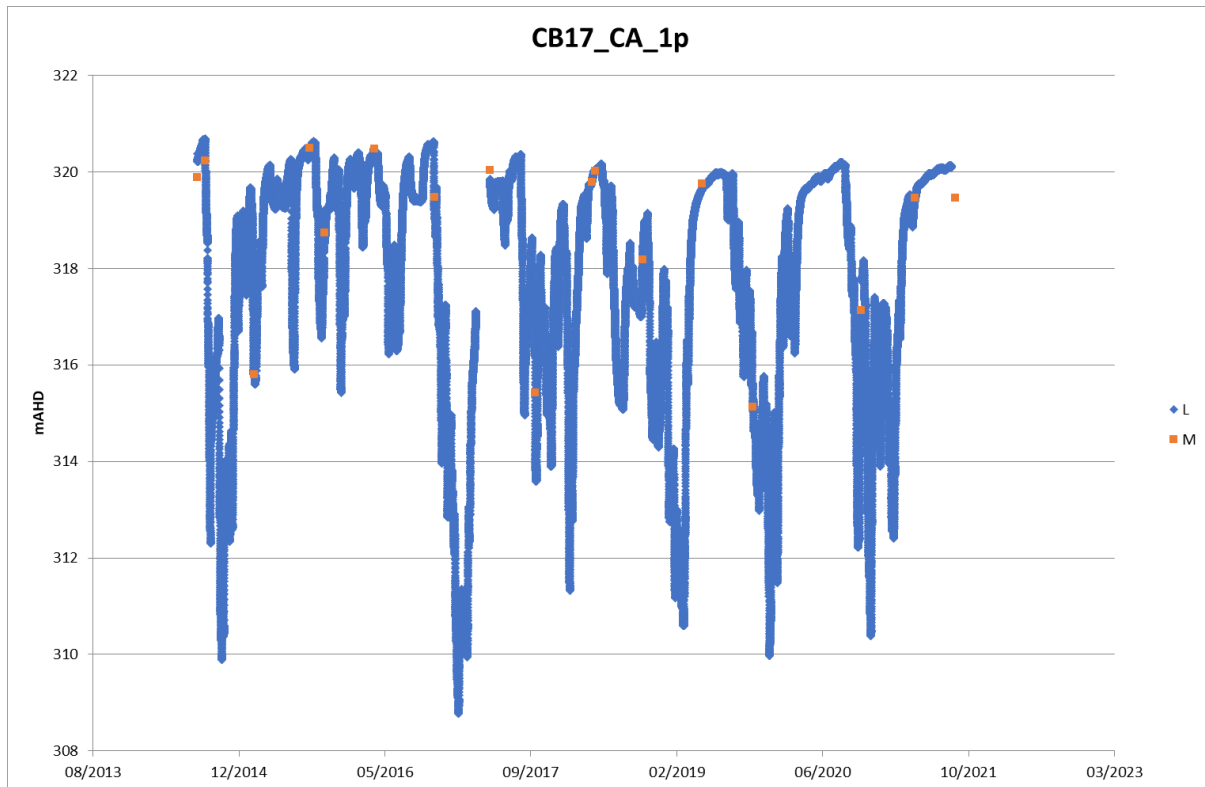


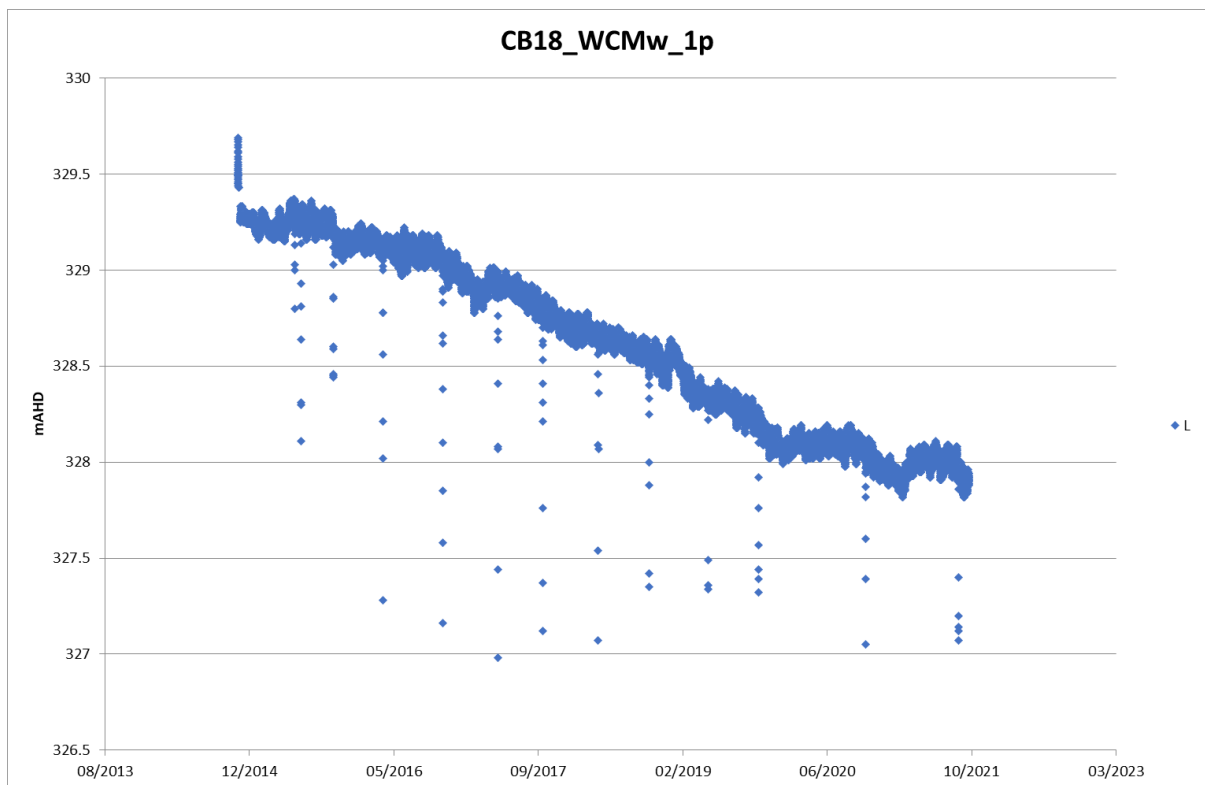
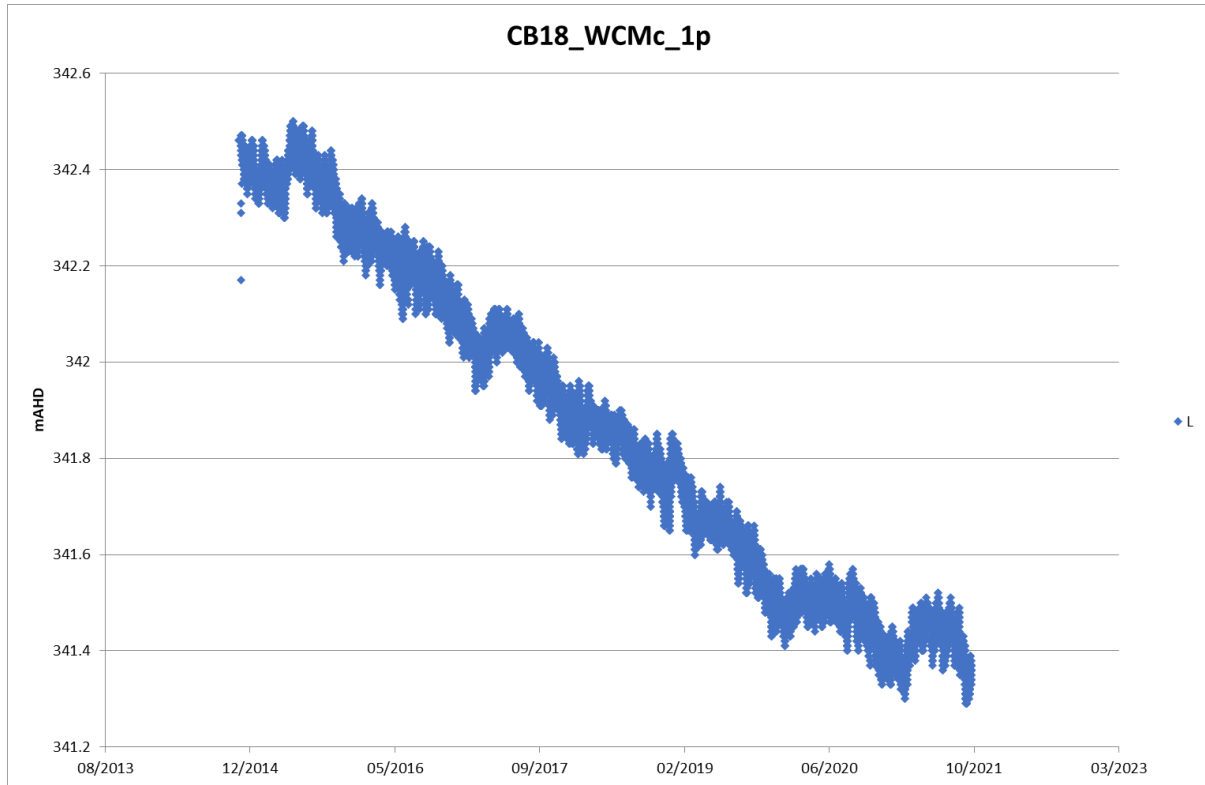


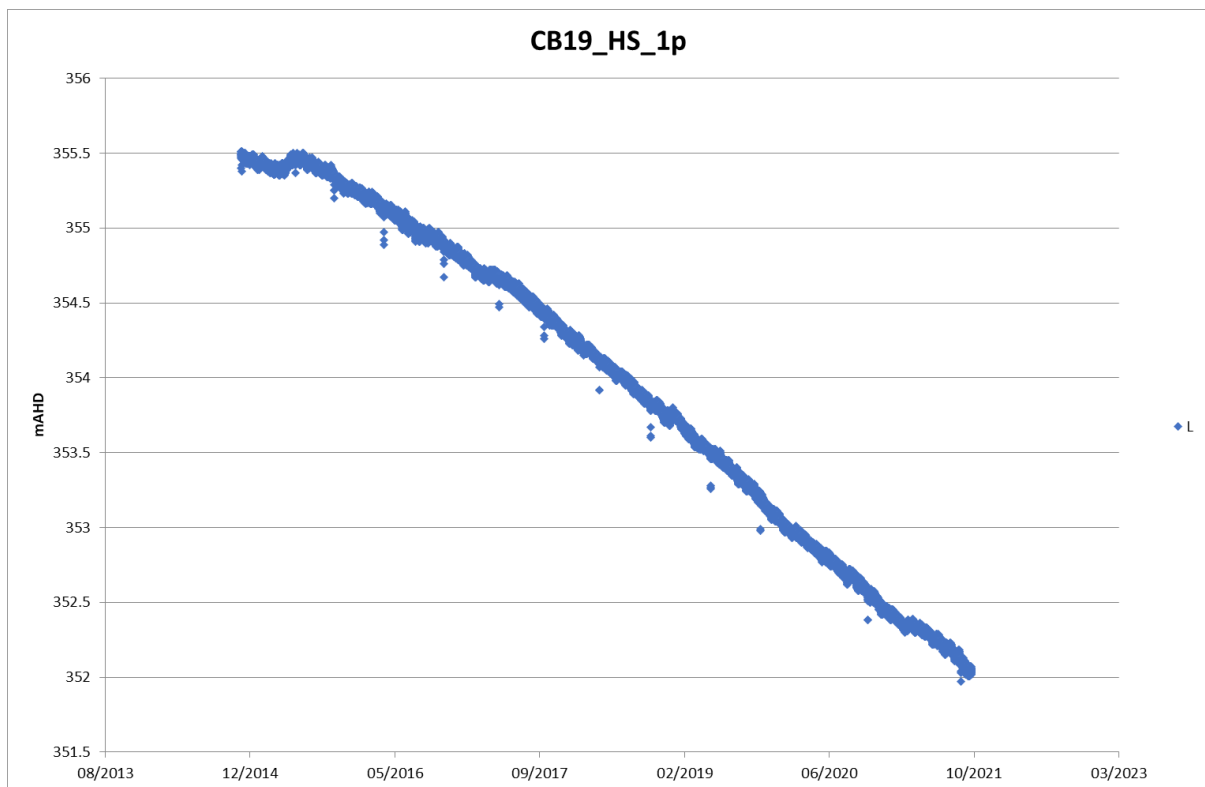
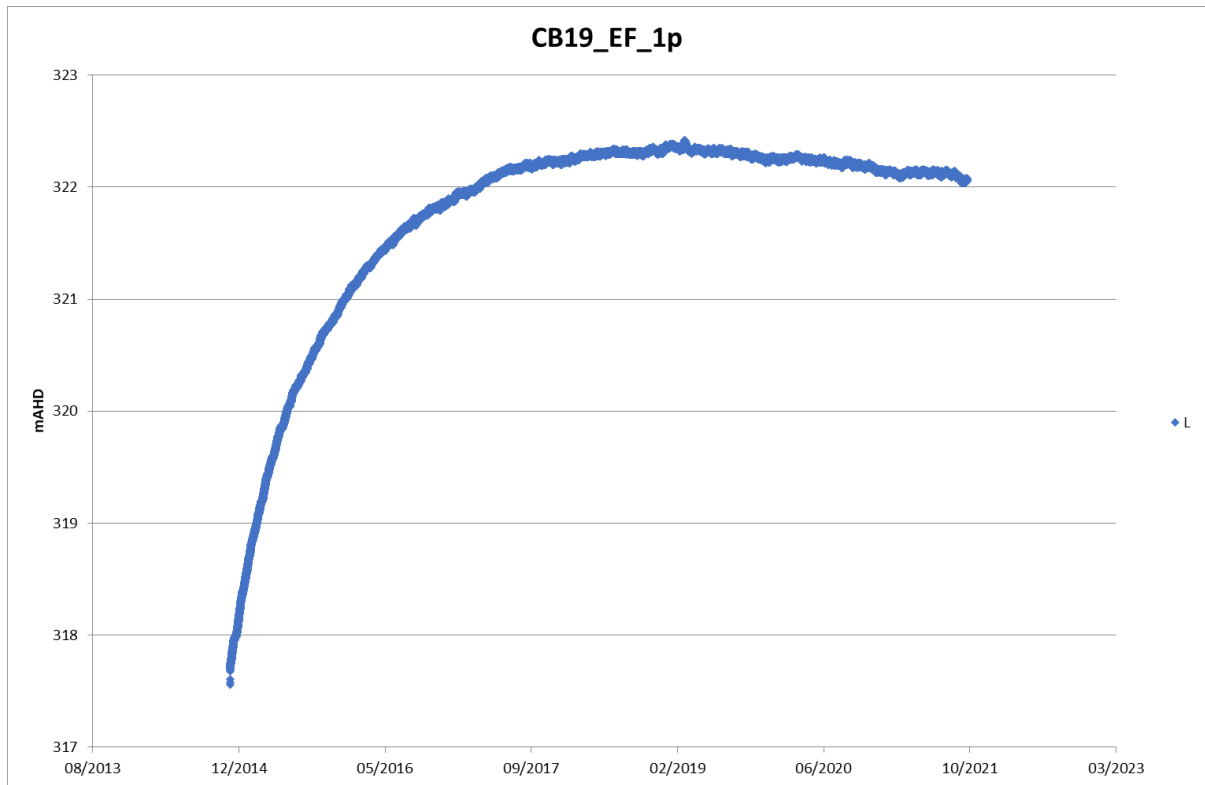


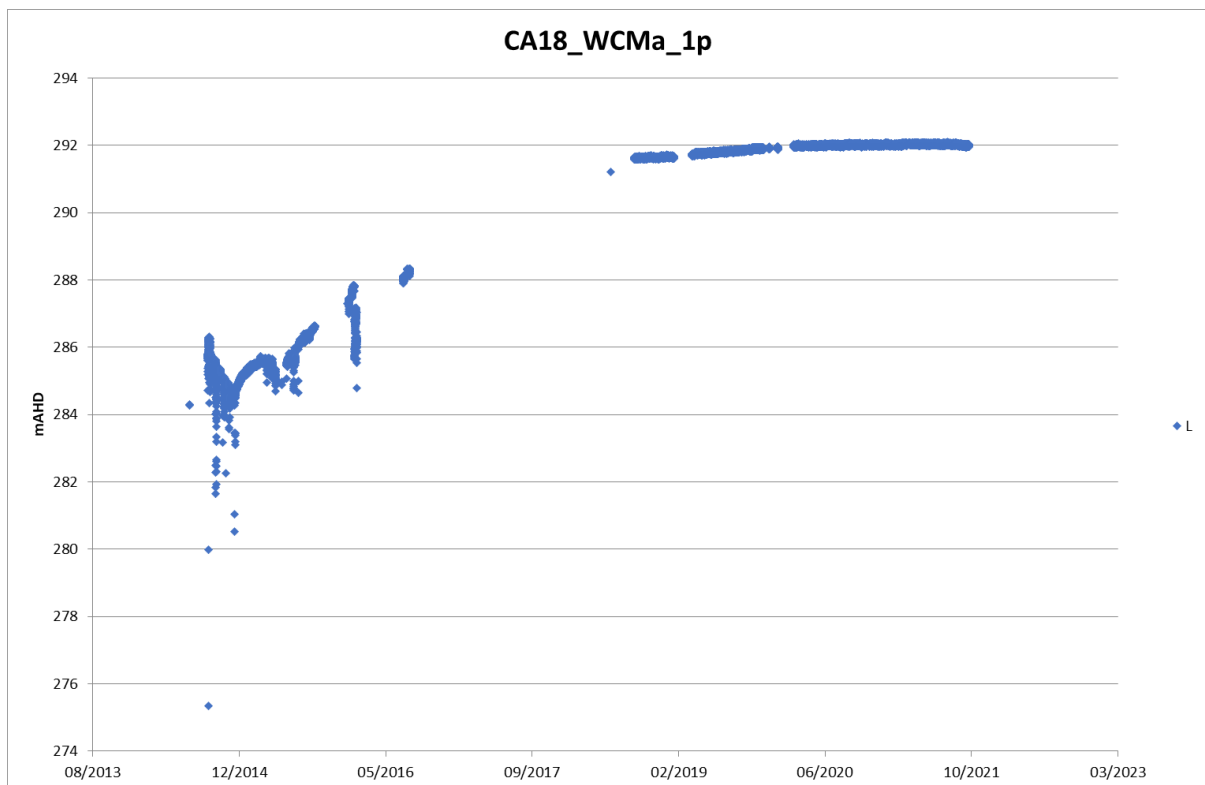
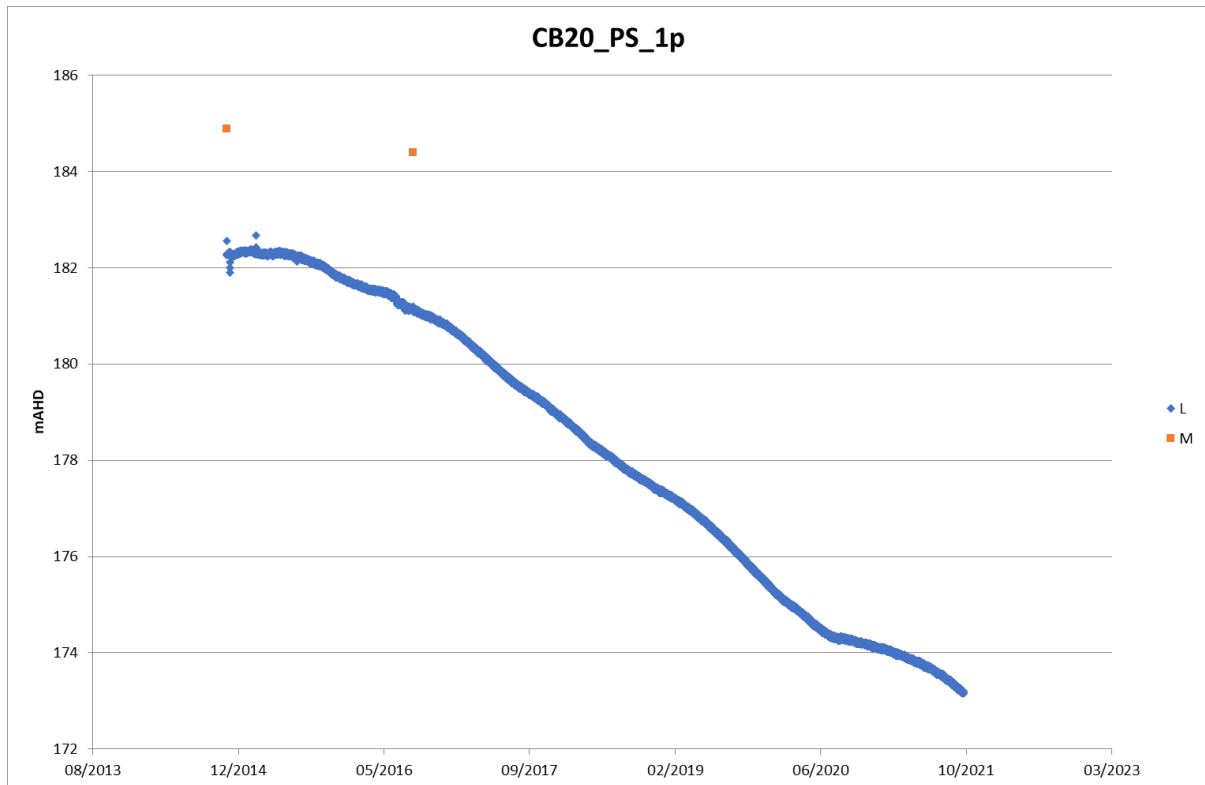


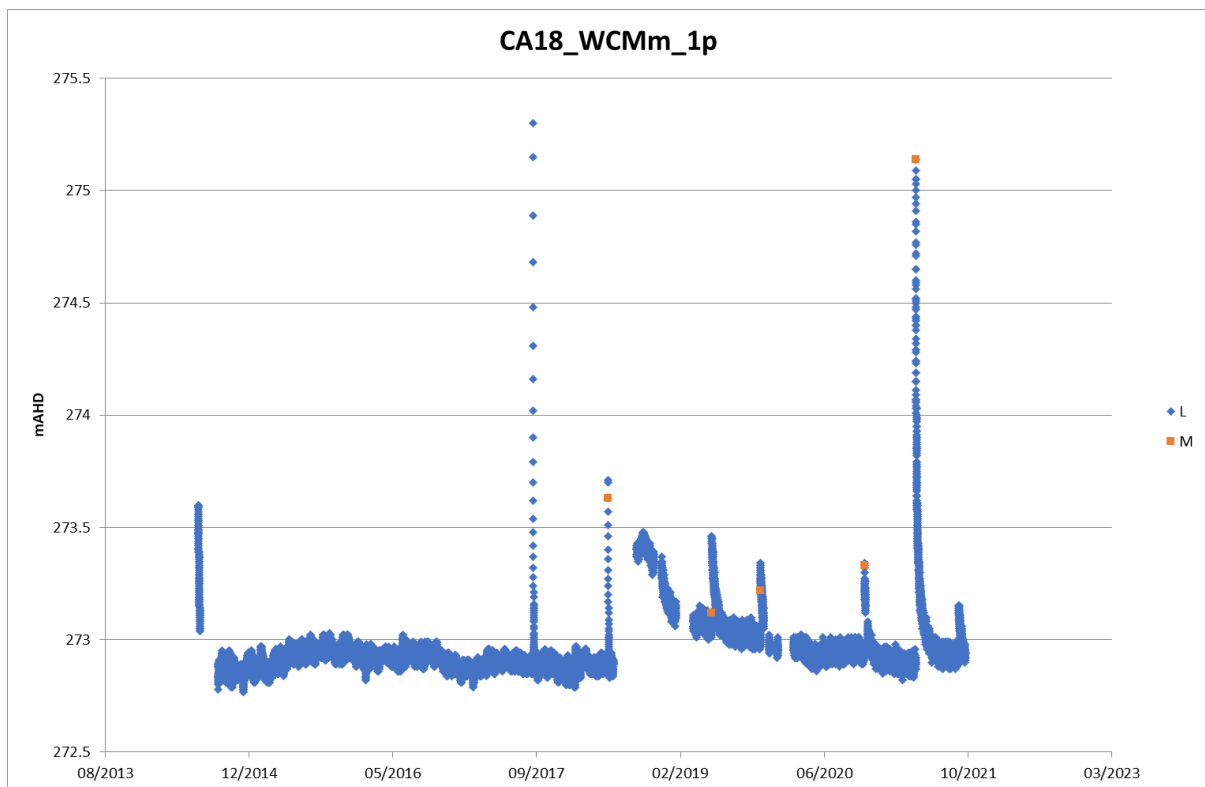
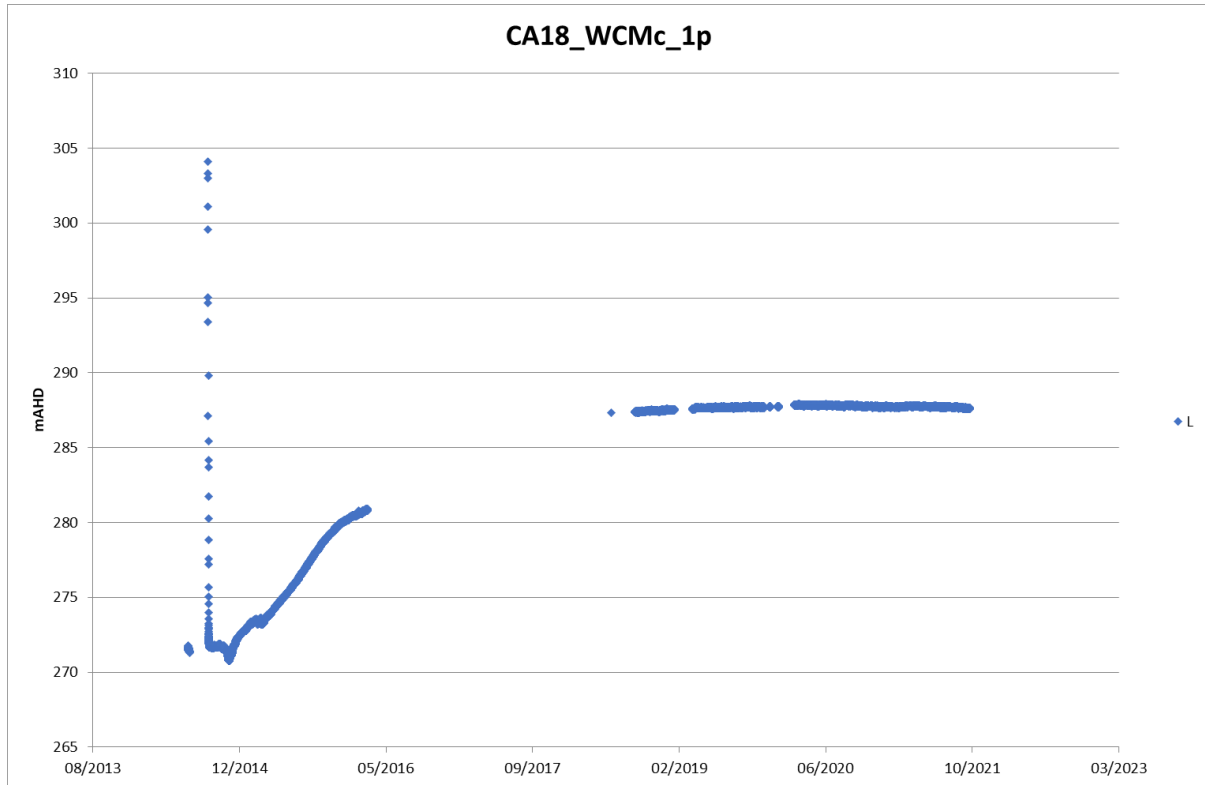


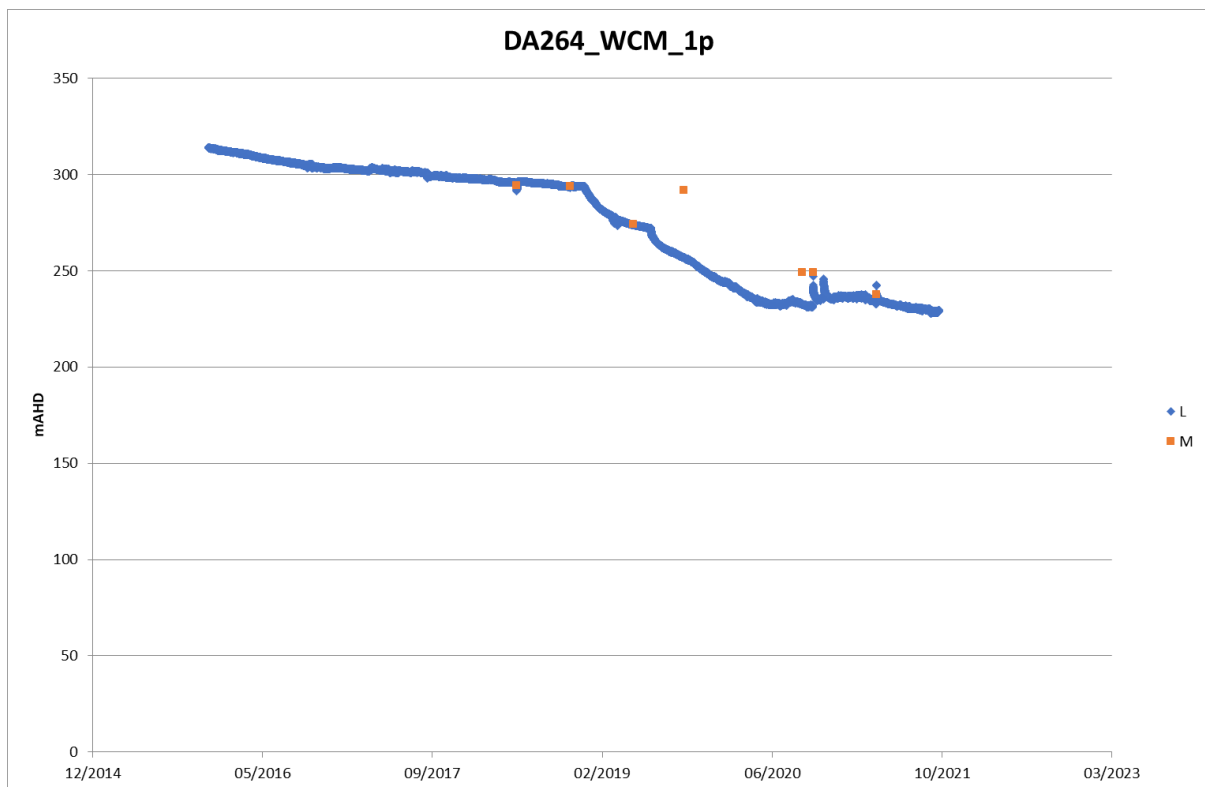
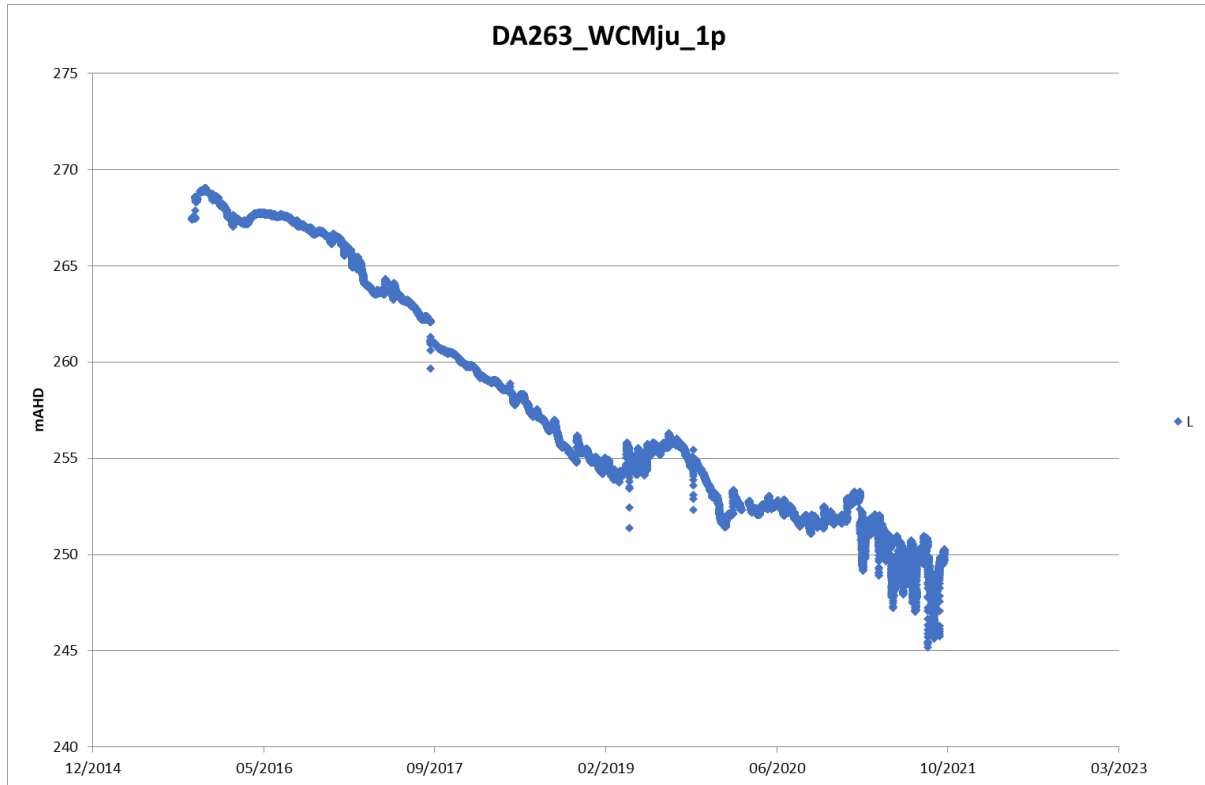


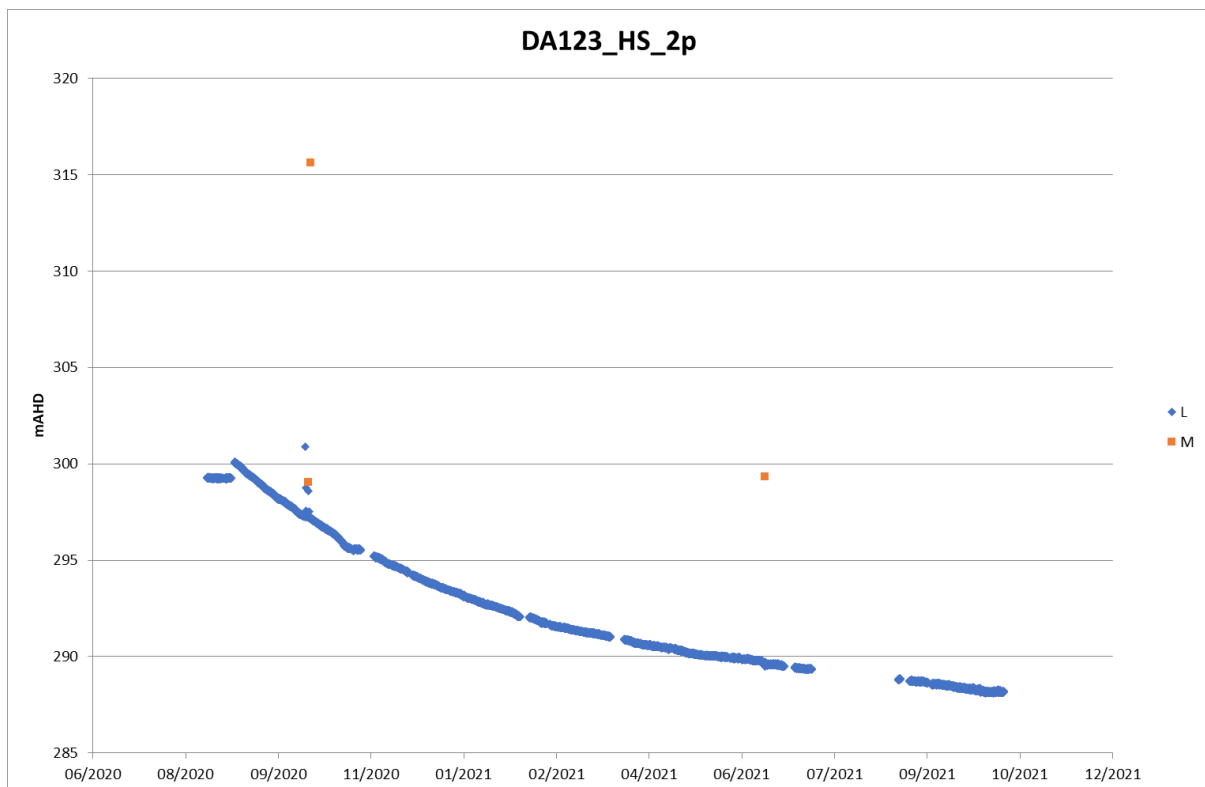
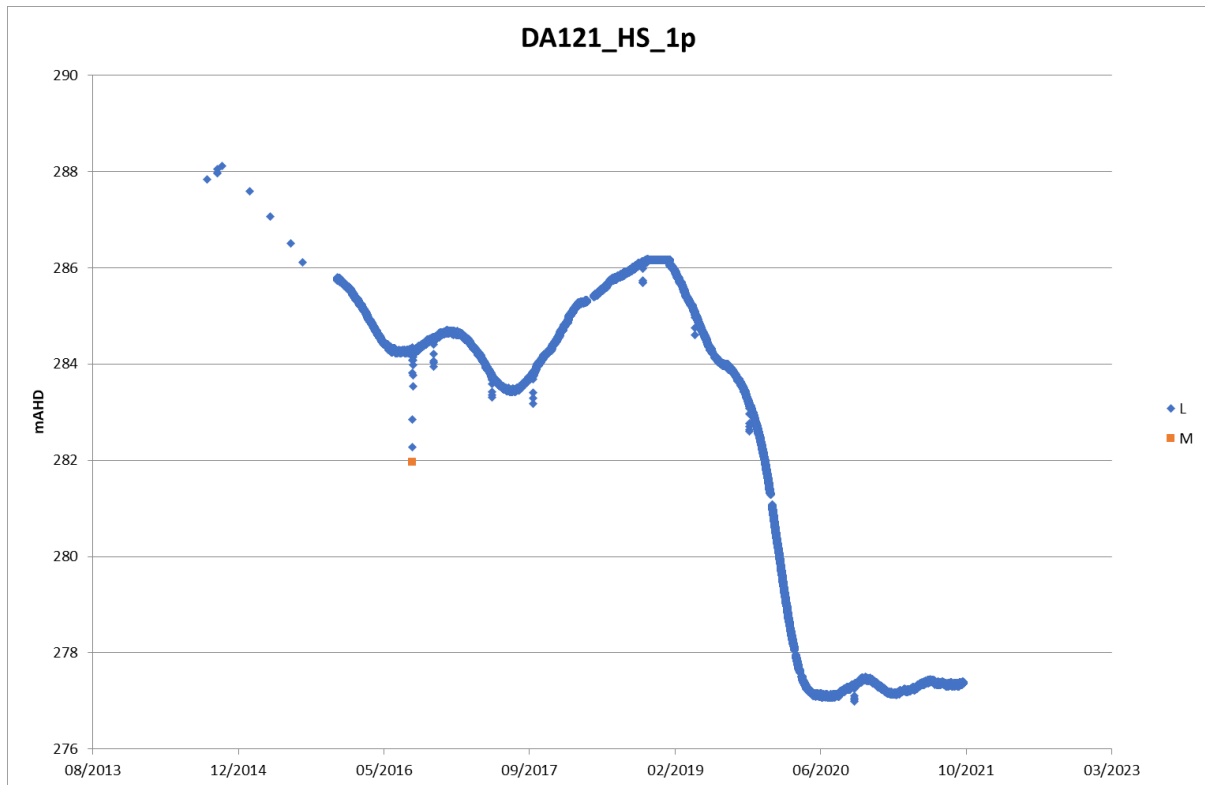


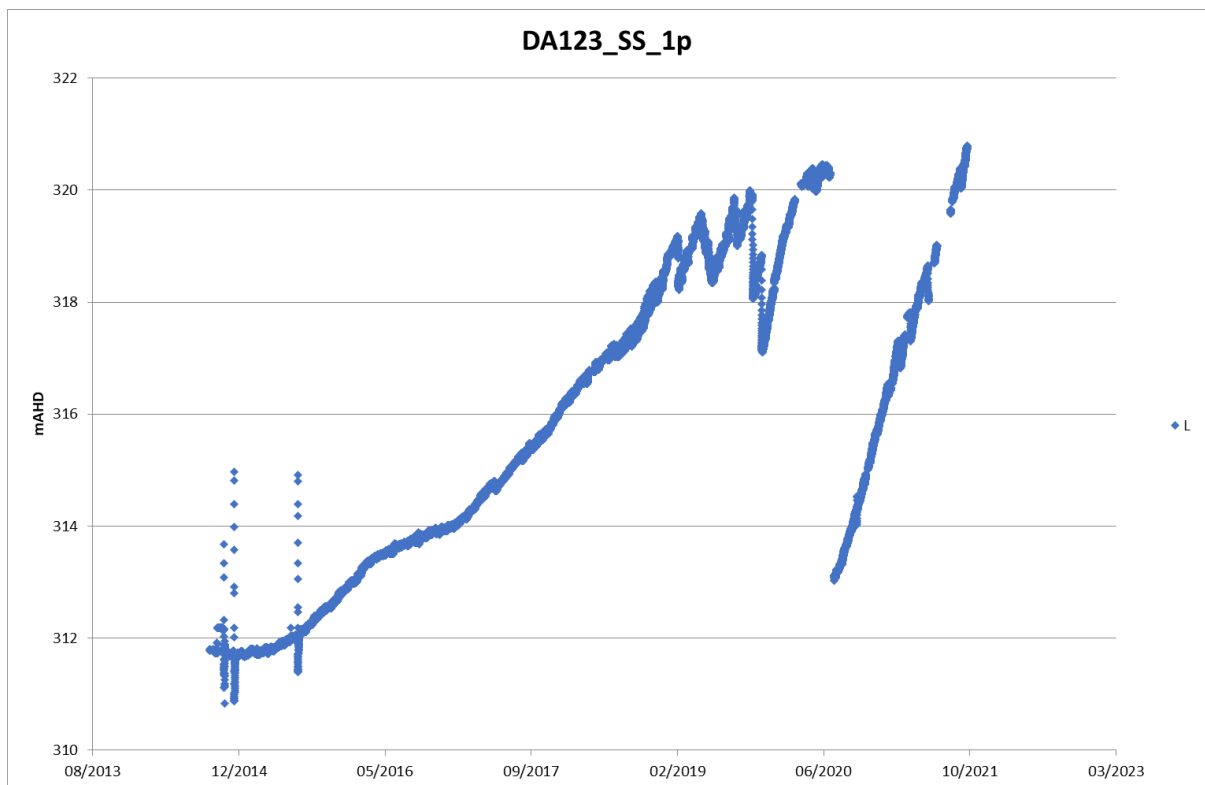
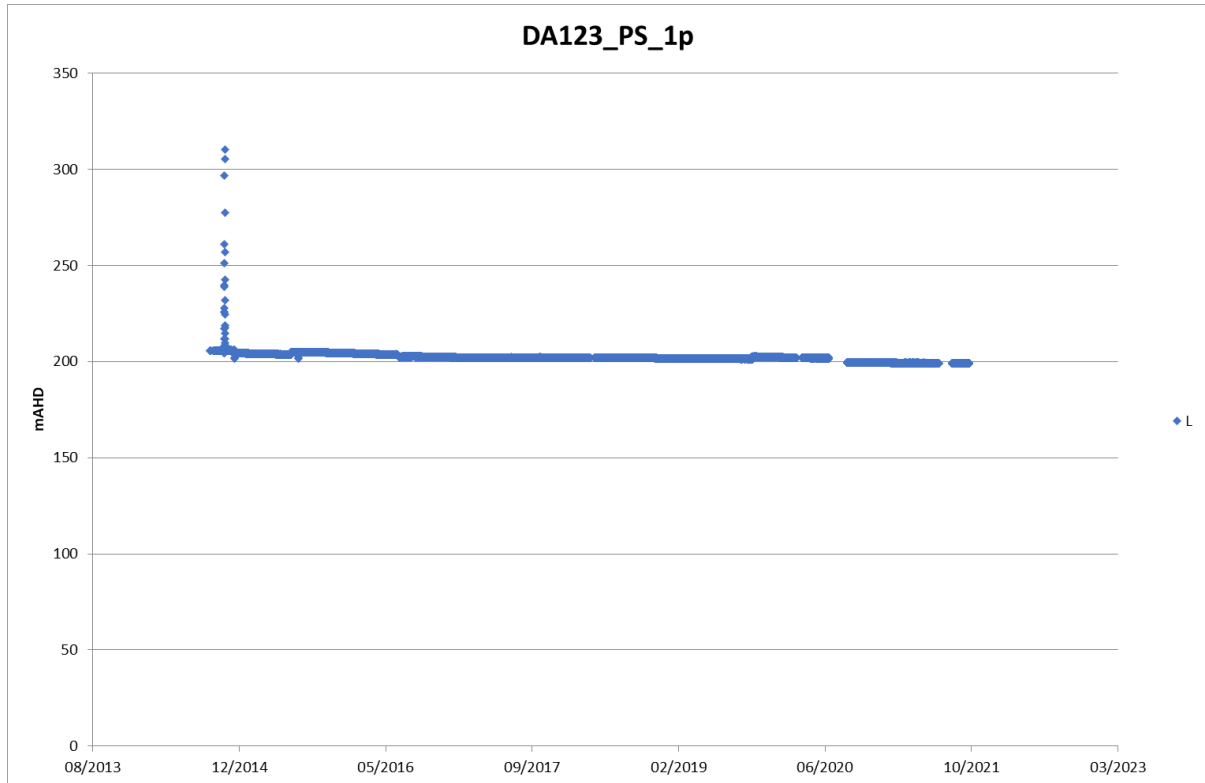




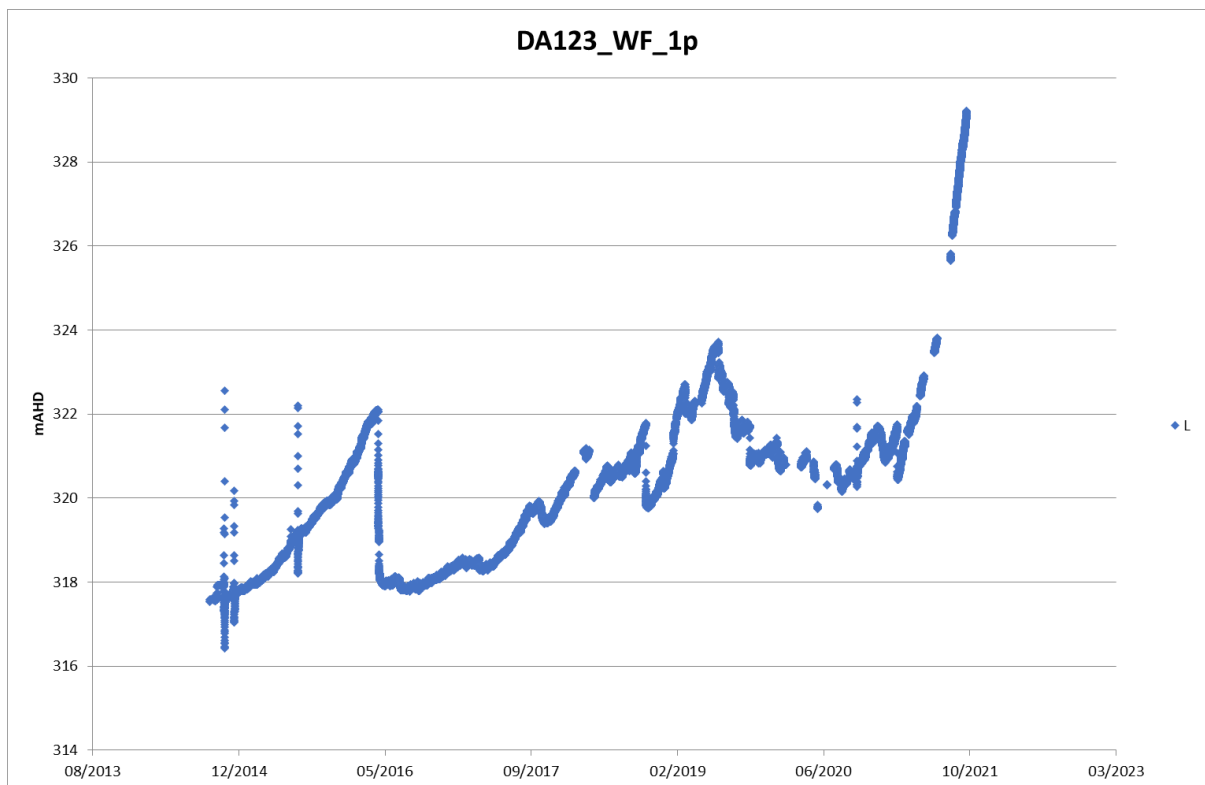
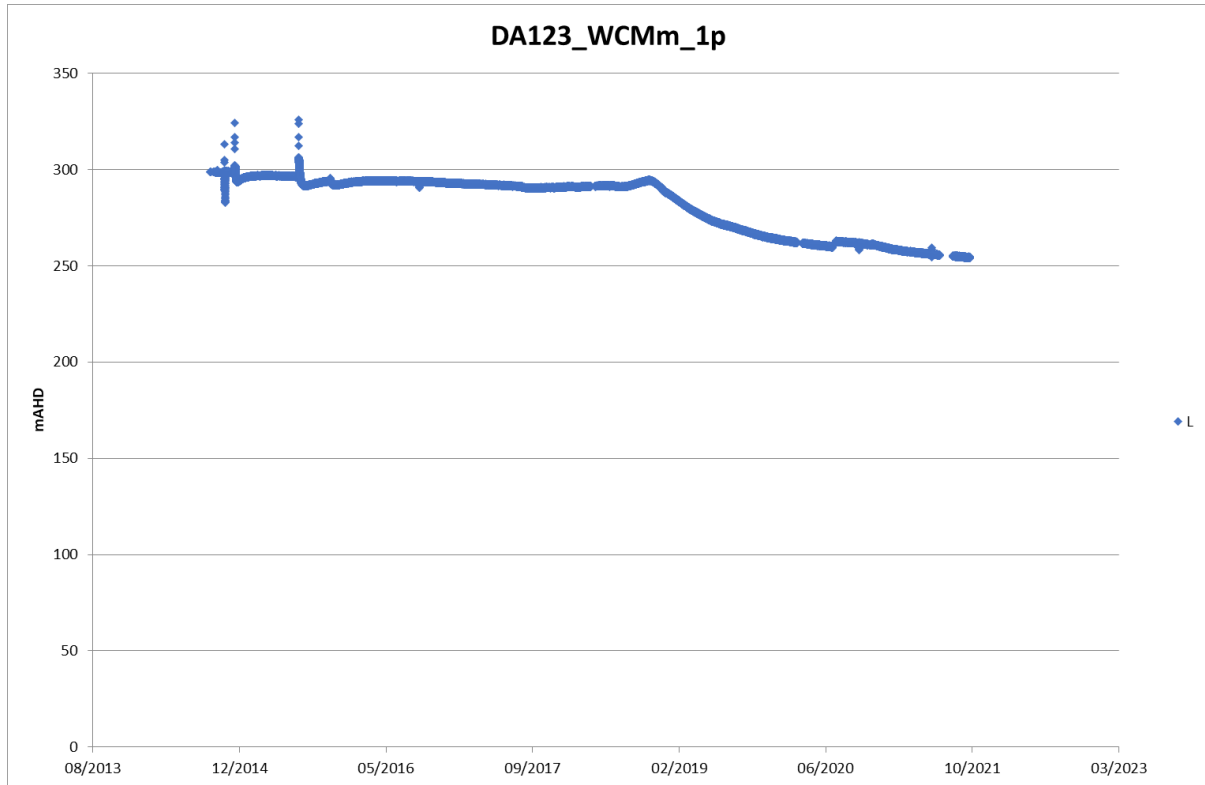


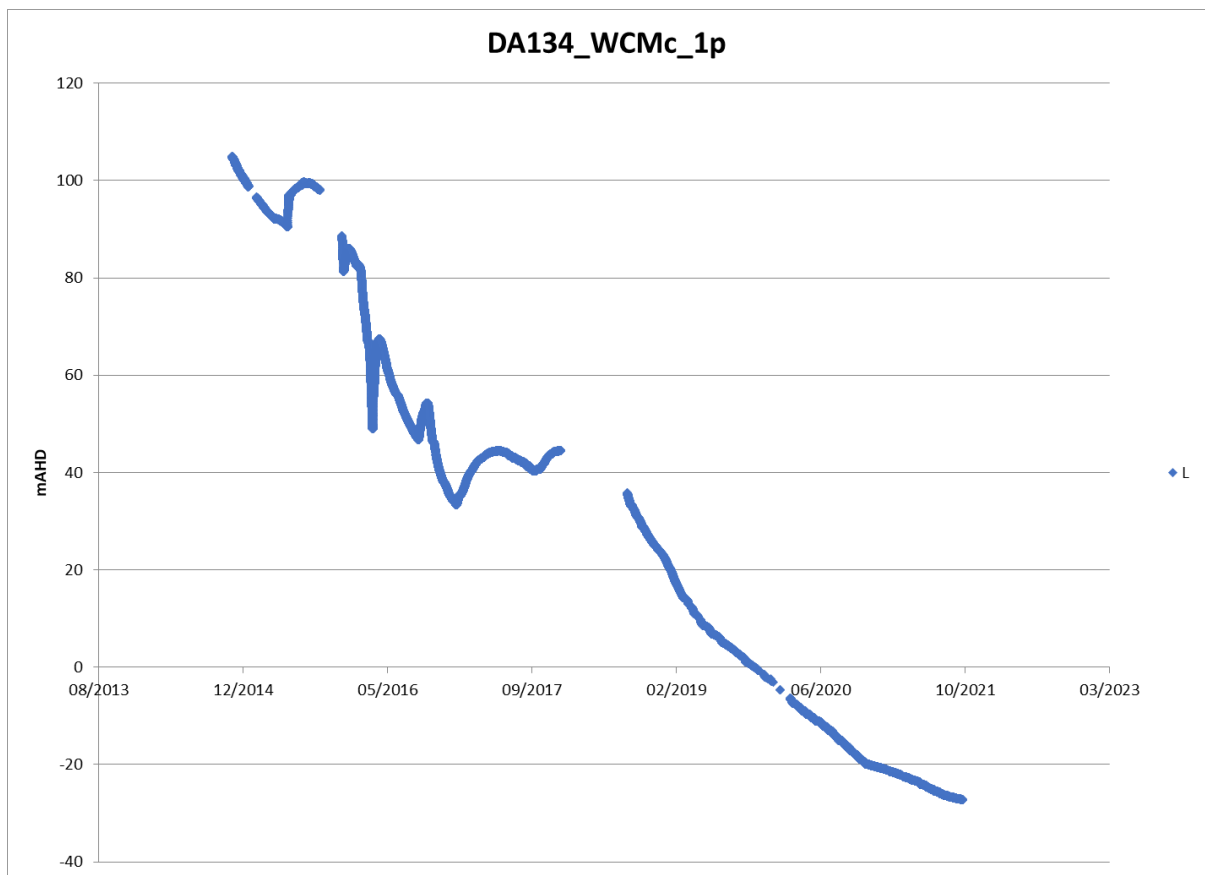
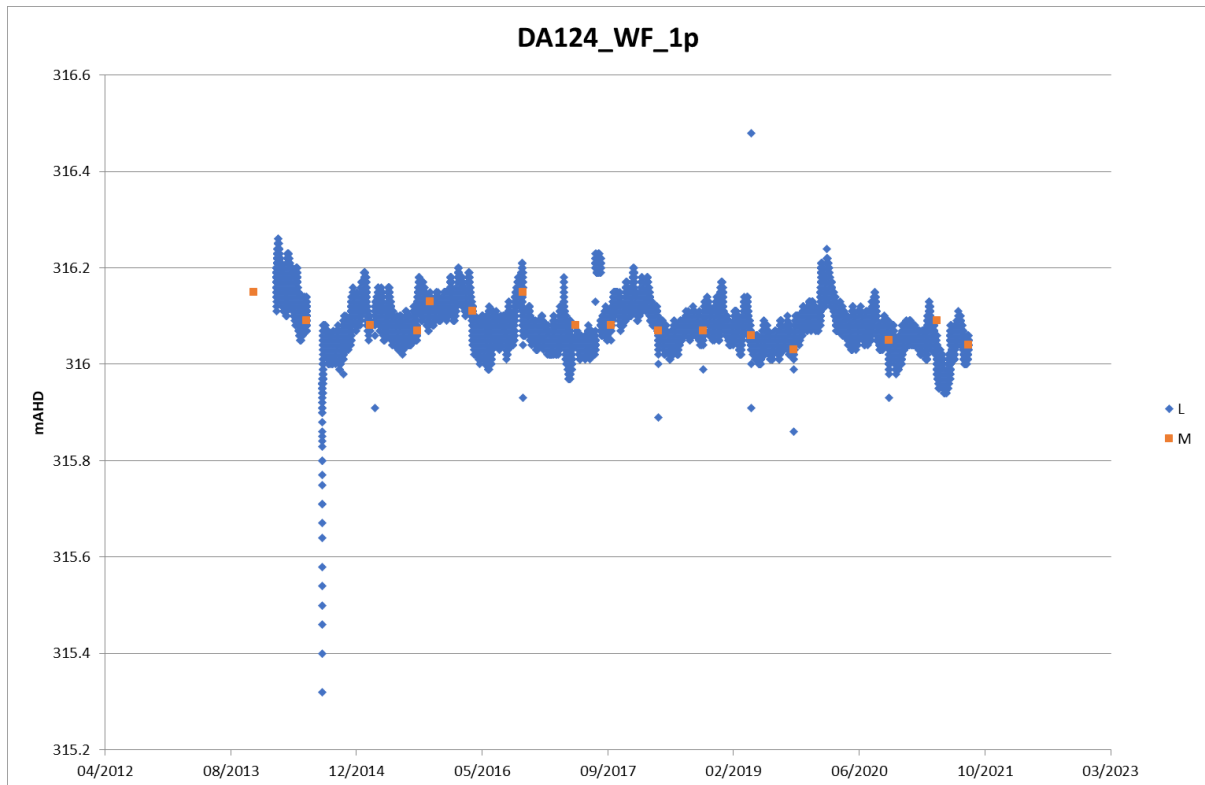


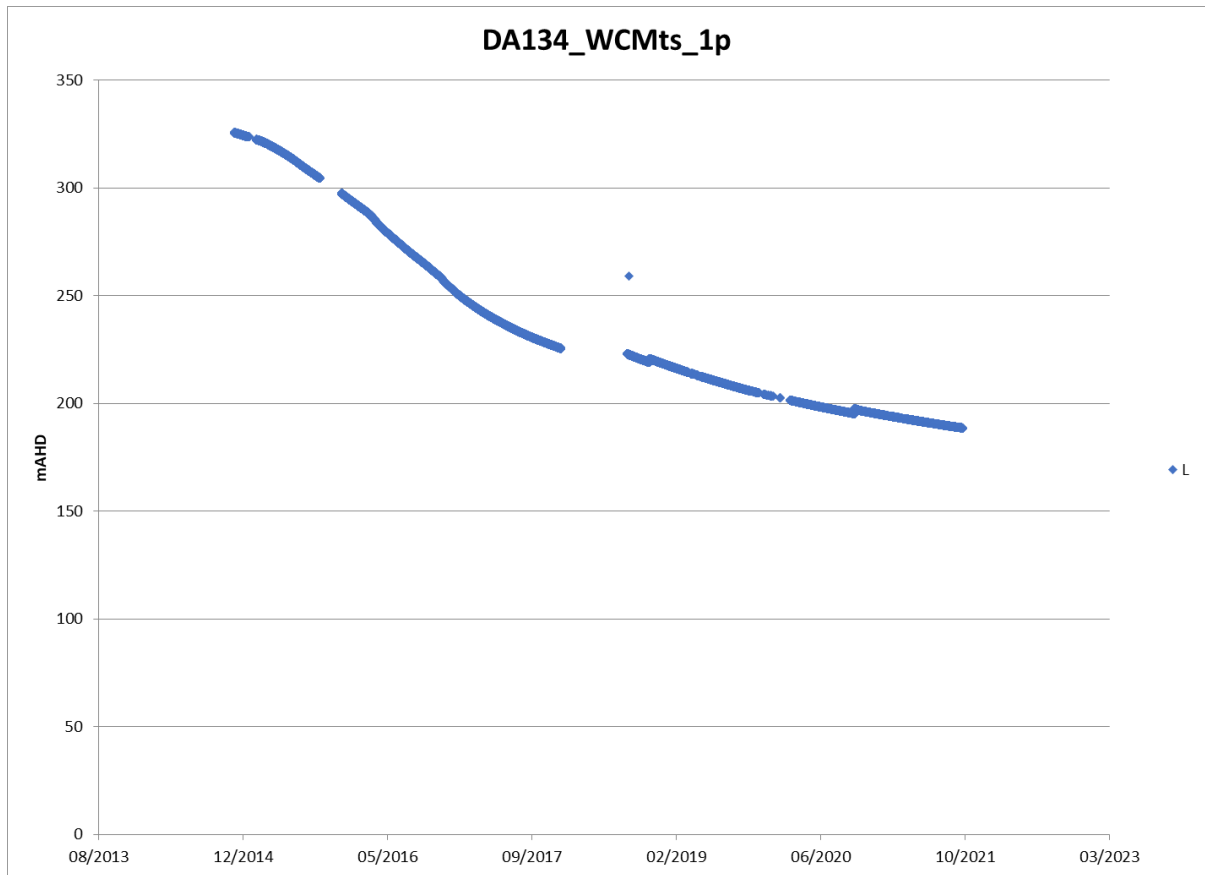
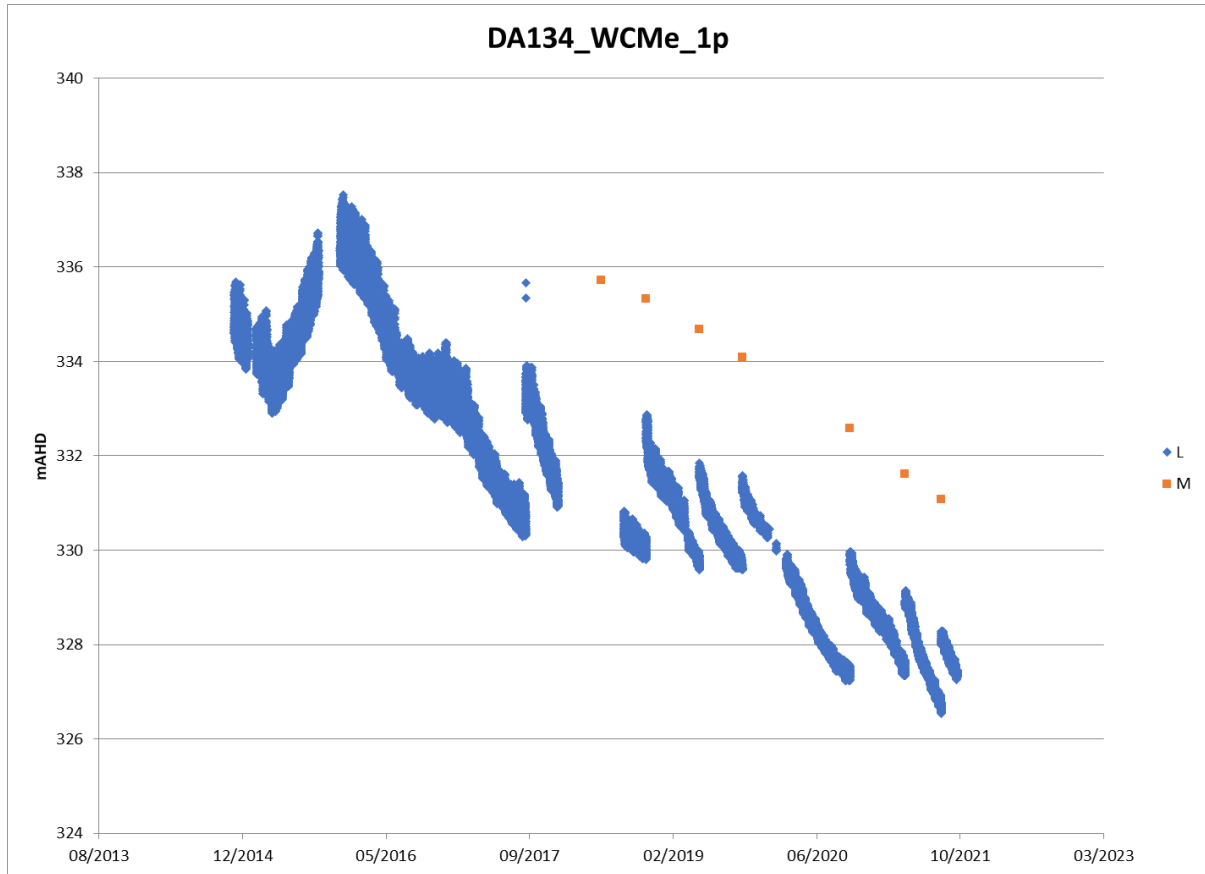


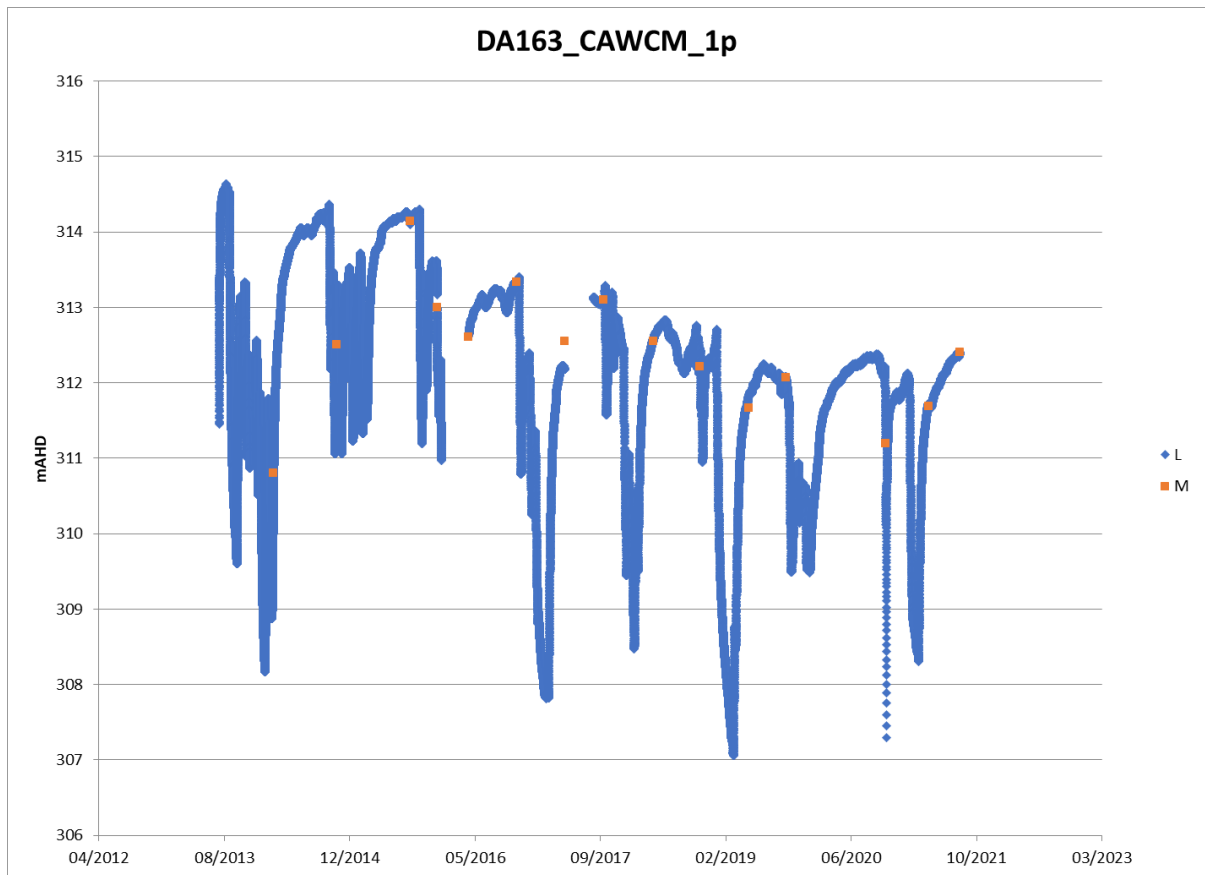
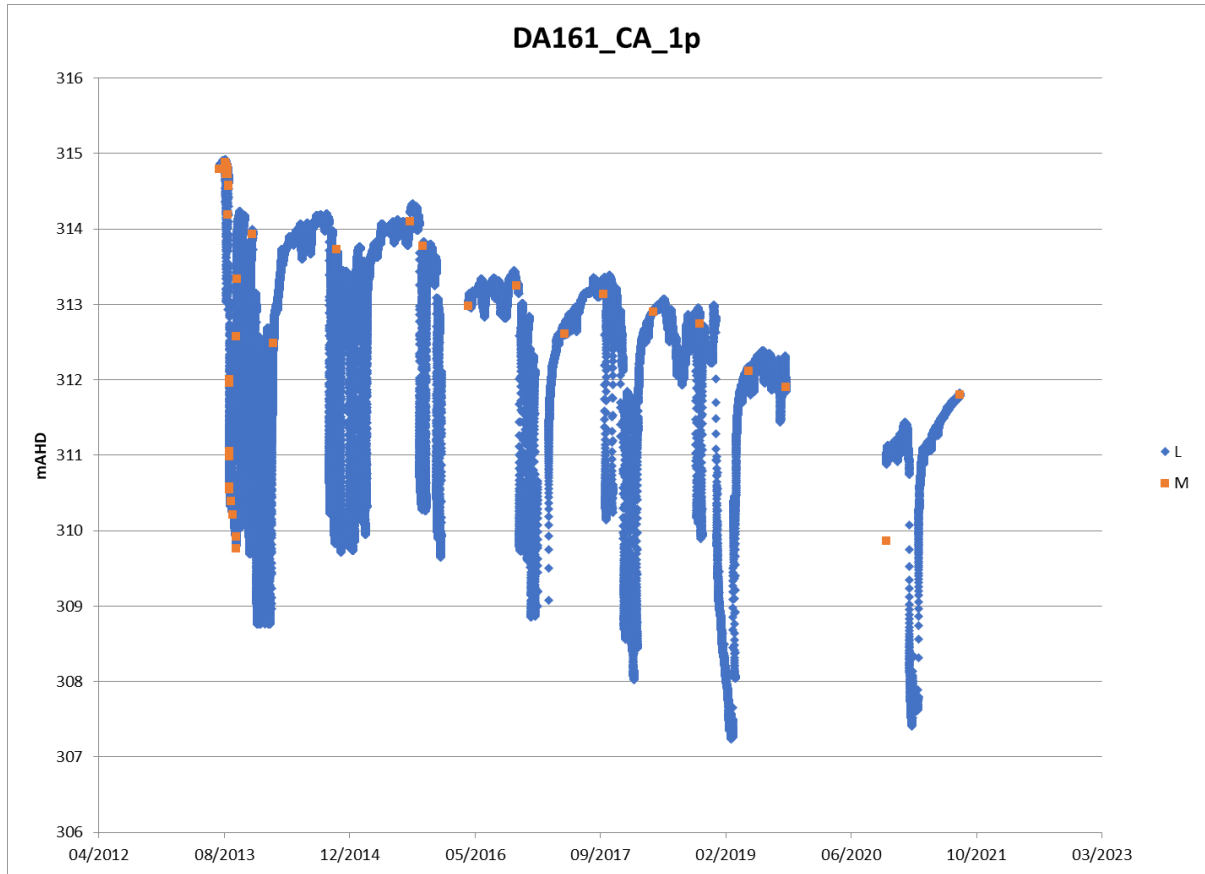


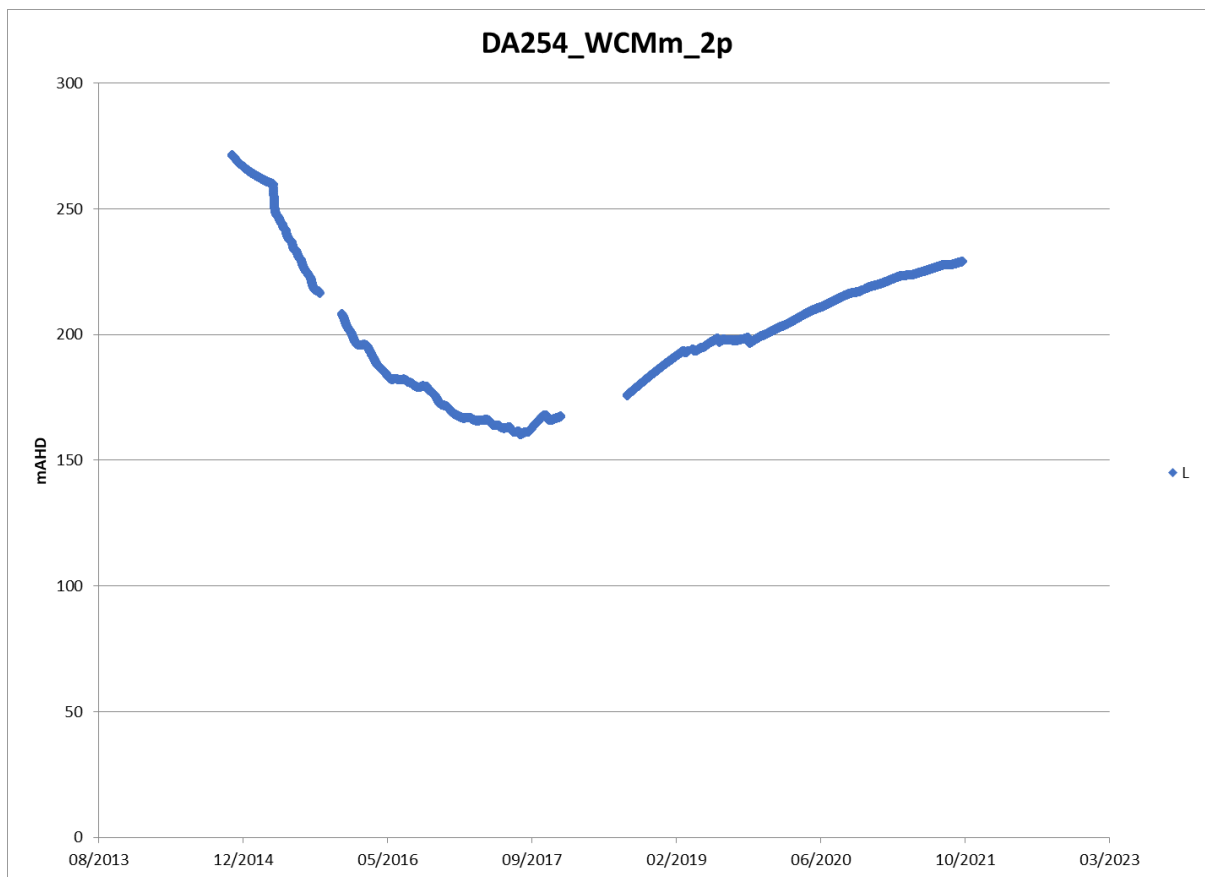
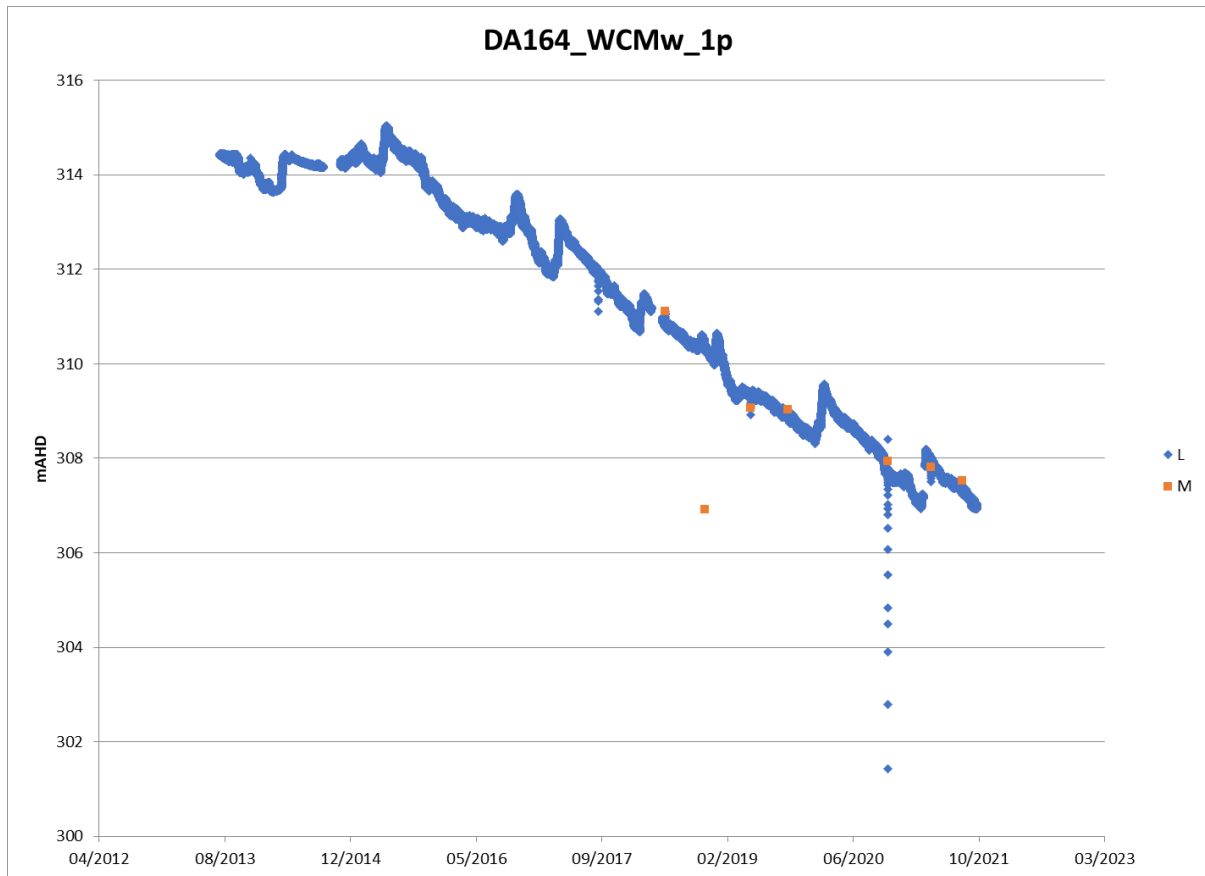


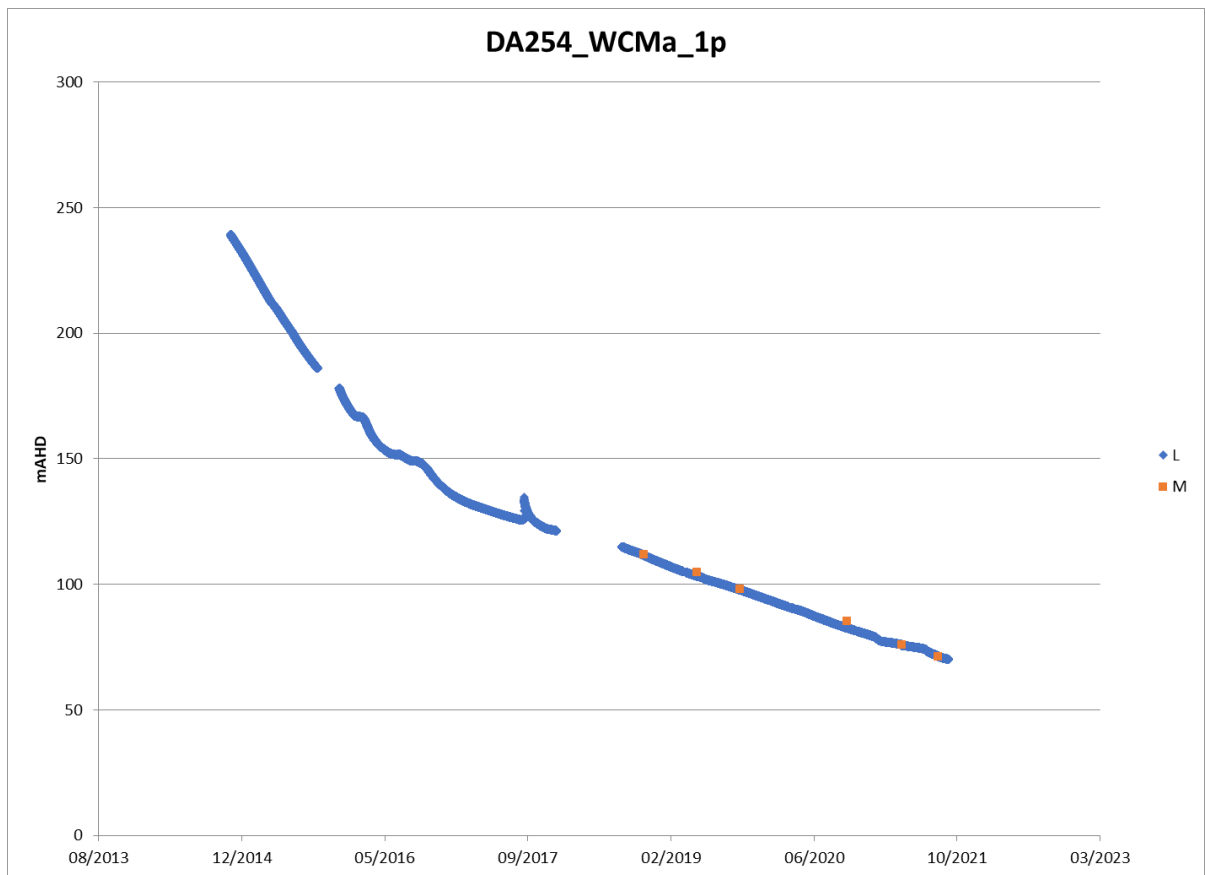
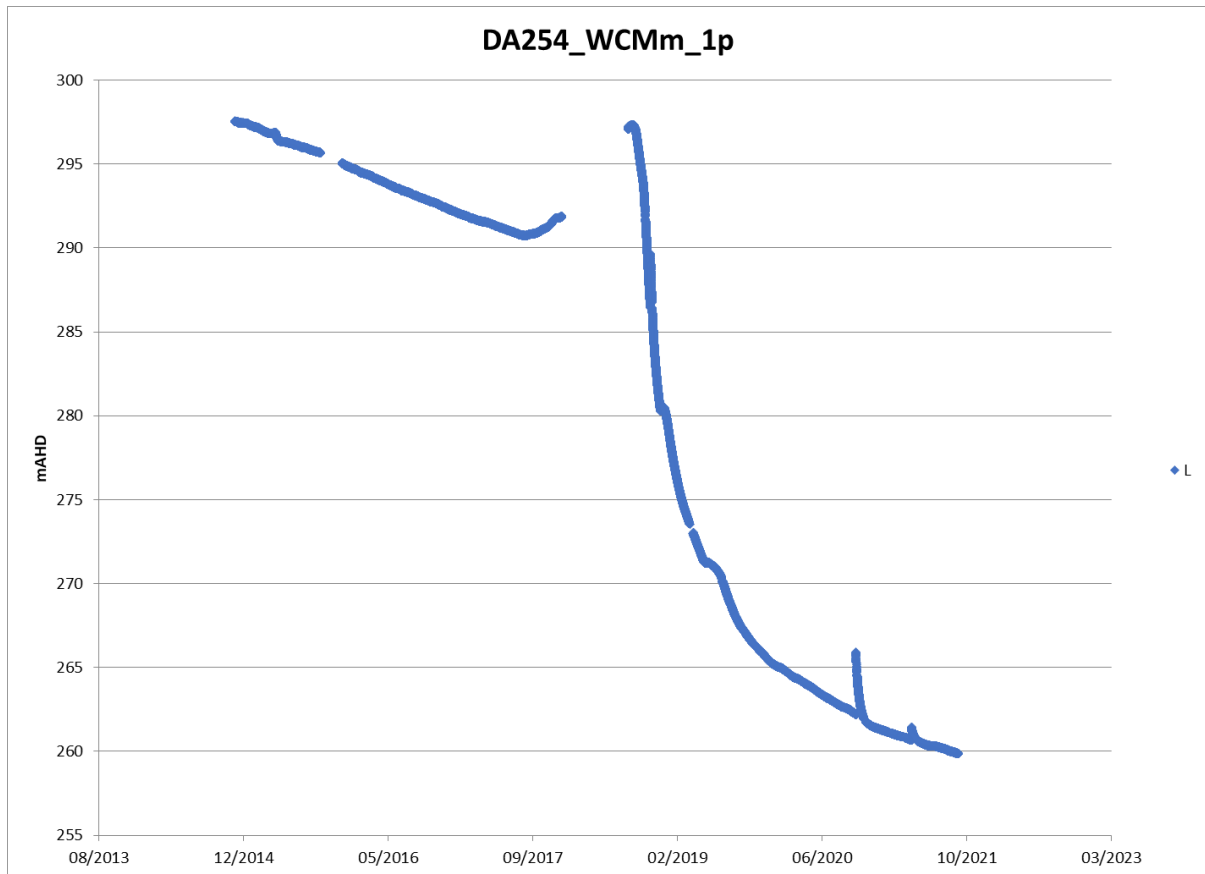




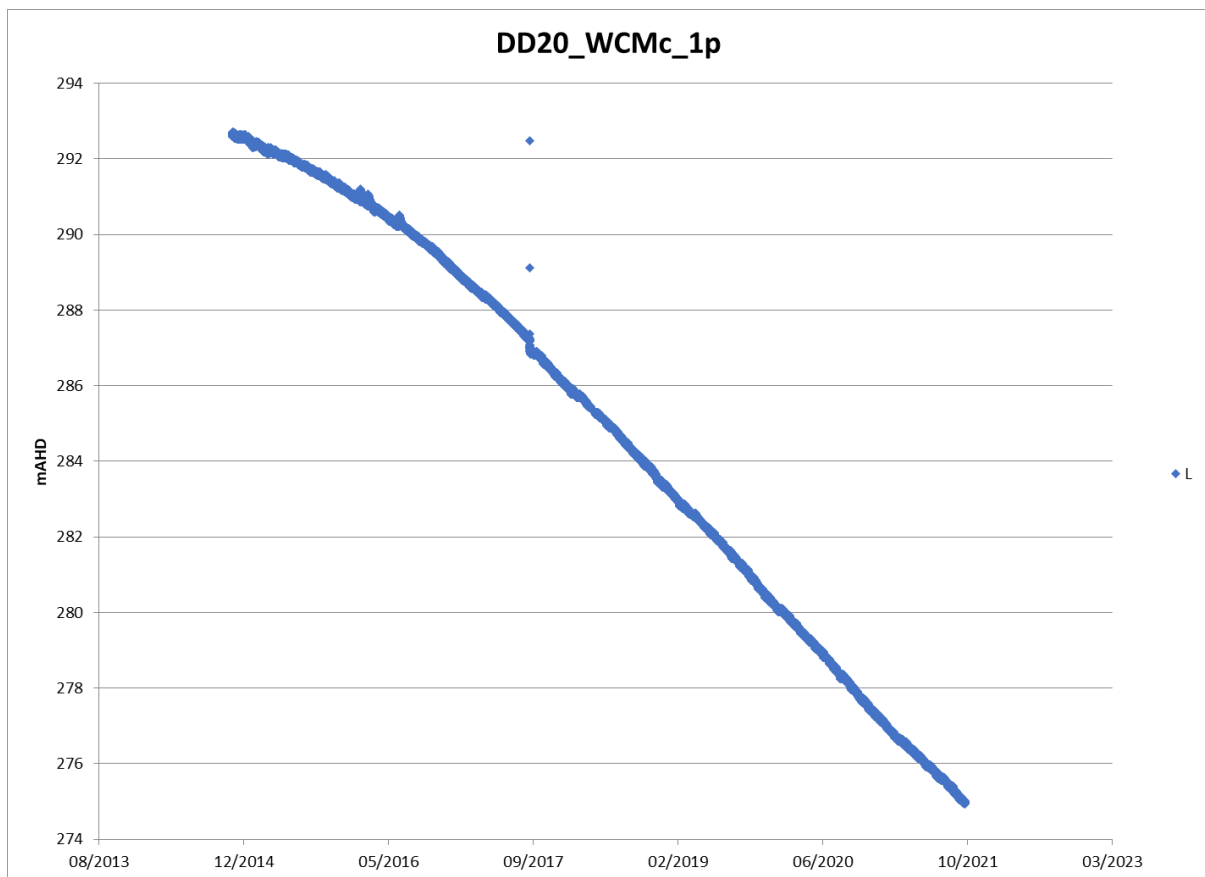
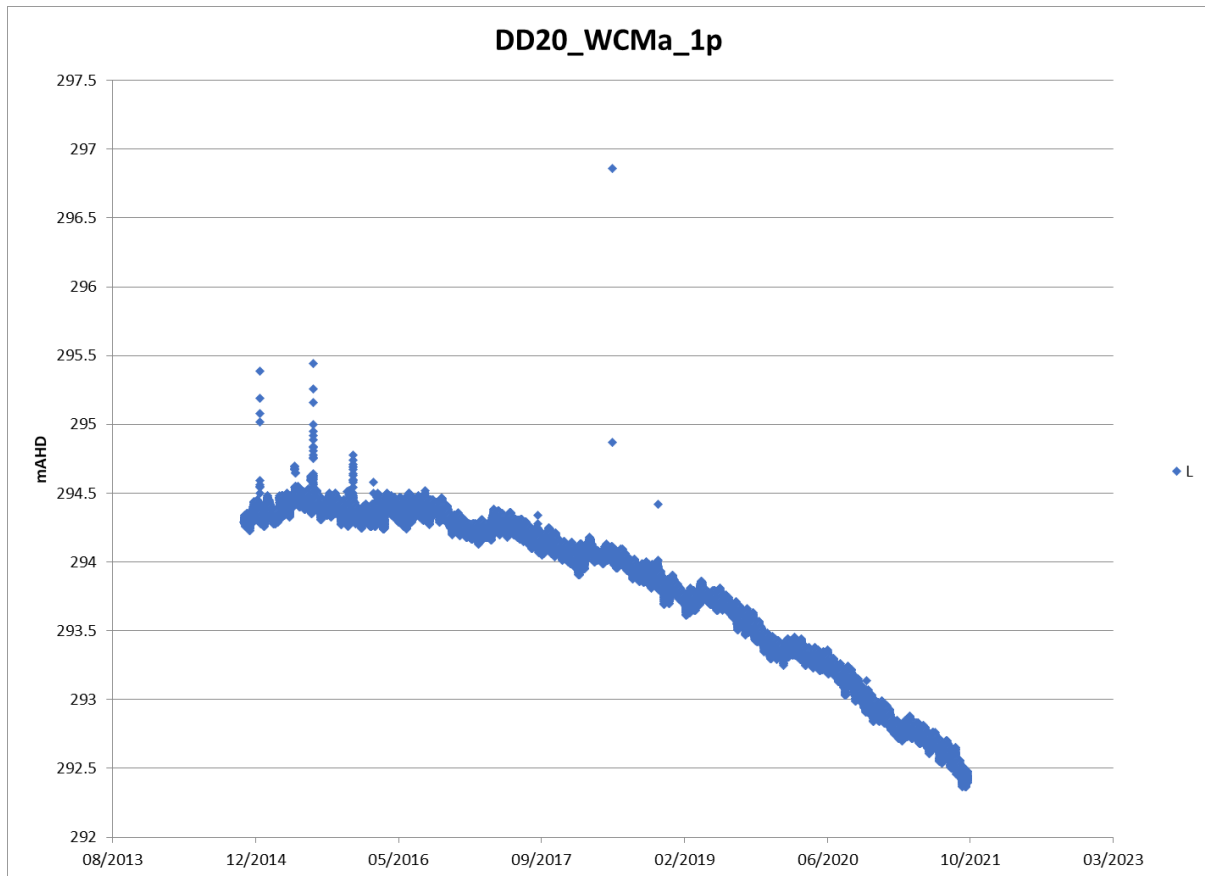


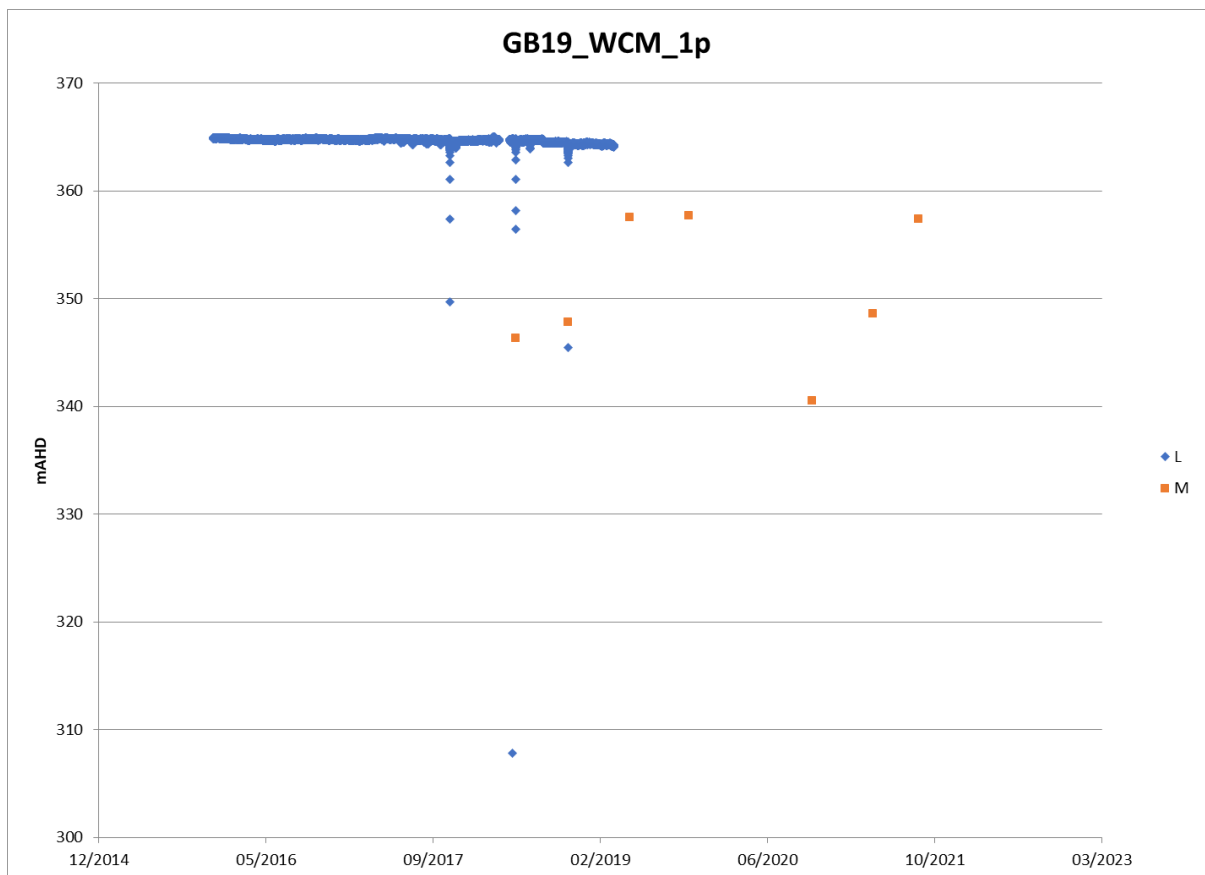
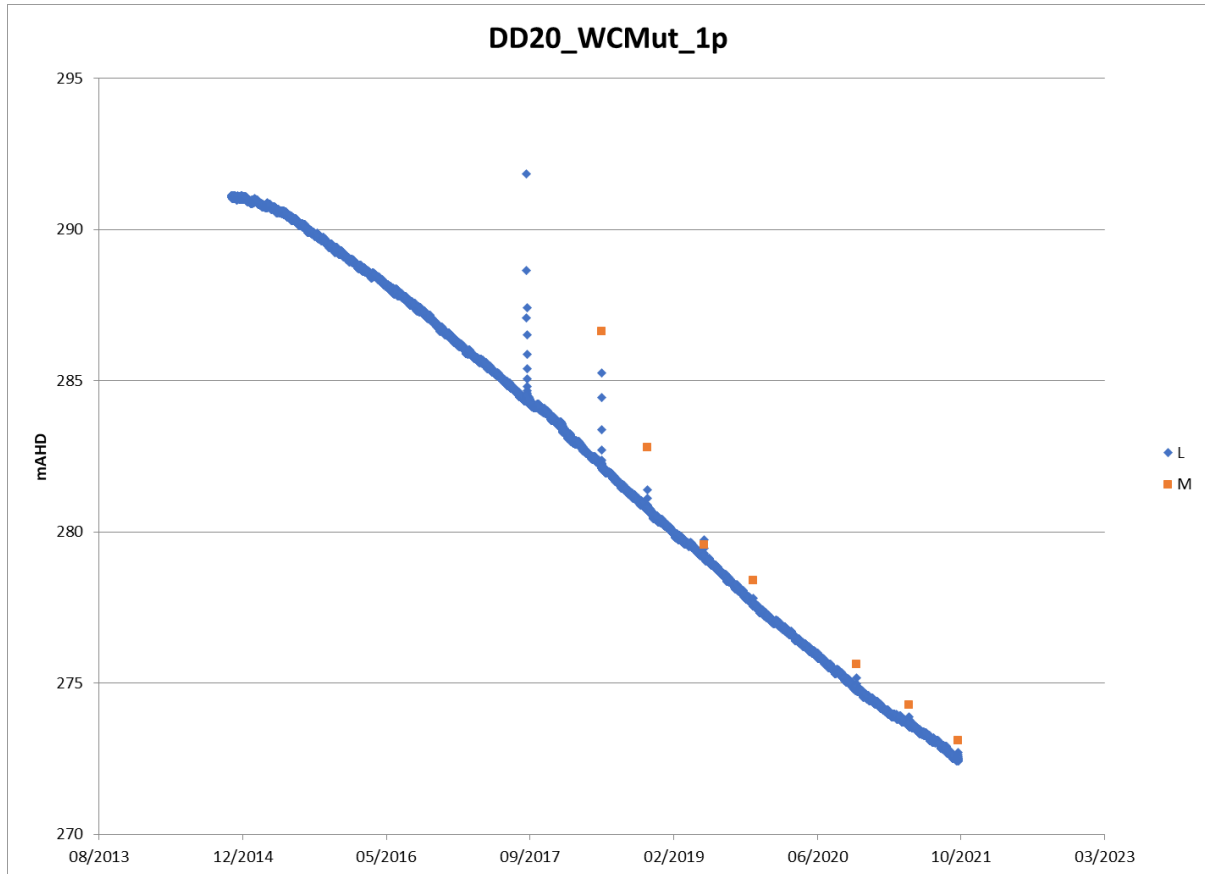


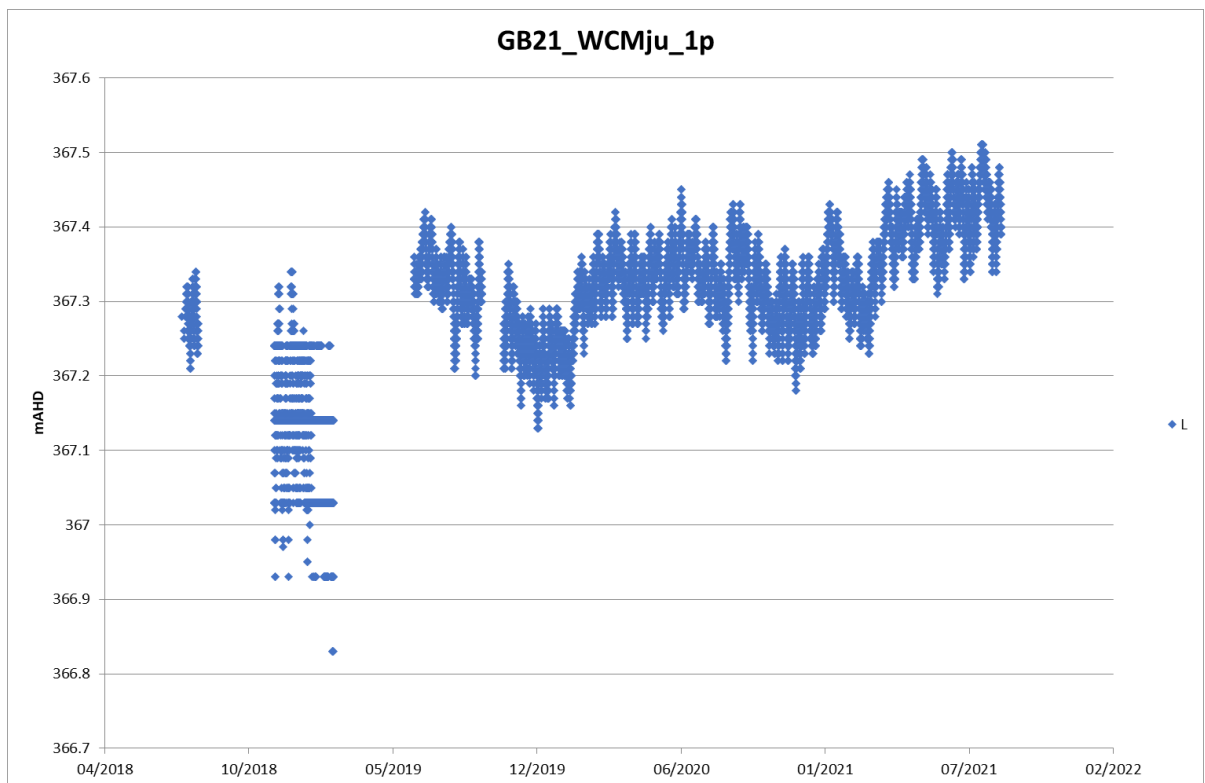
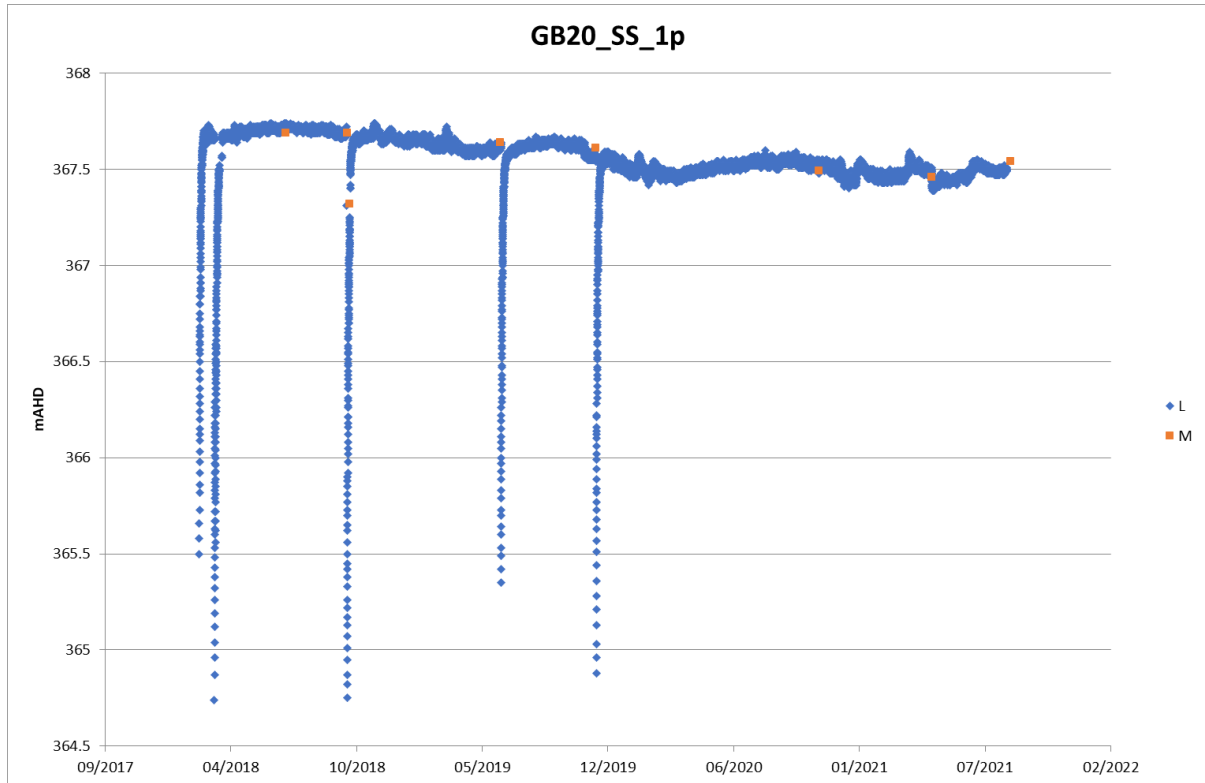


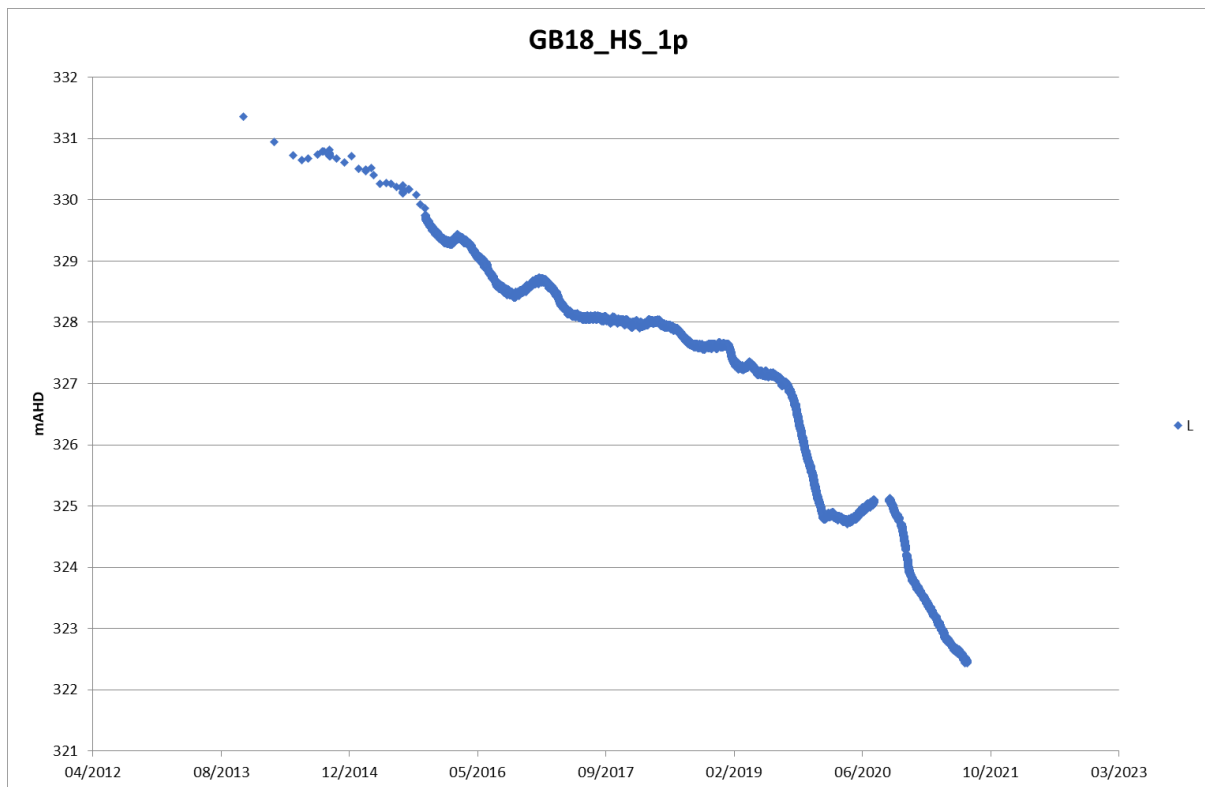
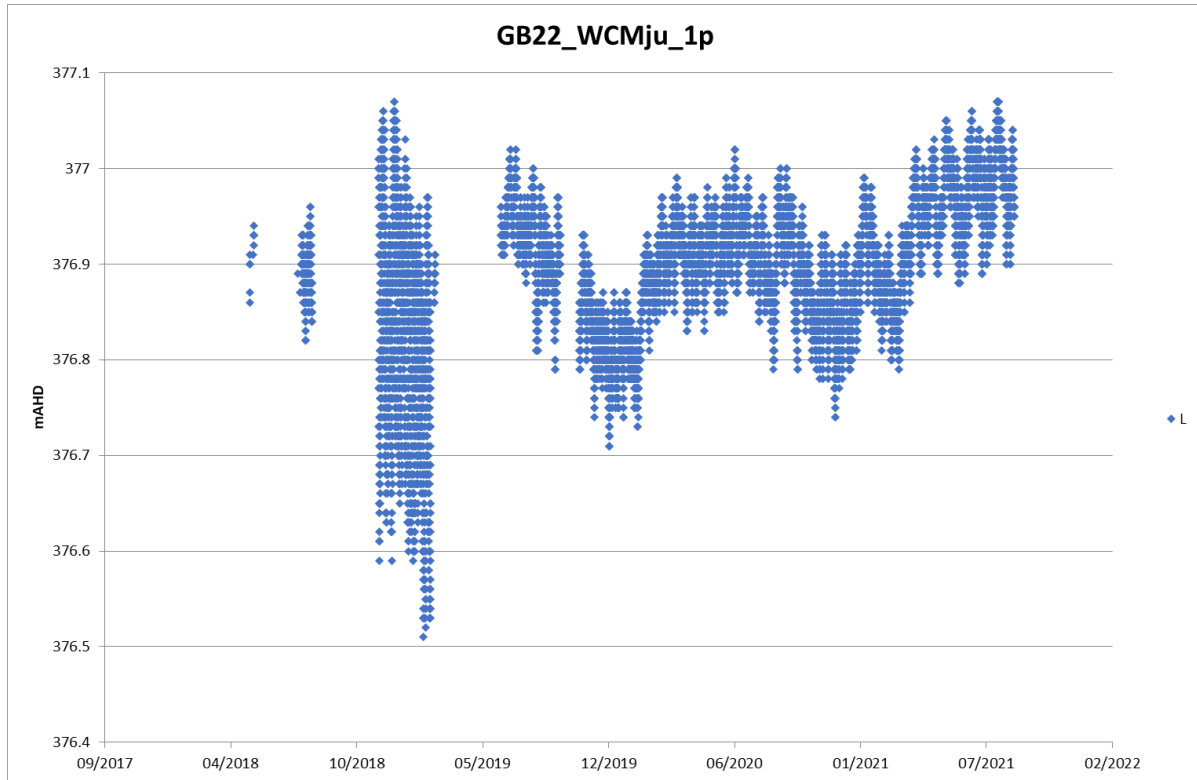


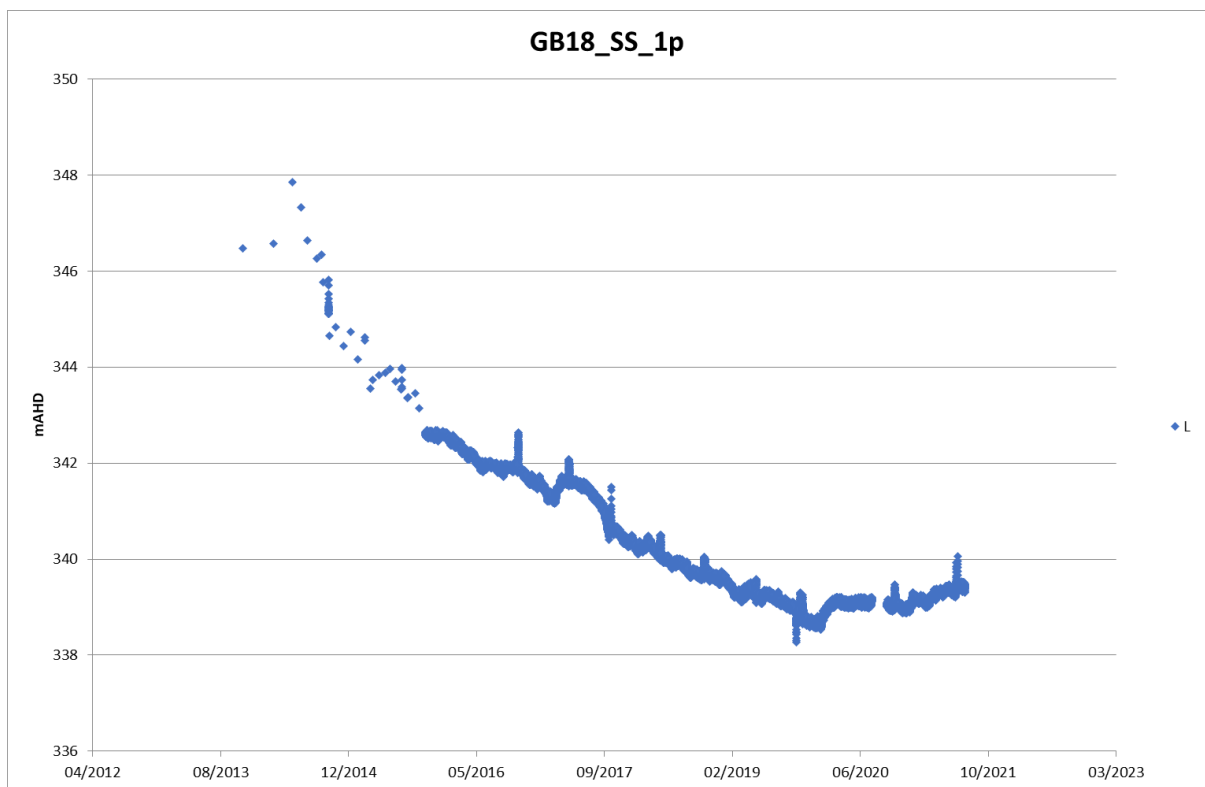
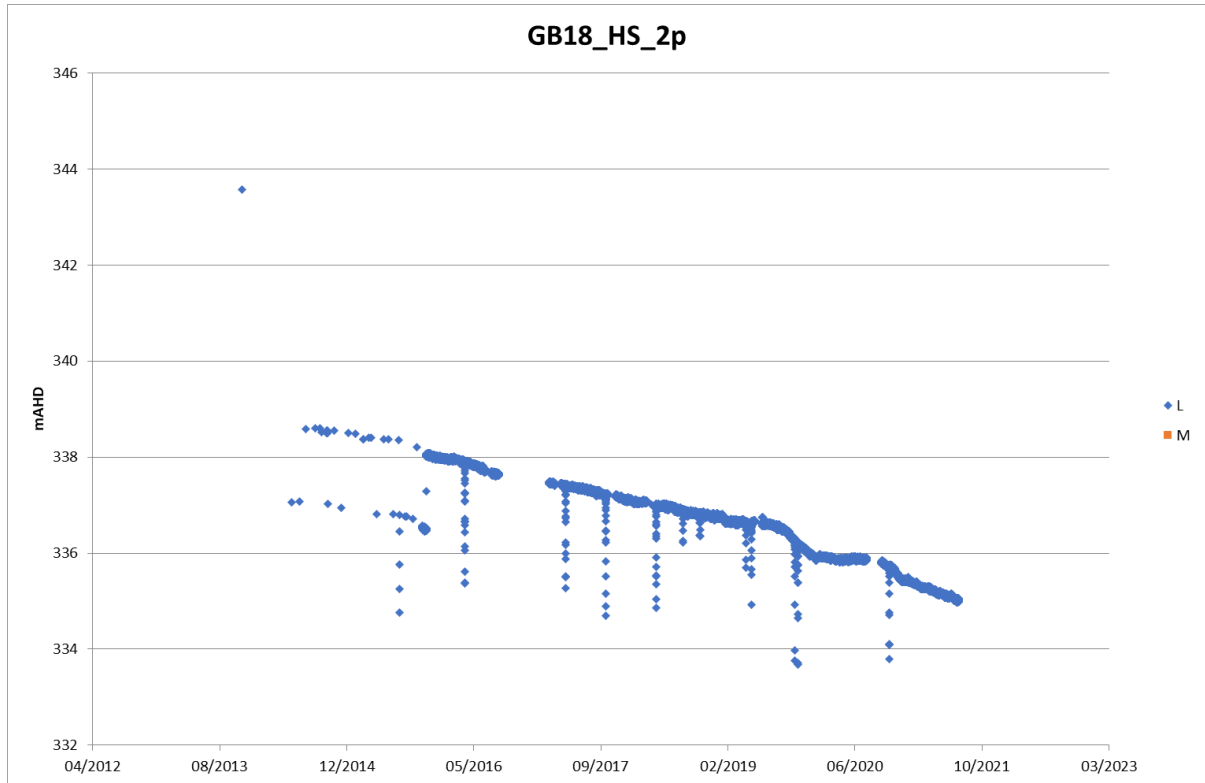


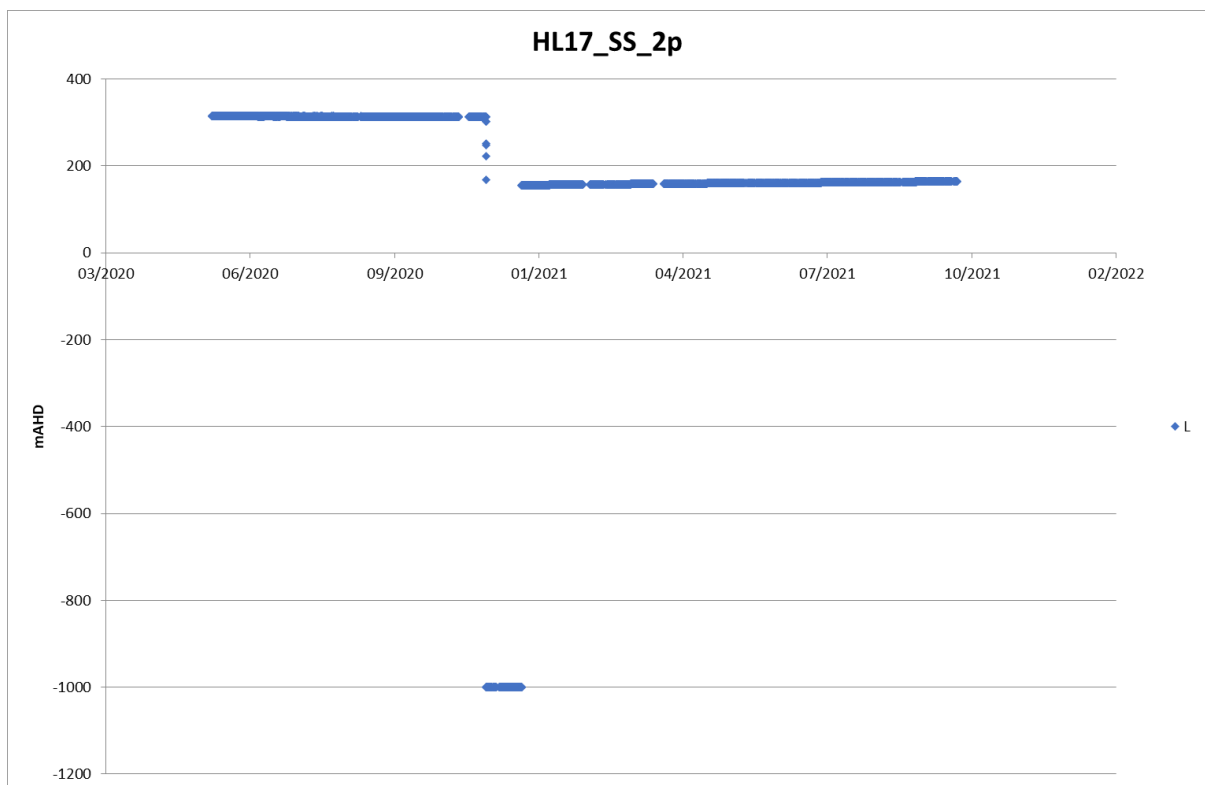
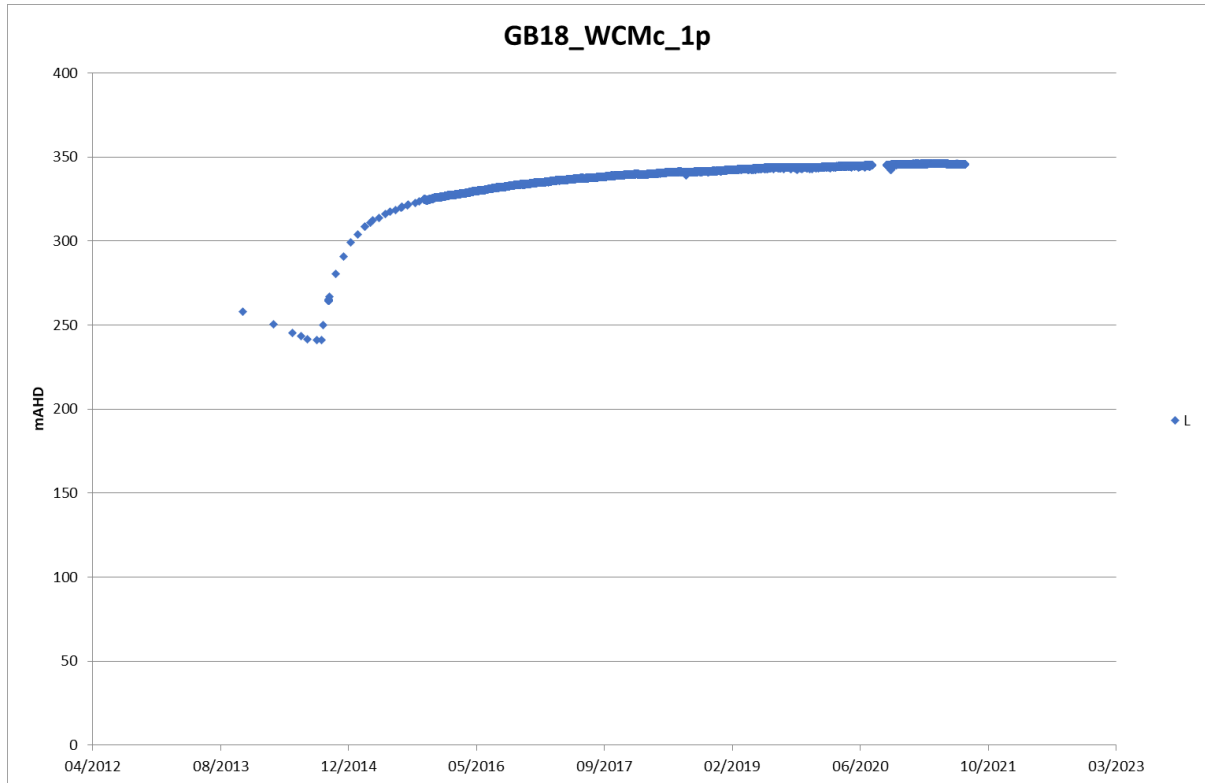




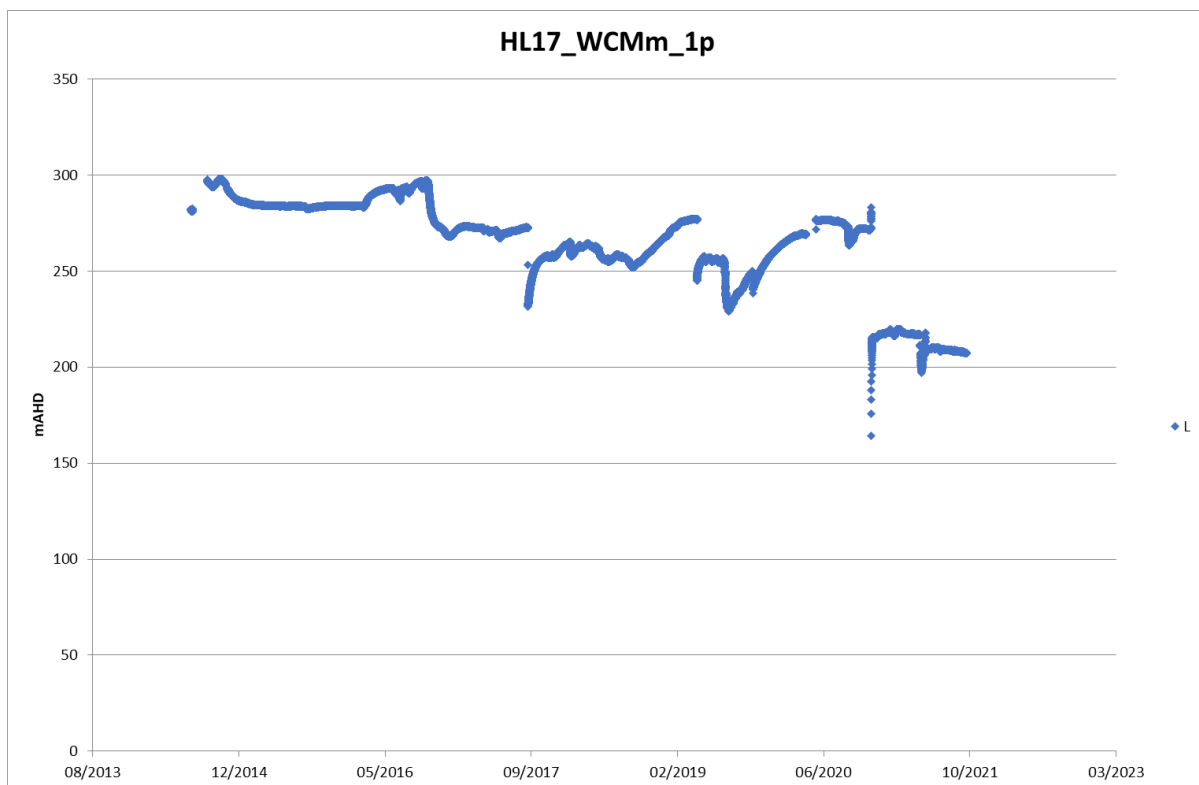
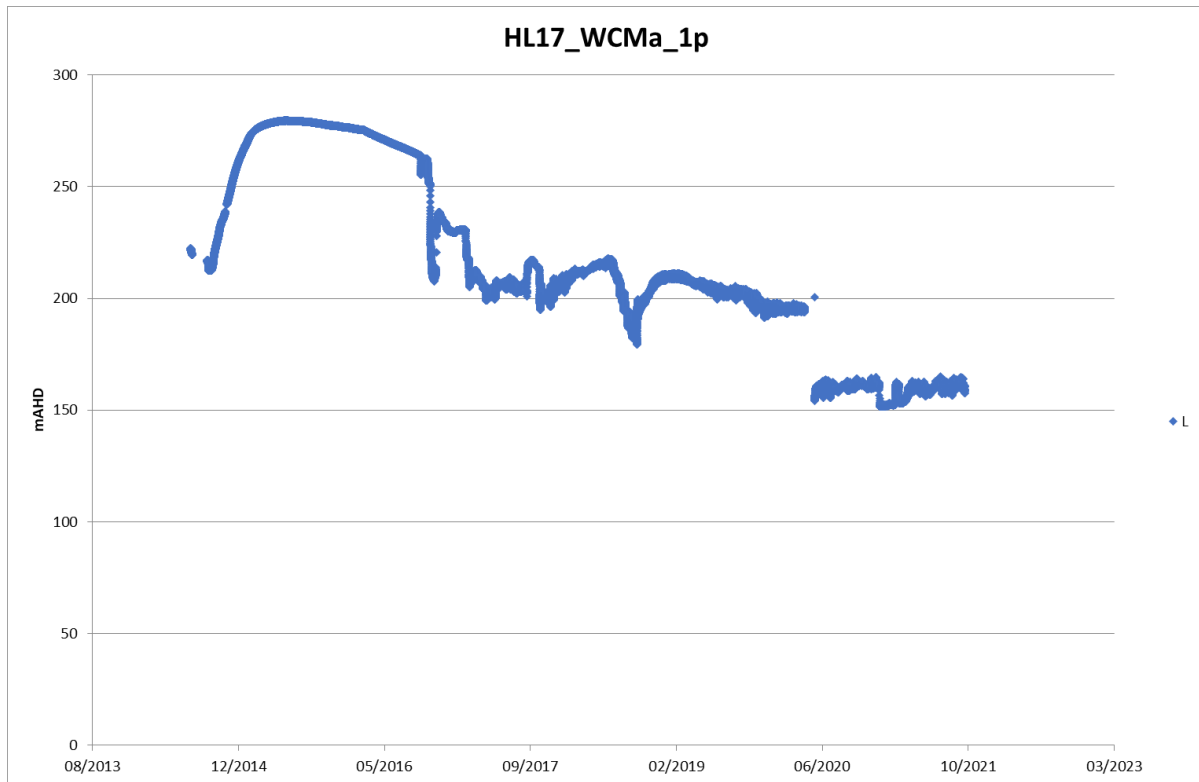


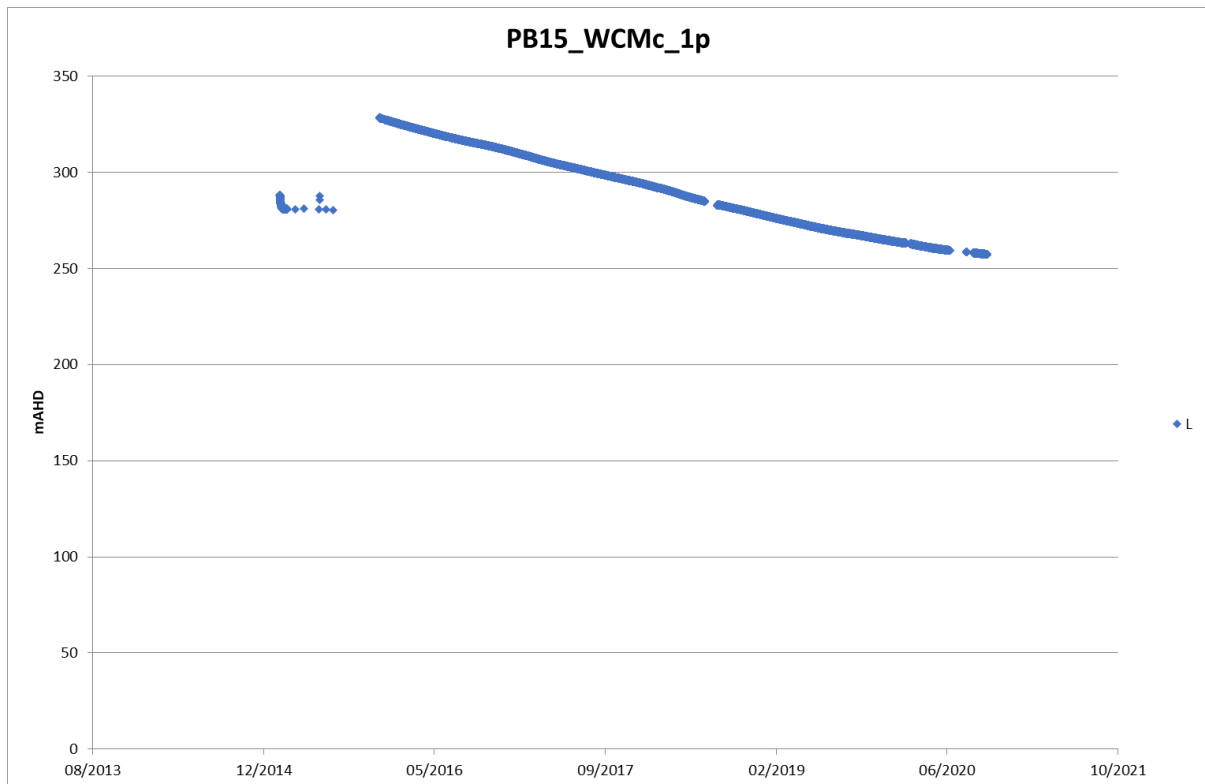
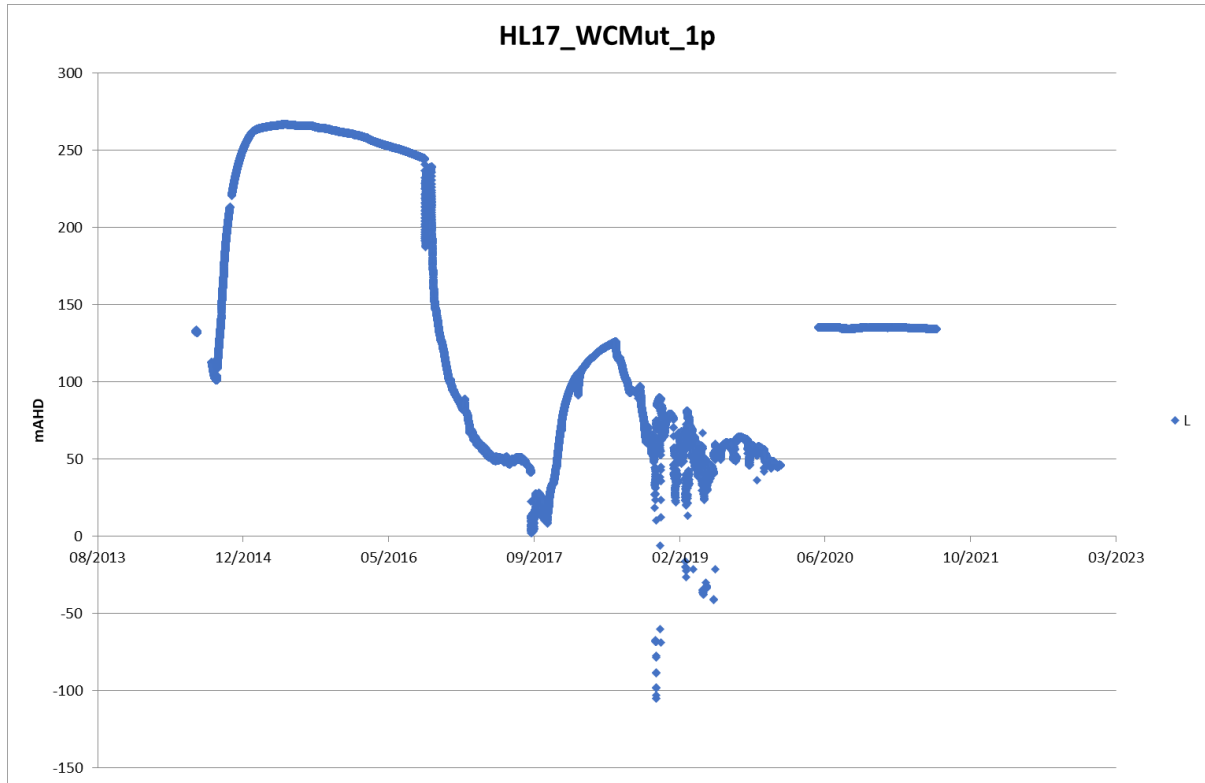


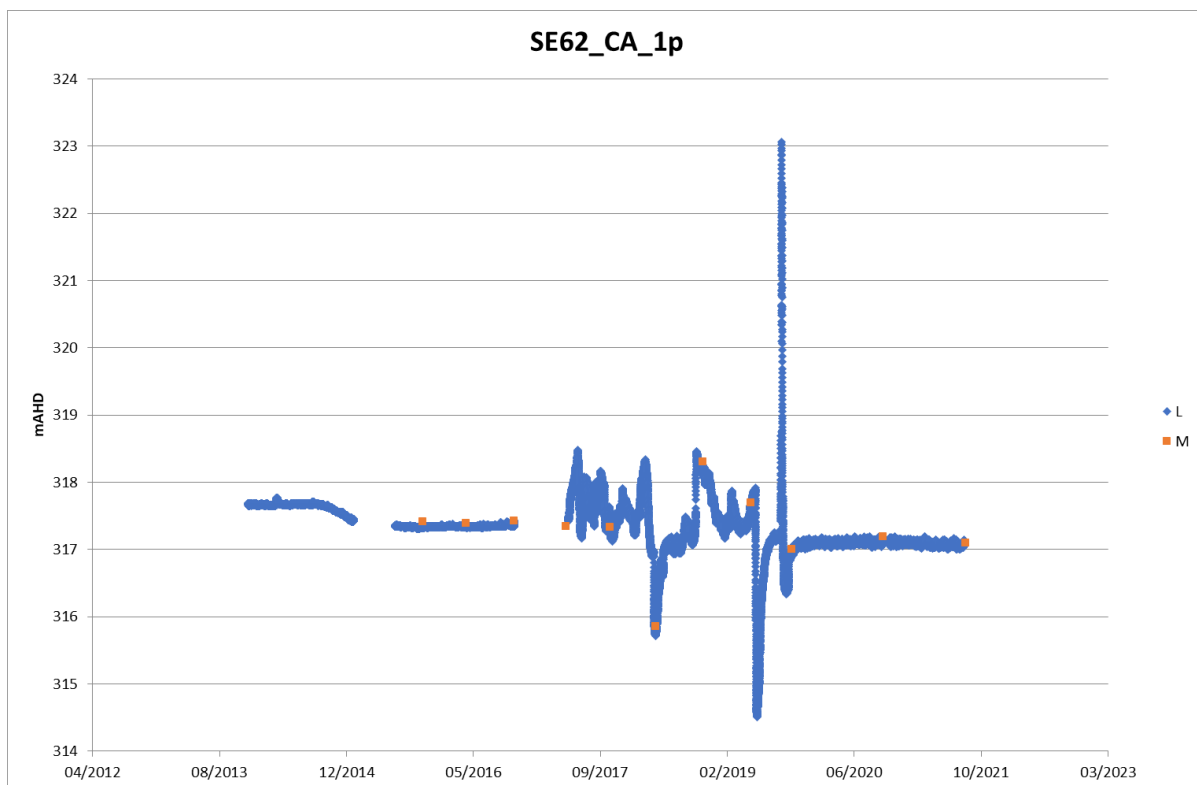
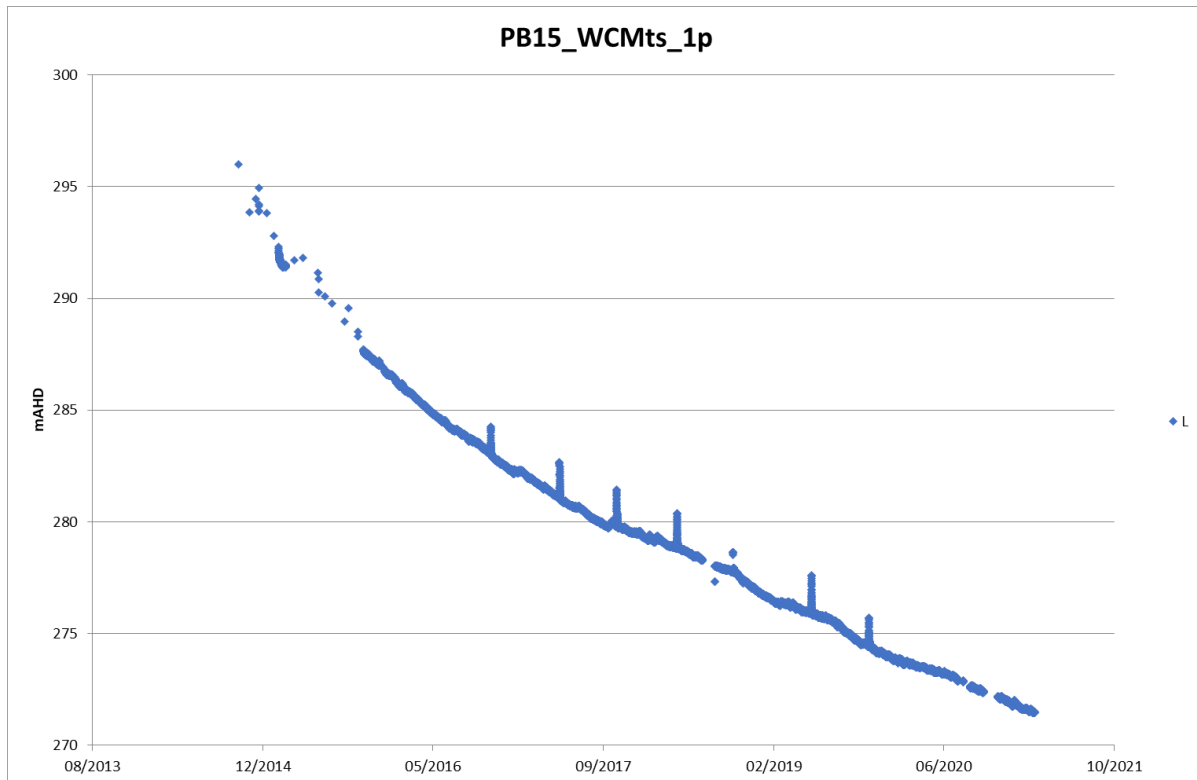


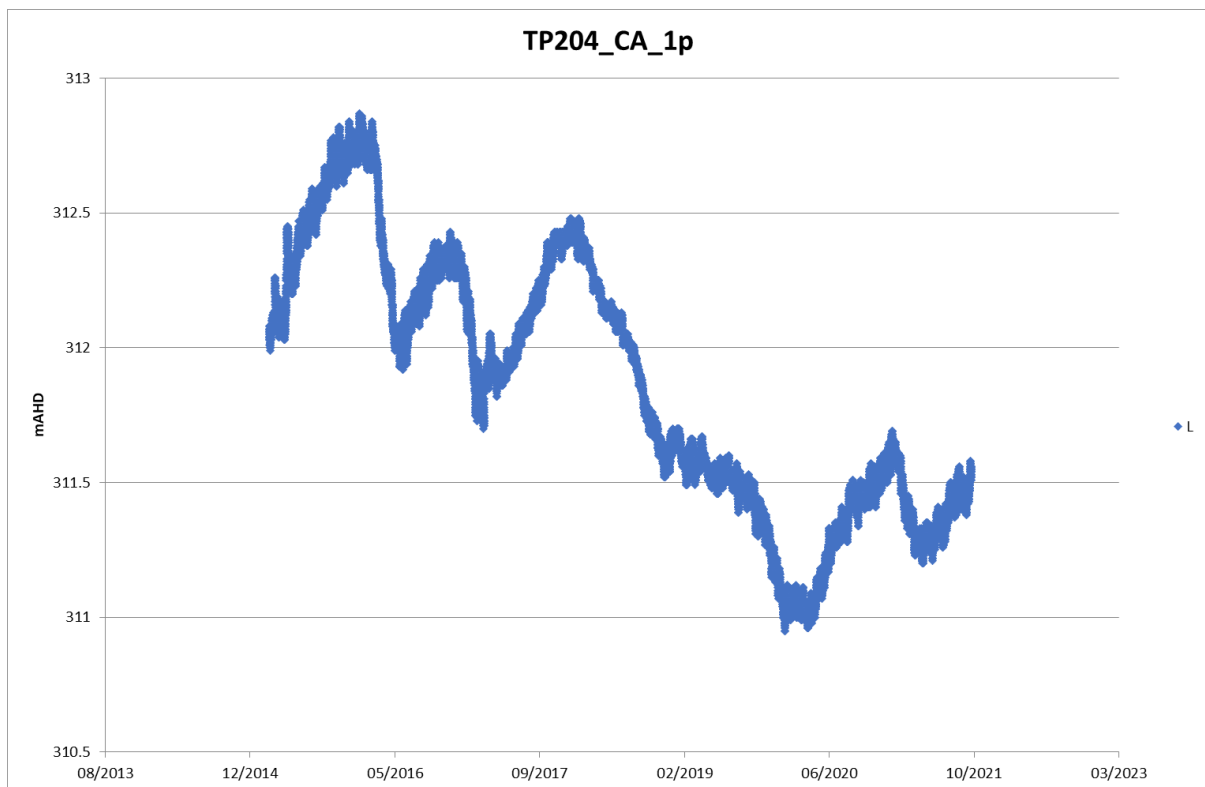
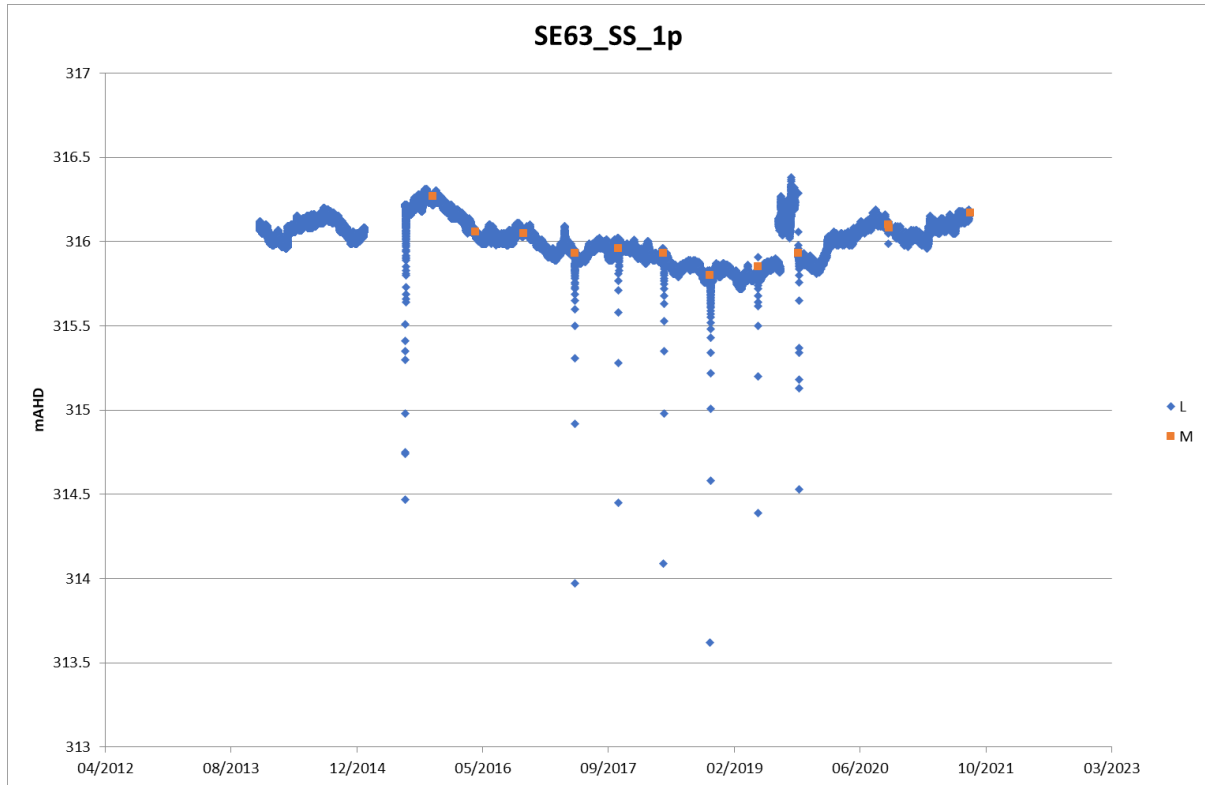


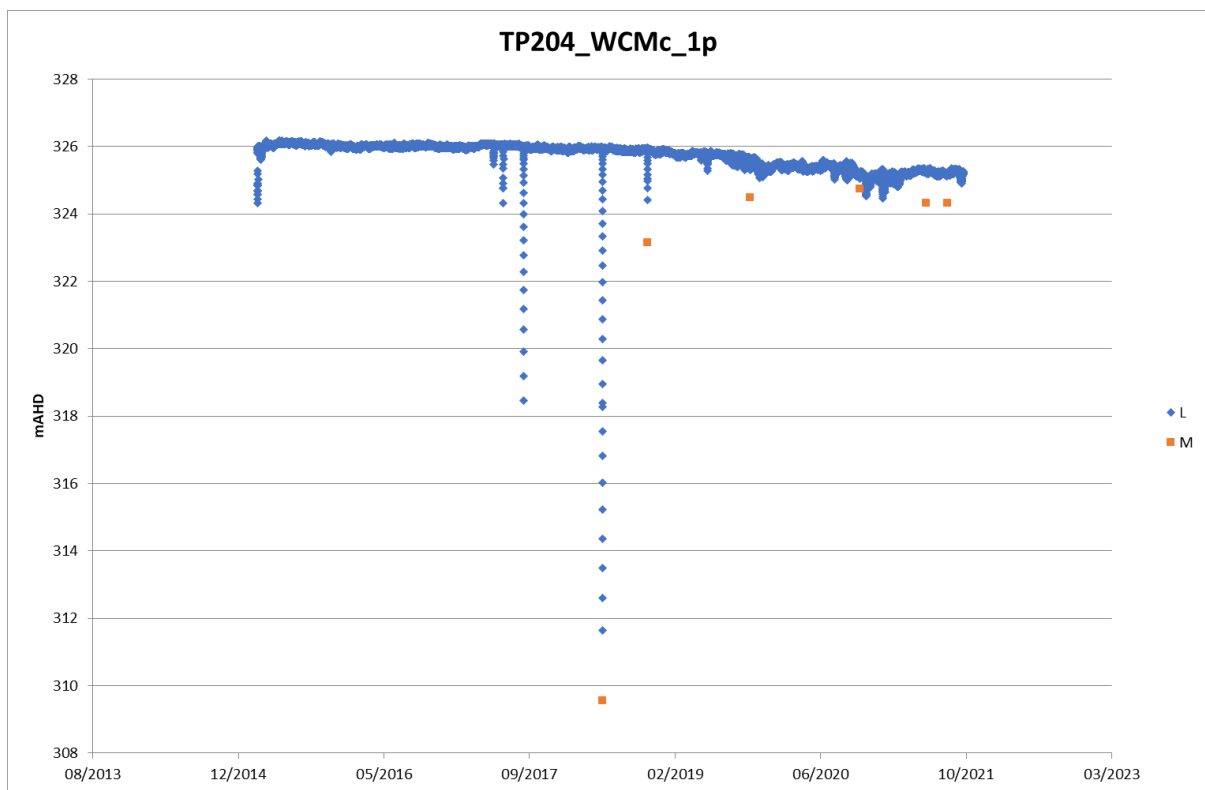
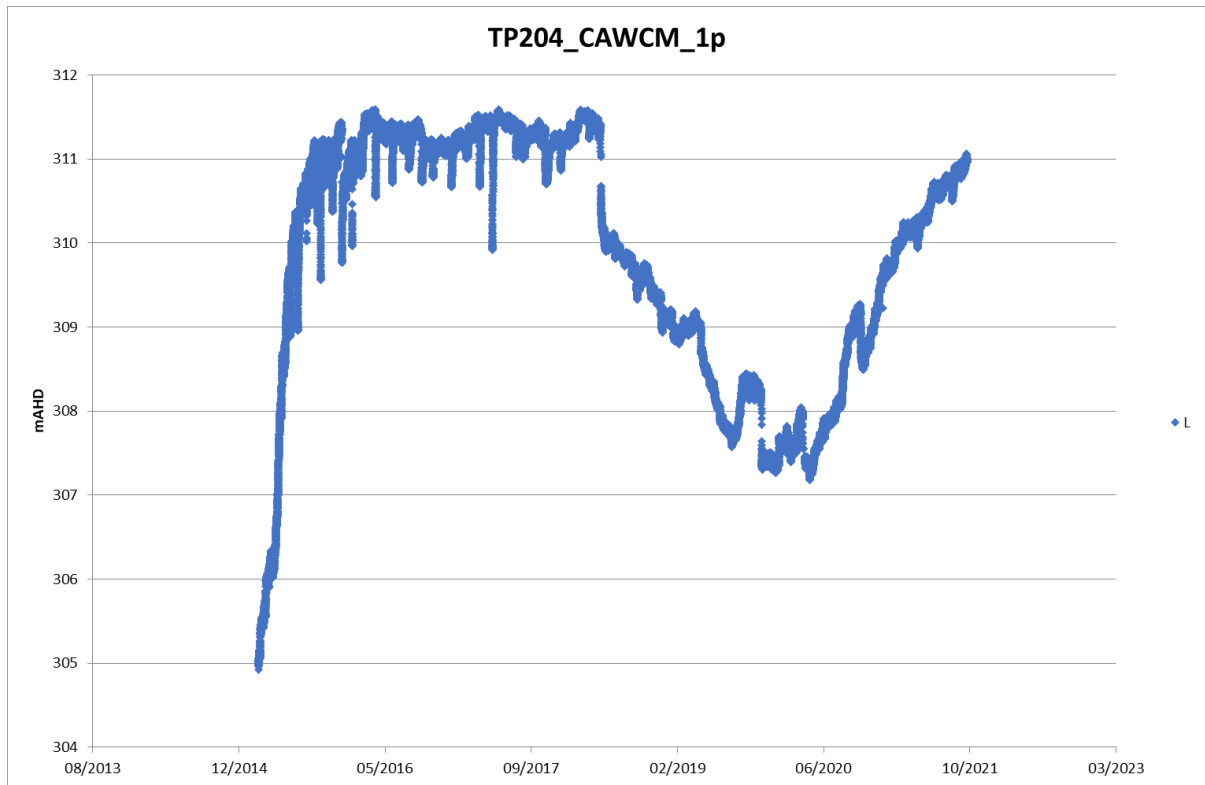


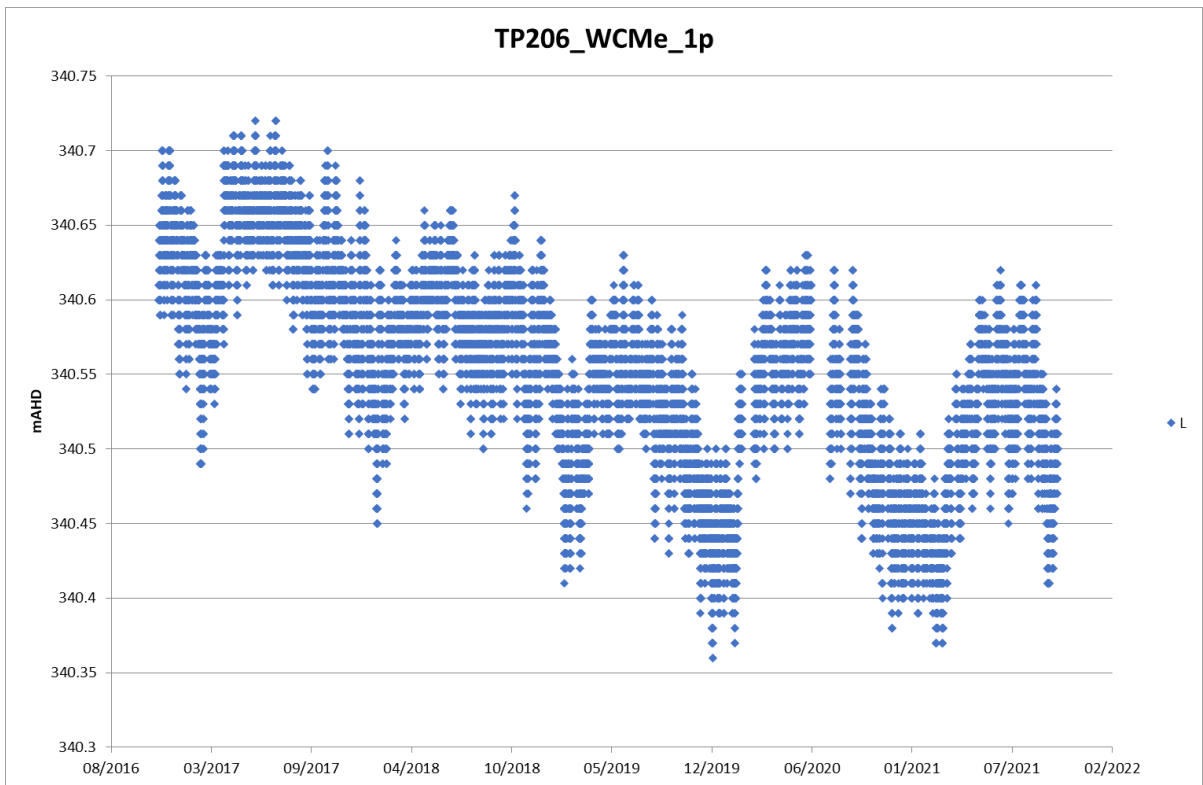
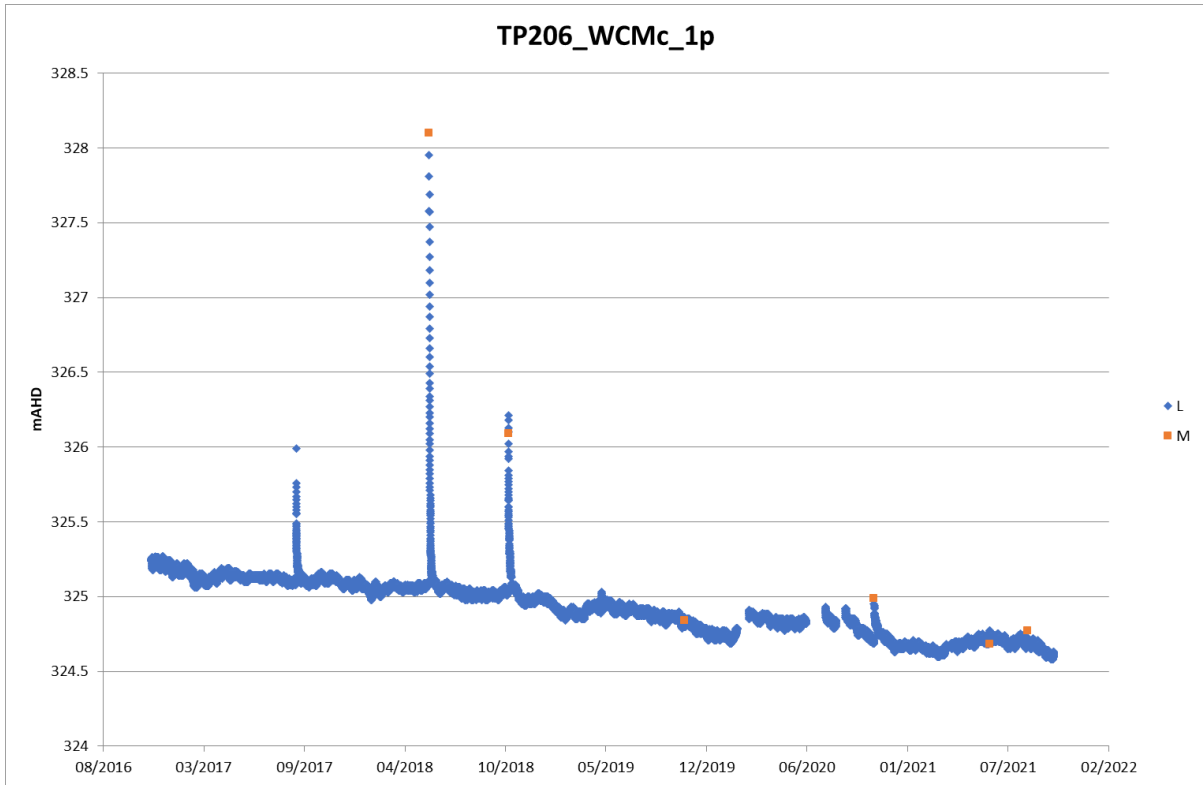




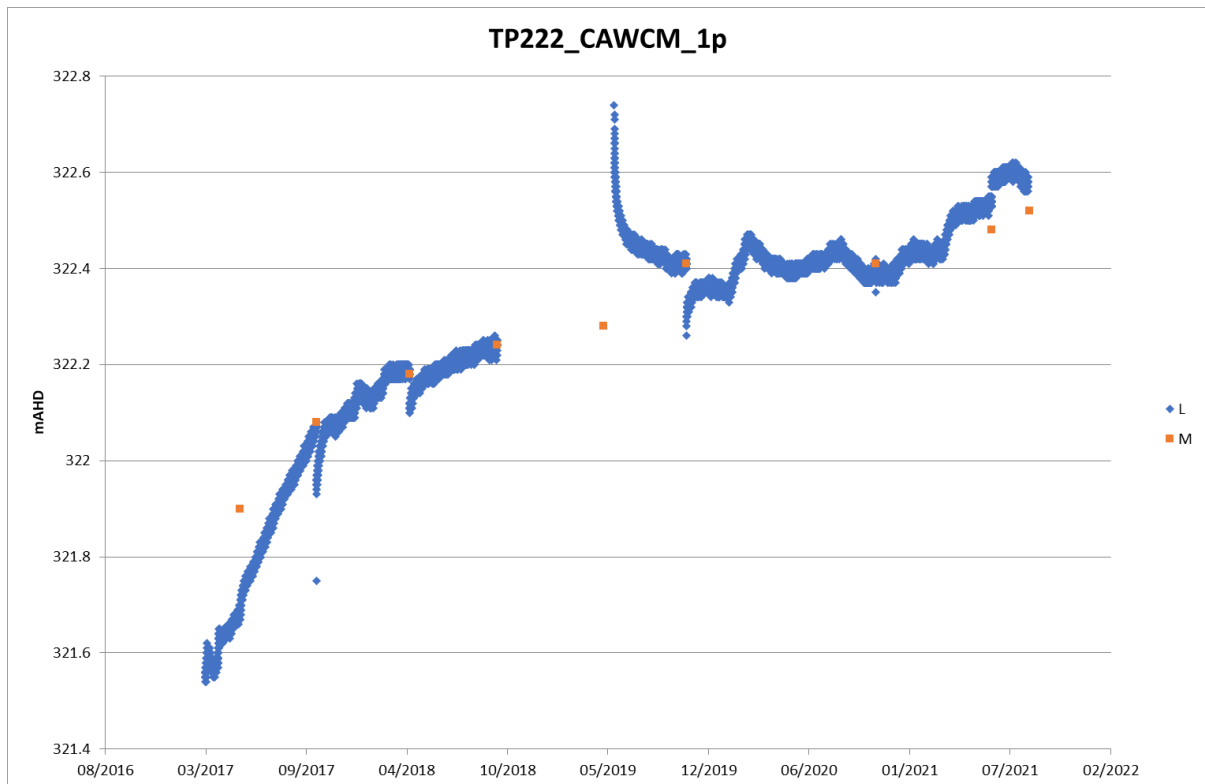
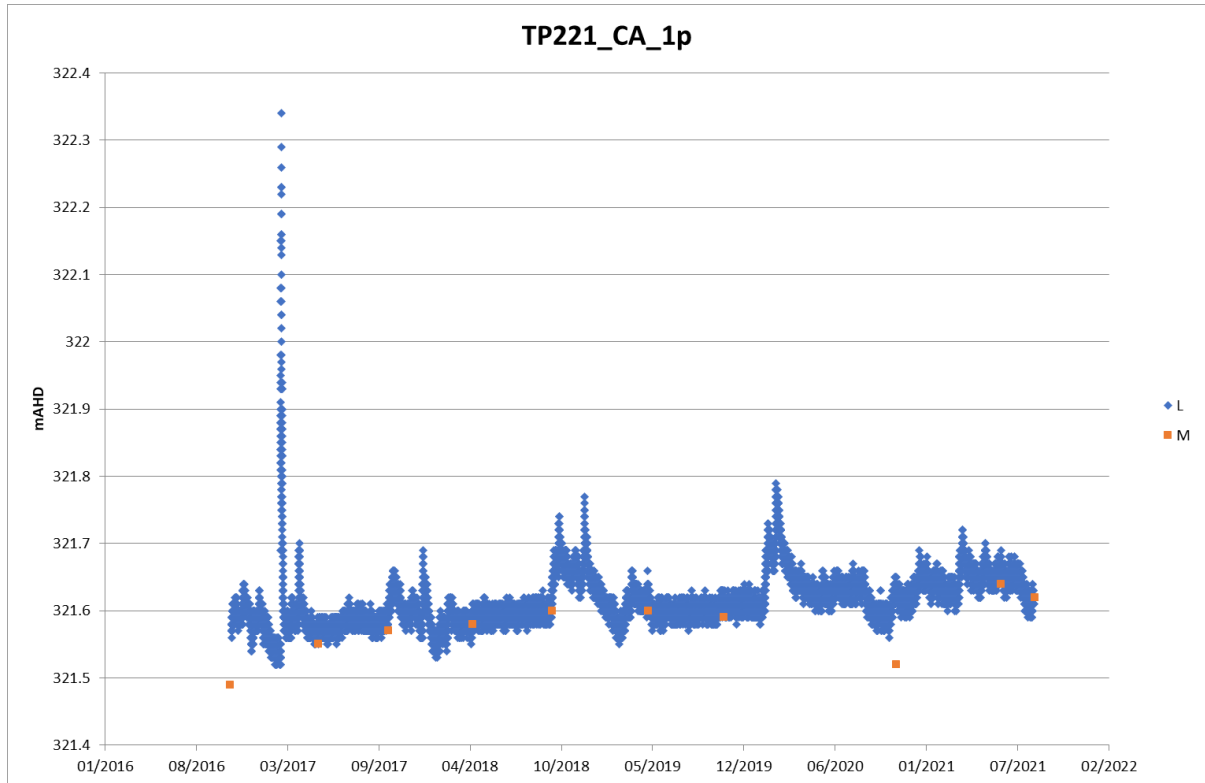


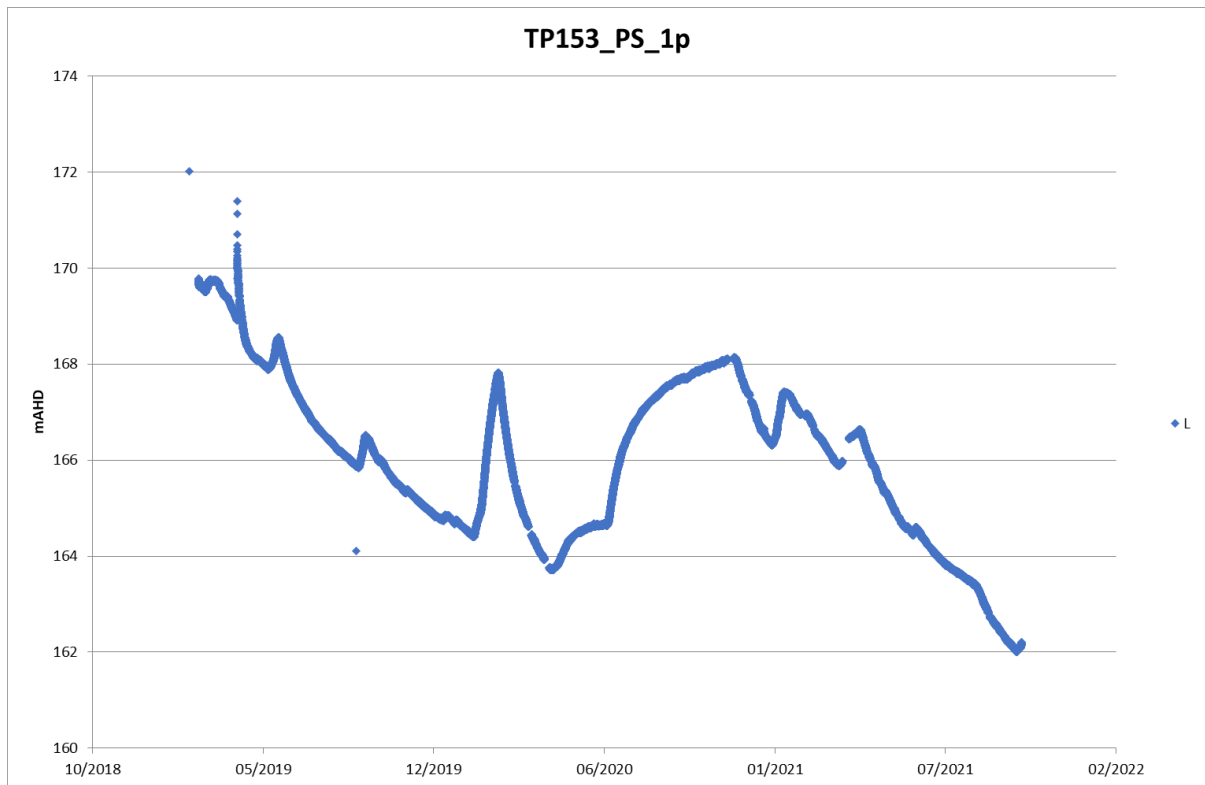
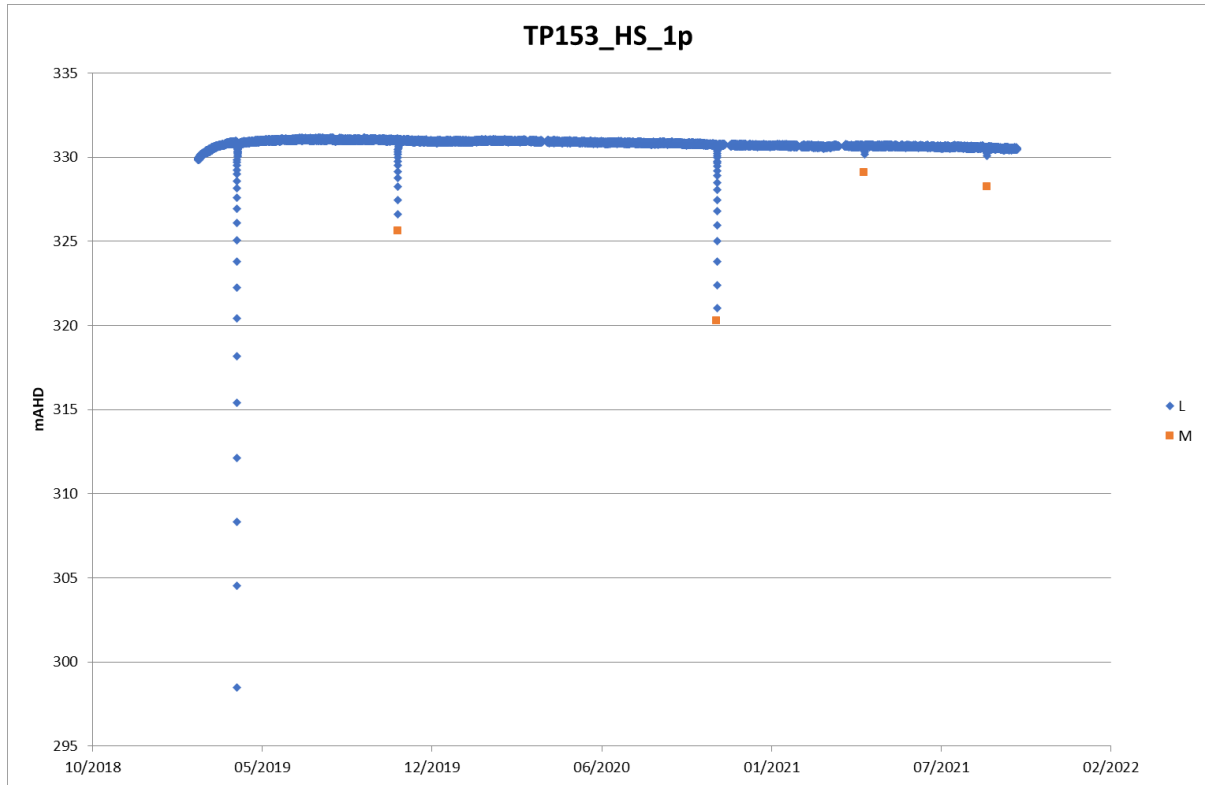


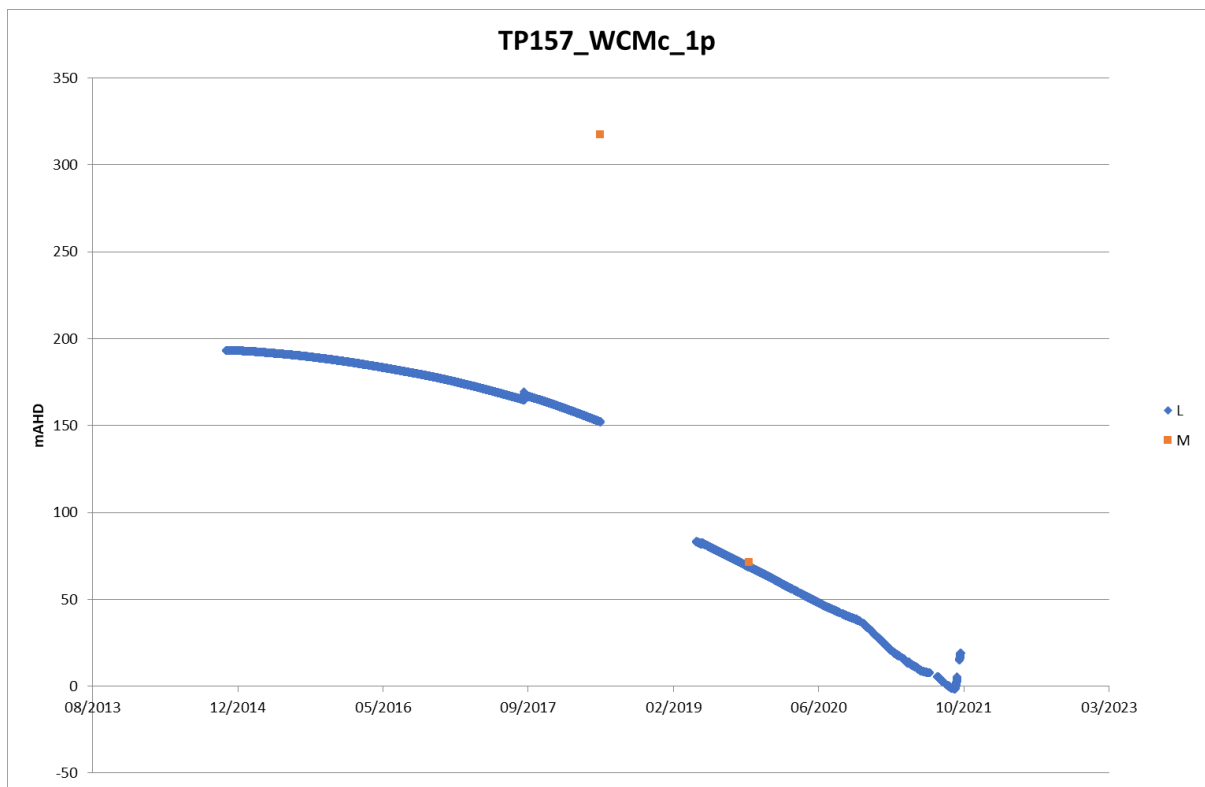
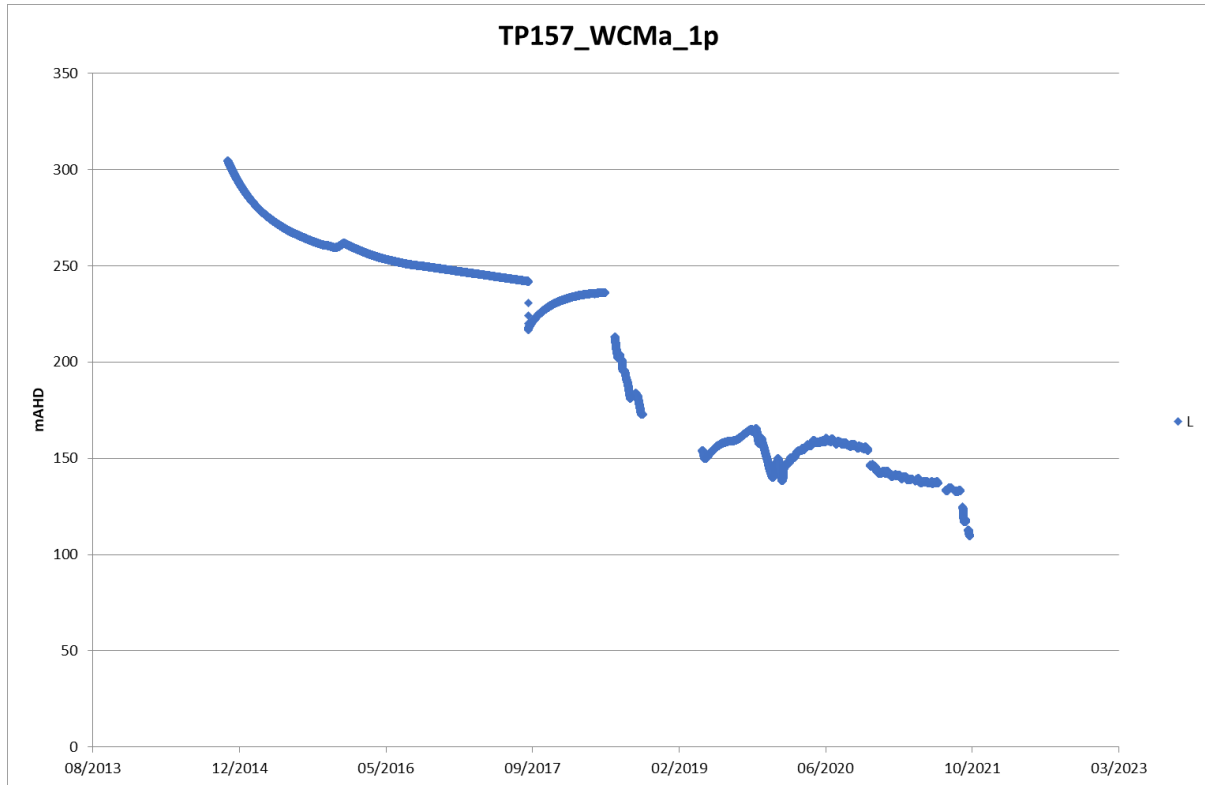


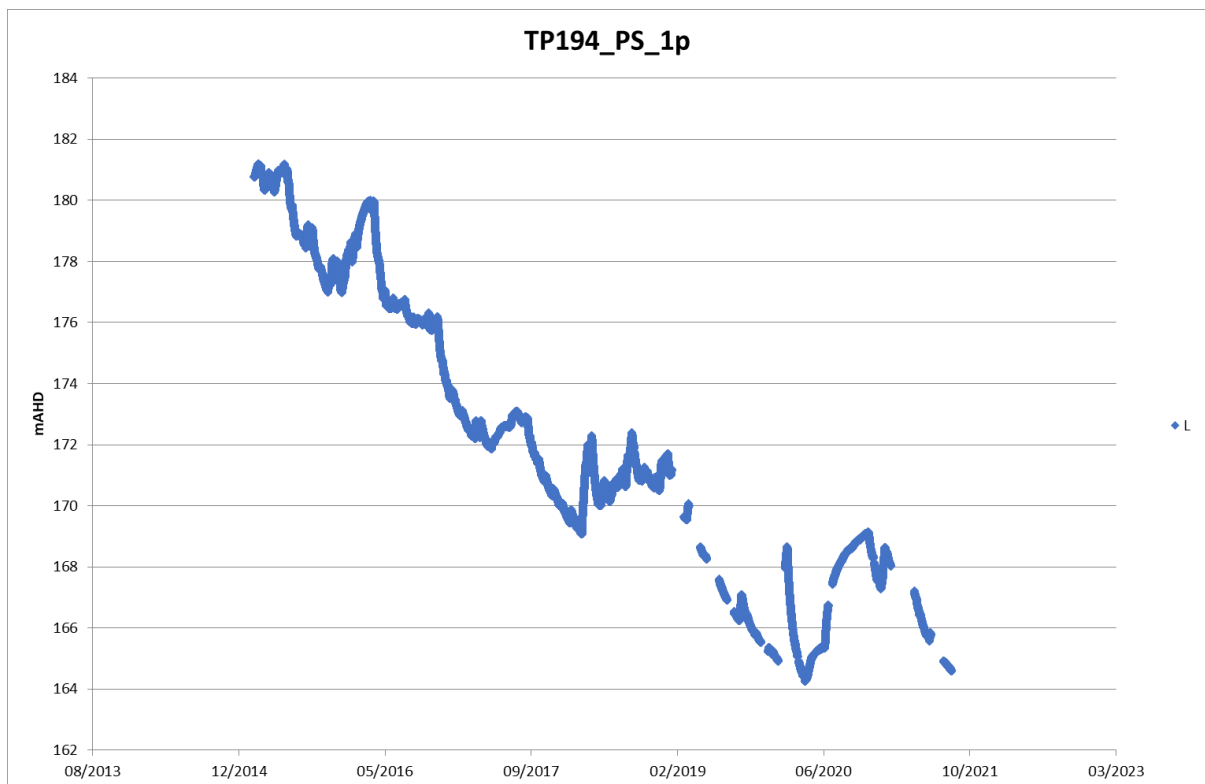
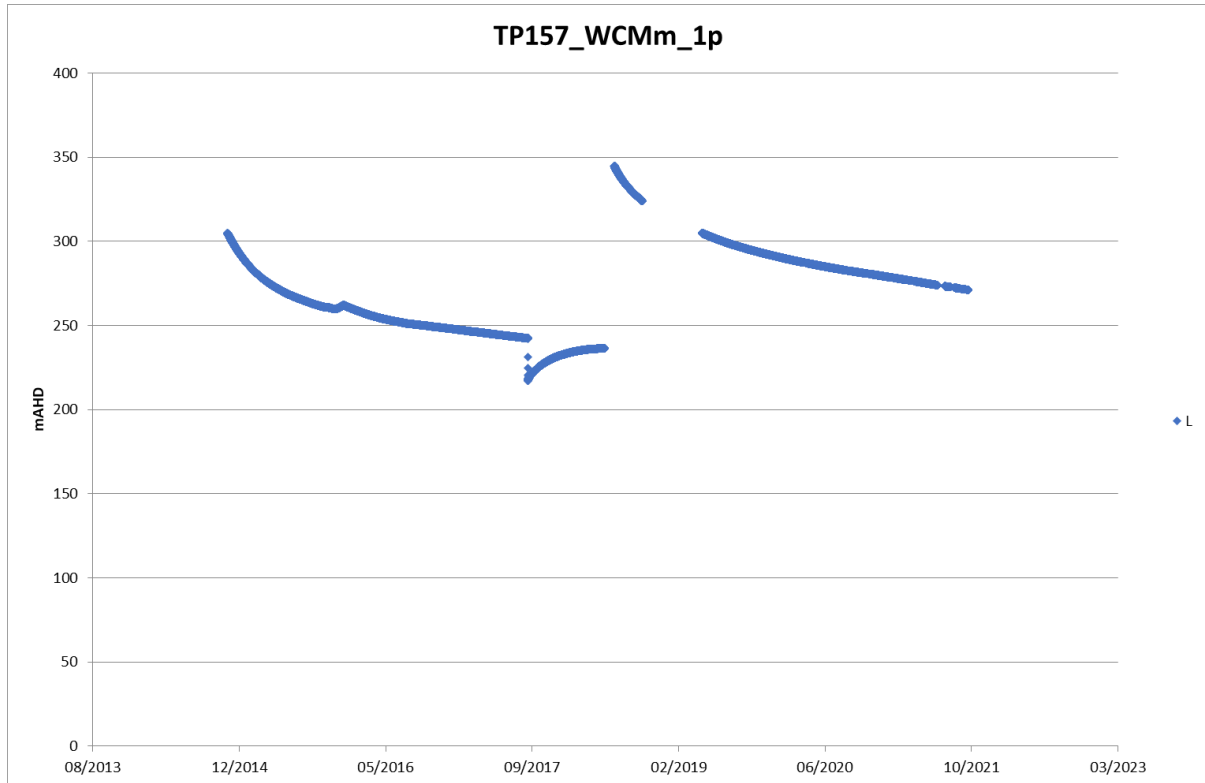


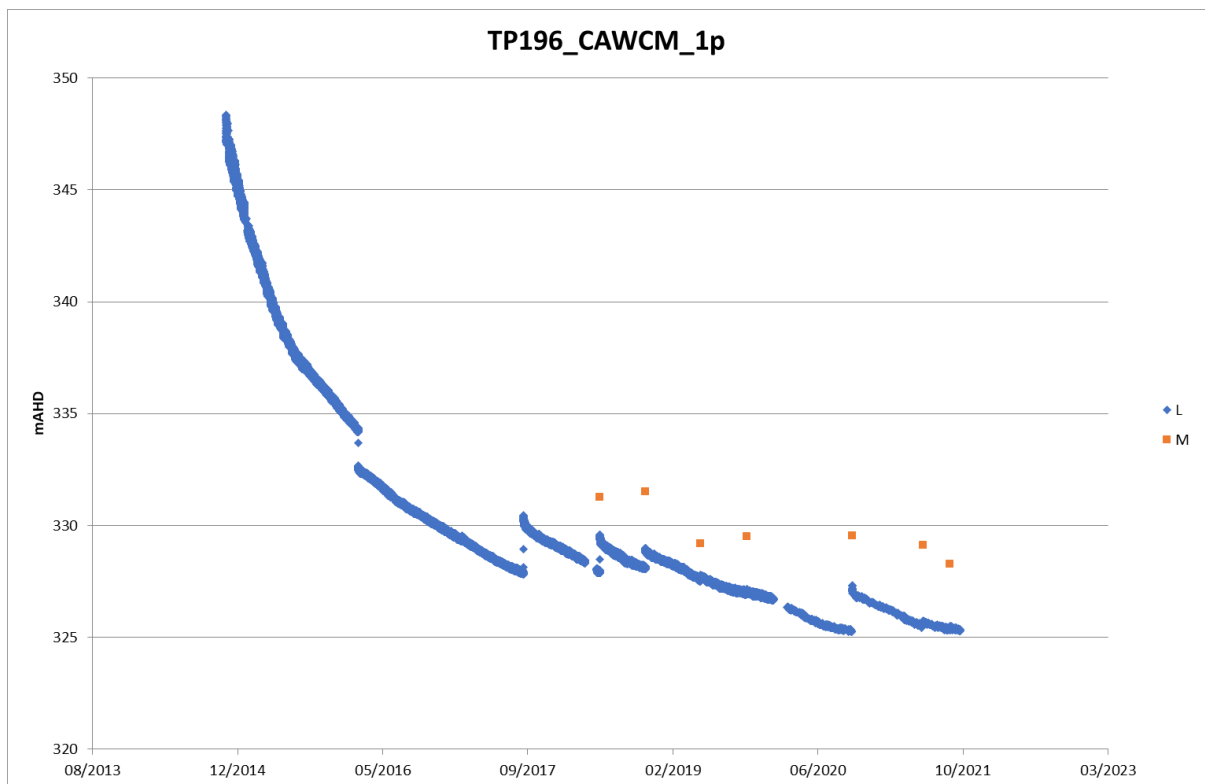
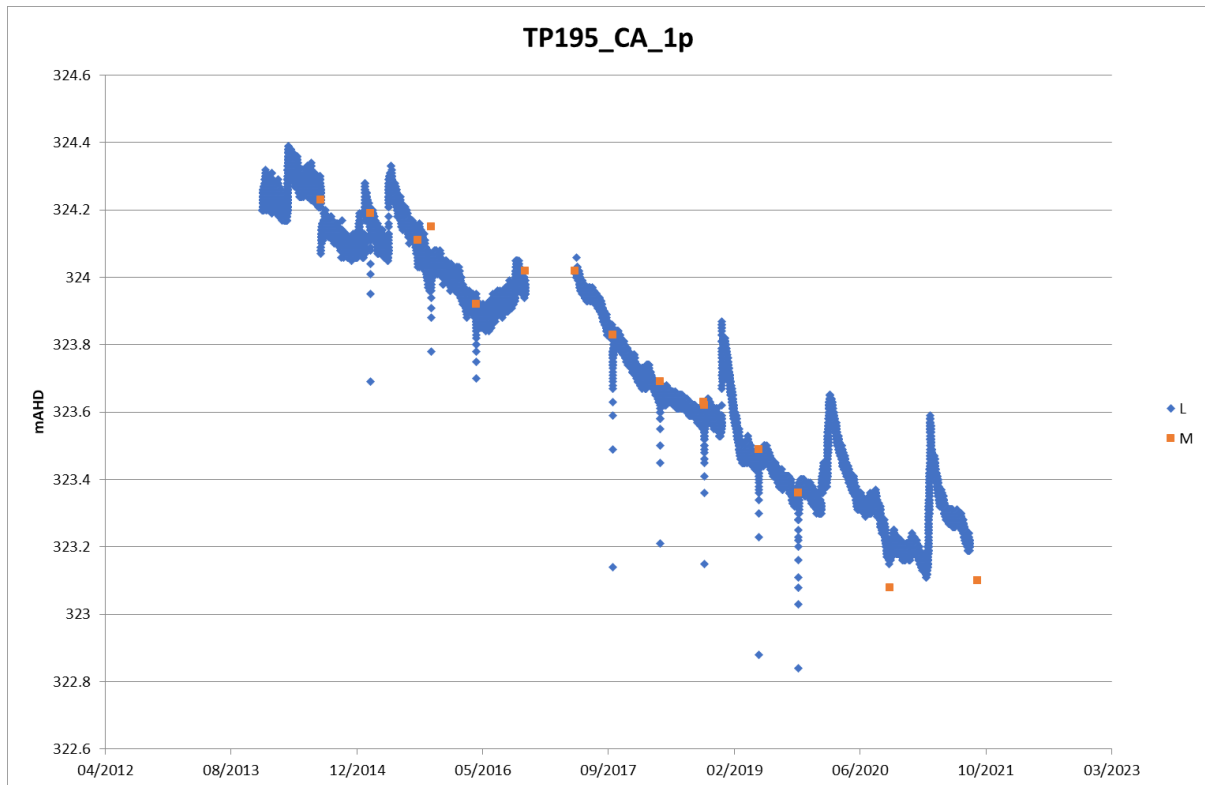


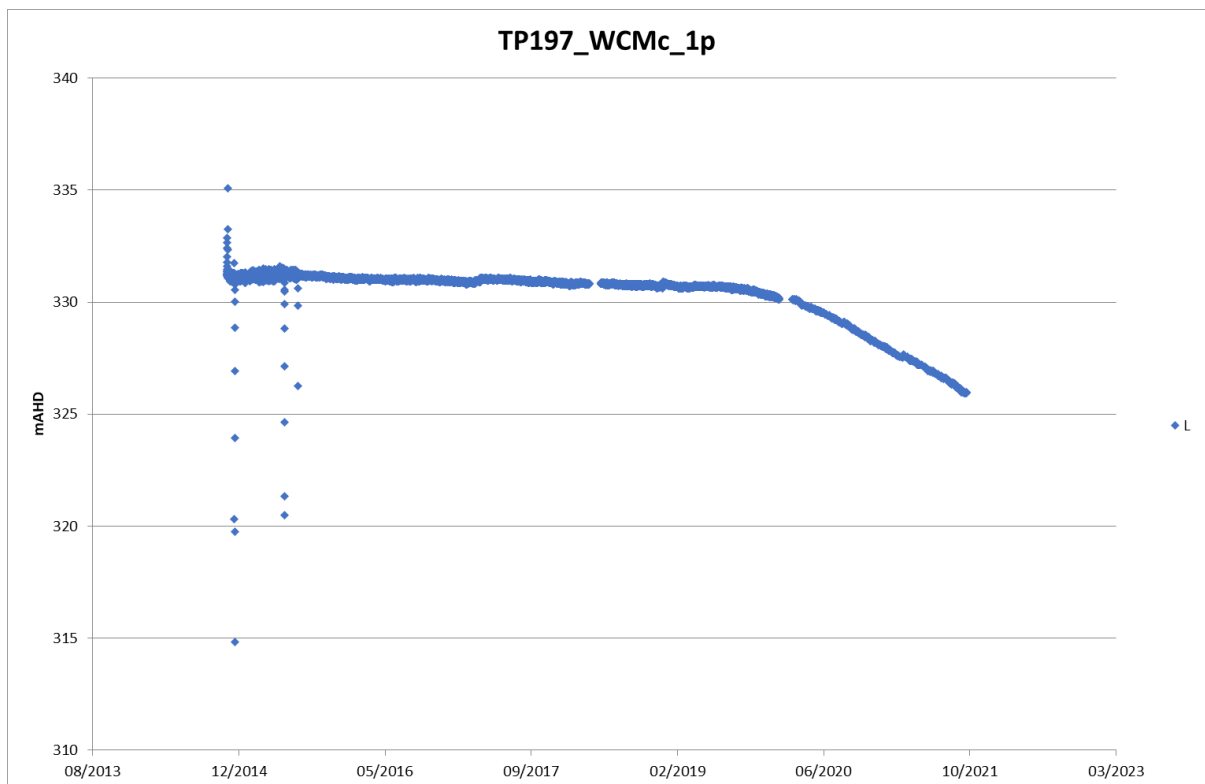
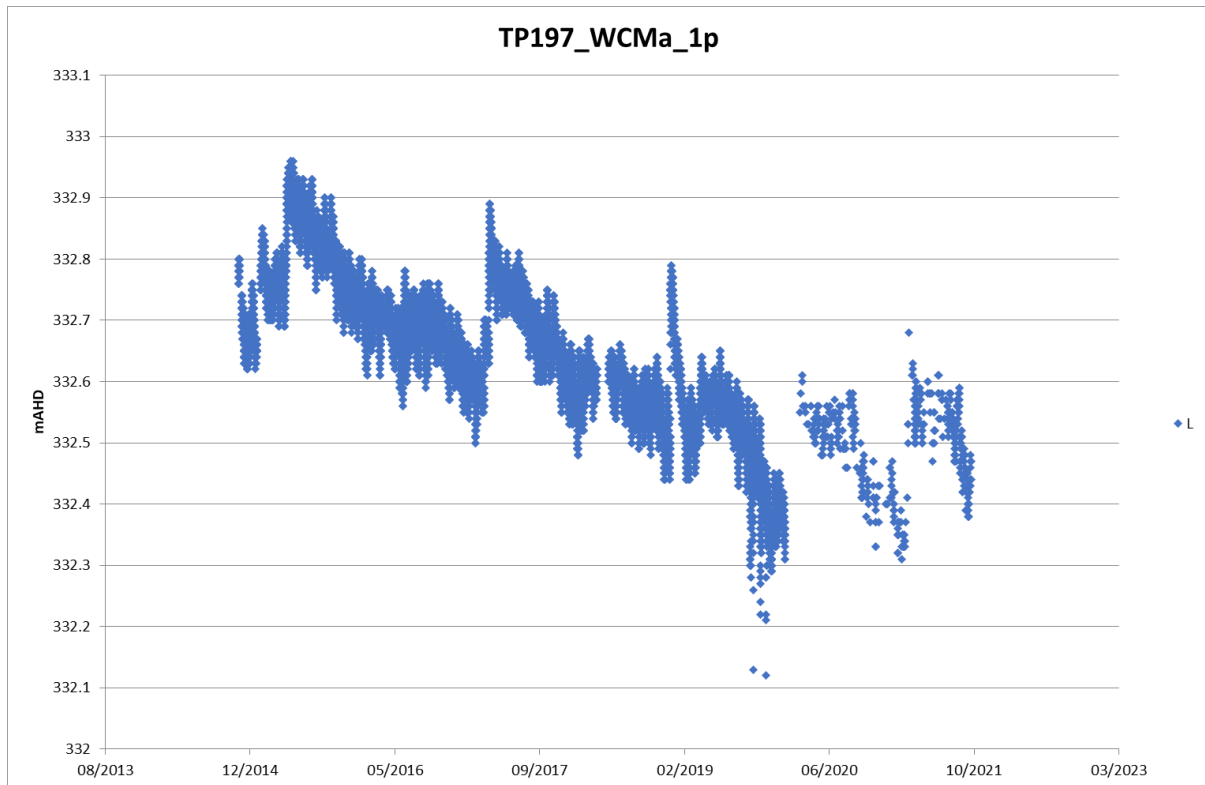


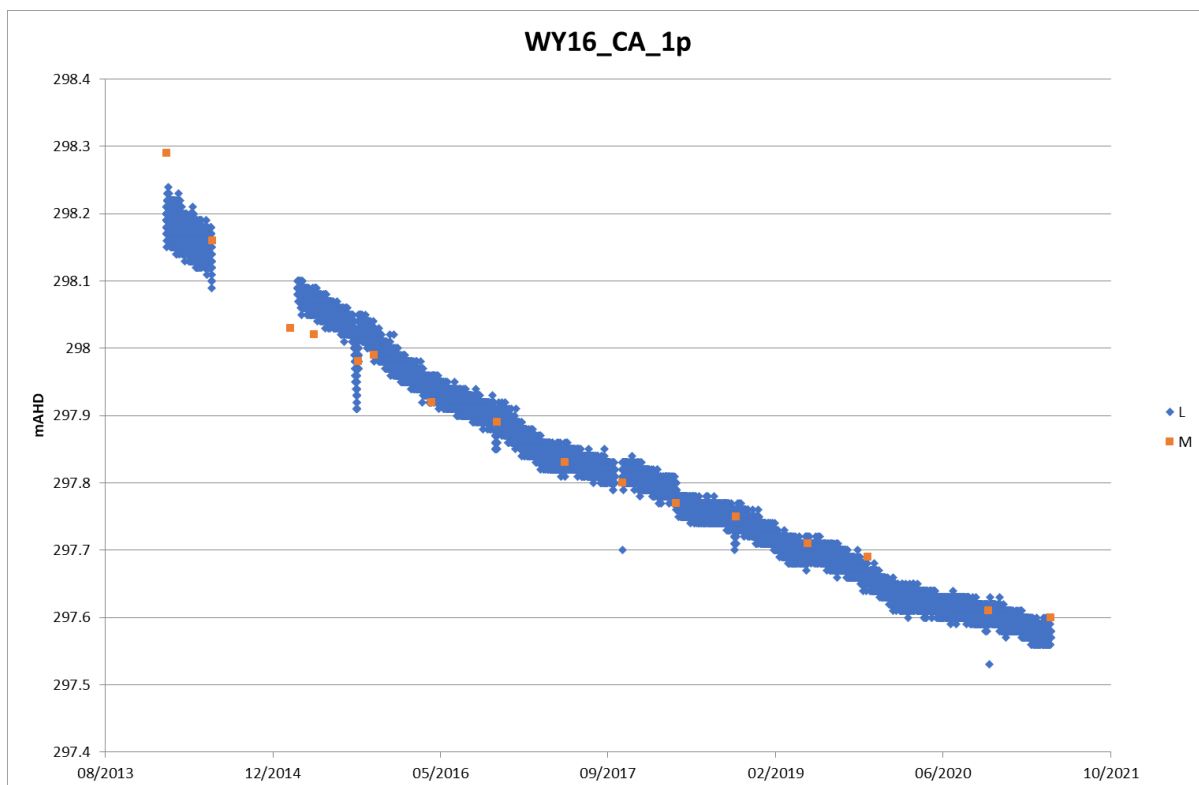
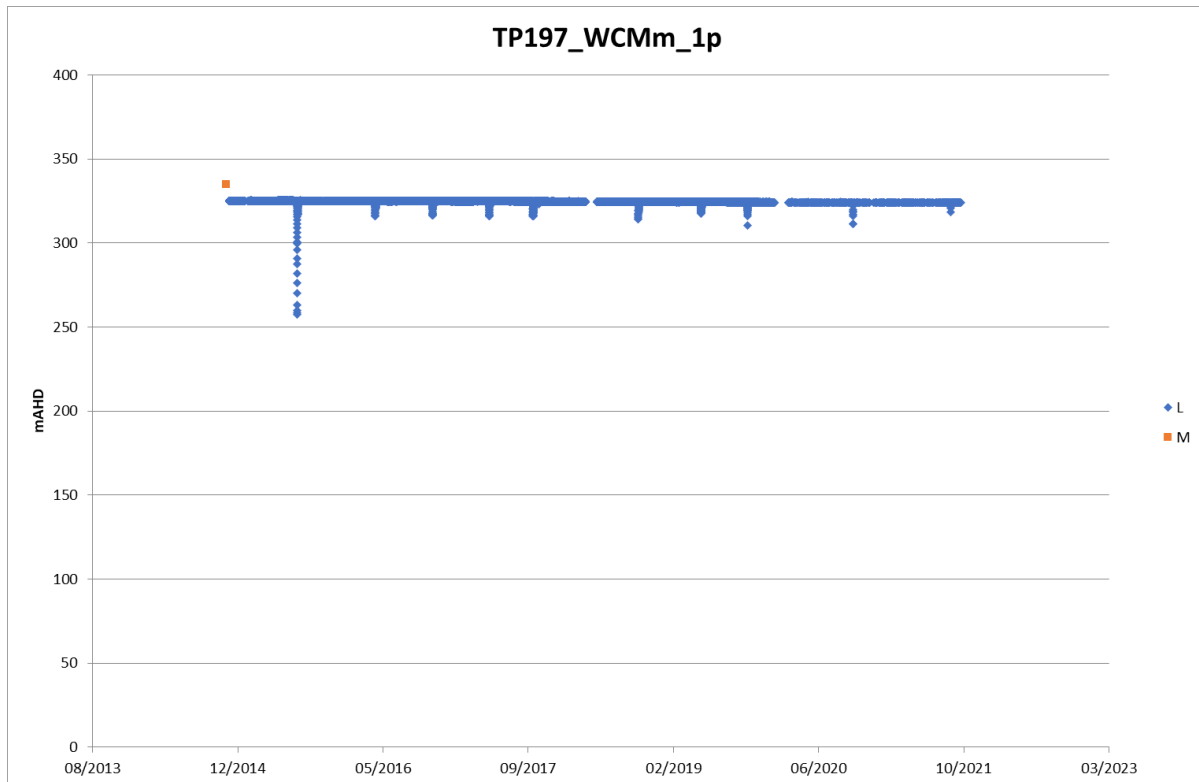






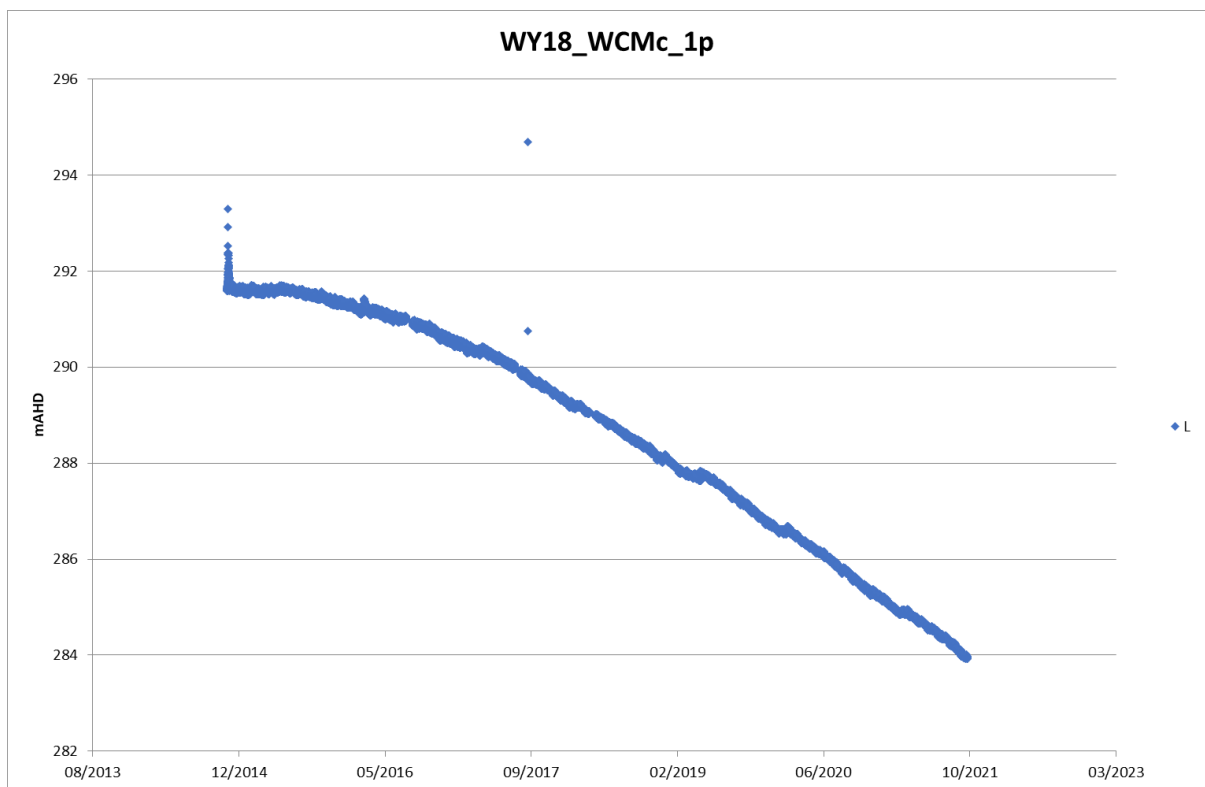
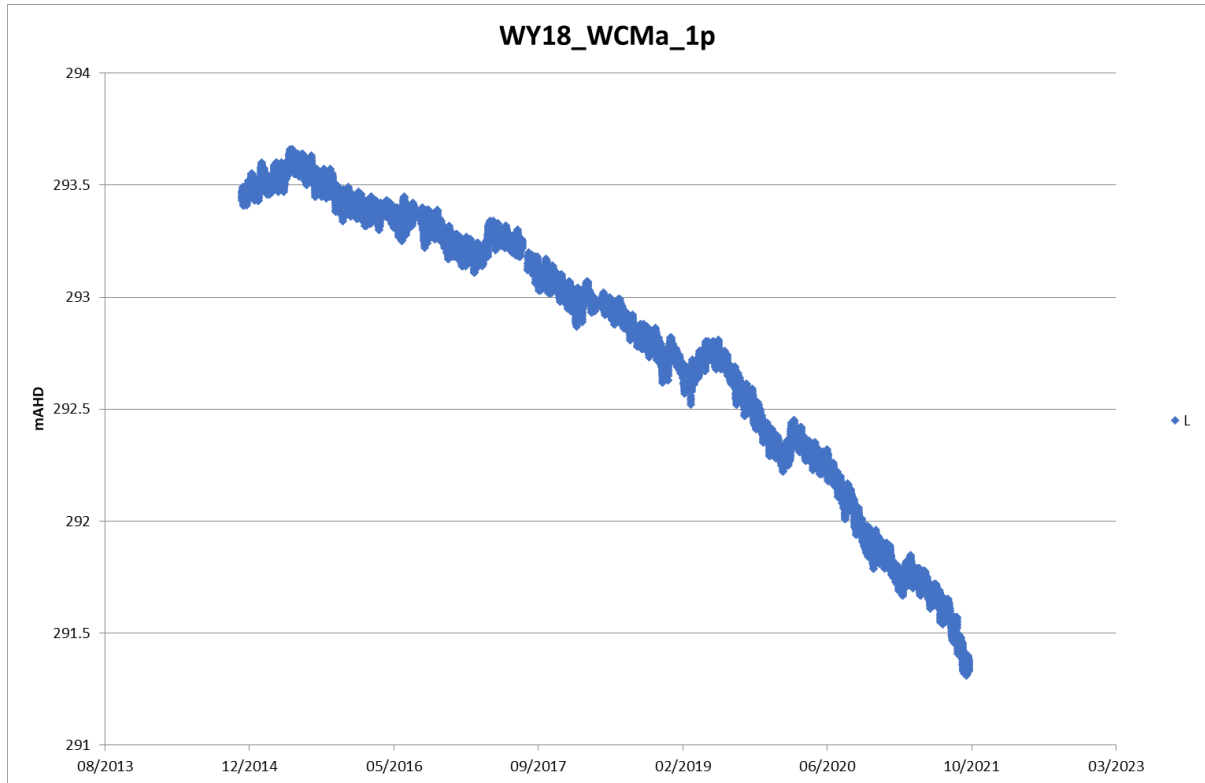


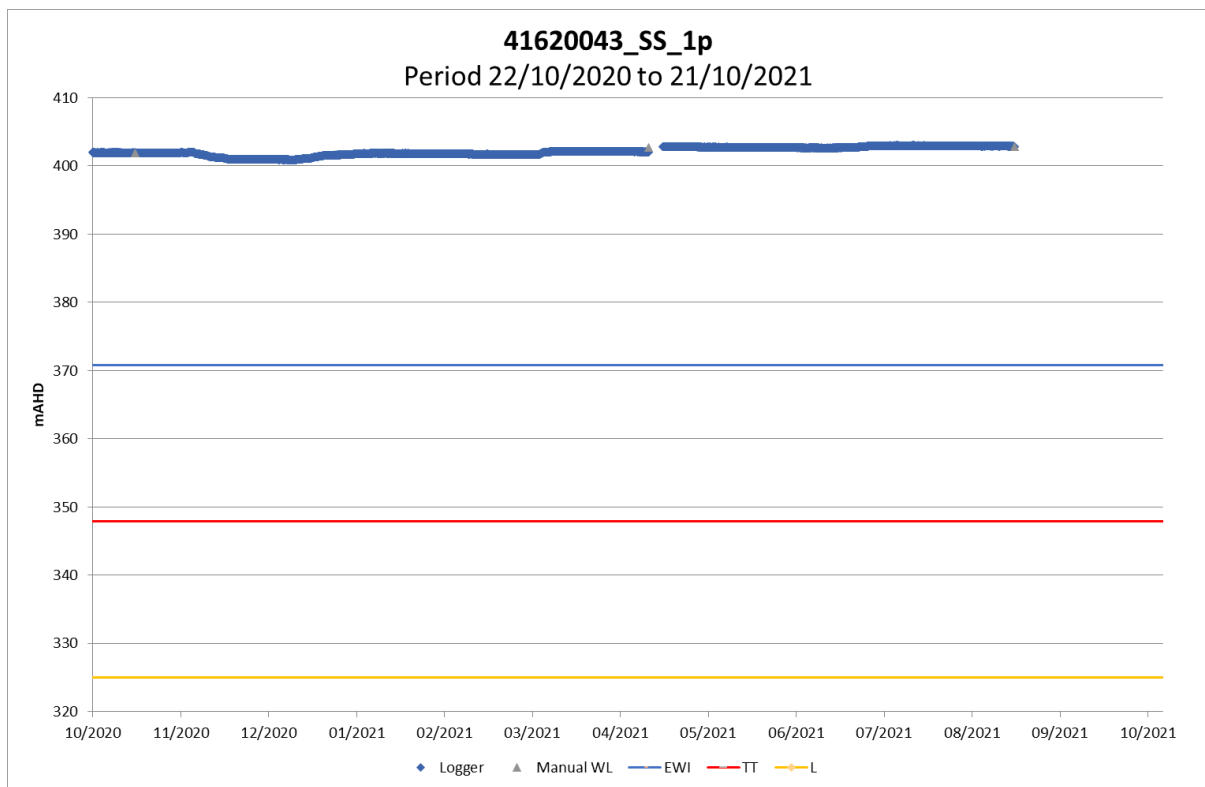
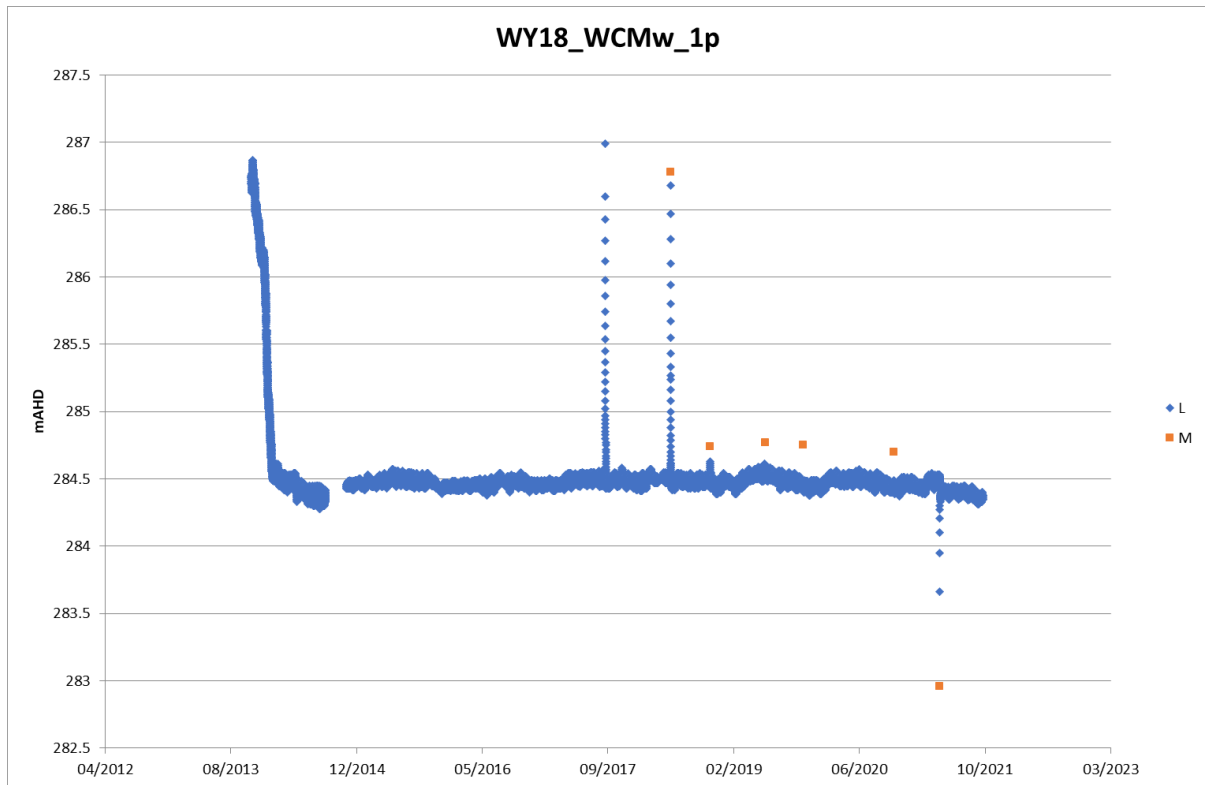


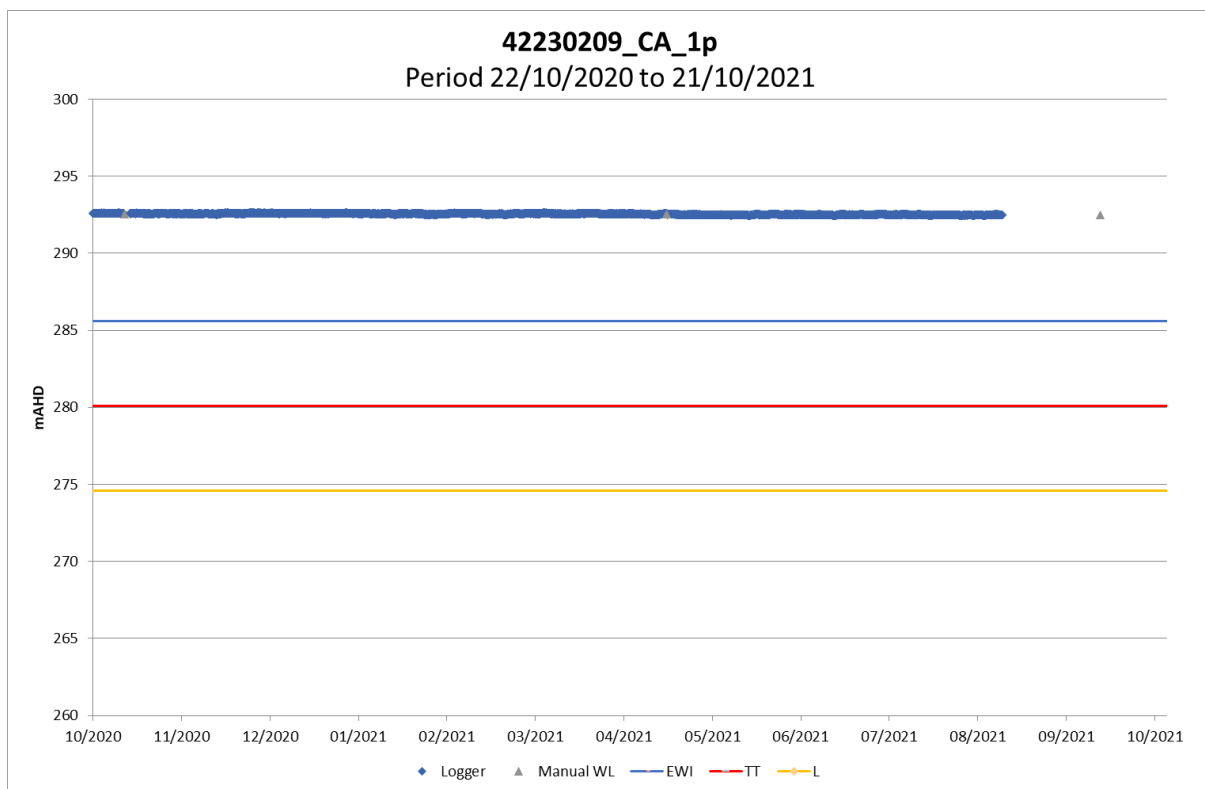
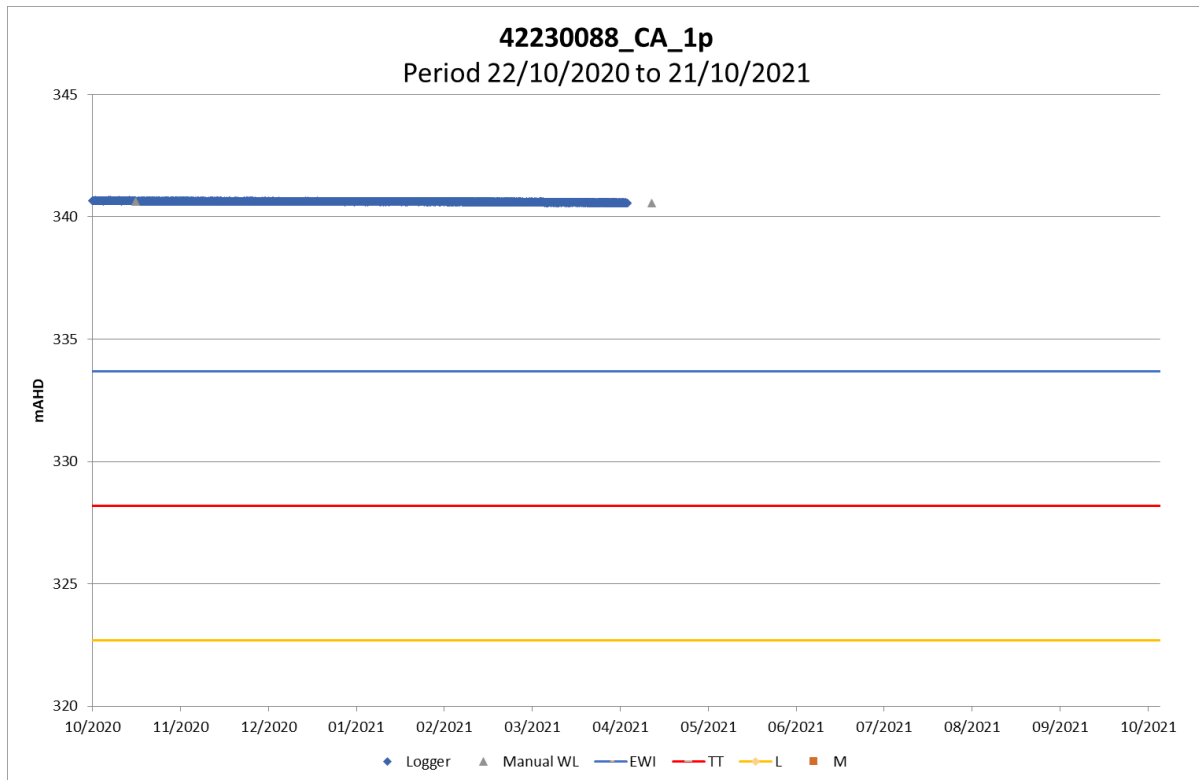


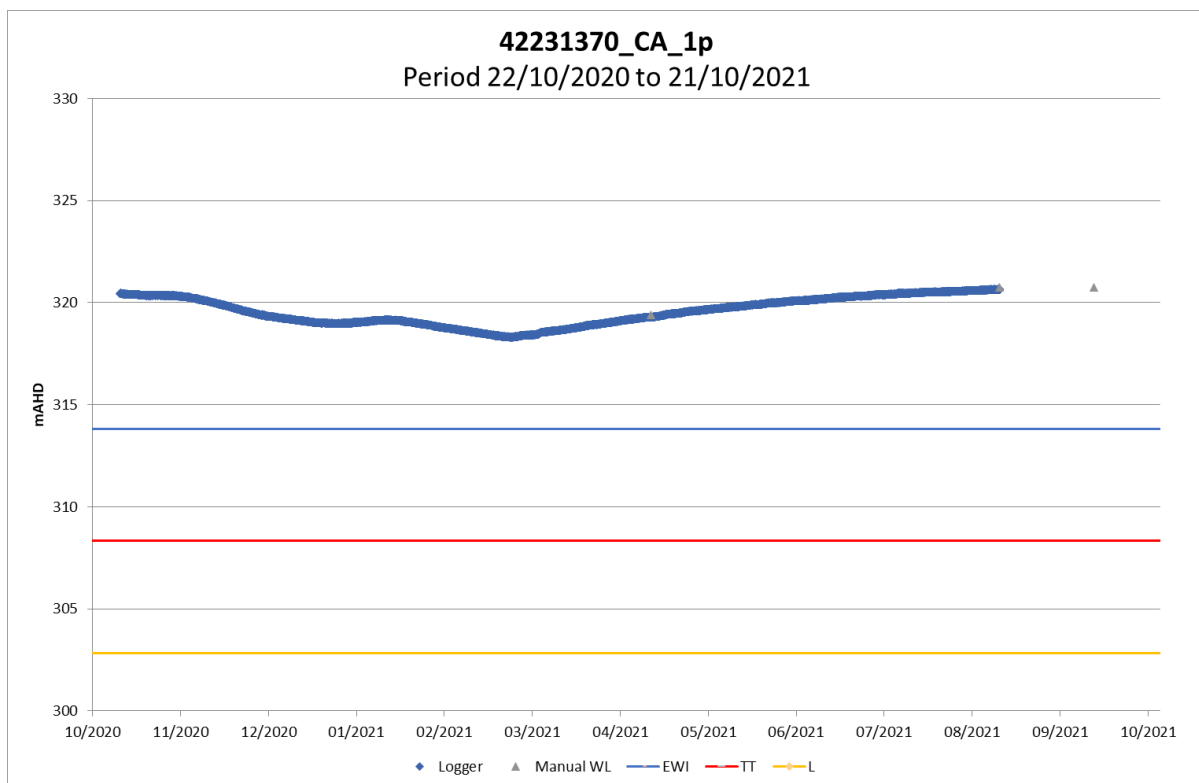
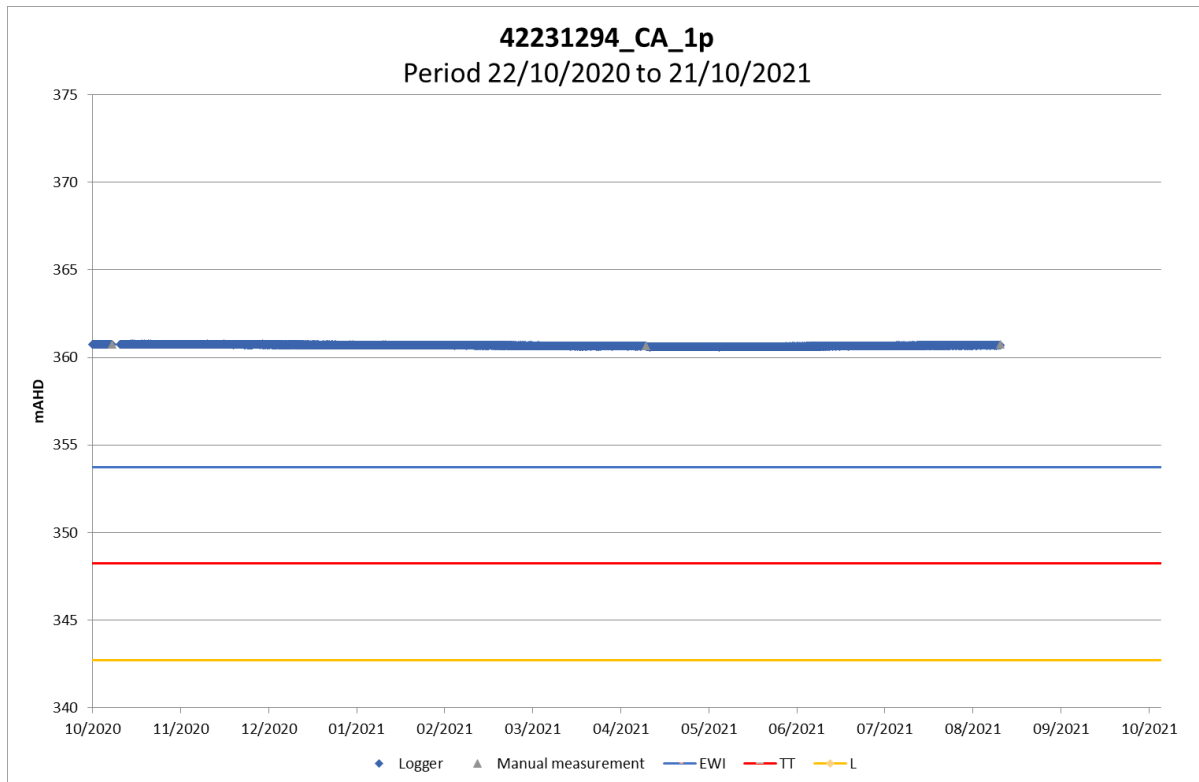


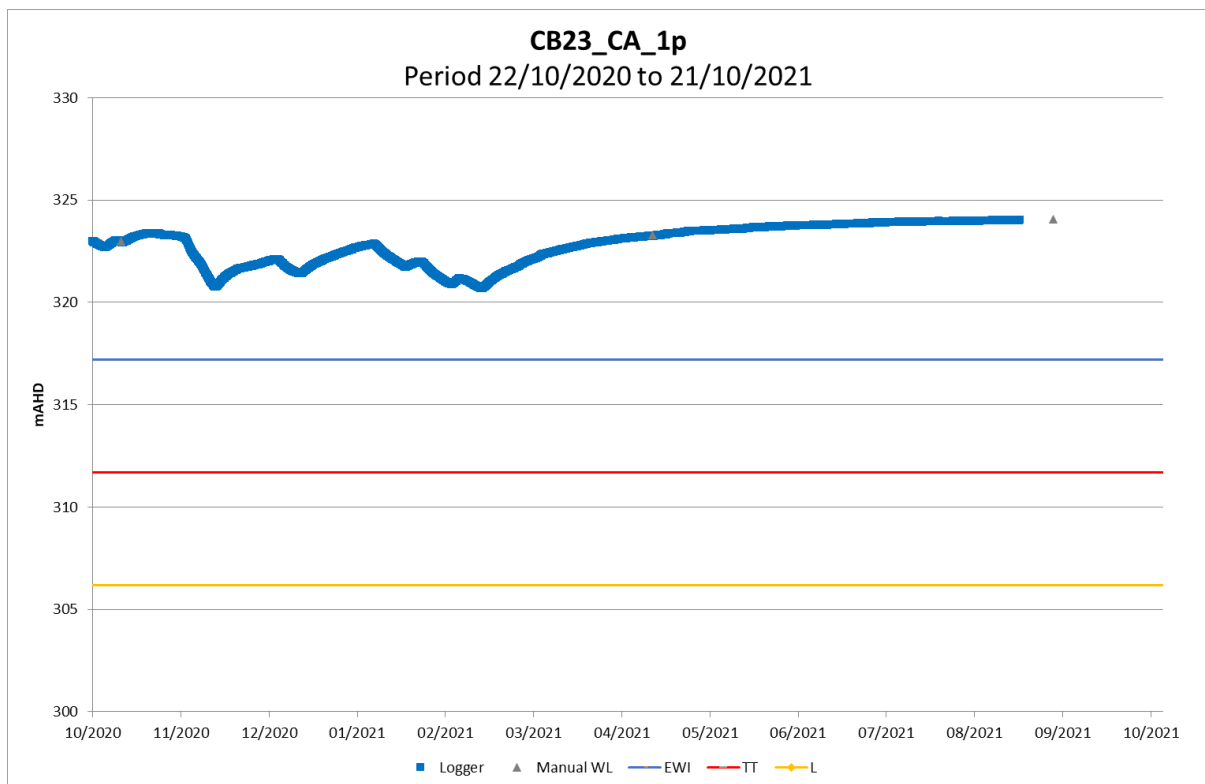
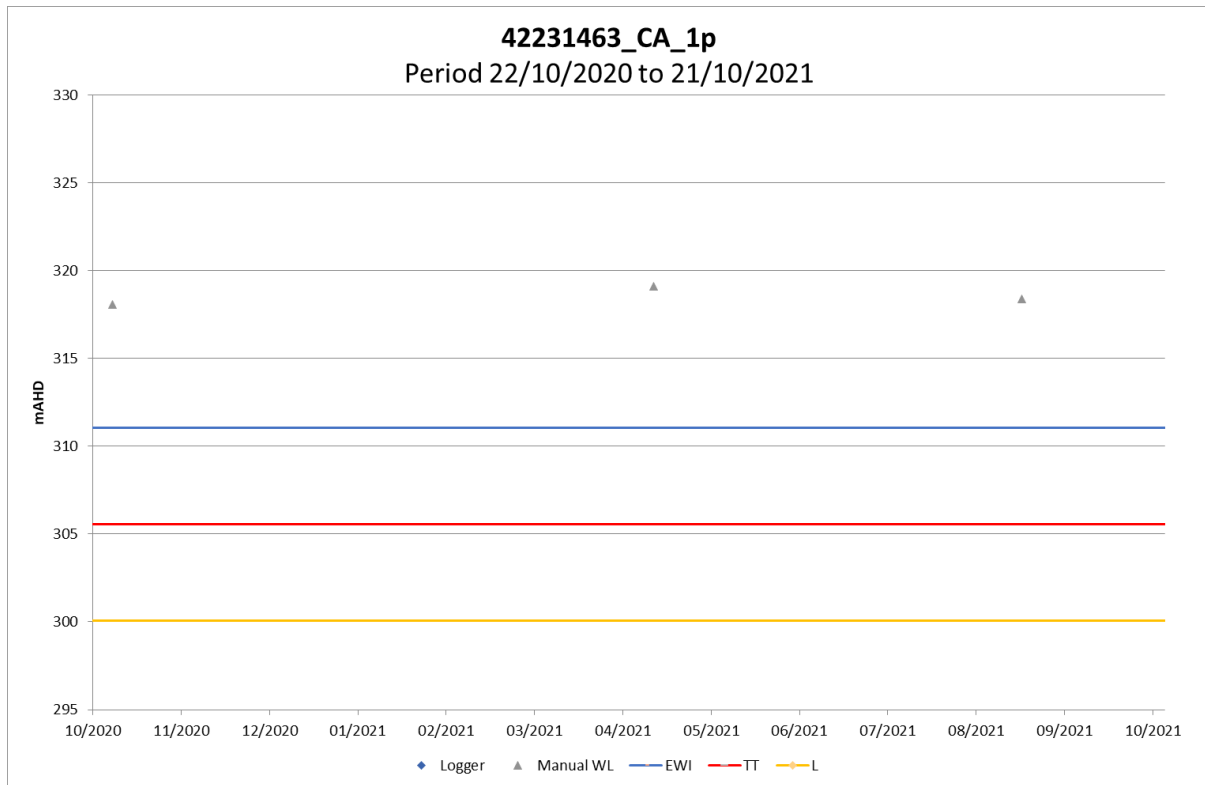


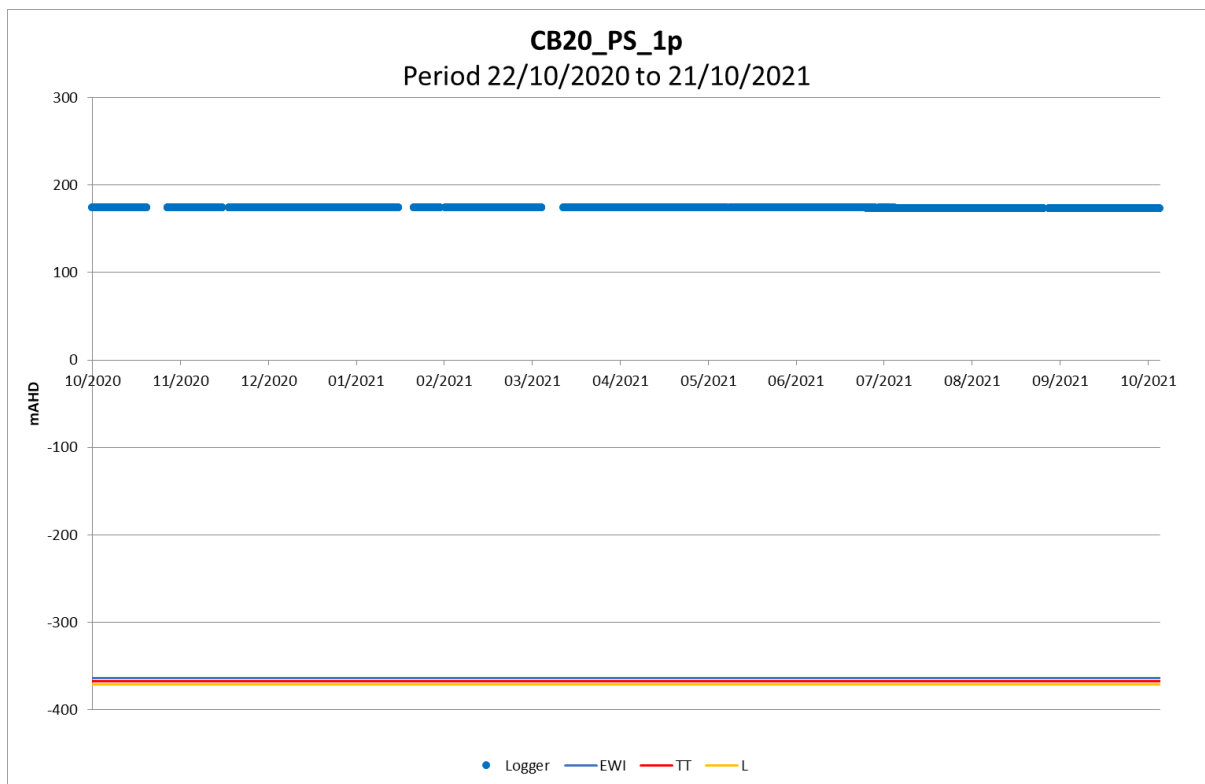
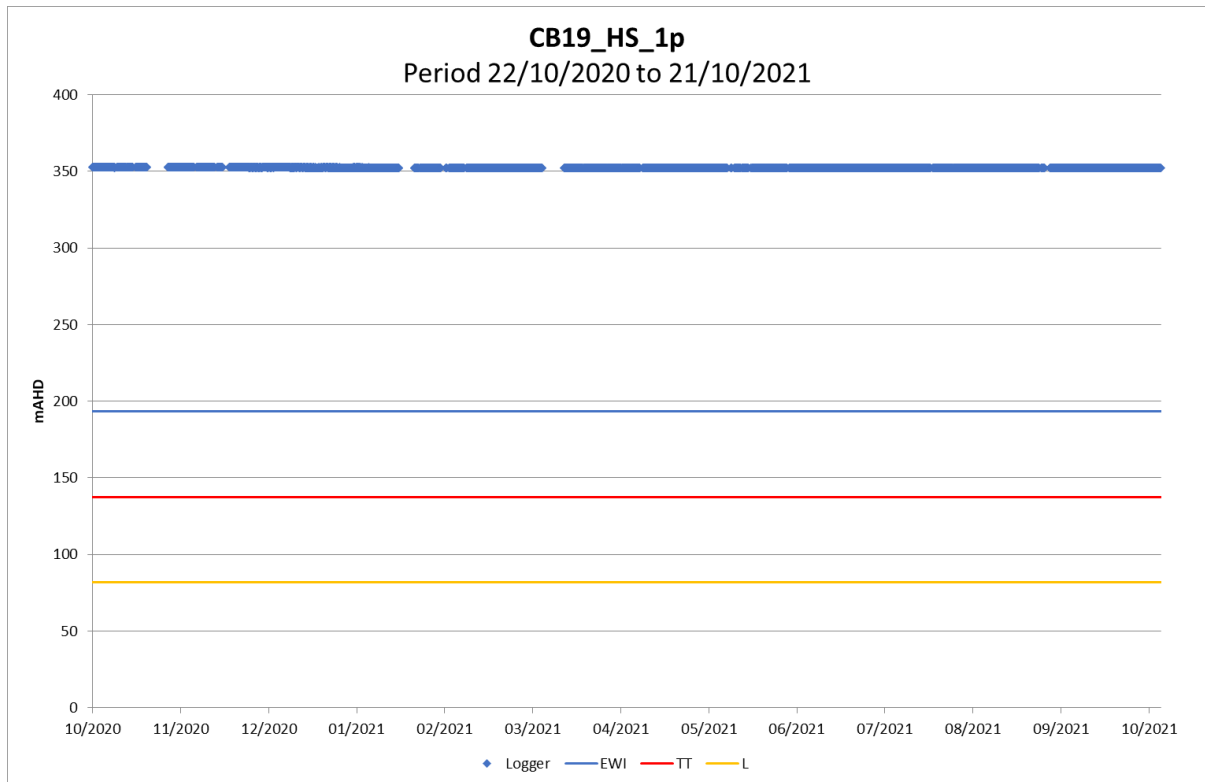




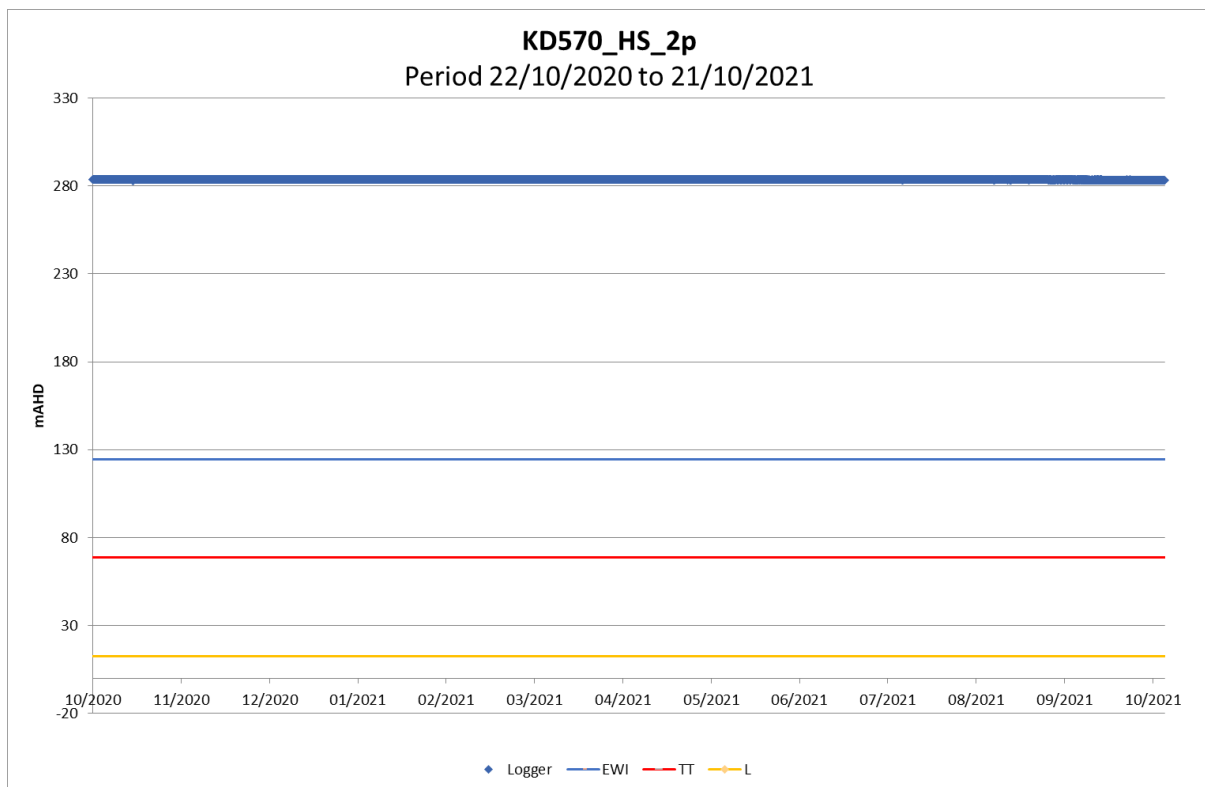
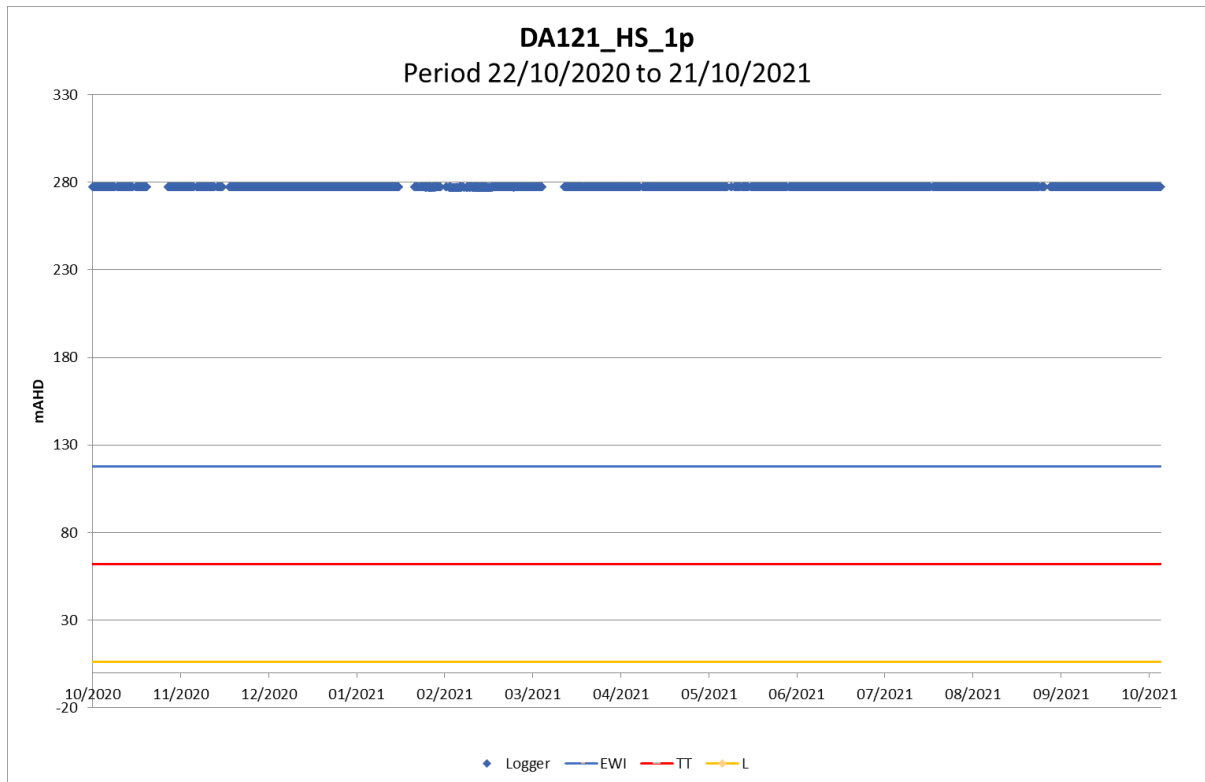


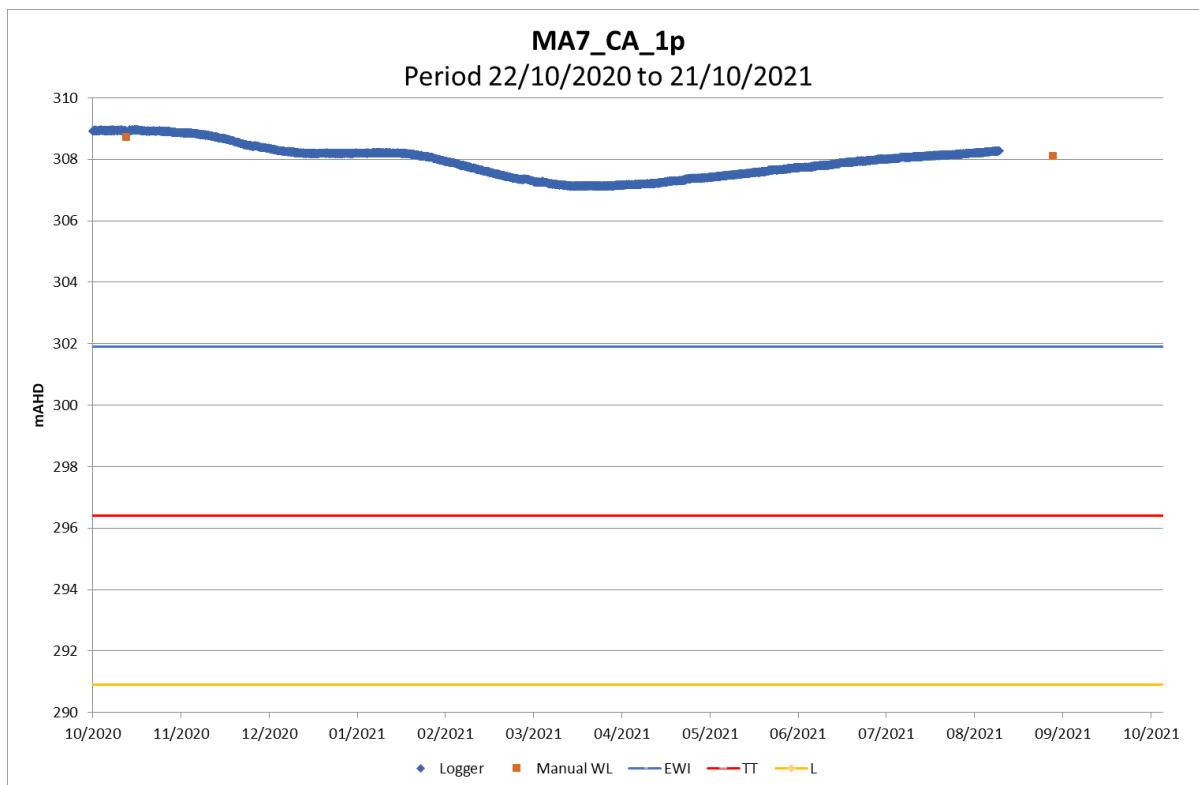
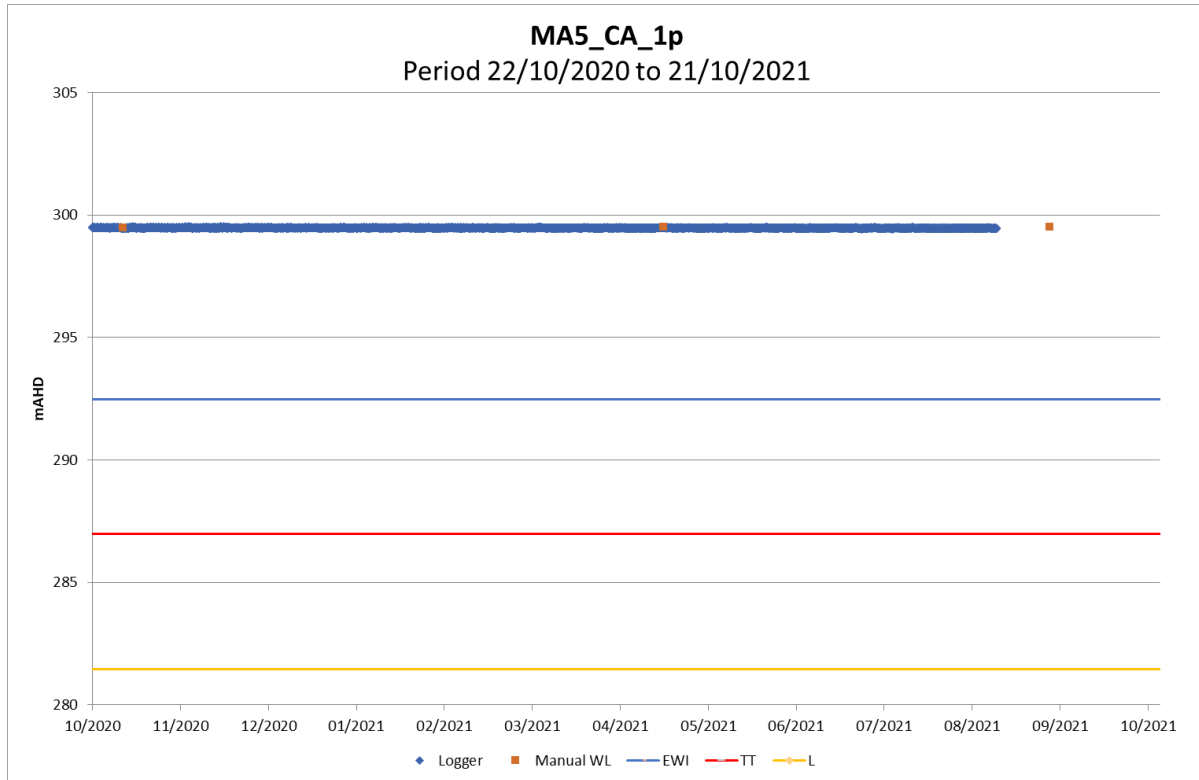


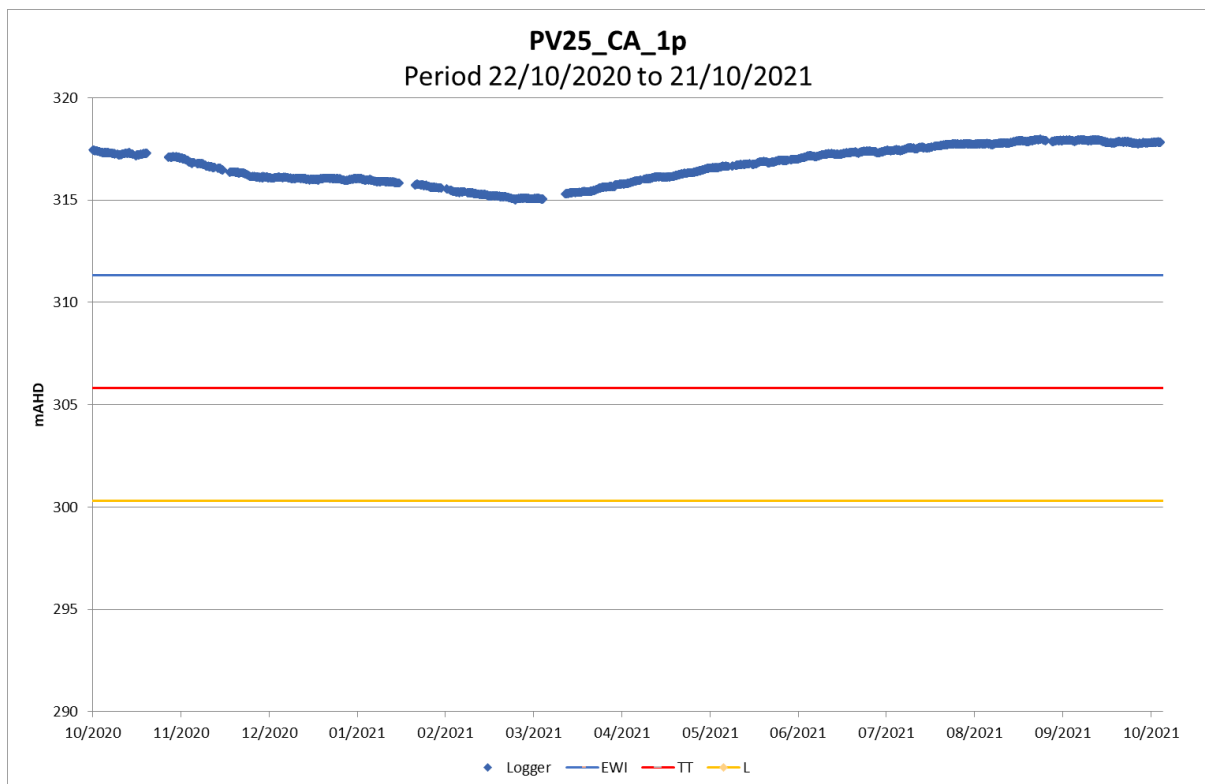
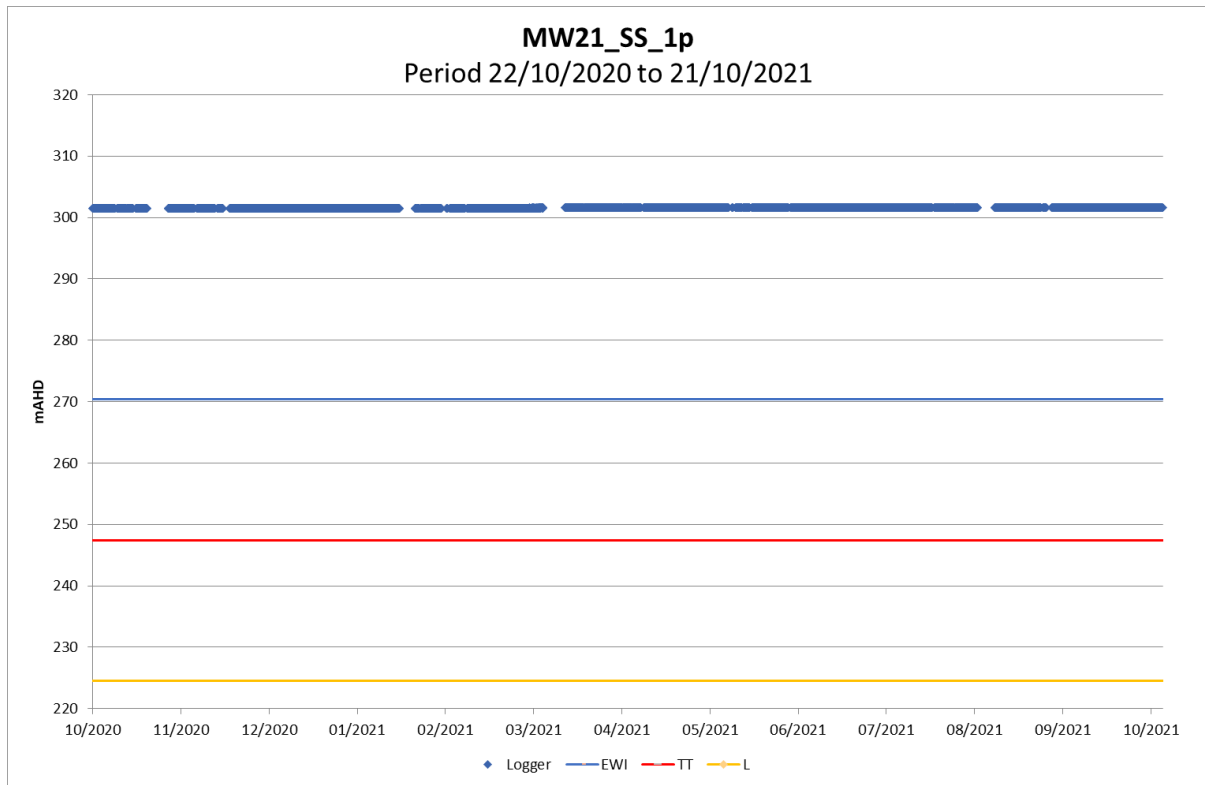


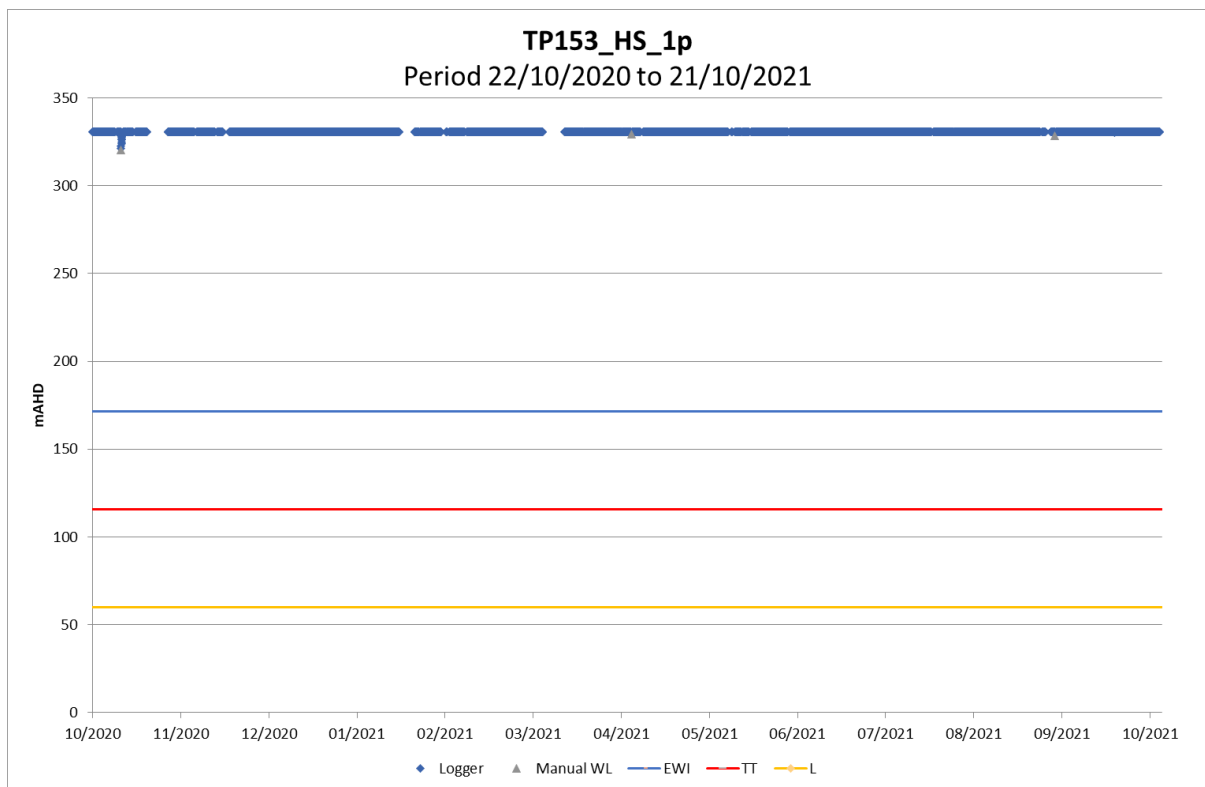
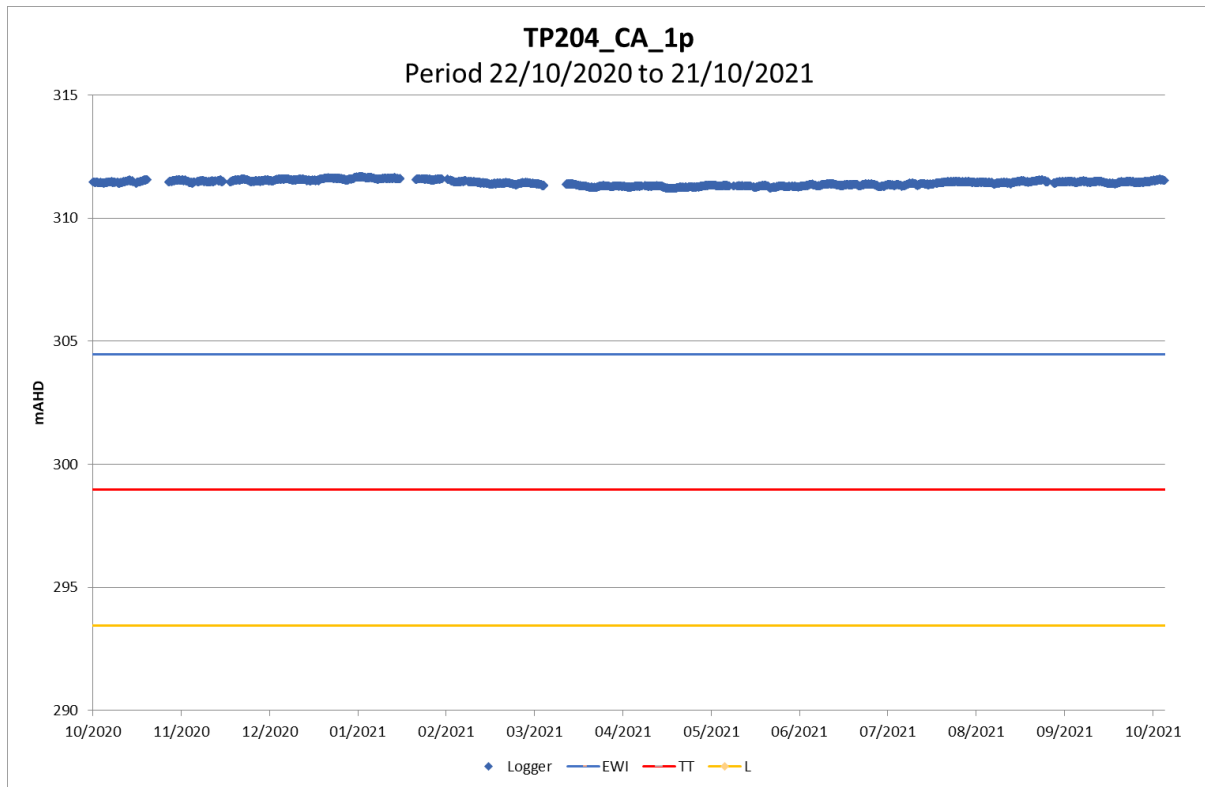


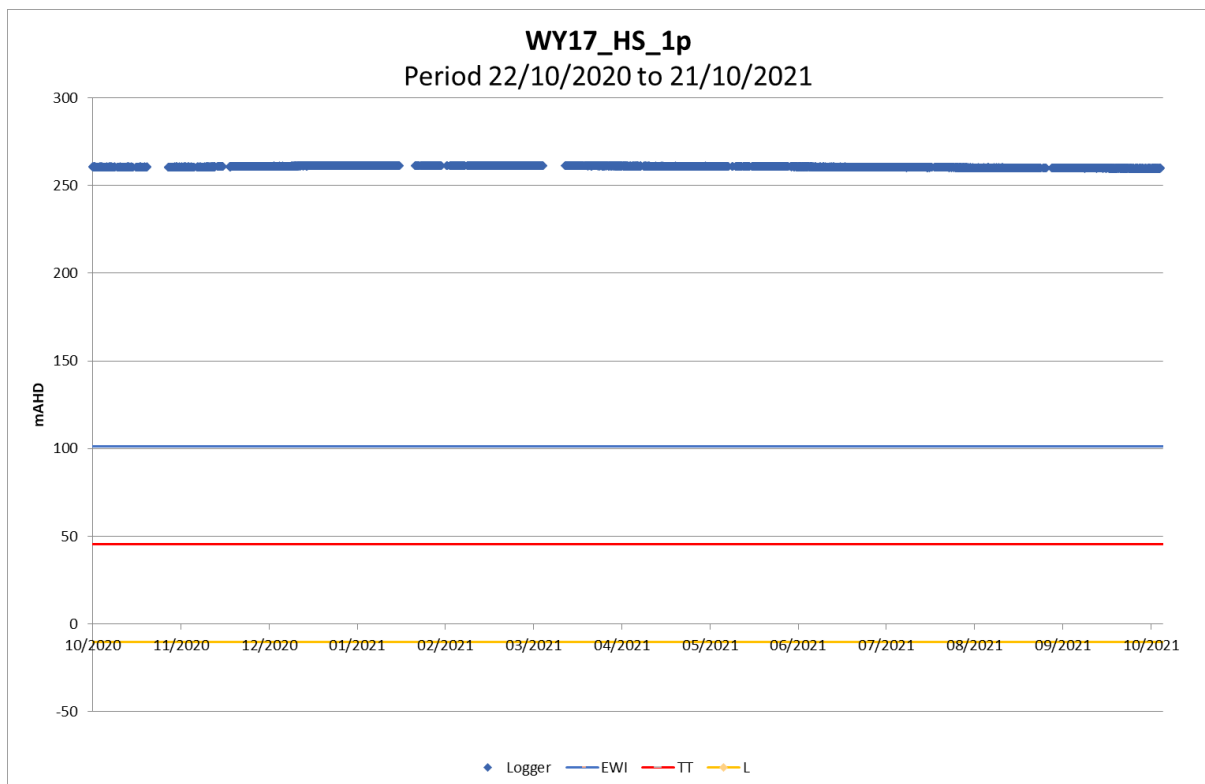
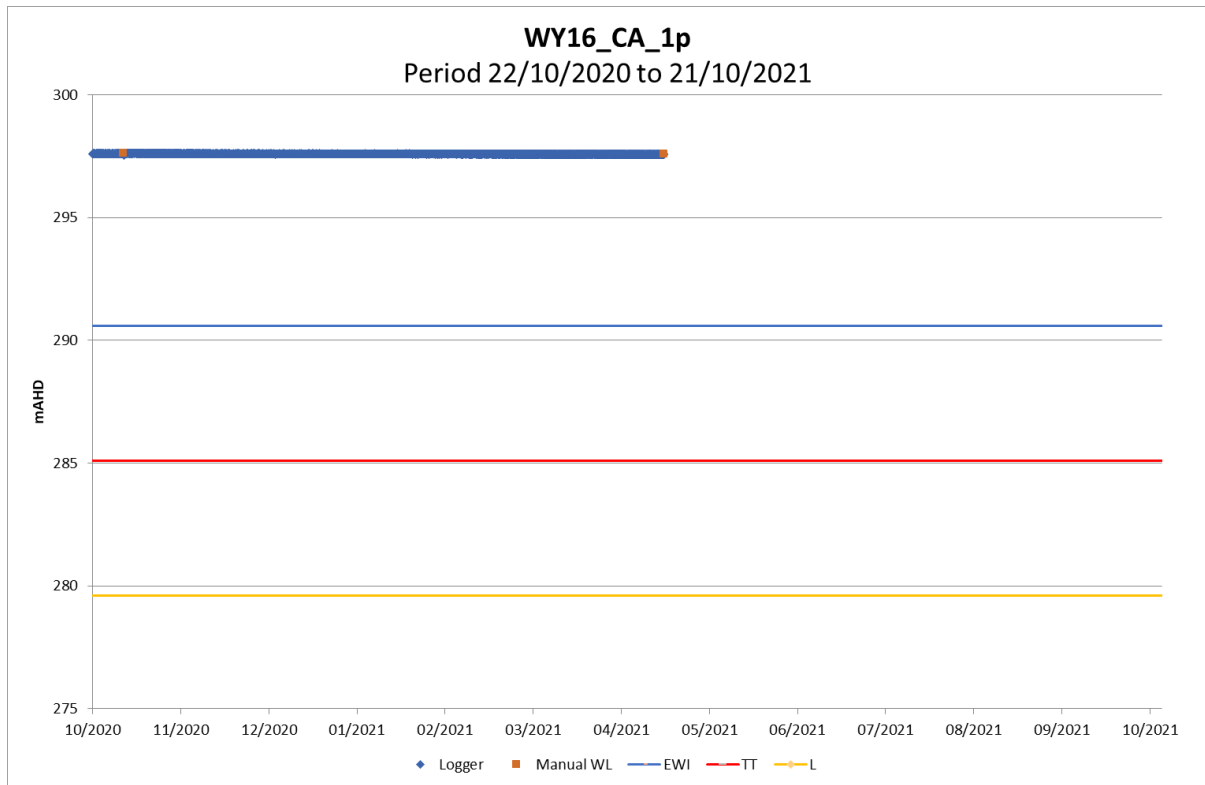


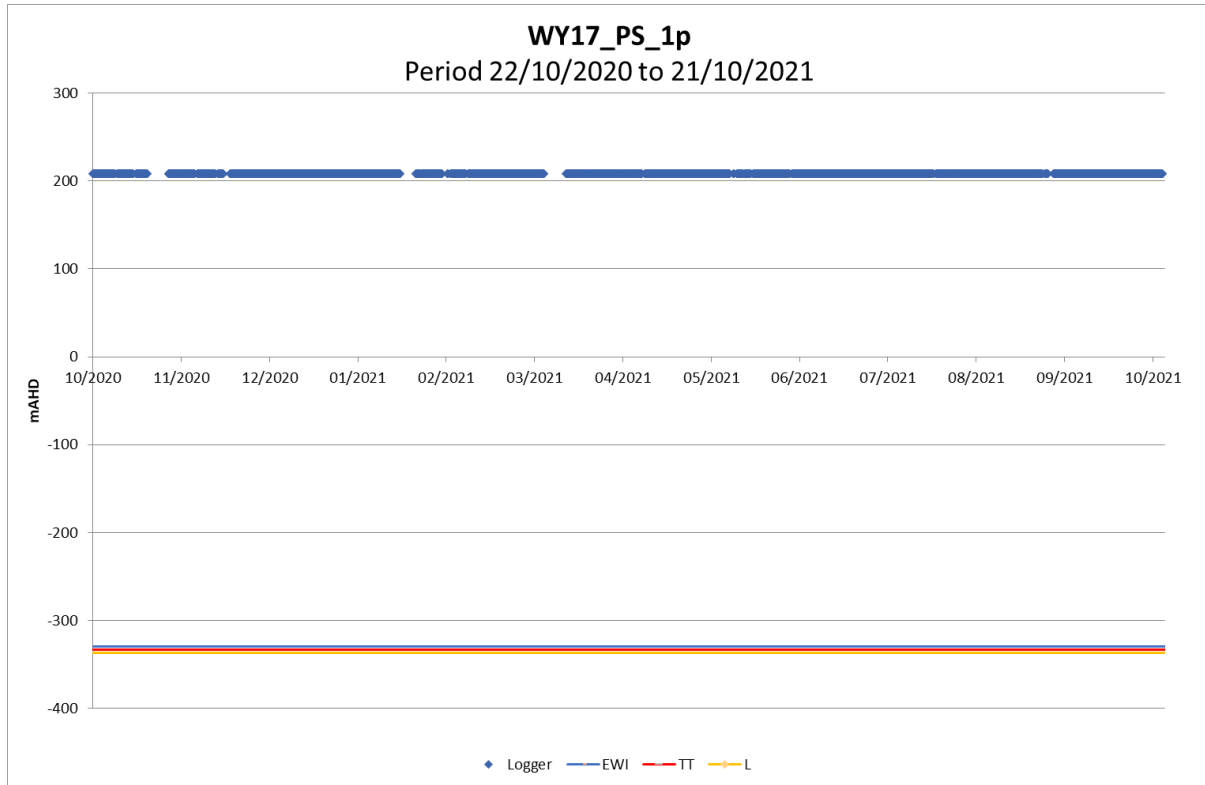












**Appendix B – Groundwater quality results**





























































































































**Appendix C – Mann-Kendall Summary**

Monitoring Unit	Field	Bore Name	Mann-Kendall Trend	Analyte	No. of data points	Mann-Kendall Statistic (S)
Precipice Sandstone	Wyalla	Wyalla-17	Up	Calcium	11	24
Precipice Sandstone	Carn Brea	Carn Brea-20	Down	Dissolved Arsenic	13	-66
Precipice Sandstone	Wyalla	Wyalla-17	Up	Dissolved Barium	11	29
Precipice Sandstone	Wyalla	Wyalla-17	Down	Dissolved Boron	11	-25
Precipice Sandstone	Carn Brea	Carn Brea-20	Down	Dissolved Chromium	9	-23
Precipice Sandstone	Wyalla	Wyalla-17	Up	Dissolved Iron	11	47
Precipice Sandstone	Wyalla	Wyalla-17	Down	Dissolved Manganese	11	-23
Precipice Sandstone	Wyalla	Wyalla-17	Up	Dissolved Methane	8	20
Condamine Alluvium	Wyalla	Wyalla-16	Up	Bicarbonate Alkalinity	14	42
Condamine Alluvium	Tipton	Tipton-195	Down	Bicarbonate Alkalinity	15	-76
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Bicarbonate Alkalinity	14	-47
Condamine Alluvium	Wyalla	42230209	Down	Bicarbonate Alkalinity	14	-36
Condamine Alluvium	Wyalla	Wyalla-16	Down	Calcium	14	-50
Condamine Alluvium	Tipton	Tipton-195	Down	Calcium	15	-65
Condamine Alluvium	Carn Brea	Carn Brea-17	Up	Calcium	14	39
Condamine Alluvium	Carn Brea	42231370	Up	Calcium	13	48
Condamine Alluvium	Wyalla	Wyalla-16	Down	Chloride	14	-72
WCM	Carn Brea	Carn Brea-18	Up	Bicarbonate Alkalinity	14	86
WCM	Tipton	Tipton-197	Down	Calcium	13	-39
WCM	Carn Brea	Carn Brea-18	Down	Calcium	14	-86
WCM	Carn Brea	Carn Brea-18	Up	Carbonate Alkalinity	14	33
WCM	Carn Brea	Carn Brea-18	Up	Chloride	14	73
WCM	Tipton	Tipton-197	Up	Dissolved Strontium	13	46
Condamine Alluvium	Tipton	Tipton-195	Up	Chloride	15	51
Condamine Alluvium	Carn Brea	Carn Brea-17	Up	Chloride	14	53
Condamine Alluvium	Carn Brea	42231370	Up	Chloride	13	44
Condamine Alluvium	Wyalla	42230209	Down	Chloride	14	-66
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Barium	15	-63
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Dissolved Barium	14	-31
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Boron	14	-41
Condamine Alluvium	Carn Brea	42231370	Down	Dissolved Cobalt	8	-16
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Iron	14	-30
Condamine Alluvium	Carn Brea	42231370	Up	Dissolved Iron	11	28
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Manganese	14	-81
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Dissolved Manganese	14	-45
Condamine Alluvium	Wyalla	42230209	Up	Dissolved Manganese	14	70
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Methane	12	-58
Condamine Alluvium	Carn Brea	42231370	Down	Dissolved Nickel	11	-26
Springbok Sandstone	Stratheden	Strathden-63	Up	Calcium	9	18
Springbok Sandstone	Stratheden	Strathden-63	Up	Sodium	9	26
Springbok Sandstone	Stratheden	Strathden-63	Down	Carbonate Alkalinity	5	-10
Springbok Sandstone	Stratheden	Strathden-63	Up	Chloride	9	23
Springbok Sandstone	Stratheden	Strathden-63	Down	Total Alkalinity	9	-18
Springbok Sandstone	Stratheden	Strathden-63	Up	Dissolved Barium	9	24
Springbok Sandstone	Stratheden	Strathden-63	Up	Dissolved Strontium	9	20
Springbok Sandstone	Stratheden	Strathden-63	Up	TDS	9	20
Westbourne Formation	Daandine	Daandine-124	Down	EC (Field)	10	-29
Westbourne Formation	Daandine	Daandine-124	Down	Dissolved Barium	14	-46
Westbourne Formation	Daandine	Daandine-124	Down	Dissolved Manganese	14	-45
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Dissolved Barium	12	35
Hutton Sandstone	Carn Brea	Carn Brea-19	Down	Dissolved Boron	11	-29
Hutton Sandstone	Carn Brea	Carn Brea-19	Down	Dissolved Copper	12	-43
Hutton Sandstone	Daandine	Daandine-121	Down	Dissolved Iron	12	-34
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Dissolved Iron	12	28
Precipice Sandstone	Carn Brea	Carn Brea-20	Up	Dissolved Methane	11	28
Precipice Sandstone	Carn Brea	Carn Brea-20	Down	Dissolved Nickel	12	-42
Precipice Sandstone	Carn Brea	Carn Brea-20	Up	Fluoride	12	26
Precipice Sandstone	Carn Brea	Carn Brea-20	Up	Magnesium	11	38
Precipice Sandstone	Wyalla	Wyalla-17	Down	Potassium	11	-49
Precipice Sandstone	Wyalla	Wyalla-17	Up	Redox (Field)	8	20
Precipice Sandstone	Carn Brea	Carn Brea-20	Up	Sodium	12	32
Hutton Sandstone	Daandine	Daandine-121	Down	Dissolved Manganese	12	-37
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Dissolved Manganese	12	40
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Dissolved Methane	11	23
Hutton Sandstone	Daandine	Daandine-121	Down	Dissolved Nickel	12	-42
Hutton Sandstone	Carn Brea	Carn Brea-19	Down	Dissolved Nickel	12	-27
Hutton Sandstone	Daandine	Daandine-121	Up	Dissolved Strontium	12	33

Monitoring Unit	Field	Bore Name	Mann-Kendall Trend	Analyte	No. of data points	Mann-Kendall Statistic (S)
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Fluoride	12	31
Hutton Sandstone	Daandine	Daandine-121	Down	Potassium	12	-26
Hutton Sandstone	Carn Brea	Carn Brea-19	Down	Redox (Field)	9	-20
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	Sodium	12	35
Hutton Sandstone	Carn Brea	Carn Brea-19	Up	TDS	12	33
Hutton Sandstone	Carn Brea	Carn Brea-19	Down	Total Alkalinity	12	-28
WCM	Carn Brea	Carn Brea-18	Down	Dissolved Arsenic	13	-60
WCM	Carn Brea	Carn Brea-18	Up	Dissolved Barium	14	77
WCM	Carn Brea	Carn Brea-18	Up	Dissolved Boron	13	40
WCM	Carn Brea	Carn Brea-18	Up	Dissolved Iron	12	58
WCM	Carn Brea	Carn Brea-18	Up	Dissolved Manganese	12	58
WCM	Tipton	Tipton-197	Down	Dissolved Nickel	7	-12
WCM	Carn Brea	Carn Brea-18	Down	Dissolved Nickel	11	-26
WCM	Carn Brea	Carn Brea-18	Up	Dissolved Strontium	14	71
WCM	Carn Brea	Carn Brea-18	Up	EC (Field)	11	39
WCM	Carn Brea	Carn Brea-18	Up	Fluoride	14	61
WCM	Carn Brea	Carn Brea-18	Up	Magnesium	10	37
WCM	Tipton	Tipton-197	Down	pH (Field)	11	-26
WCM	Carn Brea	Carn Brea-18	Up	Sodium	14	87
WCM	Tipton	Tipton-197	Down	Sulphate	13	-41
WCM	Tipton	Tipton-197	Up	TDS	13	28
WCM	Carn Brea	Carn Brea-18	Up	Total Alkalinity	14	87
Condamine Alluvium	Wyalla	42230209	Down	Dissolved Nickel	14	-30
Condamine Alluvium	Tipton	Tipton-195	Down	Dissolved Strontium	14	-81
Condamine Alluvium	Wyalla	42230209	Down	Dissolved Strontium	14	-50
Condamine Alluvium	Wyalla	42230209	Down	Dissolved Zinc	13	-41
Condamine Alluvium	Tipton	Tipton-195	Down	EC (Field)	10	-35
Condamine Alluvium	Wyalla	42230209	Down	EC (Field)	10	-37
Condamine Alluvium	Wyalla	Wyalla-16	Down	Fluoride	14	-35
Condamine Alluvium	Wyalla	Wyalla-16	Down	Magnesium	14	-38
Condamine Alluvium	Tipton	Tipton-195	Down	Magnesium	15	-63
Condamine Alluvium	Carn Brea	42231370	Up	Magnesium	13	32
Condamine Alluvium	Wyalla	42230209	Down	Magnesium	14	-41
Condamine Alluvium	Tipton	Tipton-195	Down	Potassium	15	-46
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Potassium	14	-31
Condamine Alluvium	Carn Brea	Carn Brea-17	Up	Redox (Field)	11	27
Condamine Alluvium	Wyalla	Wyalla-16	Down	Sodium	14	-41
Condamine Alluvium	Tipton	Tipton-195	Down	Sodium	15	-61
Condamine Alluvium	Wyalla	42230209	Down	Sodium	14	-52
Condamine Alluvium	Wyalla	Wyalla-16	Down	Sulphate	14	-34
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Sulphate	14	-36
Condamine Alluvium	Wyalla	42230209	Down	Sulphate	14	-49
Condamine Alluvium	Tipton	Wyalla-16	Down	TDS	14	-30
Condamine Alluvium	Tipton	Tipton-195	Down	TDS	14	-61
Condamine Alluvium	Carn Brea	42231370	Up	TDS	13	50
Condamine Alluvium	Wyalla	42230209	Down	TDS	14	-41
Condamine Alluvium	Wyalla	Wyalla-16	Up	Total Alkalinity	14	47
Condamine Alluvium	Tipton	Tipton-195	Down	Total Alkalinity	15	-74
Condamine Alluvium	Carn Brea	Carn Brea-17	Down	Total Alkalinity	14	-48
Condamine Alluvium	Wyalla	42230209	Down	Total Alkalinity	14	-52

**Appendix D - Desktop assessment of potential TGDE related to the SGP  
WMMP using the 2019 UWIR**

# FILE NOTE



<b>FROM:</b>	<b>Arrow Energy</b>
<b>DATE:</b>	<b>11/05/2021</b>
<b>SUBJECT:</b>	<b>Desktop assessment of potential terrestrial groundwater dependent ecosystems related to the Surat Gas Project Water Monitoring and Management Plan using the 2019 UWIR</b>

The purpose of this File Note is to provide a summary of the desktop assessment of potential terrestrial groundwater dependent ecosystems (TGDE) at potential risk of impact from groundwater drawdown within Arrow's Surat Gas Project (SGP) area. This assessment was undertaken as required in the SGP Updated Water Monitoring and Management Plan (WMMP) which requires the potential risk of impact from predicted groundwater drawdown to potential TGDEs be assessed upon the release of a new Underground Water Impact Report (UWIR) (and upon receiving technical files from OGIA). The 2019 UWIR (OGIA, 2019) was approved by the Department of Environment and Science (DES) on 16 December 2019 and Arrow's SGP commenced on 22 October 2020 which triggered this TGDE assessment.

The Updated WMMP outlines Arrow's commitment to adopt any TGDE assessment methodology outlined in future iterations of the UWIR to ensure alignment with the Office of Groundwater Impact Assessment (OGIA). The 2019 UWIR included an assessment of TGDE which was further revised in OGIA's 2019 UWIR Approval Condition 3 Response (OGIA, 2020) (Appendix A) released on 16 December 2020 and it is this methodology utilised in this desktop assessment. OGIA provided the details and data for this assessment to Arrow on 10 February 2021. The Updated WMMP requires the TGDE assessment to be undertaken within 90 days of receiving the technical files from OGIA which then required Arrow's assessment to be completed by 11 May 2021.

The scope of any further investigations required as a result of the desktop assessment detailed in this File Note will be reported separately inline with the SGP WMMP commitment where a revised SGP Updated WMMP (which will outline any proposed field investigations) will be submitted (if high risk sites are identified) within 90 days of the completion of the desktop assessment. A number of medium and high risk sites were identified by OGIA however after further assessing the sites against available data all but two of the sites (Sites 2 and 7) are considered to either not be at risk of impact or unlikely to represent a TGDE.

A summary of Arrow's assessment of the medium and high risk sites identified by OGIA (Figure 1) is:

- Site 1: the risk of impact to this site is considered low and, as a result, no further work is proposed for this site at this time. This assessment is based on the short term (0.03 m) and long term (1.9 m) predicted drawdown which is considered to result in a slow rate of change in groundwater level which reduces the risk to this potential TGDE.
- Site 2: given the high LAA predicted drawdown (47.4 m), the shallow depth of the WCM, small amount of water level data in the area and mapped potentially deep rooting vegetation (river red gum) this site requires further investigation of its TGDE status and / or confirmation that the water table aquifer is not hosted in the WCM.
- Site 3: given the regional depth to groundwater is likely beyond the rooting depth of terrestrial vegetation, Arrow's watercourse springs assessment conclusion that the presence of potential TGDEs in a similar setting are expected to only access a perched groundwater system (disconnected from the regional water table aquifer), formations (stratigraphically overlying the WCM) mapped across the western portion of Site 3, the risk of impact to this site is considered low and vegetation is not expected to be accessing a regional water table aquifer hosted within the WCM, as a result, no further work is proposed for this site at this time.



- Site 4: given the regional depth to groundwater is likely beyond the rooting depth of terrestrial vegetation, Arrow's watercourse springs assessment conclusion that the presence of potential TGDEs in a similar setting are expected to only access a perched groundwater system (disconnected from the regional water table aquifer), the risk of impact to this site is considered low and vegetation is not expected to be accessing a regional water table aquifer hosted within the WCM, as a result, no further work is proposed for this site at this time.
- Site 5: western area of Site 5, given the conclusion from the previous assessment completed at this site, the western area of Site 5 is not expected to be a TGDE reliant on a regional water table aquifer hosted within the Springbok Sandstone and / or potentially impacted from groundwater drawdown in the Springbok Sandstone. As a result, no further work is proposed at this part of Site 5.  
Eastern area of Site 5, given the regional depth to water in the WCM surrounding Site 5 is likely below the rooting depth of terrestrial vegetation, the eastern area of Site 5 is not expected to be a TGDE reliant on a regional water table aquifer hosted within the WCM and / or potentially impacted from groundwater drawdown in the WCM. As a result, no further work is proposed at this part of Site 5
- Site 6: given the available lithology and groundwater level data indicate the water table aquifer is hosted within the Condamine Alluvium in the vicinity of Site 6, potential TGDE in Site 6 are not expected to be potentially impacted from groundwater drawdown in the WCM. As a result, no further work is proposed at Site 6.
- Site 7: South of RN42231256, given the available lithology data in the vicinity south of RN42231256 indicate that the water table aquifer is not hosted within the WCM, potential TGDE in this southern section of Site 7 are not expected to be potentially impacted from groundwater drawdown in the WCM and no further work is proposed. North of RN42231256, given the little available lithology and water table aquifer elevation data, and modelled outcrop/subcrop of the WCM, further investigation of this area of Site 7 is required to confirm groundwater dependency of mapped vegetation and / or confirm formation the water table aquifer is hosted in.
- Site 8: the predicted groundwater drawdown is identified as 0.07 m in the short term (IAA) and 1.12 m in the long term (LAA) which is considered to result in a slow rate of change in groundwater level which reduces the risk to this potential TGDE. This is consistent with OGIA (2020) which states that where slow rates of drawdown occur vegetation communities may be resilient to change by switching to alternative sources of water. This concept is further detailed in Appendix D of Arrow's approved SGP Updated WMMP (Stream Connectivity and GDE Impact Assessment Memorandum) (Arrow, 2018). The risk of impact to this site is considered low and, as a result, no further work is proposed for this site at this time.

### **OGIA TGDE Assessment Method**

OGIA's TGDE assessment method has evolved since the 2019 UWIR and its current form is detailed in the document Attachment 1 Condition 3 Response (2020) (Appendix A). A summary of OGIA's current approach is provided here.

### *Impact Footprint*

For the UWIR 2019, OGIA completed a desktop assessment (OGIA 2019) to: integrate existing mapping of potential TGDEs with areas of predicted drawdown in the regional groundwater model; develop conceptual understanding of groundwater dependency and response to drawdown; and identify areas for improvement of knowledge.

The area of interest for TGDE assessment is the area of 0.2 m predicted drawdown, at any time during the proposed CSG development, within the outcropping aquifers. For the purposes of this assessment, only those polygons with greater than 50 per cent GDE are included, and only those polygons with component regional ecosystems that include land zones 3, 9 and 10. These land zones are known potential zones of connection with aquifers identified as affected in the UWIR 2019 (OGIA 2019).

### *Magnitude of Impacts*

The magnitude and timing of predicted impacts varies spatially and between formations. Prior to 2019, the majority of TGDE polygons predicted to experience impacts are within the Walloon Coal Measures (WCM), with drawdown predominantly less than 5 metres. In the short and longer terms, the majority of predicted impacts are less than 10 metres. However, at some locations, impacts exceed 20 m. Where TGDEs are confirmed to be accessing affected formations in these areas, this has the potential to have significant impacts on the TGDEs ecological water requirements and resultant condition.

### *Risk Assessment*

As detailed in the Attachment 1 Condition 3 Response (OGIA, 2020), a risk assessment has been applied to the assessment of impacts to TGDEs. The risk assessment builds upon the impact assessment, through the integration of ecological value information enabling priority areas to be identified for further investigation and conceptualisation.

Risk is assessed as a function of the likelihood and consequence of groundwater drawdown in the target formation for a TGDE.

The criterion for the assessment of likelihood of impact from groundwater drawdown is the magnitude of drawdown at the location of the TGDEs, as predicted by the regional groundwater flow model. Two categories are identified based on the predicted impacts: less than, and greater than, 1 m predicted drawdown.

Evaluating the consequences of the predicted drawdown on TGDEs is more complex. There are multiple uncertainties associated with detection of ecological responses, and particularly so with studies of impacts on GDEs. The sensitivity of TGDEs to changes in groundwater regime is determined by the nature of the ecohydrological relationship between groundwater and vegetation.

Consideration of an RE's biodiversity status is the first step in inferring the significance of a predicted impact on that RE. The biodiversity status reflects the condition of an RE and the extent remaining, compared with its pre-clearing extent. For more detailed evaluation of consequences, specific information is needed about the ecological response of the RE to varying degrees of groundwater drawdown.

Three risk categories are identified as follows:

- Low risk – predicted impacts at this location range between 0.2 metres and 1 metre. The biodiversity status of the associated RE may be ‘not of concern’, ‘of concern’ or ‘endangered’.
- Medium risk – predicted impacts at this location are greater than 1 metre. The biodiversity status of the associated RE is ‘no concern at present’.
- High risk – predicted impacts at this location are greater than 1 metre. The biodiversity status of the associated RE is ‘of concern’ or ‘endangered’.

OGIA note that for areas identified as medium or high risk the priority knowledge gaps for research and monitoring are:

- validation and confirmation of the GDE mapping and associated Res
- conceptualisation of the identified TGDEs in terms of:
  - quantification of their ecological water requirements – the temporal nature, quantity and quality of groundwater use
  - their likely ecological response to changes in groundwater regime.

OGIA (2020) (Appendix A) is undertaking the initial scoping and design of a pilot program to establish field sites for ongoing monitoring of priority REs that are mapped within aquifers’ Immediately Affected Areas (IAA) and Long-term Affected Areas (LAA). For each site, the water balance, ecological water requirements and ecological responses for each TGDE will be hypothesised and conceptualised. The specific hypotheses will inform the design of a monitoring program and data analysis to in turn inform more detailed risk assessment in future iterations of the UWIR.

### **Evaluation of Medium and High Risk Sites**

The medium and high risk sites identified by OGIA in the Attachment 1 Condition 3 Response (2020) (Appendix A) are detailed in the following sections. These sites have been further assessed by Arrow to evaluate the assigned risk rating and / or status of groundwater dependency. Assessment is based on the expectation that only those sites located within Arrow tenure are assigned to Arrow.

The medium and high risks identified by OGIA (2020) located within Arrow tenure are shown in Figure 1.

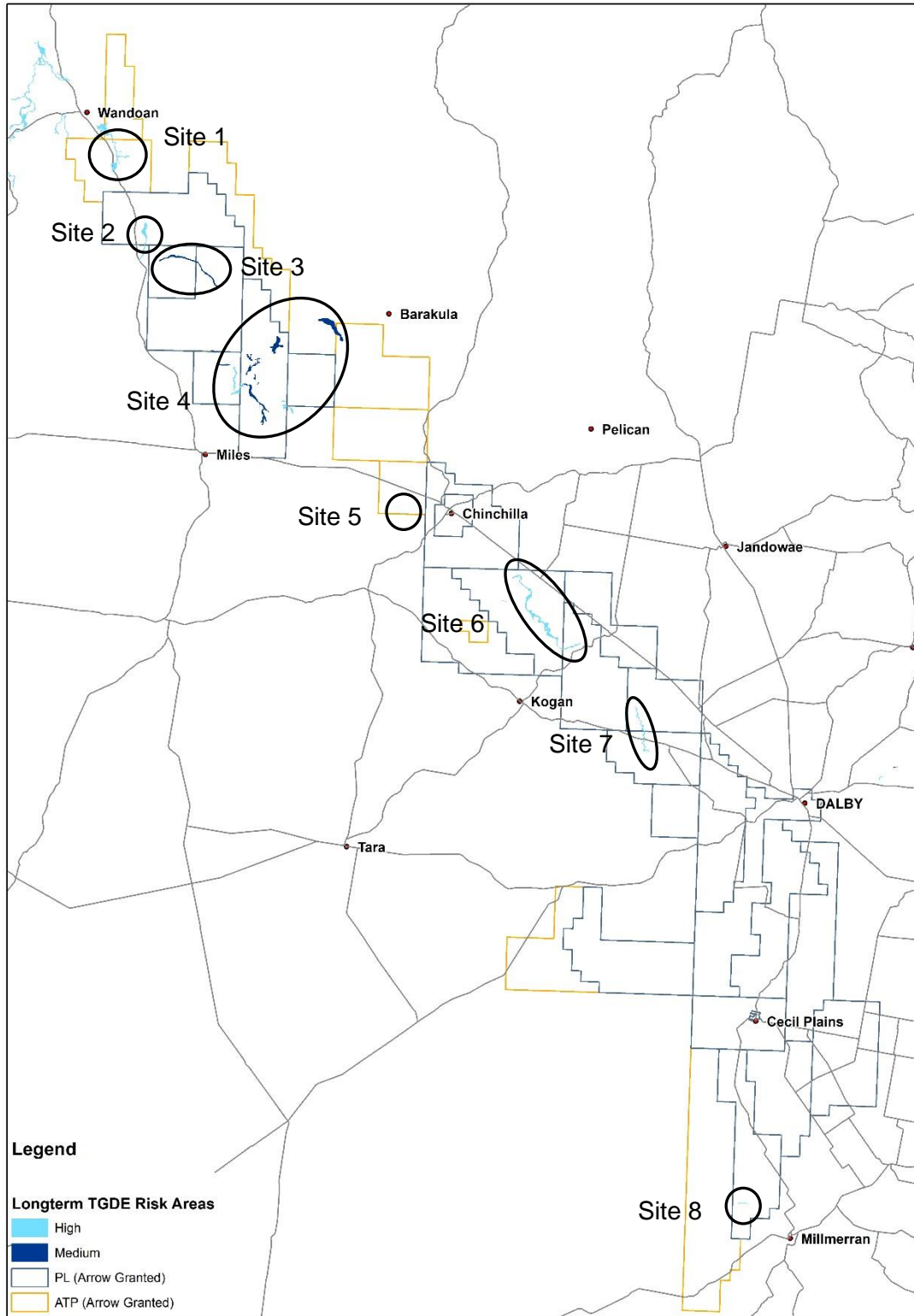


Figure 1: Medium and high risks sites identified by OGIA (2020) located within Arrow tenure

## Site 1

Site 1 is located south of Wandoan across ATP747 and ATP810 predominantly associated with Juandah Creek (Figure 2). The site's attributes are shown in Table 1. The risk of impact to this site is considered low and, as a result, no further work is proposed for this site at this time. This assessment is based on the short term (0.03 m) and long term (1.9 m) predicted drawdown which is considered to result in a slow rate of change in groundwater level which reduces the risk to this potential TGDE. This is consistent with OGIA (2020) which states that where slow rates of drawdown occur vegetation communities may be resilient to change by switching to alternative sources of water. This concept is further detailed in Appendix D of Arrow's approved SGP Updated WMMP (Stream Connectivity and GDE Impact Assessment Memorandum) (Arrow, 2018).

Arrow's SGP Stage 1 WMMP (2018) assessed multiple areas (Arrow only impact risk area 4) straddling Site 1 and concluded that the area may be at risk of impact from groundwater drawdown in the WCM. This conclusion was predominantly made based on the potential rate of groundwater drawdown of up to 4 m per year coupled with the presence of *E. camaldulensis* (river red gum). Arrow's resultant field investigation of this area (Burunga Lane GDE investigation site, 4 km to the south of Site 1) initially identified this site as not being a GDE however ongoing monitoring showed the river red gums shifting their water source to groundwater during a prolonged dry period.

Two additional high risks sites are located to the west of Site 1 with almost all of the polygons located outside of Arrow tenure. Both of these sections extend into Arrow tenure approximately 70 m and clarification is required as to if Arrow are required to assess the sections of these sites within Arrow tenure.

**Table 1:** Site 1 attributes (OGIA, 2020)

Site Attribute	Site 1
Regional Ecosystem (RE) code	11.3.2 Eucalyptus populnea woodland on alluvial plains and 11.3.25 Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines
GDE Confidence	Derived GDE – moderate confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.03 m, layer 12 (upper WCM)
Maximum LAA drawdown (anytime) and model layer	1.9 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	High

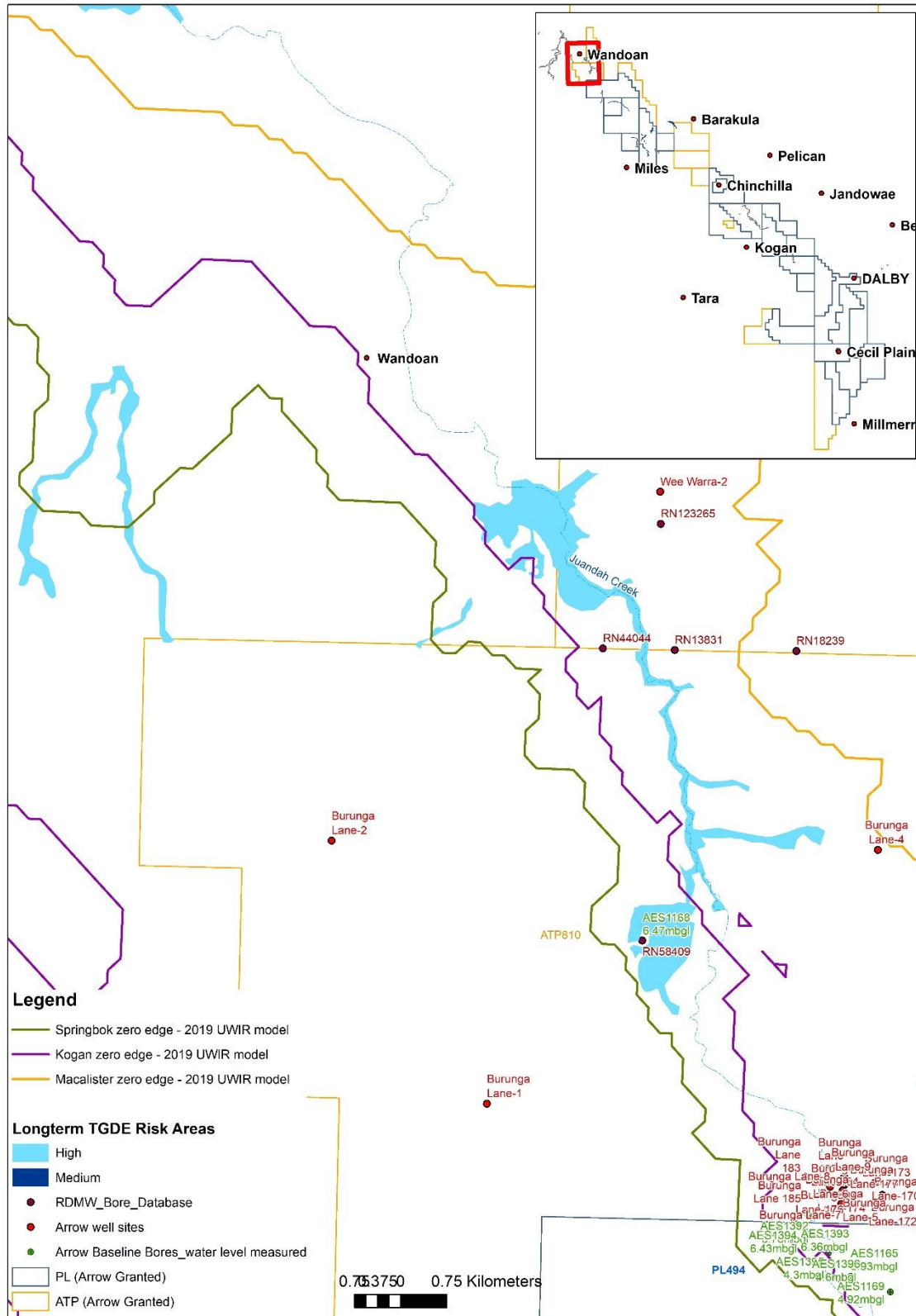


Figure 2: Site 1 overview

## Site 2

Site 2 is located south of Wandoan (10 km south of Site 1) across PL494 predominantly associated with Juandah Creek (Figure 3). The Site's polygon extends beyond Arrow's tenement boundary. The site's attributes are shown in Table 2. Assessment of Site 2 shows:

- Although the section of Site 2 located off tenure is not required to be assessed by Arrow, the Department of Regional Development, Manufacturing and Water (RDMW) bore card for RN13030806 shows Quaternary alluvium from surface to 3.8 m overlying Orallo Formation to 13 m. This bore is screened across the Orallo Formation and its depth to water measurement was 3.8 mbgl indicating that the water table aquifer is hosted within the Orallo Formation in this area. Furthermore, a section immediately upstream of Site 2 along Juandah Creek was assessed as a potential GDE in Arrow's Stage 1 WMMP (2018) for potential impact from groundwater drawdown. This assessment showed that the water table aquifer is also hosted within the Orallo Formation in this area and not the WCM.
- Regarding the section of Site 2 located within Arrow tenure, the RDMW bore card for RN48950 shows 28 m of sandstone is present from surface overlying mudstone and coal. However the surface elevation at RN48950 is approximately 20 m higher than the channel base elevation of Juandah Creek indicating that the top of the WCM is approximately 8 mbgl. RN48807 shows alluvium is present to at least 5 m (total depth of bore) and RN58128, located 800 m north of Site 2 along Juandah Creek, shows alluvium overlies the WCM to 11 mbgl.
- The RDMW bore card for RN48807 (constructed in the alluvium) states a water level of 2.4 mbgl which shows the water table aquifer is potentially hosted in the alluvium. This water level was collected in 1973.
- Although it appears the water table aquifer is hosted within the alluvium, given the high LAA predicted drawdown (47.4 m), the shallow depth of the WCM, small amount of water level data in the area and mapped potentially deep rooting vegetation (river red gum) this site requires further investigation of its TGDE status and / or confirmation that the water table aquifer is not hosted in the WCM.

**Table 2:** Site 2 attributes (OGIA, 2020)

Site Attribute	Site 2
Regional Ecosystem (RE) code	11.3.2 Eucalyptus populnea woodland on alluvial plains and 11.3.25 Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines
GDE Confidence	Derived GDE – moderate confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.02 m, layer 12 (upper WCM)
Maximum LAA drawdown (anytime) and model layer	47.4 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	High



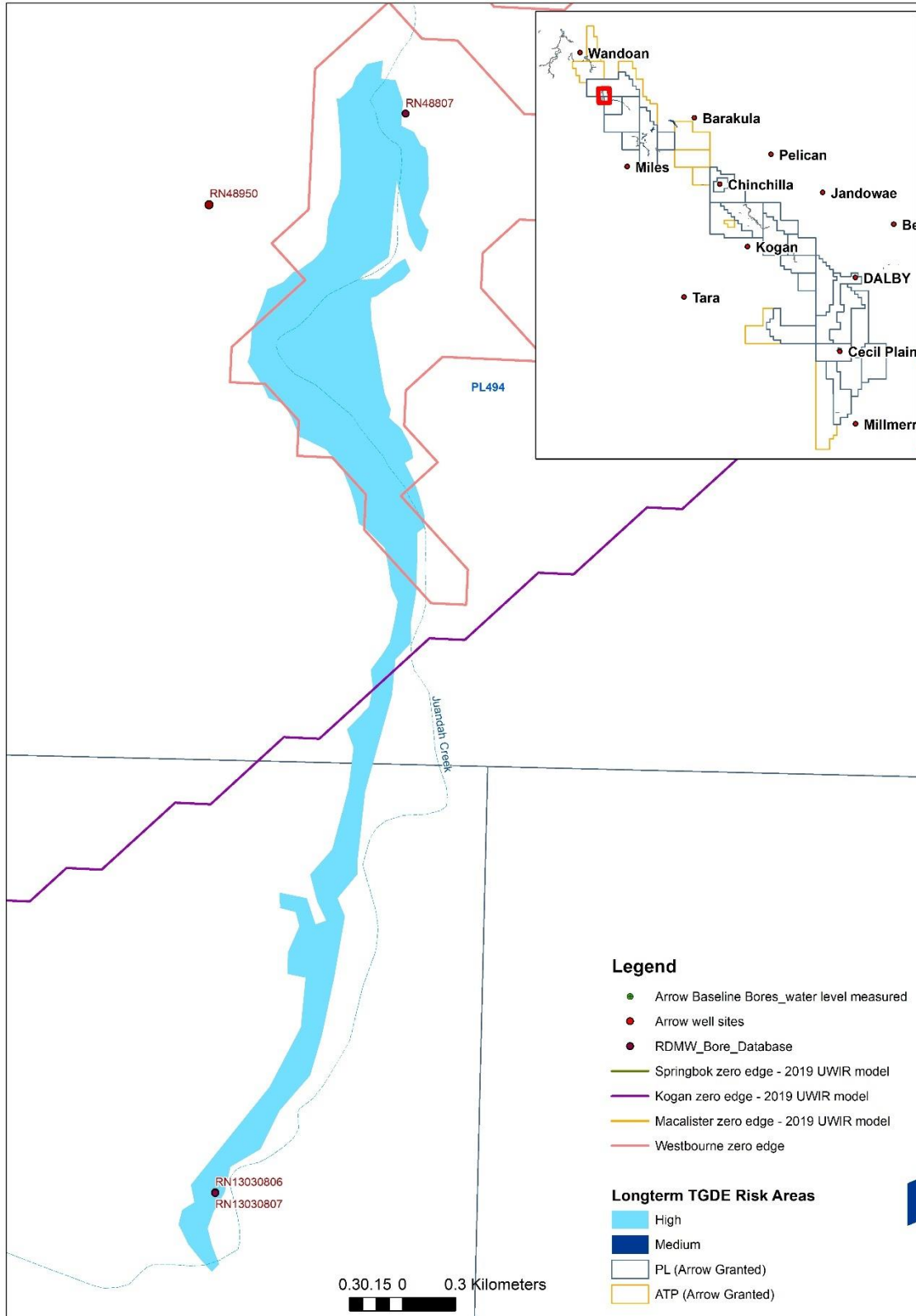


Figure 3: Site 2 overview

### Site 3

Site 3 is located approximately 6 km north of Arrow’s Kedron Pilot across PL304 and PL491 predominantly associated with Bottle Tree Creek (Figure 4). The site’s attributes are shown in Table 3. Assessment of Site 3 shows:

- An area located to the northeast of Site 3 (risk area 8) was assessed in Arrow’s SGP Updated WMMP (2019) as part of the TGDE assessment. This assessment concluded that the depth to water data (albeit a small dataset) indicates a regional groundwater elevation between 40-60 mbgl within the WCM which is beyond the rooting depth of TGDE.
- As part of Arrow’s watercourse springs assessment, required under the 2019 UWIR, a section of Tin Hut Creek / Bottle Tree Creek (approximately 1.2 km south of Site 3) was assessed for the existence of a watercourse spring. As part of this assessment, it was noted that there is potential for vegetation to be accessing groundwater situated within a perched system disconnected from the regional water table aquifer (3D Environmental, 2021). Similar vegetation was observed in these assessment areas to that noted in Table 3.
- The western portion (approximately 4 km) of Site 3 is located within the Westbourne Formation and Springbok Sandstone mapped extent within the 2019 UWIR model which would result in the water table aquifer not being hosted within the WCM at this location. The GDE assessment undertaken in Arrow’s Stage 1 WMMP included a site (risk area 1), located less than 1 km south of the western portion of Site 3, concluded that the water table aquifer is likely hosted in formations located stratigraphically above the Springbok Sandstone (i.e. Westbourne Formation or Gubberamunda Sandstone) and the RDMW database showed groundwater levels in the area range from 42 to 63 mbgl which is beyond the rooting depth of terrestrial vegetation in the area.
- Given the regional depth to groundwater is likely beyond the rooting depth of terrestrial vegetation, Arrow’s watercourse springs assessment conclusion that the presence of potential TGDEs in a similar setting are expected to only access a perched groundwater system (disconnected from the regional water table aquifer), formations (stratigraphically overlying the WCM) mapped across the western portion of Site 3, the risk of impact to this site is considered low and vegetation is not expected to be accessing a regional water table aquifer hosted within the WCM, as a result, no further work is proposed for this site at this time.

**Table 3:** Site 3 attributes (OGIA, 2020)

Site Attribute	Site 3
Regional Ecosystem (RE) code	11.3.14 Eucalyptus spp., Angophora spp., Callitris spp. Woodland alluvial plains
GDE Confidence	Derived GDE – low confidence
Biodiversity Status	No concern at present
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.04 m, layer 12 (upper WCM)
Maximum LAA drawdown (anytime) and model layer	69 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	Medium

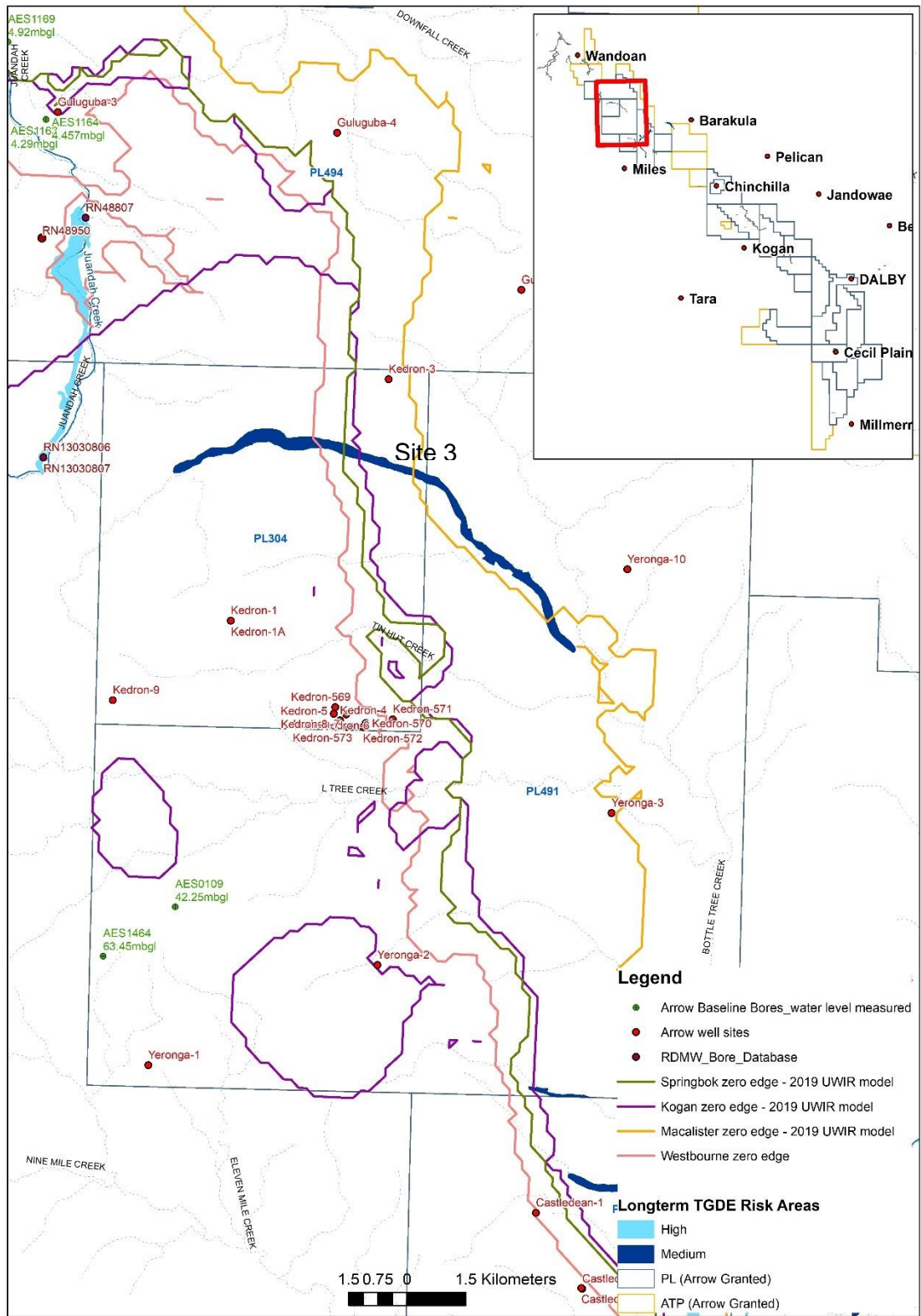


Figure 4: Site 3 Overview

**Site 4**

Site 4 is located northeast of Miles near Arrow’s Castledean Pilot across PL266, PL305 and PL492 predominantly associated with Dogwood Creek and its tributaries (Figure 5). The site’s attributes are shown in Table 4. Assessment of Site 4 shows:

- Lithology and formation data from Arrow drill holes confirms presence of shallow WCM.
- Groundwater monitoring data shows the regional water table aquifer is hosted within the WCM. Depth to water measurements at Arrow monitoring bores, monitoring the water table aquifer, Castledean-11 (43.5 mbgl) and Punch Bowl 13 (26 mbgl) / 14 (36 mbgl) show the regional groundwater elevation is below the rooting depth of terrestrial vegetation.
- As part of Arrow’s watercourse springs assessment, required under the 2019 UWIR, sections of Dogwood Creek (located in the same area as Site 4) was assessed for the existence of a watercourse spring. As part of this assessment, it was noted that there is potential for vegetation to be accessing groundwater situated within a perched system disconnected from the regional water table aquifer (3D Environmental, 2021). Similar vegetation was observed in these assessment areas to that noted in Table 4.
- Given the regional depth to groundwater is likely beyond the rooting depth of terrestrial vegetation, Arrow’s watercourse springs assessment conclusion that the presence of potential TGDEs in a similar setting are expected to only access a perched groundwater system (disconnected from the regional water table aquifer), the risk of impact to this site is considered low and vegetation is not expected to be accessing a regional water table aquifer hosted within the WCM, as a result, no further work is proposed for this site at this time.

**Table 4:** Site 4 attributes (OGIA, 2020)

Site Attribute	Site 4
<i>Medium risk sites</i>	
Regional Ecosystem (RE) code	11.3.14 Eucalyptus spp., Angophora spp., Callitris spp. Woodland alluvial plains, 11.3.26 Eucalyptus moluccana or E. microcarpa woodland to open forest on margins of alluvial plains
GDE Confidence	Derived GDE – low confidence
Biodiversity Status	No concern at present
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.9 to 5.0 m, layer 12, 13 and 15 (upper and middle WCM)
Maximum LAA drawdown (anytime) and model layer	2.1 to 30.9 m, layer 12 and 13 and 15 (upper and middle WCM)
Long term risk of predicted drawdown on Res	Medium
<i>High risk sites</i>	
Regional Ecosystem (RE) code	11.3.4 Eucalyptus tereticornis and / or Eucalyptus spp. Woodland on alluvial plains, 11.3.2 Eucalyptus populnea woodland on alluvial plains, 11.3.25 Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines
GDE Confidence	Derived GDE – low and high confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.9 to 27 m, layer 12 (upper WCM)

<b>Site Attribute</b>	<b>Site 4</b>
Maximum LAA drawdown (anytime) and model layer	2.1 to 42.3 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	High

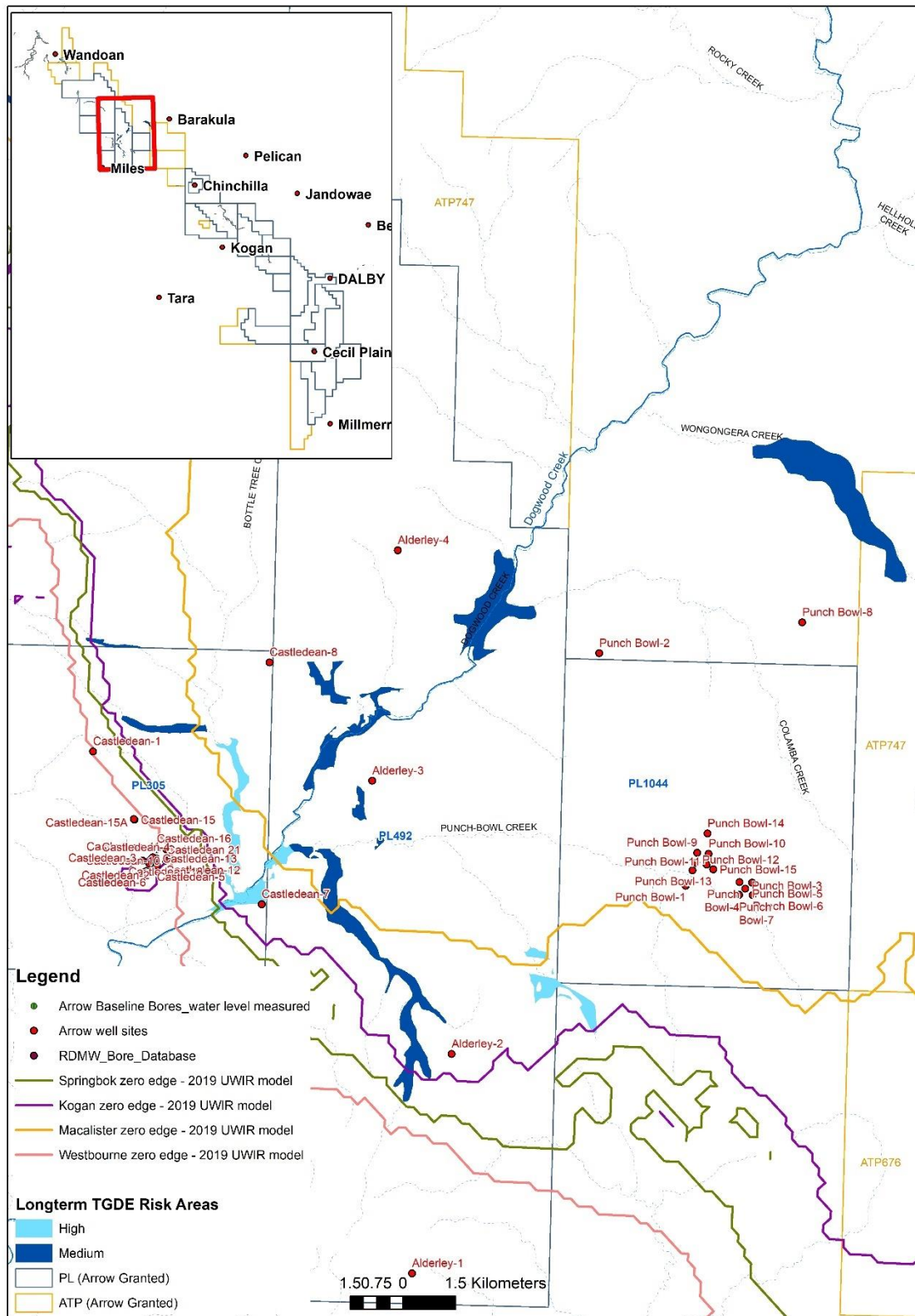


Figure 5: Site 4 overview

## **Site 5**

Site 5 is located west of Chinchilla on ATP747 associated with a tributary of Charleys Creek (Figure 6). Site 5 consists of two areas with the western area's predicted impacted model layer being layer 10 (lower Springbok Sandstone) and the eastern area's predicted impacted model layer being layer 12 (upper WCM). The site's attributes are shown in Table 4.

Assessment of the western area of Site 5 shows:

- The western area of Site 5 is located to the east of the Springbok Sandstone zero edge as mapped in the 2019 UWIR model.
- This area was assessed in the Stage 1 WMMP (Arrow, 2018) TGDE assessment for potential impacts to potential TGDE associated with predicted groundwater drawdown in the Springbok Sandstone (cumulative risk area 4). The assessment concluded that it is considered unlikely that the area contains ecosystems that area reliant on a watertable hosted in the Springbok Sandstone.

There is no depth to groundwater information available within this area for the Springbok Sandstone, however RN160547A located 7 km to the west of this area indicates a depth to groundwater in the Springbok Sandstone of >40 m. Whilst this is some distance from the risk area, the borehole log indicates >60m thickness of Cretaceous and Jurassic sediments overlying the Springbok Sandstone. The conceptualisation of the Springbok Sandstone being at a depth not accessible to terrestrial GDEs is also supported by CSG well Talinga 20 located <700m west of the area which indicates >20m of alluvium and Westbourne Formation overlying the Springbok Sandstone.

Few mapped potential GDEs exist in this risk area, and the majority are dominated by RE types 11.5.1, 11.7.4, 11.9.4, 11.9.5 and 11.9.7, all of which are not usually associated with the potential for groundwater interaction due to their position in landscape, shallow rooting depths and reliance on shallow soil moisture.

3D Environmental and Earth Search (see Stage 1 WMMP for reference) do not identify ecosystems in this area as having likely groundwater interaction, consistent with their description that River Red Gums accessing groundwater are likely to occur on lower alluvial terraces rather than the more elevated areas of this area.

- Given the conclusion from this previous assessment, the western area of Site 5 is not expected to be a TGDE reliant on a regional water table aquifer hosted within the Springbok Sandstone and / or potentially impacted from groundwater drawdown in the Springbok Sandstone. As a result, no further work is proposed at this part of Site 5.

Assessment of the eastern area of Site 5 shows:



- Bore card information from surrounding RDMW bores show that the WCM is likely present from near surface and the eastern area of Site 5 is located within the WCM model layers in the 2019 UWIR model.
- Available groundwater level data show the elevation of the regional groundwater table is likely deeper than 20 mbgl and therefore below the rooting depth of terrestrial vegetation:
  - Nested WCM monitoring bores RN192083 and RN192084, located 5.1 km north of Site 5 and a similar distance as Site 5 from the modelled Springbok Sandstone extent in the 2019 UWIR model, display groundwater levels of 28.5 and 50.0 mbgl respectively (collected in 2020).
  - RN34651 (located 4.5 km northwest of Site 5) has an OGIA assigned aquifer attribution of WCM. Arrow baseline water level measurements show depth to water at this site range from 38.295 to 43.1 mbgl.
  - An unregistered landholder bore (Arrow landholder bore ID AES1808) located 3.5 km northeast of the Site recorded a depth to water measurement of 20.875 mbgl in December 2017.
- Given the regional depth to water in the WCM surrounding Site 5 is likely below the rooting depth of terrestrial vegetation, the eastern area of Site 5 is not expected to be a TGDE reliant on a regional water table aquifer hosted within the WCM and / or potentially impacted from groundwater drawdown in the WCM. As a result, no further work is proposed at this part of Site 5.

**Table 5: Site 5 attributes (OGIA, 2020)**

Site Attribute	Site 5
<i>Western area</i>	
Regional Ecosystem (RE) code	11.9.5 Acacia harpophylla and / or Casuarina cristata open forest on fine-grained sedimentary rocks, 11.9.7 Eucalyptus populnea, Eremophila mitchelli shrubby woodland on fine-grained sedimentary rocks
GDE Confidence	Derived GDE – low confidence
Biodiversity Status	Endangered, of concern
Landzone	9 – Undulating country on fine grained sedimentary rocks
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.18 m, layer 10 (lower Springbok Sandstone)
Maximum LAA drawdown (anytime) and model layer	3.1 m, layer 10 (lower Springbok Sandstone)
Long term risk of predicted drawdown on Res	High
<i>Eastern area</i>	
Regional Ecosystem (RE) code	11.3.4 Eucalyptus tereticornis and / or Eucalyptus spp. Woodland on alluvial plains
GDE Confidence	Derived GDE – high confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.17 m, layer 12 (upper WCM)
Maximum LAA drawdown	11.8 m, layer 12 (upper WCM)

<b>Site Attribute</b>	<b>Site 5</b>
(anytime) and model layer	
Long term risk of predicted drawdown on Res	High

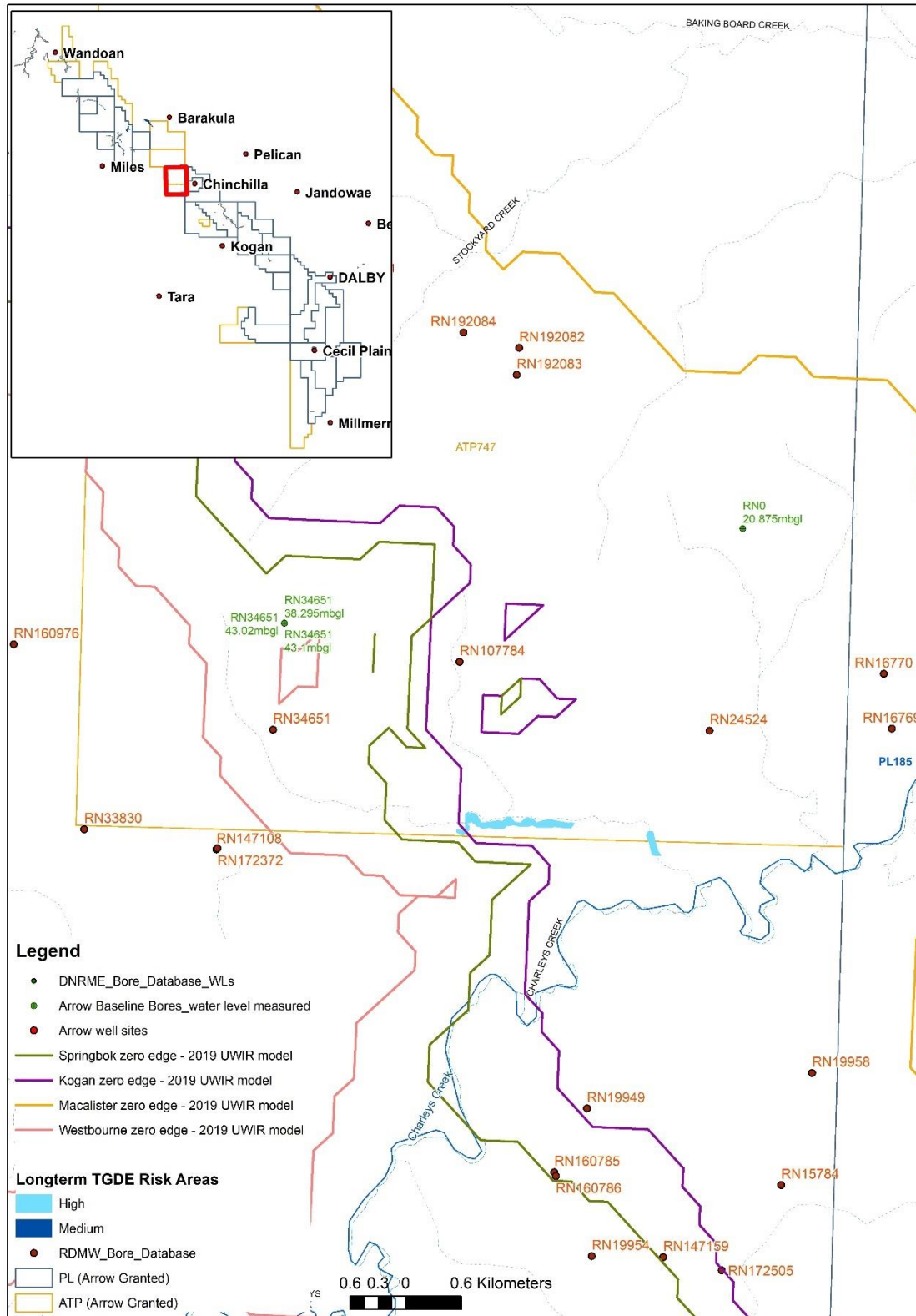


Figure 6: Site 5 overview

## Site 6

Site 6 is located southeast of Chinchilla on PL493 associated with the Condamine River (Figure 7). The site's attributes are shown in Table 6. Assessment of Site 6 shows:

- Parts (cumulative risk area 10) of Site 6 were previously assessed in Arrow's SGP Updated WMMP (2019) for potential TGDE potentially impacted from predicted groundwater drawdown in the WCM. The assessment concluded that, based on the lithology and groundwater level monitoring data collected from Arrow monitoring bore Wyalla-16, the water table aquifer is hosted within the Condamine Alluvium. As a result, no potential impacts to potential TGDEs as a result of predicted groundwater drawdown in the WCM was expected.
- Lithology information collected from Arrow holes flanking either side of Site 6 support the above conclusion and show that sufficient Condamine Alluvium is present within Site 6 north of Wyalla-4 to host the water table aquifer:
  - Wyalla-17 and 18 (same pad as Wyalla-16) recorded 21.27 m and 20.87 m of alluvium from surface;
  - Wyalla-1 recorded 16 m of alluvium from surface;
  - Wyalla-5 recorded 22.15 m of alluvium from surface;
  - Wyalla-4 recorded 34 m of alluvium from surface; and
  - Wyalla-3 has 9.86 m of alluvium from surface.
- South of Wyalla-4, RDMW bore cards show there is also likely sufficient thickness of Condamine Alluvium and presence of groundwater to host the water table aquifer:
  - RN16136 has a total depth of 14.33 m within the Condamine Alluvium. The water level measured in the bore at the time of drilling (1964) was 12.8 mbgl;
  - RN16137 has a total depth of 14.6 m within the Condamine Alluvium. The water level measured in the bore at the time of drilling (1965) was 12.8 mbgl;
  - RN42230194 has a total constructed depth of 11.3 m within the Condamine Alluvium. Longterm groundwater level monitoring has been undertaken in this bore and the latest water level measurement was 5.88 mbgl in 2016; and
  - RN42230198 has a total constructed depth of 14.6 m within the Condamine Alluvium. Longterm groundwater level monitoring has been undertaken in this bore and the latest water level measurement was 10.6 mbgl.
- Given the available lithology and groundwater level data indicate the water table aquifer is hosted within the Condamine Alluvium in the vicinity of Site 6, potential TGDE in Site 6 are not expected to be potentially impacted from groundwater drawdown in the WCM. As a result, no further work is proposed at Site 6.

**Table 6:** Site 6 attributes (OGIA, 2020)

<b>Site Attribute</b>	<b>Site 6</b>
Regional Ecosystem (RE) code	11.3.25 Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines, 11.3.4 Eucalyptus tereticornis and / or Eucalyptus spp. Woodland on alluvial plains, 11.3.3 Eucalyptus coolabah woodland on alluvial plains
GDE Confidence	Derived GDE – high confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	3.3 m, layer 13 (middle WCM)
Maximum LAA drawdown (anytime) and model layer	27.5 m, layer 13 (middle WCM)
Long term risk of predicted drawdown on Res	High

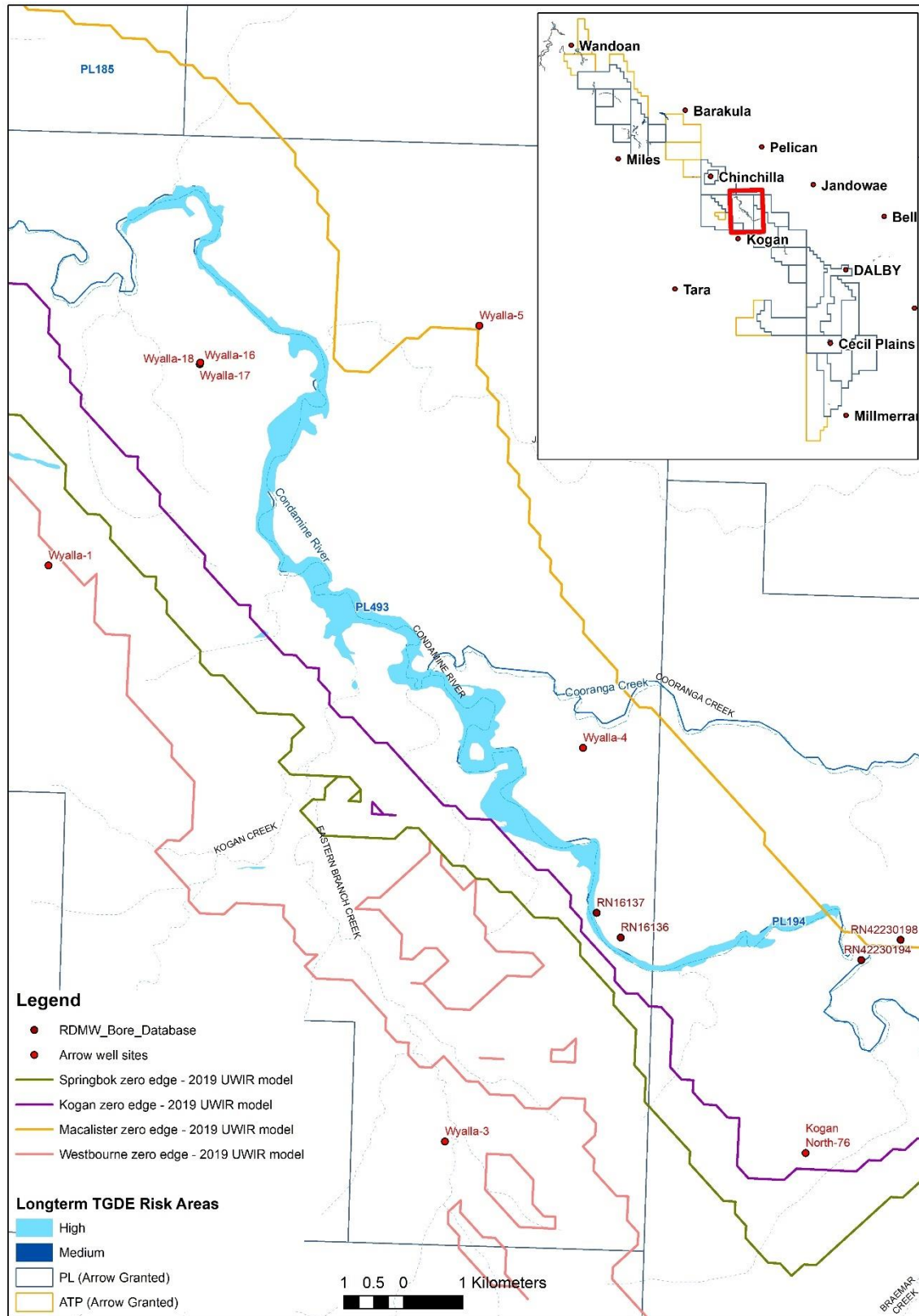


Figure 7: Site 6 overview

## Site 7

Site 7 is located to the east of Arrow's Daandine field on PL194 and PL230 associated with the Wilkie Creek (Figure 8). The site's attributes are shown in Table 7. Assessment of Site 7 shows:

- South of RDMW monitoring bore RN42231256, drilling information from this monitoring bore and Arrow holes show the WCM is overlain by alluvium / Westbourne Formation / Springbok Sandstone indicating the water table is not hosted within the WCM:
  - Daandine-74 shows alluvium to 6 m, Westbourne Formation to 16 m and Springbok Sandstone to 61 m;
  - Daandine-68 shows alluvium to 6 m and Springbok Sandstone to 46 m;
  - Daandine-108 shows alluvium to 39.63 m overlying WCM; and
  - RN42231256 shows sandstone from 0 to 25 m, mudstone from 25 to 28 m and sandstone (base of weathering) to 28 to 32 m.
- North of RN42231256, there is uncertainty as to the potential for the water table aquifer to be hosted within the WCM based on the following information:
  - Both the Arrow geological model and the 2019 UWIR model show the Springbok Sandstone pinches out north of RN42231256. Where the Springbok Sandstone pinches out, the 2019 UWIR model shows WCM from surface with the Arrow model showing the WCM subcropping beneath a thin layer of Westbourne Formation (Figure 9);
  - Little lithology data are available in the immediate vicinity of Site 7 and the available lithology data do not explicitly identify the depth to the top of WCM. Furthermore, the western mapped spatial extent of the Condamine Alluvium is less than 900 m to the east of Site 7 which restricts the applicability of RDMW bores on the edge of the Condamine Alluvium. The available lithology data are:
    - RDMW bore card for RN86828 (1.9 km west of Site 7) shows white and red clay from surface to 28 m underlain by light grey shale and coal. The white and red clay may be interpreted as Westbourne Formation;
    - Arrow's bore assessment of RN94135 (adjacent to the northern tip of Site 7) identified the stratigraphy as alluvium from surface to 11 m overlying WCM; and
    - RDMW bore card for RN119448 (855 m east of Site 7) shows soil and brown clay from surface to 2.9 m, sand to 3.5 m, clay to 13.5 m, sand to 15.2 m, clay and grey shale to 17 m and coal to 17.3 m.
  - There is little water table aquifer groundwater level data in the area to sufficiently identify the groundwater elevation of the water table aquifer.
- Given the available lithology data in the vicinity south of RN42231256 indicate that the water table aquifer is not hosted within the WCM, potential TGDE in this southern section of Site 7 are not



expected to be potentially impacted from groundwater drawdown in the WCM and no further work is proposed.

- North of RN42231256, Given the little available lithology and water table aquifer elevation data, and modelled outcrop/subcrop of the WCM, further investigation of this area of Site 7 is required to confirm groundwater dependency of mapped vegetation and / or confirm formation the water table aquifer is hosted in.

**Table 7:** Site 7 attributes (OGIA, 2020)

<b>Site Attribute</b>	<b>Site 7</b>
Regional Ecosystem (RE) code	11.3.25 Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines, 11.3.2 Eucalyptus populnea woodland on alluvial plains
GDE Confidence	Derived GDE – high confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	54.5 m, layer 12 (upper WCM)
Maximum LAA drawdown (anytime) and model layer	66.8 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	High

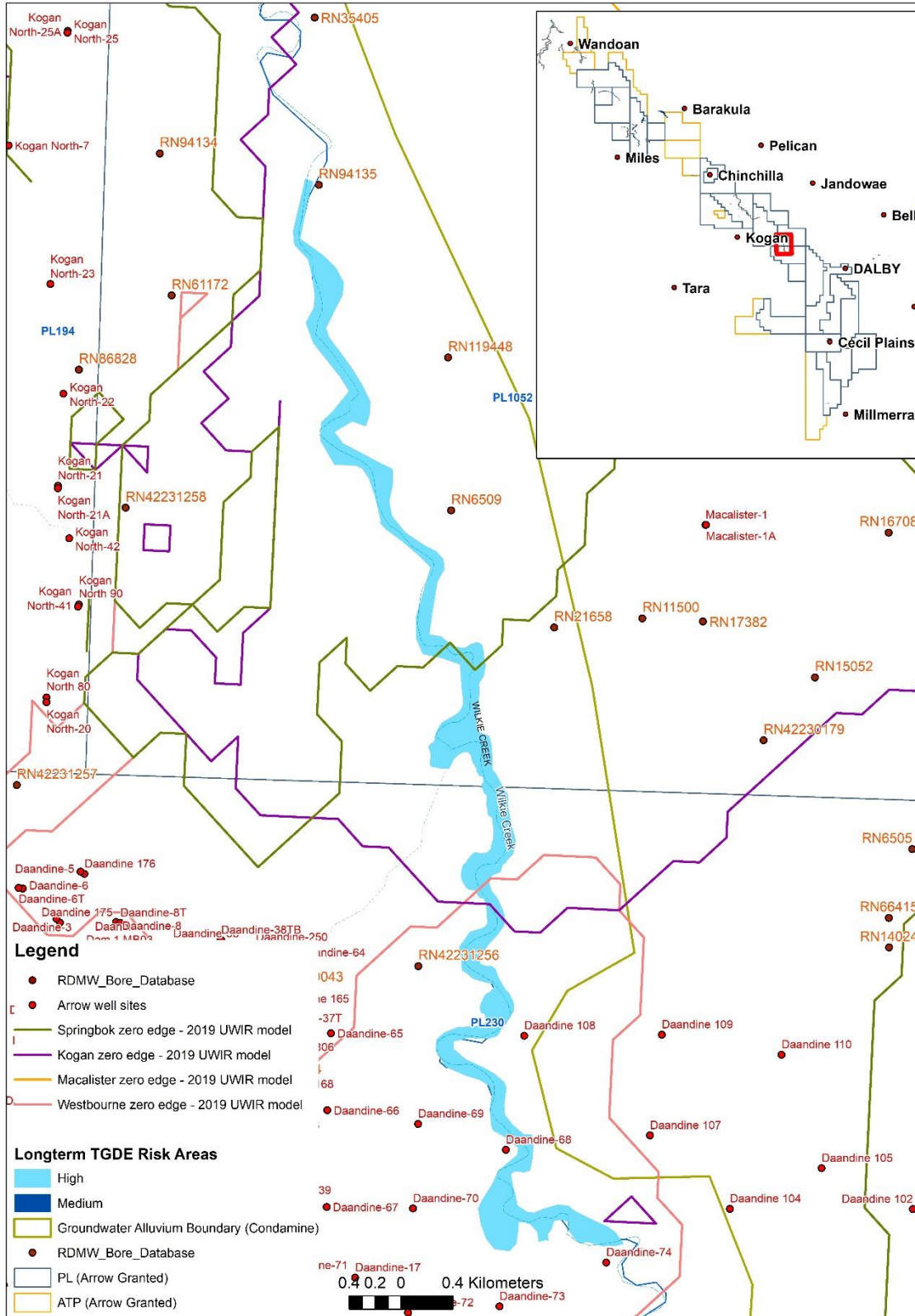


Figure 8: Site 7 Overview

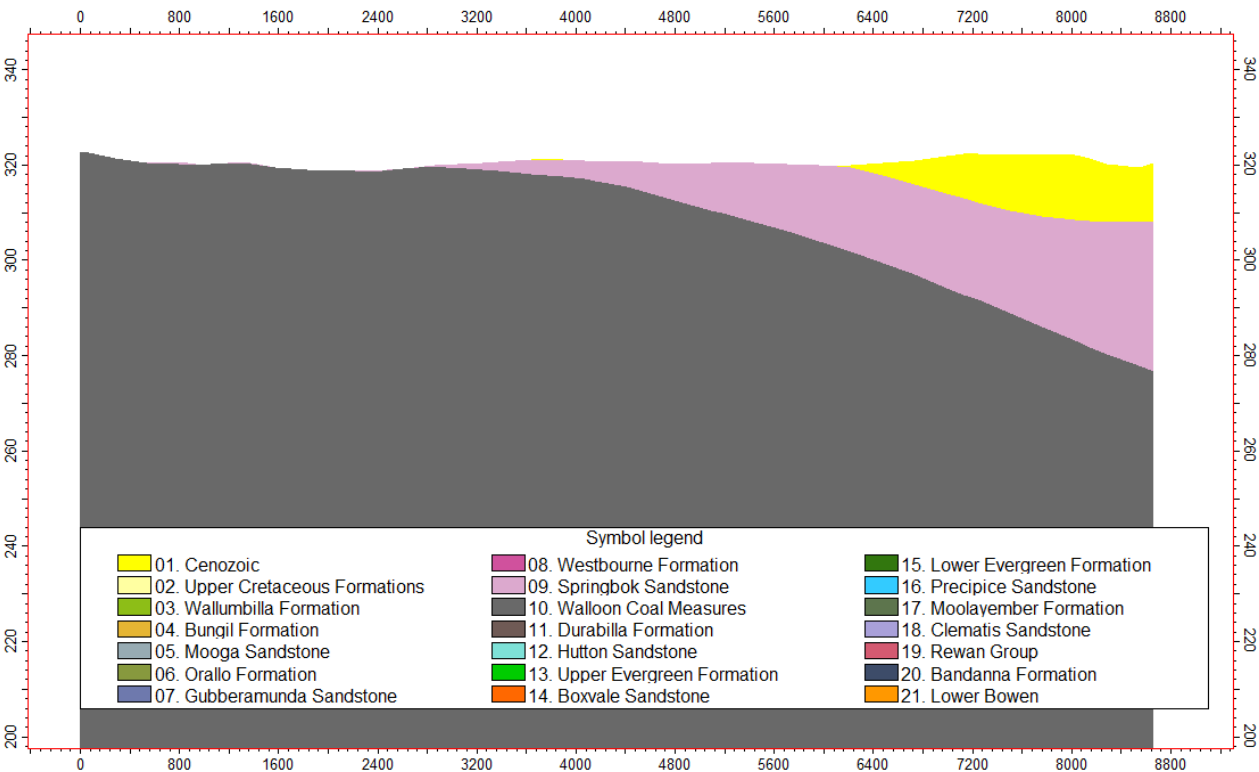
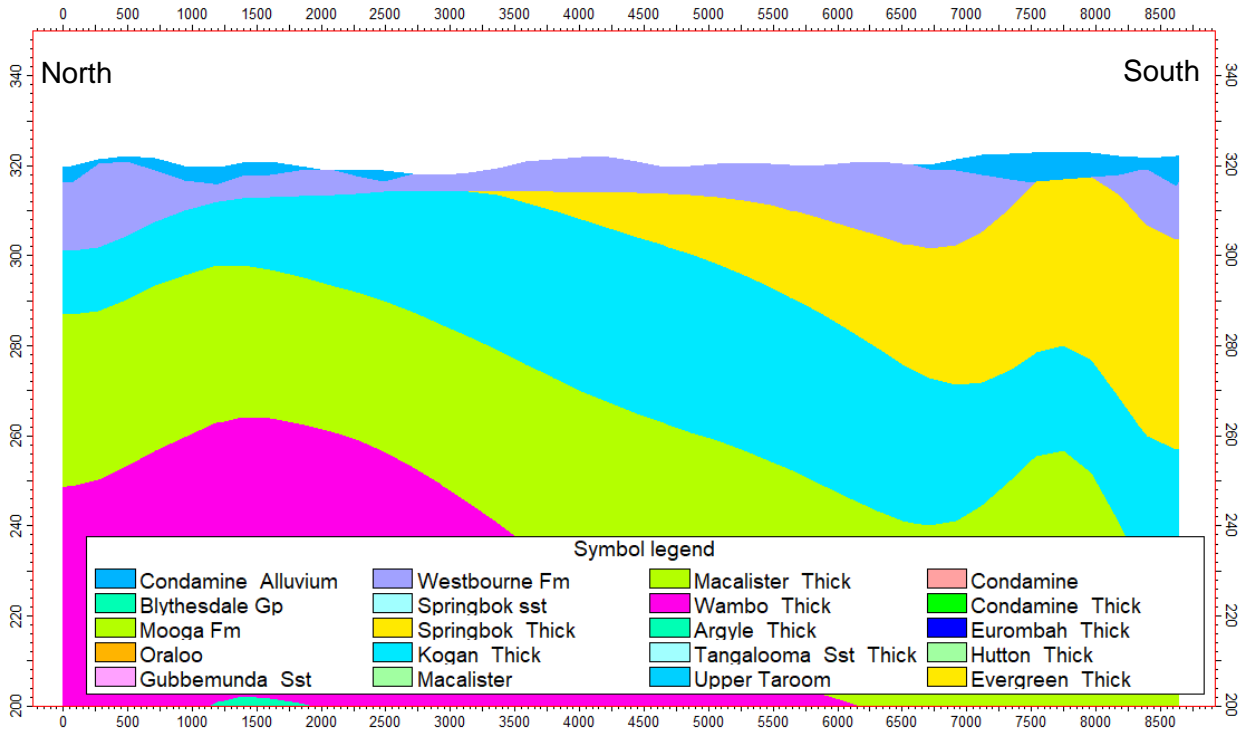


Figure 9: North-south cross section through Site 7 using Arrow geological model (top) and the 2019 UWIR model (bottom)

**Site 8**

Site 8 is located to the northwest of Millmerran and is a 1.8 km strip of vegetation flanking Western Creek Road within PL1041 (Figure 10). The site’s attributes are shown in Table 8. Assessment of Site 8 shows:

- Adjacent Arrow hole Turallin-1 shows alluvium is present to 11 m overlying WCM.
- The mapped vegetation at Site 7 is Poplar Box which Arrow’s Stage 1 WMMP (2018) states this species rooting depth is less than 12m.
- Groundwater level data show the groundwater elevation of the regional water table aquifer, hosted within the WCM, is deeper than 12 m:
  - Bora Creek-10: 44.5 mbgl
  - Glenburnie 21: 17 mbgl
- The predicted groundwater drawdown is identified as 0.07 m in the short term (IAA) and 1.12 m in the long term (LAA) which is considered to result in a slow rate of change in groundwater level which reduces the risk to this potential TGDE. This is consistent with OGIA (2020) which states that where slow rates of drawdown occur vegetation communities may be resilient to change by switching to alternative sources of water. This concept is further detailed in Appendix D of Arrow’s approved SGP Updated WMMP (Stream Connectivity and GDE Impact Assessment Memorandum) (Arrow, 2019). The risk of impact to this site is considered low and, as a result, no further work is proposed for this site at this time.

**Table 8:** Site 8 attributes (OGIA, 2020)

Site Attribute	Site 8
Regional Ecosystem (RE) code	11.3.2 Eucalyptus populnea woodland on alluvial plains
GDE Confidence	Derived GDE – low confidence
Biodiversity Status	Of concern
Landzone	3 – Alluvium (river and creek flats)
Maximum IAA drawdown (within three years from the 2019 UWIR)	0.07 m, layer 12 (upper WCM)
Maximum LAA drawdown (anytime) and model layer	1.12 m, layer 12 (upper WCM)
Long term risk of predicted drawdown on Res	High

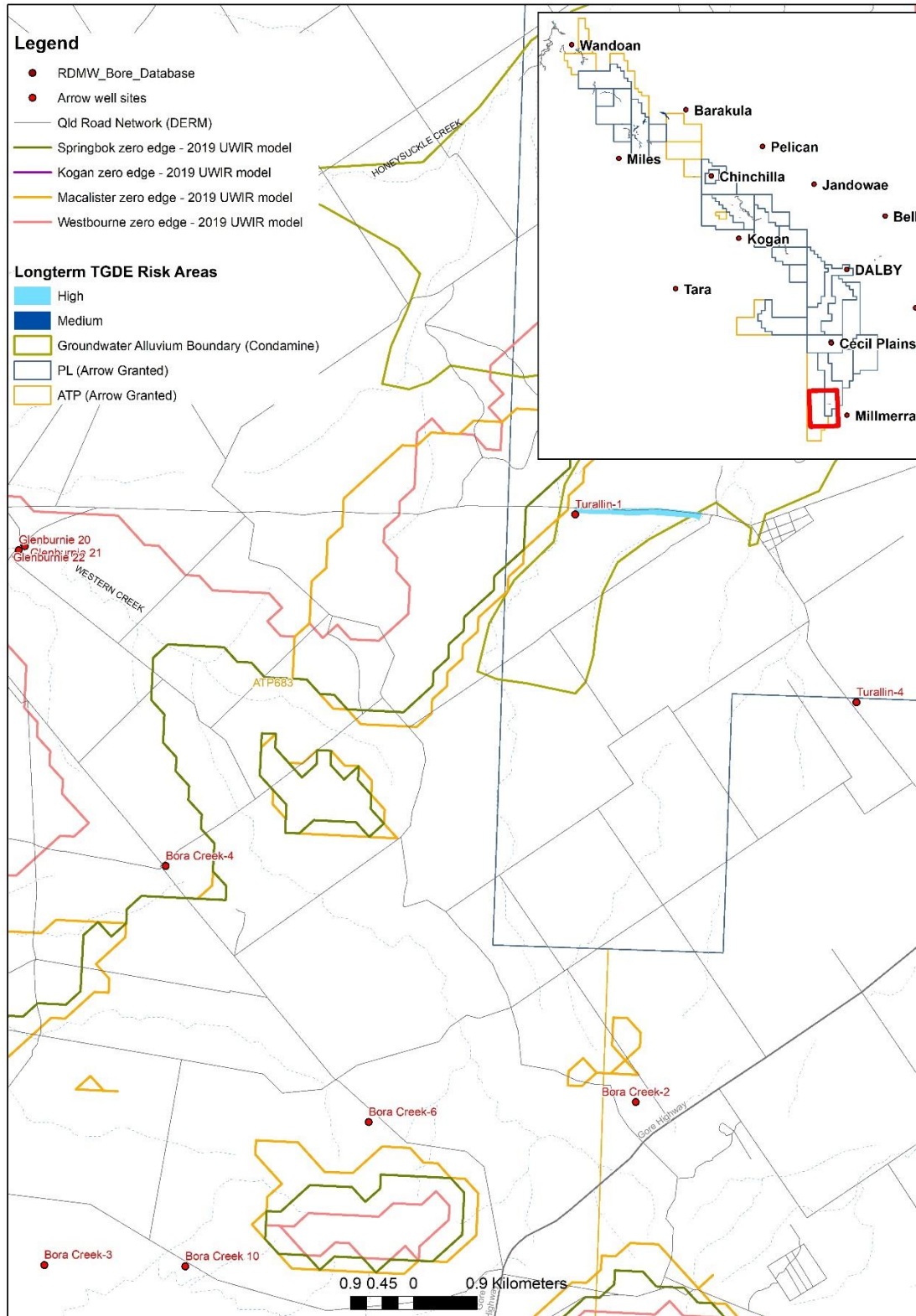


Figure 10: Site 8 Overview

## **References**

3D Environmental, 2021. *File Note: Field assessment of potential watercourse springs identified in the 2019 Underground Water Impact Report on Arrow Energy Tenements.*

Arrow Energy, 2018. Stage 1 CSG Water Monitoring and Management Plan. December 2018

Arrow Energy, 2019. Updated CSG Water Monitoring and Management Plan. October 2019

Office of Groundwater Impact Assessment, 2019. *Underground Water Impact Report for the Surat Cumulative Management Area*, July 2019. Office of Groundwater Impact Assessment

Office of Groundwater Impact and Assessment, 2020. *Attachment 1 (Condition 3 response) to the Annual Report 2020 for the Surat Underground Water Impact Report 2019*. December 2020, Office of Groundwater Impact Assessment

**Appendix A - Attachment 1 (Condition 3 response) to the Annual Report 2020 for the Surat Underground Water Impact Report 2019 (OGIA, 2020)**

## Attachment 1: Response to Condition 3

This is a response to Condition 3 of the Notice of approval of Underground Water Impact Report (UWIR) for the Surat Cumulative Management Area (CMA) (Reference 101/00308656) which states:

*The responsible entity must submit an environmental values assessment with the first annual review that updates the assessment of impacts presented in the approved UWIR on the following environmental values:*

- a) *Terrestrial groundwater-dependent ecosystems*
- b) *Changes in water quality of each aquifer (including water quality objectives, groundwater flow direction, rate, and movement): and*
- c) *Irrigation land.*

*In addition to the information presented in the approved UWIR, the environmental values assessment must specifically differentiate between the impacts over the following time periods:*

- *Impacts that have occurred or are likely to occur because of any previous exercise of underground water rights pursuant to s.371(1)(da) of the Water Act 2000;*
- *Impacts that will occur or are likely to occur because of the exercise of underground water rights during the three (3) year period starting on the consultation day of the report pursuant to s.376(1)(db)(i) of the Water Act 2000; and*
- *Impacts that will occur or are likely to occur because of the exercise of underground water rights over the projected life of the resource tenures pursuant to s.376(1)(db)(ii) of the Water Act 2000.*



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# 1 Terrestrial groundwater-dependent ecosystems

## 1.1 Introduction

Groundwater-dependent ecosystems (GDE) that depend on the sub-surface presence of water (terrestrial GDEs) were included as environmental values for the first time in the UWIR 2019. Terrestrial GDEs (TGDE) occur where vegetation requires access to groundwater, either intermittently or permanently, to maintain ecological composition and function.

In contrast to springs, which are usually relatively localised features, TGDEs may be extensive and may intergrade with non-GDE vegetation communities, depending on variations in surface geology, landform and soil. TGDEs occur where aquifers outcrop at the surface or underlie shallow alluvium associated with watercourses, and where the water table is shallow enough to be accessed by roots.

This section of the response provides the following:

- a description of the TGDEs within the area of interest
- a narrative on the conceptual understanding of how TGDEs access groundwater and their likely response to a change in the groundwater regime
- the methodology and risk assessment of predicted impacts across three timeframes – impacts that have occurred, are predicted to occur in next three years, and are predicted over the life of industry
- a summary of the outcomes from the risk assessment and knowledge gaps.

## 1.2 Identification and description of TGDEs

### 1.2.1 Queensland GDE mapping

In the Surat CMA, areas of likely groundwater-dependent vegetation have been mapped by the Queensland Herbarium as polygons attributed with regional ecosystem (RE) information. REs are groupings of vegetation communities that are associated with a particular combination of geology, landform and soil type. Each individual RE has a biodiversity status, reflecting its condition and remaining extent.

Each identified TGDE is attributed in the Queensland GDE mapping with a level of confidence indicating whether the assigned dependency is based on field data or expert opinion. Field-verified areas are attributed higher confidence. The distribution of mapped TGDEs within the Surat CMA is shown in Figure 1-1.

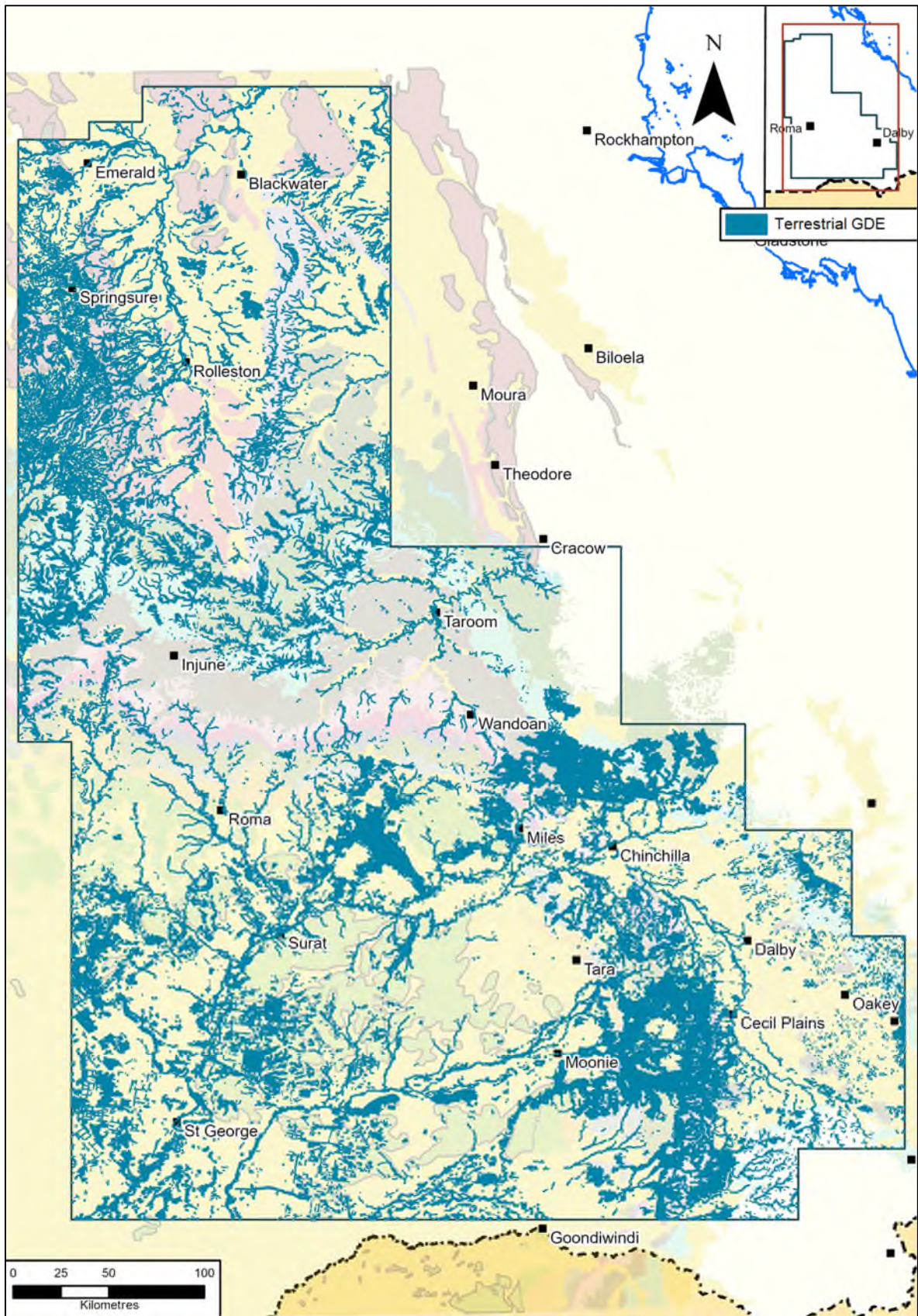


Figure 1-1 Mapped TGDEs within the Surat CMA



## 1.2.2 Hydrogeological setting

There are two primary groundwater systems in the area of identified TGDEs:

- Great Artesian Basin (GAB): a Jurassic to Cretaceous age hydrogeological basin comprising alternating aquifers and aquitards of various geologic formations of Surat Basin sediments and their equivalents
- Cenozoic sediments including alluvium and basalts.

The TGDEs identified in the areas where drawdown is predicted within the next three years are predominantly within the Brigalow bioregion and within the outcrops of the Springbok Sandstone and the Walloon Coal Measures – the target formation for coal seam gas (CSG) extraction in the Surat Basin. Over the life of the industry, additional areas of predicted drawdown are mapped within the Brigalow and South East Queensland bioregions and within the outcrops of the Walloon Coal Measures, the Springbok and Hutton sandstones and the Evergreen Formation (Boxvale Sandstone Member).

The Springbok Sandstone is highly stratified and includes significant proportions of siltstone and mudstone. It is a tight aquifer with medium to low transmissivity. The Hutton Sandstone comprises an upper partial aquifer and a lower tight aquifer. Both the Springbok and Hutton sandstones have limited interconnectivity with the Walloon Coal Measures. Water quality in the sandstones is distinctly fresher and less chemically evolved than that of the Walloon Coal Measures. The Boxvale Sandstone Member of the Evergreen Formation is a partial aquifer of medium transmissivity, displaying a high degree of heterogeneity.

The geology of the Walloon Coal Measures is complex, comprising siltstone, mudstone, fine to medium-grained lithic sandstone and coal. Permeability within the Walloon Coal Measures varies among its component geological units and is dominated by the presence of fractures within coal seams.

## 1.2.3 Ecohydrological conceptual models

As detailed in section 10.2.1 of the UWIR 2019, water accessed by vegetation mapped on shallow aquifers may be sourced from groundwater, infiltrating rainwater, or surface water bodies. Thus, the relationship between a TGDE and its source aquifer depends on botanical characteristics (such as root morphology), the groundwater regime, proximity of surface water, and rainfall characteristics. Consideration of these characteristics allows for ecological water requirements of particular REs to be hypothesised.

Water levels in unconfined aquifers fluctuate at a variety of time scales, including daily, and in response to rainfall events. The ability of vegetation to switch water sources is a key adaptation in areas of highly variable rainfall and soil moisture conditions. As a result, vegetation may only use groundwater for short periods or opportunistically during dry periods. The ecological water requirement of terrestrial vegetation may not only be volumetric, but importantly may have a timing component. Access to groundwater during dry periods may have a crucial role in the maintenance of aspects of plant life cycles, such as sapling establishment and growth.

The ability to access groundwater is conferred by the root architecture and rooting depth. Processes affecting root architecture are complex and depend on a range of site-specific variables. A widely adopted rule of thumb is that vegetation use of groundwater is likely where the depth-to-water is less

than 10 metres below ground level (mbgl), possible at 10 to 20 mbgl, and unlikely at >20 mbgl (D Eamus et al. 2006) (s10.2.2, UWIR 2019).

### 1.2.4 Response to a change in the groundwater regime

Where TGDEs are confirmed through field investigation, impacts are conceptualised into three categories of response: productivity and growth; biodiversity; and reproduction and recruitment (Figure 1-2). In the short term, decreased availability of groundwater is more likely to be evident in changes in the productivity of vegetation. Drawdown is associated in the short term with reduced leaf production and in the longer term with an absence of saplings, loss of biodiversity and changes in community structure and composition.

Where predicted impacts are minor and the rate of change in the groundwater level is slow, some vegetation communities may have the ability to adapt to the new water level. Within the outcropping aquifers, when groundwater levels are impacted, TGDEs may be sustained by infiltrating rainfall. Given the seasonality of the rainfall, however, this may only provide a short-term buffer and may not compensate for a reduction in water level during dry periods. Further research into responses is required to clarify the resilience of these TGDEs.

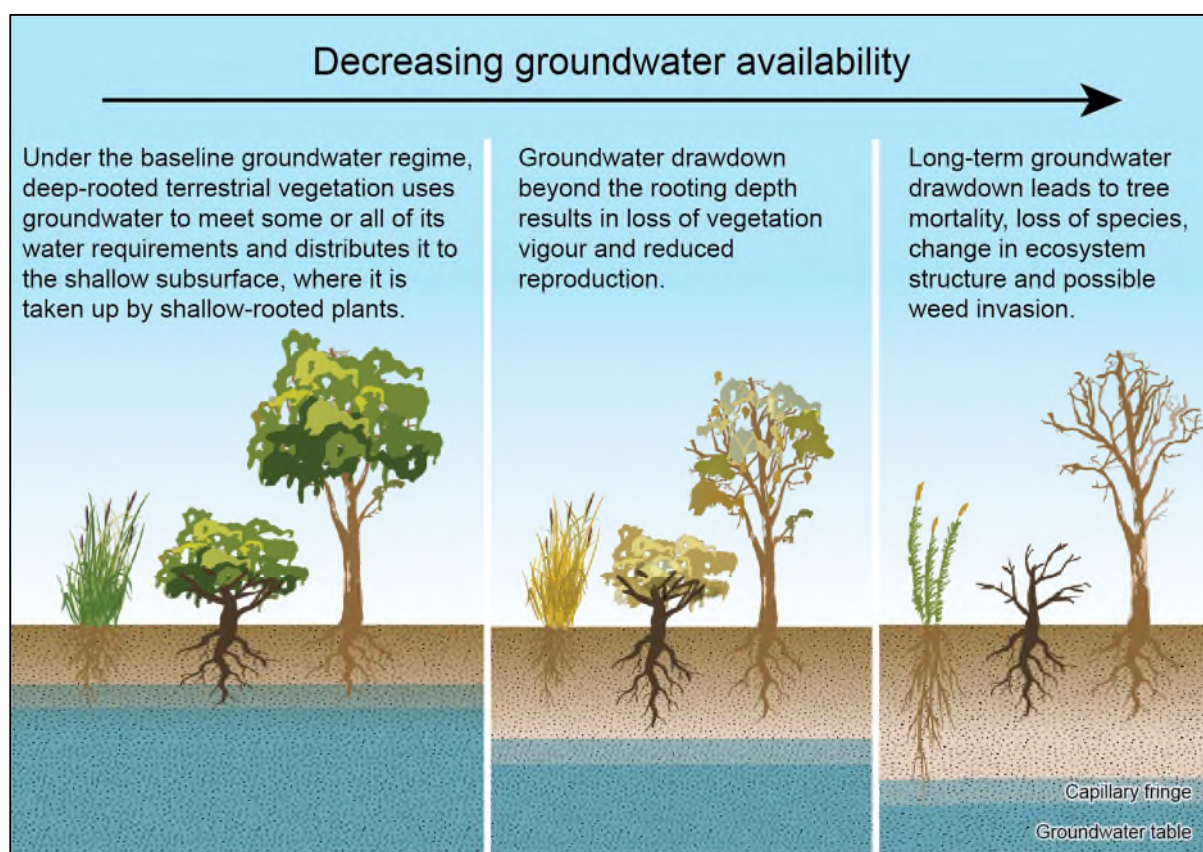


Figure 1-2 Conceptual model of TGDE response to a reduction in water level, after Eamus et al. (2006) and Rohde et al. (2017) (after OGIA 2019b)

## 1.3 Potential impacts

### 1.3.1 Impact footprint

For the UWIR 2019, OGIA completed a desktop assessment (OGIA 2019b) to: integrate existing mapping of potential TGDEs with areas of predicted drawdown in the regional groundwater model;

develop conceptual understanding of groundwater dependency and response to drawdown; and identify areas for improvement of knowledge.

The area of interest for TGDE assessment is the area of 0.2 m predicted drawdown, at any time during the proposed CSG development, within the outcropping aquifers. For the purposes of this assessment, only those polygons with greater than 50 per cent GDE are included, and only those polygons with component regional ecosystems that include land zones 3, 9 and 10. These land zones are known potential zones of connection with aquifers identified as affected in the UWIR 2019 (OGIA 2019b). The distribution of TGDEs within the area of interest is shown in Figure 1-4.

### 1.3.2 Magnitude of impacts

The magnitude and timing of predicted impacts varies spatially and between formations. Prior to 2019, the majority of TGDE polygons predicted to experience impacts are within the Walloon Coal Measures, with drawdown predominantly less than 5 metres. In the short and longer terms, the majority of predicted impacts are less than 10 metres. However, at some locations, impacts exceed 20 m. Where TGDEs are confirmed to be accessing affected formations in these areas, this has the potential to have significant impacts on the TGDEs ecological water requirements and resultant condition.

### 1.3.3 Risk assessment

For the purposes of this response, a risk assessment has been applied to the assessment of impacts to TGDEs. The risk assessment builds upon the impact assessment, through the integration of ecological value information enabling priority areas to be identified for further investigation and conceptualisation.

Risk is assessed as a function of the likelihood and consequence of groundwater drawdown in the target formation for a TGDE. A summary of the risk assessment methodology, including input datasets and risk categories, is provided in Figure 1-3.

The criterion for the assessment of likelihood of impact from groundwater drawdown is the magnitude of drawdown at the location of the TDGEs, as predicted by the regional groundwater flow model. Two categories are identified based on the predicted impacts: less than, and greater than, 1 m predicted drawdown.

Evaluating the consequences of the predicted drawdown on TGDEs is more complex. There are multiple uncertainties associated with detection of ecological responses, and particularly so with studies of impacts on GDEs. The sensitivity of TGDEs to changes in groundwater regime is determined by the nature of the ecohydrological relationship between groundwater and vegetation.

Consideration of an RE's biodiversity status is the first step in inferring the significance of a predicted impact on that RE. The biodiversity status reflects the condition of an RE and the extent remaining, compared with its pre-clearing extent. For more detailed evaluation of consequences, specific information is needed about the ecological response of the RE to varying degrees of groundwater drawdown.

Three risk categories are identified as follows:

- **Low risk** – predicted impacts at this location range between 0.2 metres and 1 metre. The biodiversity status of the associated RE may be 'not of concern', 'of concern' or 'endangered'.



- **Medium risk** – predicted impacts at this location are greater than 1 metre. The biodiversity status of the associated RE is ‘no concern at present’.
- **High risk** – predicted impacts at this location are greater than 1 metre. The biodiversity status of the associated RE is ‘of concern’ or ‘endangered’.

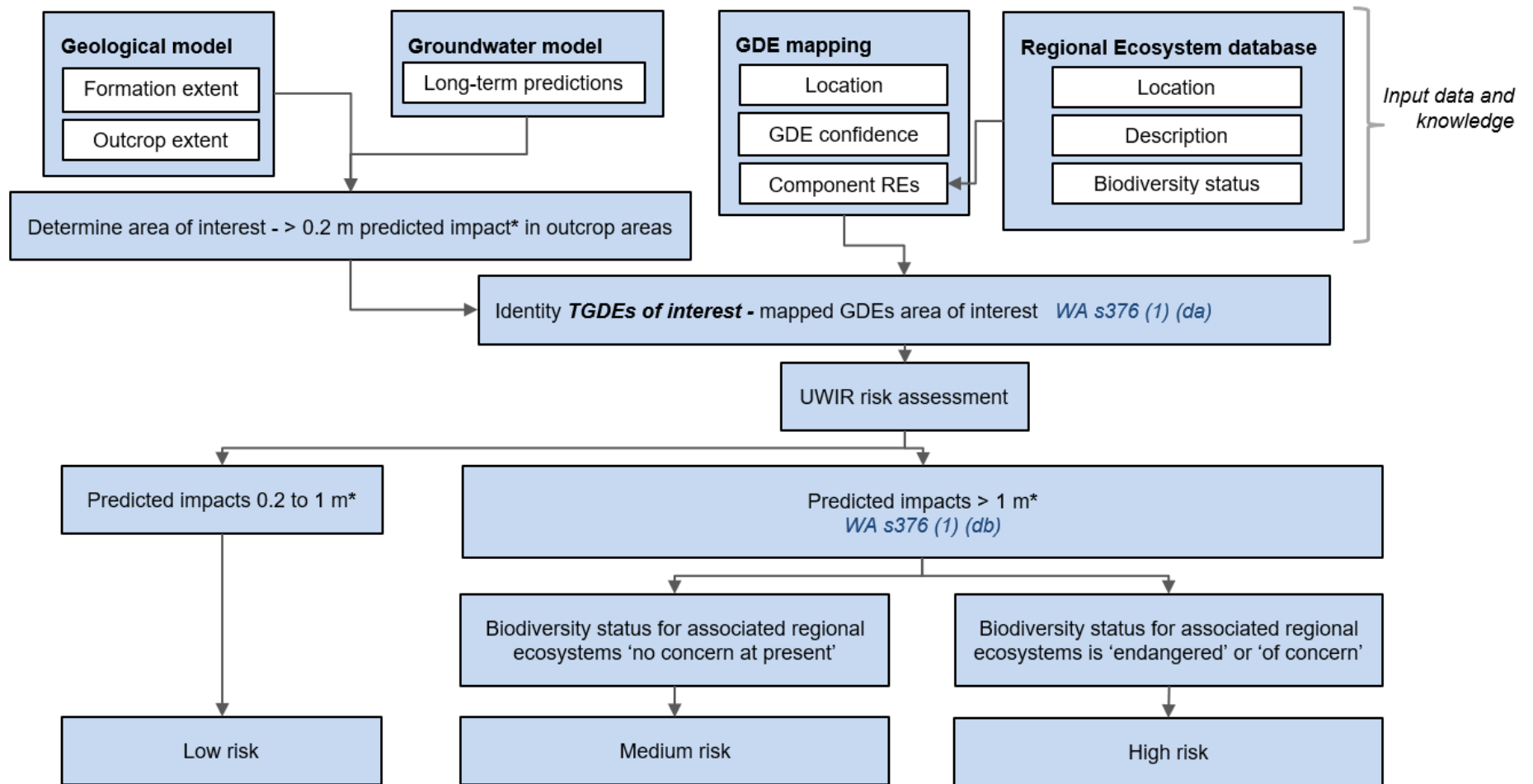


Figure 1-3 Framework for the assessment of risks to TGDEs

### 1.3.4 Outcomes of risk assessment

The outcomes from the risk assessment on the identified TGDEs are shown for the three statutory timeframes in Figure 1-4. Generally, decreasing groundwater availability has the potential to result in loss of productivity, vigour and reduced reproduction in the short term. Long-term drawdown leads to tree mortality, loss of species, and change in ecosystem structure (Figure 1-2). The ecological values of the identified TGDEs may be impacted through change in community health and composition, and potentially complete loss of the community in the long term. Where predicted impacts are minor and the rate of change in groundwater regime is slow, some vegetation communities may be resilient to change by switching to alternative sources of water if they are available.

Risk of impacts are identified in terms of three time steps as described further: impacts that occurred prior to the UWIR 2019; impacts predicted to occur in next three years (from the UWIR release date); and long-term impacts. Outputs are presented as a regional-scale footprint of TGDEs.

In some cases, TGDE polygons are extensive and overly multiple formations with only a portion of the polygon predicted to be impacted. In these cases, a conservative approach has been applied and the most impacted formation has been used in the risk assessment. The outputs are also made available to DES as spatial dataset for further local scale refinement where appropriate.

#### 1.3.4.1 Impacts prior to the UWIR 2019

Within the area of interest, impacts exceeding 0.2 m prior to the UWIR 2019 occur within the Walloon Coal Measures, the Precipice Sandstone and the Lower Evergreen Formation (Figure 1-4).

- In the Walloon Coal Measures, more than 1,000 hectares are identified as low risk, 1,300 hectares identified as medium risk and around 4,500 hectares identified as high risk. Of those areas identified, 14 per cent are high-confidence TGDEs.
- In the Precipice Sandstone, around 6,100 hectares are identified as low risk. Of those areas identified, 8 per cent are high-confidence TGDEs.
- In the Lower Evergreen Formation, around 10 hectares are identified as low risk.

#### 1.3.4.2 Impacts predicted to occur in the short term

Within three years from the UWIR 2019, predictions of impact exceeding 0.2 m occur within the Walloon Coal Measures and the Precipice Sandstone and the Lower Evergreen Formation (Figure 1-4). Including the previous impacts, short-term predicted impacts are summarised as follows:

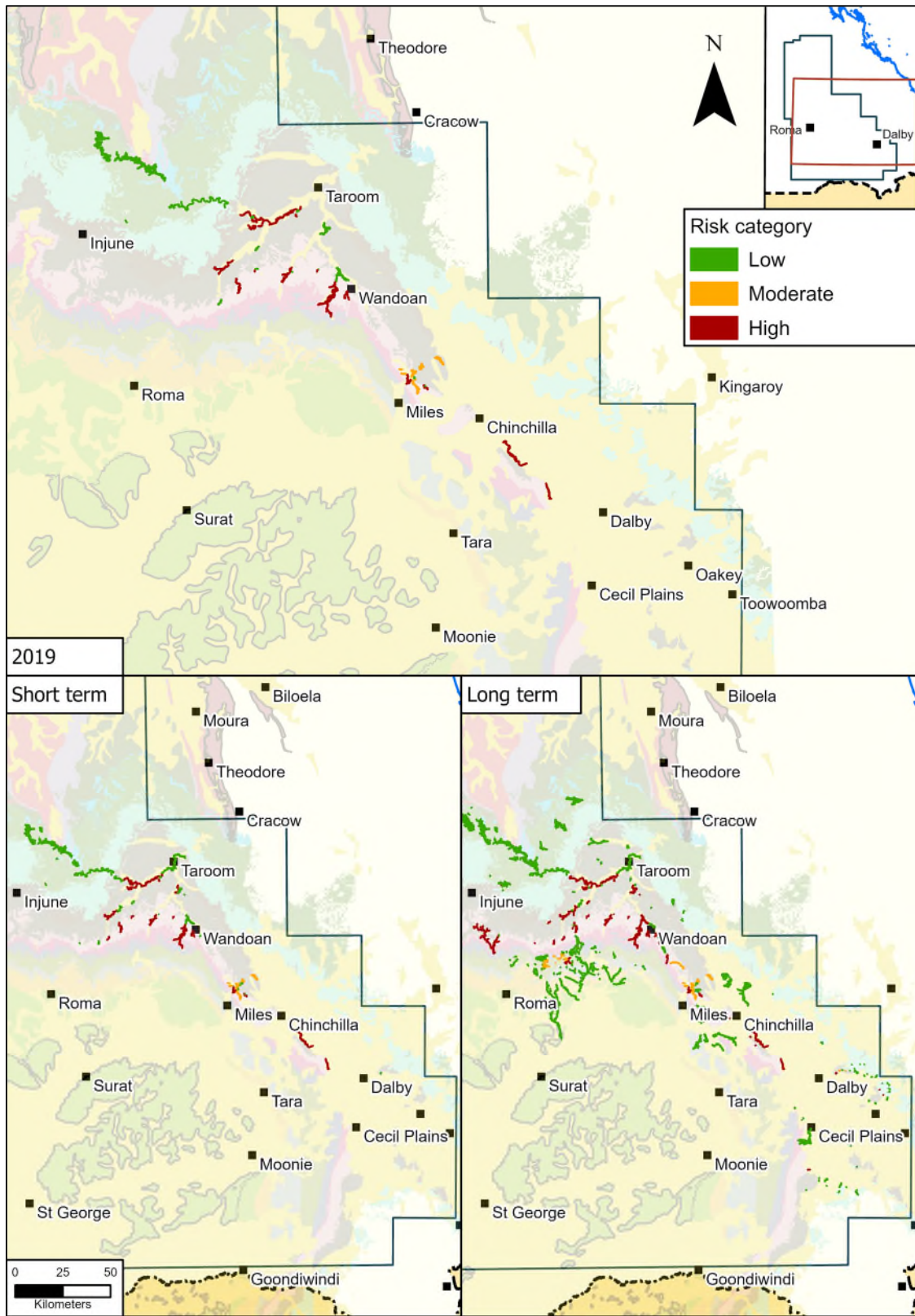
- In the Walloon Coal Measures, more than 2,300 hectares are identified as low risk, 1,300 hectares identified as medium risk and around 4,900 hectares identified as high risk. Of those areas identified, 12 per cent are high-confidence TGDEs. These generally represent expansion of those areas identified in the previous period.
- Some of the identified TGDE polygons occur across both the Walloon Coal Measures and the Springbok Sandstone. As the most affected aquifer is the Walloon Coal Measures, these polygons are represented in the above statistics.
- In the Lower Evergreen Formation, around 10 hectares are identified as low risk. Of those areas identified, all are moderate-confidence TGDEs. These are small areas north of Injune.
- In the Precipice Sandstone, around 7,000 hectares are identified as low risk. Of those areas identified, 8 per cent are high-confidence TGDEs.

### **1.3.4.3 Impacts predicted to occur in the long term**

Over the life of the industry, predictions of impact exceeding 0.2 m occur within the Alluvium, the Bungil, Mooga, and Orallo formations, the Gubberamunda, Springbok and Hutton sandstones, the Walloon Coal Measures and the Evergreen Formation (including the Boxvale Sandstone Member) and the Precipice Sandstone (Figure 1-4).

Including the previously predicted impacts, long-term predicted impacts are summarised as follows:

- Around 1,900 hectares identified as medium risk and around 9,200 hectares are identified as high risk. Twenty-seven per cent are high-confidence TGDEs.
- Around 35,100 hectares are identified as low risk. Thirty per cent are high-confidence TGDEs.



**Figure 1-4 Outcomes from the risk assessment for TGDEs prior to the UWIR 2019, in the short term and in the long term**

## 1.4 Improvements in knowledge

There are uncertainties regarding the identification of source aquifers for GDEs and uncertainties resulting from the scale and the level of confidence of GDE mapping. Large error terms are associated with estimation of the ecohydrological relationship between groundwater and vegetation. The conceptual models, estimated ecological water requirements, hypothesised ecological responses and resilience are drawn from the available literature, including Queensland Herbarium products, and are associated with high uncertainty. Ongoing monitoring is important to test, validate and refine this assessment.

The Queensland GDE mapping dataset has been developed using available datasets and an expert elicitation approach (Glanville et al. 2016). Of the putative TGDEs identified, only a small percentage have been field verified. Consistent with the national GDE toolbox (Richardson et al. 2011), effective management of TGDEs requires three key knowledge components – location, groundwater dependency and characterisation of their likely response to changes in the groundwater regime.

The Queensland GDE mapping provides the basis for the identification of TGDEs. The priority knowledge gaps for research and monitoring in moderate to high risk areas are as follows:

- validation and confirmation of the GDE mapping and associated REs
- conceptualisation of the identified TGDEs in terms of:
  - quantification of their ecological water requirements – the temporal nature, quantity and quality of groundwater use
  - their likely ecological response to changes in groundwater regime.

OGIA is undertaking the initial scoping and design of a pilot program to establish field sites for ongoing monitoring of priority REs that are mapped within aquifers' Immediately Affected Areas (IAA) and Long-term Affected Areas (LAA). For each site, the water balance, ecological water requirements and ecological responses for each TGDE will be hypothesised and conceptualised. The specific hypotheses will inform the design of a monitoring program and data analysis to in turn inform more detailed risk assessment in future iterations of the UWIR.

## 2 Changes in water quality

### 2.1 Introduction

The UWIR 2019 provided a summary of the water quality for each aquifer across the Surat CMA (Chapter 5 and Appendix D.2, UWIR 2019). Additional components presented in this section of the response include the following:

- snapshots of available water quality data for each aquifer for two points in time:
  - prior to the commencement of CSG in the Surat Basin (2005)
  - between 2005 and 2018 (current state)
- risks and potential for water quality changes in response to predicted changes in groundwater flow regime over time (within the next three years and in the long term).

Groundwater is accessed from most formations across the Surat CMA. Water quality within the aquifers varies, with the primary factors influencing water quality being the formation mineralogy, proximity to areas where the formation is recharged, and groundwater flow dynamics within the formation.

Groundwater within the recharge areas is generally fresh, characterised by lower salinity, as represented through total dissolved solids (TDS). As groundwater moves through the formations, its water chemistry evolves differently for individual formations.

Sandstone-dominated or permeable formations, such as the Precipice, Clematis and Hutton sandstones, the Condamine Alluvium and the Main Range Volcanics, generally contain better water quality compared to other formations – TDS of less than 1,000 mg/L and sodium adsorption ratio (SAR) of less than 10. For human consumption, a TDS of less than 1,000 mg/L is required, whereas up to 4,000 mg/L TDS is acceptable for stock purposes. These key formations are suitable for drinking and/or irrigation purposes and account for more than 90% of non-stock and domestic water use in these units.

For the purposes of this response, the term ‘water quality’ is used where a reference or discussion relates to the characterisation of water for direct or indirect consumption. The term ‘water chemistry’ is used where the context is around the chemical characteristics of water more broadly.

### 2.2 Potential for impacts to water quality from CSG development

As presented in the UWIR 2019 (Chapter 2), CSG development requires a reduction in the reservoir water pressure to enable gas to be released from the coal. The development generates a significant vertical gradient in groundwater pressure between the CSG target formations (the Walloon Coal Measures or the Bandanna Formation) and the adjacent aquifers. A lateral pressure gradient is also developed towards the gasfields within the CSG target formations. These gradients induce lateral groundwater flow towards the gasfields – predominantly within the CSG target formations themselves.

The induced groundwater flow has the potential to change the water quality along the flow pathways through a range of complex processes including advection, diffusion, dispersion and ion-exchange – primarily the advection process. In general, the potential for changes in water quality in surrounding aquifers is considered low, because the pressure gradients generated across aquifers due to CSG depressurisation are low. However, over longer timeframes, there is some potential for ion-exchange



processes within and/or between the CSG formations and adjacent aquifers due to change in pressure gradient and flow directions.

## 2.3 Methodology for assessing impacts on water quality

To characterise water quality changes, OGIA undertook a multivariate k-means statistical cluster analysis to partition samples into unique cluster classes which differentiate water quality between major formations. In contrast with the uni-variant methods (such as TDS, pH, etc.), this approach offers the inherent ability to comprehensively analyse concentrations and relationships across samples for all the major ions contributing to water quality, and to provide statistical analysis for evaluating differences in overall water chemistry.

The analysis results in five distinct cluster classes based on eight major ions, such that the water quality remains more or less similar within a cluster class, but significantly differs between the cluster classes. Class 1 represents freshly recharged to slightly brackish water, whereas class 5 is highly evolved saline water.

Groundwater chemistry data has been sourced from the Queensland Groundwater Database and tenure holder monitoring reports provided in accordance with the UWIR. Only high-confidence data from around 14,800 samples was used for the analysis, following an initial quality-assurance/quality-check screening of all available data. A statistical summary of groundwater chemistry in each aquifer across the Surat CMA is provided across two time periods – prior to 2005 and post-2005 – in Appendix A.

Changes to water quality are analysed in the context of changes to groundwater flow that are induced by CSG depressurisation, and the potential for ion-exchange processes within and/or between the CSG formations and adjacent aquifers, as described earlier.

## 2.4 Changes in water quality prior to the UWIR 2019

Changes in water quality between 2005 and 2018 (representing past exercise of underground water rights by the P&G industry) are assessed based on water chemistry monitoring data collected during those periods and comparison with pre-2005 data.

The data was statistically partitioned into five cluster classes as detailed earlier, for each of the 19 formations corresponding to each of the above two time periods. Based on the cluster classification, most (60 to 100 per cent) water quality samples are classified into Class 1.

Results of cluster analysis are presented in Appendix A as Table A-1 and A-2 respectively for the two time periods. Some of the conclusions drawn, in relation to water quality changes from P&G production, are summarised below for each of the formations.

### 2.4.1 Alluvium

Minimal change is observed in water chemistry of the Alluvium with the majority of samples across both periods indicating fresh locally recharged water (Class 1). The changes are unlikely to be related to the exercise of underground water rights by P&G tenure holders.

### 2.4.2 Main Range Volcanics

Similar to the Alluvium, water chemistry across both periods shows minimal change, with more than 90 per cent of samples within Class 1 (fresher water). The changes are unlikely to be related to the exercise of underground water rights by P&G tenure holders.

### **2.4.3 Upper Cretaceous**

There are limited available samples post-2005. Pre-2005 data indicates 26 per cent of samples are Class 1, while around 70 per cent are in the more evolved cluster classes (3, 4 and 5). This may be due to the influence of increased evapotranspiration or limited recharge at sampled locations. These changes are unlikely to be related to the exercise of underground water rights by P&G tenure holders.

### **2.4.4 Wallumbilla Formation**

There are limited available samples post-2005. Pre-2005 indicated around 60 per cent of samples have slightly brackish water (TDS of around 1,400 mg/L) in Class 1. The exercise of underground water rights by P&G tenure holders is unlikely to have caused any changes to water quality.

### **2.4.5 Bungil Formation**

Water chemistry in this formation remained consistent across the pre- and post-2005 periods. Around 60 per cent of samples indicate slightly brackish water, with TDS around 1,500 mg/L (Class 1). The exercise of underground water rights by the P&G tenure holders unlikely to have caused any changes to water quality.

### **2.4.6 Mooga Sandstone**

Similar to previous formations, water chemistry samples in the Mooga Formation show minimal changes between the two reporting periods. Around 74 per cent of pre-2005 and 90 per cent of post-2005 samples are partitioned into Class 1, showing slightly brackish water. Similarly, no impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### **2.4.7 Orallo Formation**

Similar to previous formations, water chemistry samples in the Orallo Formation show minimal changes between the two reporting periods. Around 70 per cent of samples in the pre-2005 period and 90 per cent of samples in the post-2005 period indicate slightly brackish water (Class 1). No impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### **2.4.8 Gubberamunda Sandstone**

Similar to previous formations, water chemistry samples in the Gubberamunda Sandstone show minimal changes between the two reporting periods. Samples across both periods indicate around 90 per cent of samples with relatively good quality water (Class 1). No impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### **2.4.9 Westbourne Formation**

There are limited samples across both reporting periods in the Westbourne Formation. Pre-2005 samples indicate significantly fresher water (Class 1), compared with slightly brackish water for the post-2005 samples. Post-2005 samples indicate higher concentrations of sodium (Na), bicarbonate ( $\text{HCO}_3$ ) and chloride (Cl) and higher Sodium Adsorption Ratio (SAR) values. No impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### **2.4.10 Springbok Sandstone**

Across both periods, the available samples from the Springbok Sandstone indicate 60 to 65 per cent are slightly brackish water (Class 1). However, significant reductions in Ca and Mg, and increases in

Na concentrations, have resulted in higher SAR values in the Class 1 samples in the post-2005 period. Additionally, increased  $\text{HCO}_3$  concentration indicates the potential for ion-exchange to have occurred.

Ion-exchange may result from the movement and mixing of water within the formation or between formations where connectivity exists. The most likely scenario is the intra-formational movement of water in response to water extraction. However, in locations where CSG depressurisation has occurred, there is potential for ion-exchange to have occurred between formations over longer timeframes. This will be further evaluated as part of OGIA's trend analysis.

Although changes between the pre- and post-2005 Class 1 water samples may be significant in relation to concentrations of Ca, Mg, Na and SAR, the change in overall water chemistry is minor. The change in TDS and variability in other individual parameters are within the range of natural variability for this cluster class. At this stage, none of the changes are likely to have occurred from the exercise of underground water rights by the P&G tenure holders.

#### **2.4.11 Walloon Coal Measures**

Non-CSG Walloon Coal Measures samples in the pre-2005 period indicate around 60 per cent are slightly brackish in Class 1, compared with around 40 per cent in the post-2005 period. In both periods, a considerable number of samples are partitioned into evolving (Class 2) to highly evolved (Class 4) cluster classes, with significantly high SAR values (greater than 50) – a unique chemical signature for the Walloon Coal Measures compared with other formations.

Post-2005, Class 3 shows significant reductions in Ca and Mg and an increase in  $\text{HCO}_3$ , resulting in increased SAR values compared with the pre-2005 samples. Similar to the Springbok Sandstone, these changes indicate the possibility of ion-exchange processes.

It is important to note that bore construction prior to 2005 may be dominated by relatively shallower bores when compared with the post-2005 period. Therefore, differences in the depth of sampling will also result in changes in water chemistry across the two periods.

There were very few CSG samples prior to 2005. Post-2005, CSG samples are predominantly within classes 2 and 3, with distinct characteristics of very low concentrations of Ca and Mg and very high SAR values (>100). This significant difference from non-CSG samples is likely due to significant differences in the depth of bore construction and resulting hydrogeological conditions (less than 100 m for non-CSG and greater than 200 m for CSG samples).

During the preparation of the UWIR 2019, a separate temporal water quality trend analysis was also undertaken for samples in the Walloon Coal Measures. Trends with statistical confidence were noted for Cl concentrations. This analysis indicated that the majority (around 80 per cent) of the bores did not show any trend, whereas the trends in the rest of the bores showed increasing and decreasing Cl concentrations. These changes were within the natural range of Cl concentrations, indicating no specific correlation with trends in groundwater pressure.

In conclusion, the observed differences in pre- and post-2005 water chemistry samples are likely due to the effects of depressurisation causing horizontal water movements and ion-exchange processes.

Water quality changes remain, however, within the same cluster classes for the pre- and post-2005 CSG samples and are within the natural variability. Therefore, despite some mixing and changes, there is no material influence on the environmental values as yet.

### 2.4.12 Hutton Sandstone

Across both periods, around 70 to 80 per cent of samples are within Class 1, with relatively fresher water (average TDS around 1,000–1,200 mg/L). Post-2005 samples showed decreased Ca and Mg and increased SAR values, compared with pre-2005 samples. These changes again indicate the presence of ion-exchange processes, with a degree of movement and mixing of water either within or between formations. There is no indication of impacts from the exercise of underground water rights by P&G tenure holders.

### 2.4.13 Evergreen Formation

Across both periods, the available data indicates around 90 per cent of samples indicate fresh quality water (Class 1). Between periods, salinity appears to have slightly increased within Class 1, due to increased concentrations of most major ions Ca, Mg, Na, HCO<sub>3</sub>, Cl and sulphate (SO<sub>4</sub>), indicating increased evapotranspiration or limited recharge in the post-2005 period. No impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### 2.4.14 Precipice Sandstone

Samples from the Precipice Sandstone indicate 90 to 100 per cent fresh water, with an average TDS of around 250 mg/L. No changes are observed across the two periods. No impacts are likely to have occurred from the exercise of underground water rights by P&G tenure holders.

### 2.4.15 Moolayember Formation

The limited available data for this formation indicates fresh conditions (Class 1). There is no likelihood of CSG impacts occurring from the exercise of underground water rights by P&G tenure holders.

### 2.4.16 Clematis Group

Similar to the Precipice Sandstone, the Clematis Sandstone is dominated by samples classified as Class 1. However, with relatively higher concentrations of Ca and Mg than the Precipice Sandstone, the Clematis Sandstone has the lowest SAR values (<3). There is no likelihood of CSG impacts occurring from the exercise of underground water rights by P&G tenure holders.

### 2.4.17 Rewan Group

There are limited samples available from this formation. The available samples in the pre-2005 period indicate 45 per cent were slightly brackish (Class 1) and 35 per cent represented highly evolved saline water (Class 4). There is no likelihood of CSG impacts occurring from the exercise of underground water rights by P&G tenure holders.

### 2.4.18 Upper Permian

Pre-2005 samples showed slightly brackish water in these formations.

### 2.4.19 Bandanna Formation

There are a limited number of non-CSG water samples from the Bandanna Formation. However, CSG samples (mainly post-2005) show similar characteristics to those of the CSG samples from the Walloon Coal Measures – very low concentrations of Ca, Mg and SO<sub>4</sub>, higher concentrations of Na and HCO<sub>3</sub>, and high SAR values (>140).

## 2.4.20 Basement

There are limited samples available from the Basement. The pre-2005 samples indicate 60 per cent are slightly brackish (Class 1) with around 30 per cent representing highly evolved saline water (Class 4). There is no likelihood of CSG impacts occurring from the exercise of underground water rights by the P&G tenure holders.

## 2.5 Predicted impacts

As stated in earlier sections, CSG depressurisation creates a gradient in groundwater pressure towards the gasfields – laterally within the CSG target formations, and from the adjacent aquifers. The induced groundwater flow has the potential to change the water quality along the flow pathways, through a range of complex processes. The primary mechanisms to drive water quality changes are:

- lateral movement of water within the CSG target formations induced by pressure gradients towards the production areas
- potential mixing of water in the CSG target formations where flow is induced from the surrounding aquifers to the CSG formation, provided there is a degree of hydraulic connectivity between them
- ion-exchange processes.

The analysis presented earlier for pre-2019 suggested that there has been little change in water quality, and that water quality is unlikely to have influenced the environment values in the past (excluding the influences from migrating gas).

In general, water quality in the CSG target formations in and around production areas is poorer compared to surrounding aquifers, although the Walloon Coal Measures is widely used for stock and domestic purposes – particularly near the outcrop areas where water is relatively fresher. Conceptually, therefore, depressurisation is likely to result in movement of water from better water quality areas to poorer water quality areas. Water pressure gradients towards the gasfields will prohibit movement of water from CSG target formations to surrounding aquifers.

A technique used for quantitative prediction of water quality changes resulting from groundwater movement is solute transport modelling. However, given the negligible risk of mobilisation of poorer quality water from CSG reservoirs to surrounding aquifers, the complexity of processes and the effort involved in solute transport modelling for a large area, this technique is not considered feasible for predicting changes to water quality. Instead, a subjective analysis of anticipated changes in water quality, and risk of deterioration in water quality, is provided below for two specific time steps: short-term (within three years from the UWIR 2019, as required under Condition 3) and long-term (any time in future).

### 2.5.1 Short-term Impacts

In the short term, the effect of depressurisation is represented by IAA, as shown in section 7.2 and Figure 7-1 of the UWIR 2019. Pressure impacts in the short term (i.e. three years from the UWIR 2019) are predicted in the Walloon Coal Measures, the Bandanna Formation, the Cattle Creek Formation and the Springbok Sandstone. Predicted and observed impacts are tightly wrapped around the current CSG production areas.

Based on the analysis of water quality changes in response to the pre-2019 CSG development period, it can be reasonably concluded that although some changes in water chemistry are likely in

the short term, no discernible or material water quality changes are expected for environmental values. This excludes any changes that may result from gas migration or local-scale mobilisation of contaminants.

### **2.5.2 Long-term Impacts**

In the long term, the effect of depressurisation is represented by LAA, as shown in section 7.3 and Figure 7-2 of the UWIR 2019. In addition to the CSG target formations, material impacts are predicted in surrounding aquifers – the Springbok, Clematis and Precipice sandstones. This impact will be accompanied by the induced flow of water from those surrounding aquifers to the Walloon Coal Measures or the Bandanna Formation, and some flow between the aquifers.

Similar to the short-term changes, the long-term pressure changes and induced flow would also cause some changes to water quality. As stated previously, the processes and mechanisms affecting those changes are likely to be complex. At a regional scale, the movement of water from shallower parts of the formation to deeper parts, or from shallow outcrop areas to more confined gasfield areas – combined with ion-exchange processes – are more likely to result in little change or the marginal lowering of salinity in water bores and other environmental values. This excludes any changes that may result from gas migration or local-scale mobilisation of contaminants.

## **2.6 Ongoing groundwater quality monitoring**

The UWIR 2019 includes a groundwater chemistry monitoring network for implementation by tenure holders. The network includes sampling from 103 groundwater monitoring sites and 157 CSG production wells. The primary objective of this network is to provide background hydrogeochemical characterisation of aquifers and to use hydrochemistry to identify connectivity between the reservoirs and adjacent formations. OGIA will continue to use this data for assessing changes in water quality.

## 3 Assessment of impacts to irrigation land

### 3.1 Introduction

Depressurisation associated with CSG water extraction may result in compaction within reservoirs. Depending upon the magnitude of the change in groundwater pressure, and the thickness and type of formations overlying the reservoir, there is the potential for subsidence at the land surface.

The UWIR 2019 includes an assessment of subsidence on environmental values. In accordance with Condition 3 and further work by OGIA since the UWIR 2019, the following additional components to that assessment are provided in this section:

- Updated risk assessment based on the refined risk assessment methodology and additional information on the potential consequences of subsidence to irrigation land in the Condamine Alluvium.
- The subsidence assessment presented in terms of three timeslots: current impacts (prior to UWIR 2019); short-term (the next three years from the UWIR 2019); and long-term.
- A summary of a range of subsidence monitoring activities (on-ground and satellite) being undertaken by industry to meet Queensland and Australian government conditions of approval.

In parallel with this technical assessment, OGIA collaborated with the GasFields Commission Queensland to hold a workshop in November 2020 with irrigators in the western Condamine Alluvium. The purpose of the workshop was to further understand the potential consequences of subsidence on dryland, furrow and overhead irrigation practices. OGIA will continue to engage with the community during the preparation of the UWIR 2021.

#### 3.1.1 Nomenclature

Several terms are used to discuss the methodology and results in this response. The following are the key terms and definitions:

- *Compaction* – the compression of sediments in the subsurface. In the case of this assessment, compaction relates to the compression of coal portions of the Walloon Coal Measures in response to depressurisation.
- *Subsidence* – a general term for downward movements of the ground surface.
- *Surface movement, deformation, ground motion or ground movement* – the vertical movement of the ground surface, including both uplift and subsidence.

#### 3.1.2 Mechanism for CSG-induced subsidence

As stated in the UWIR 2019, depressurisation associated with CSG water extraction may result in reservoir **compaction**. This has the potential to cause some **subsidence** at the land surface. The potential for subsidence to occur is influenced by two primary factors: the magnitude of change in groundwater level; and the thickness and type of formations overlying the reservoir. Where consolidated sandstone formations are located above the reservoir, these are likely to attenuate impacts, as the strength of these consolidated formations is likely to result in a 'bridging effect' and reduce the degree to which compaction at depth in the coal measures manifests as subsidence at the



ground surface. Therefore, compaction within the CSG formations represents upper limits of estimates of potential subsidence at the surface.

It is to be noted that changes in ground level are caused by a combination of influences on the ground surface, including both natural and human-induced motion (Masoudian et al. 2019). In the context of the Surat Basin, natural influences on the ground motion signal may include tectonic and seismic action and shrinking or swelling of high clay-content soils due to changes in saturation; human-induced ground motion may include development such as depressurisation from groundwater extraction in the alluvium from irrigation and/or CSG development, as well as farming and land management practice (e.g. irrigation, tillage and land contouring).

### 3.1.3 Irrigation land in the Condamine Alluvium

Within the footprint of predicted impacts in the Surat CMA, the primary area of irrigation land is within the Condamine Alluvium and tributaries. Irrigation land in this area is characterised by very low gradients, with soils dominated by black or grey vertisols ('cracking clays'), which have very high moisture-holding capacity. Following rainfall or irrigation, water enters the soil through large, vertical shrinkage cracks; it then sorbs into the soil matrix, displacing air from the root zone and causing waterlogging that may persist for several days unless the excess water is drained. Soil profiles in the Condamine have the capacity to expand and contract by up to 20 per cent in the upper soil profile. Within this area, irrigated crops include cotton, sorghum, maize, soybean, sunflower, barley, oats, wheat, canary grass and lucerne (SunWater 2019).

## 3.2 Subsidence assessment in the UWIR 2019

Consistent with the DES guideline on UWIRs and final reports (Department of Environment and Science 2017), the UWIR 2019 used a risk-based approach for assessing impacts from subsidence. The method involved establishing the likelihood of subsidence occurring using two risk factors: an estimate of compaction within the reservoir (the Walloon Coal Measures); and the presence or absence of overlying consolidated sandstone formations that may attenuate any potential impacts to the surface. The compaction estimates were based on a one-dimensional assessment.

The assessment resulted in identifying footprints for three risk classes:

- *Low risk* where predicted compaction is -
  - less than 0.1 metres in the Walloon Coal Measures and no consolidated formation above, or
  - between 0.1 and 0.2 metres in the Walloon Coal Measures and presence of a consolidated formation above
- *Medium risk* where predicted compaction is -
  - between 0.1 and 0.2 metres in the Walloon Coal Measures and no consolidated formation above, or
  - greater than 0.2 metres in the Walloon Coal Measures and presence of a consolidated formation above
- *High risk* where predicted compaction is -
  - greater than 0.2 metres in the Walloon Coal Measures and no overlying consolidated formation.

At the time of the UWIR 2019, there was insufficient data and understanding to assess the resilience or susceptibility of those environmental values to subsidence, i.e. to assess the consequence of the predicted impacts from subsidence.

### 3.3 Update to risk assessment

#### 3.3.1 Refinement of risk assessment approach

Since the UWIR 2019, landholders have raised – primarily through the Gasfields Commission Queensland (GFCQ) – issues in relation to subsidence and its consequences for irrigation land in the Condamine Alluvium. In response, GFCQ recently organised, with OGIA and the University of Queensland (UQ), multiple landholder information sessions on the matter. OGIA has also been engaging with landholders directly to seek more clarity on the issues being raised and to better understand the consequences of ground movement on farming systems more broadly.

Following these engagements, OGIA has identified three components in relation to assessing risk of CSG-induced subsidence:

- **Predictions** of subsidence – based on industry development plans and water pressure decline predictions by OGIA
- Establishing **consequences** – to assess overall risk of subsidence
- **Monitoring** – establishment of baseline data and unpacking of monitored ground movement for potential CSG-induced subsidence.

A range of other related issues have also emerged in relation to management of identified risks and establishing associated statutory responsibilities of tenure holders. These issues are outside OGIA's scope of work and are not discussed further in this section.

In relation to the predictions, OGIA is currently in the process of refining the method for a more sophisticated prediction of CSG-induced subsidence in preparing the UWIR 2021. OGIA organised a workshop with landholders to seek data and information on the consequences of land movement on dryland, furrow and overhead irrigation practices. A similar workshop is also planned for early 2021 on monitoring techniques and results from the measurement of ground movement in the Surat CMA.

The data and information on various elements of the above three components are being collected and compiled by OGIA and other organisations for further analysis that will support assessment for the UWIR 2021. In the interim, OGIA has refined the risk assessment approach as presented below. The refinements include the following:

- The assessment of consequences through integrating predicted changes to slope and aspect in irrigation land. The magnitude of these two elements was highlighted by landholders as important in terms of understanding potential consequences.
- Assessment of predicted impacts for three time periods as required under Condition 3:
  - past (prior to the UWIR 2019)
  - short-term (three years from the UWIR 2019)
  - long-term (maximum impacts any time in future).

For the purposes of this response, compaction, change in slope and aspect are considered across the three statutory timeframes for the 'likelihood' component of the risk assessment. Outputs are

presented as sub-regional-scale irrigation areas. The outputs are also made available to DES as a spatial dataset.

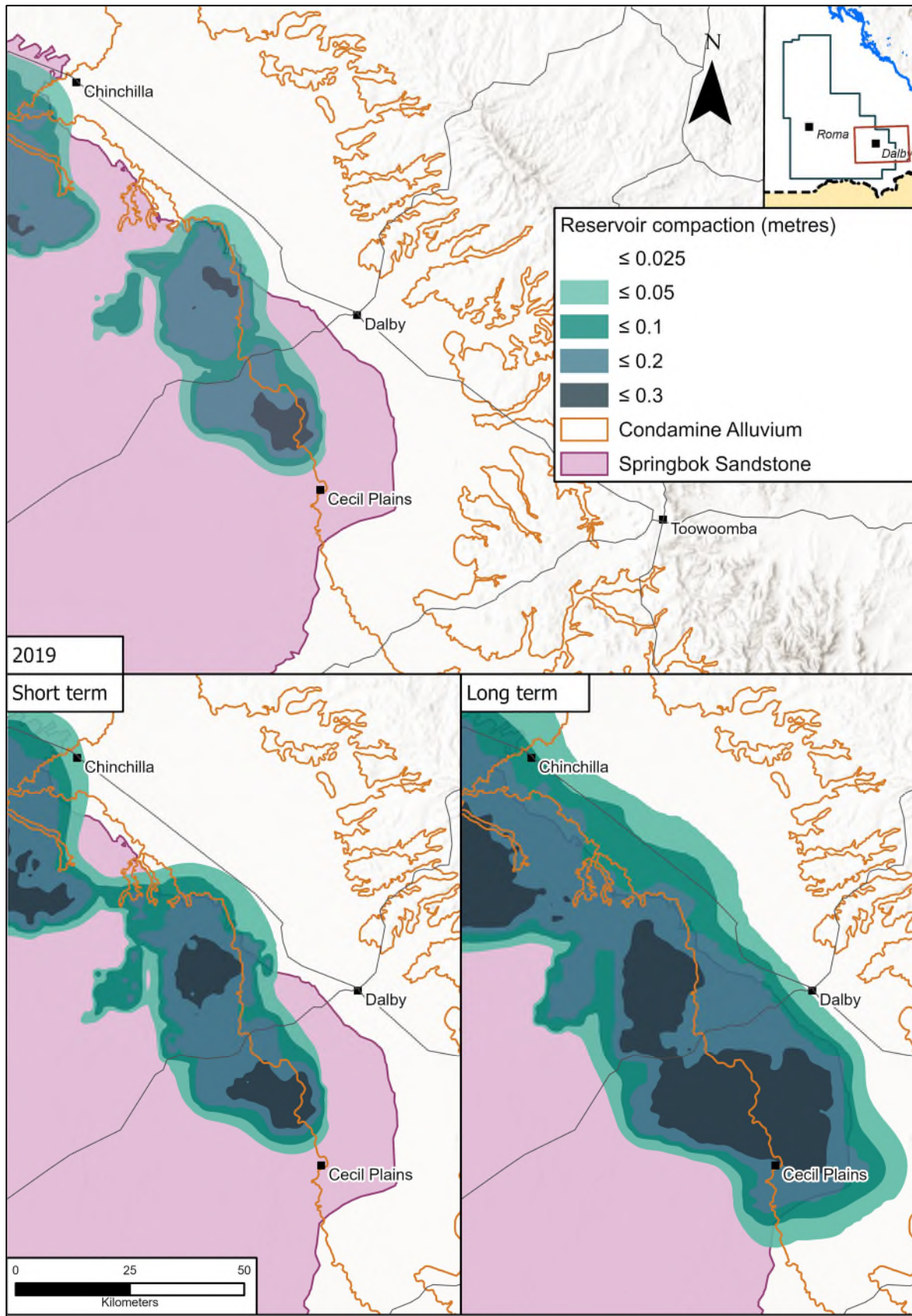
### 3.3.2 Likelihood

As discussed in section 3.2, the UWIR 2019 assessed the likelihood of subsidence through the use of an estimate of compaction and the presence or absence of overlying consolidated sandstone formations that may attenuate potential impacts to the surface. While more sophisticated approaches are being developed for the UWIR 2021, the same approach is applied in this response.

As presented in the UWIR 2019, compaction within the Walloon Coal Measures is an upper estimate of potential subsidence at the surface because the estimate of reservoir compaction is likely to be higher than the subsidence experienced at the surface. A summary of the methodology used to estimate compaction is provided in Appendix B.

Compaction estimates across the three time periods are shown in Figure 3-1. A summary of the key observations from these results are as follows:

- As expected, the pattern of predicted compaction reflects the drawdown predictions in the Walloon Coal Measures. Maximum compaction is predominantly outside the western margin of the Condamine Alluvium, except north–northwest of Cecil Plains.
- More importantly, the maximum compaction areas within the Condamine Alluvium footprint are also overlain by the Springbok Sandstone, which is a competent overburden and will attenuate the vertical propagation of compaction to surface. Any surface subsidence that may be caused by compaction at depth is likely to be significantly less than estimated compaction.
- Predicted compaction advances to a maximum of around 0.3 m in 2045 within the reservoir under the Condamine Alluvium. As expected, the pattern of predicted compaction reflects the drawdown predictions in the Walloon Coal Measures.
- In the past and in the short term (three years), the dominant area of compaction is constrained to an area north of Cecil Plains. In the longer term, the area of compaction expands to the east and north between Cecil Plains and Dalby.



**Figure 3-1 Predictions of reservoir compaction prior to the UWIR 2019, in the short term and in the long term**

### 3.3.3 Consequence

There have been few studies in coal seam gasfields on surface subsidence and its impact on surface infrastructure and the environment (Wu, Jia & Wu 2019). To better understand the potential consequences of subsidence in the Surat CMA, OGIA held a workshop in November 2020 with irrigators in the western Condamine Alluvium.

Across the group of stakeholders, there were varied perspectives on the potential for impacts from subsidence, but identified two important considerations – **changes to land slope; and aspect** i.e. changes in the direction of surface water flow – as summarised in the following sub-sections. Further details on the key outcomes from the workshop are provided in Appendix B.

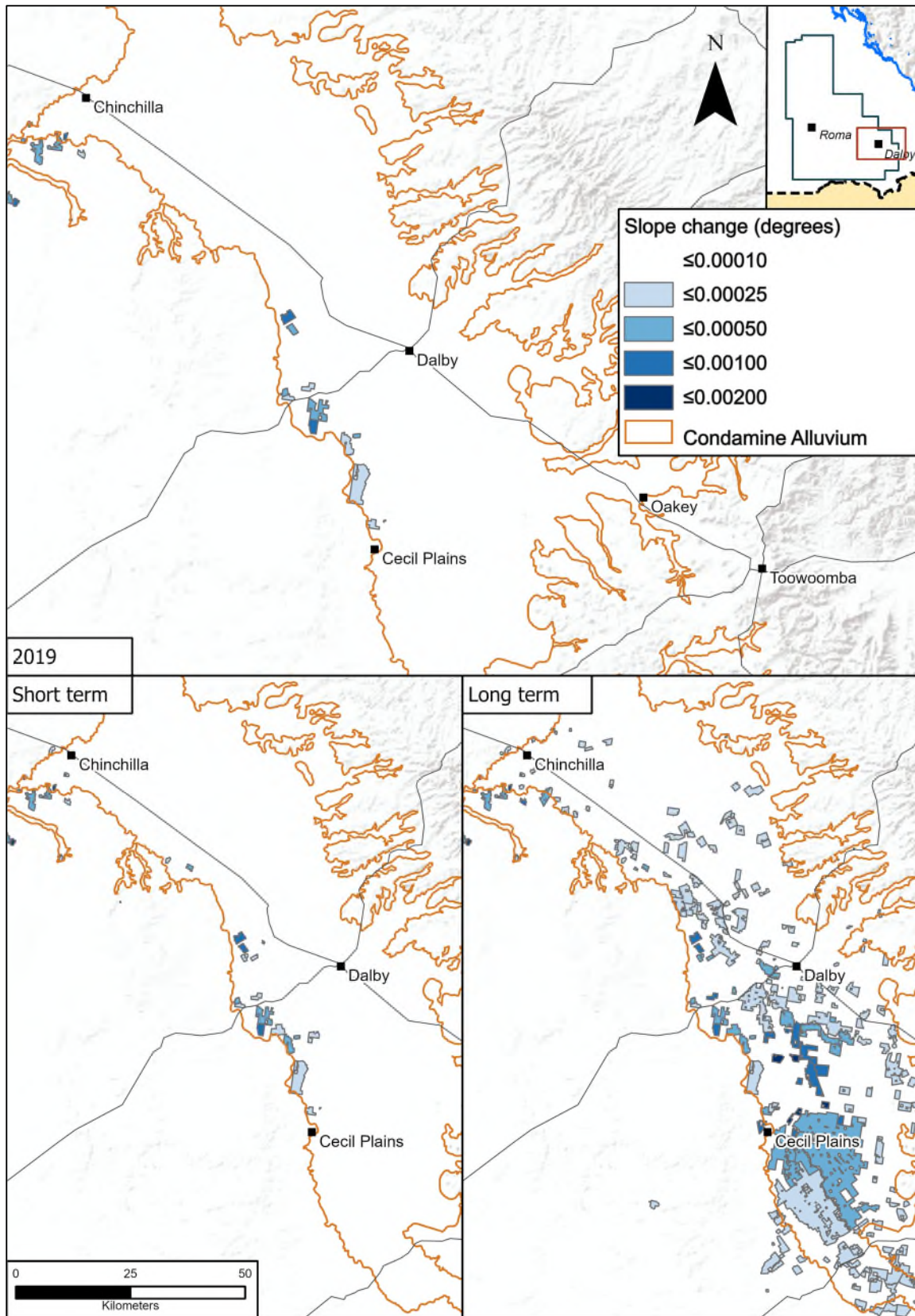
In relation to irrigation land, the areas most susceptible to subsidence are those farms with very low initial surface gradients. Subsidence has the potential to affect irrigation through modification of the surface slope. A change in slope may change the velocity and direction of water flow, resulting in prolonged inundation (waterlogging), erosive flooding or sediment deposition.

Using the estimate of compaction, OGIA has further estimated change in slope and aspect to assess potential consequences on irrigation land at the spatial scale of 30x30 m. Given the available resolution for surface elevation and predictions of impact in the Walloon Coal Measures, these derived products are indicative and used only to support the identification of high and low risk areas. A summary of the methodology used to estimate slope and aspect is provided in Appendix B.

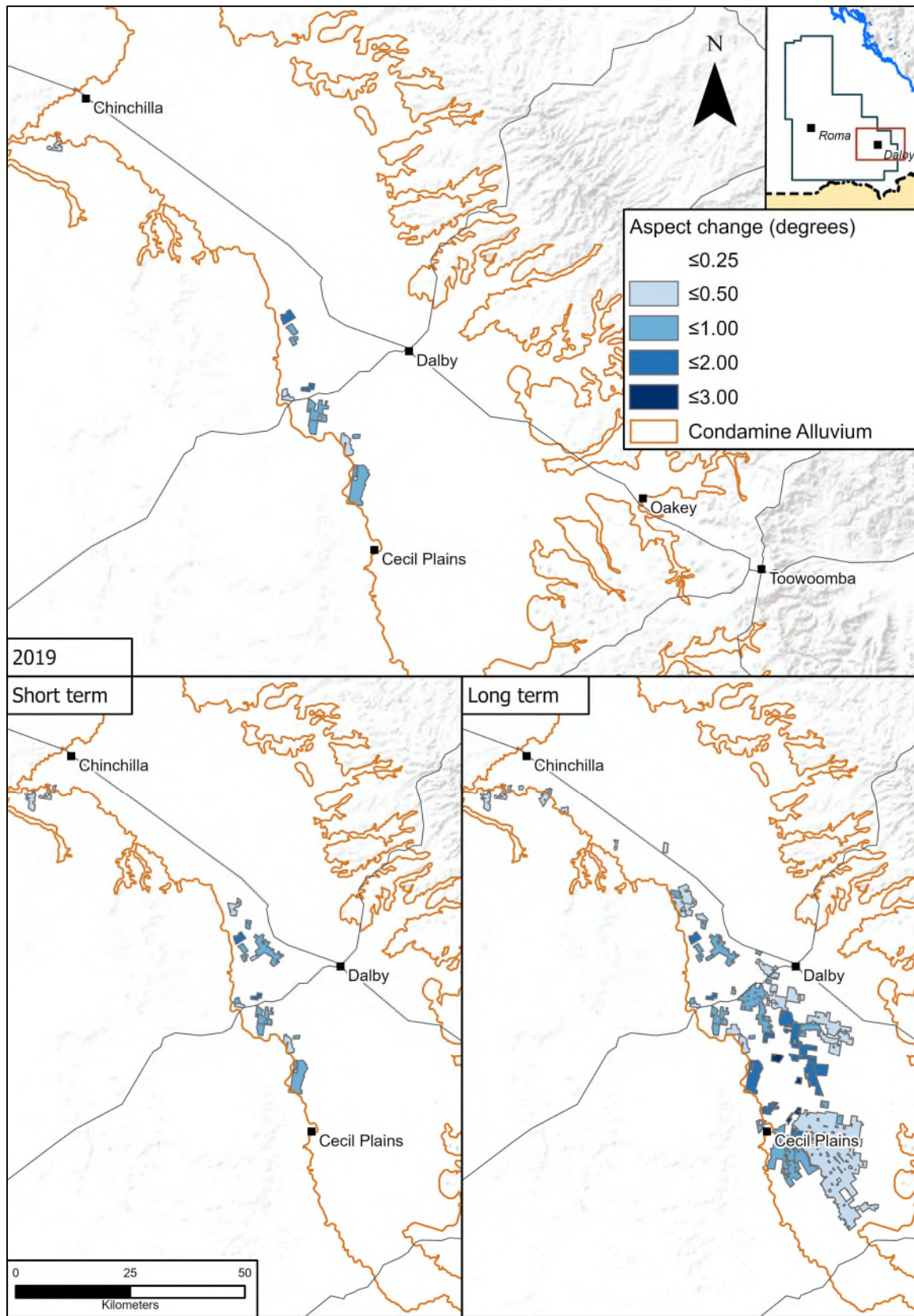
Slope and aspect estimates across the three time periods are shown in Figure 3-2 and Figure 3-3. These figures also show the distribution of irrigation land. Key observations from those results include the following:

- In the period prior to the UWIR 2019, and in the short term, the maximum predicted change in slope within irrigation areas is about 0.002 degrees. This is equivalent to a change of approximately 3.5 millimetres over a 1-km-long paddock. The majority of these occur along the western fringe of the Condamine Alluvium between Cecil Plains and Dalby.
- Similarly, the change in aspect prior to 2019, and in the short-term, is limited to irrigation areas on the western margins of the Condamine Alluvium. The maximum predicted change in aspect during this period is 1.1 degrees.
- Over the longer term, irrigation areas of aspect changes are predicted to occur on the western margins of the Condamine Alluvium between Cecil Plains and Dalby. The maximum predicted change in aspect is less than 3 degrees, with a mean change across irrigation lands of around 0.2 degrees.
- Again, similar to compaction, in most of the areas where maximum change in slope and aspect is estimated, there is overlying competent Springbok Sandstone which would further reduce the likelihood of change at the land surface.





**Figure 3-2 Estimates of mean change in slope prior to the UWIR 2019, in the short and in the long term**



**Figure 3-3 Estimates of changes in aspect and surface flow directions prior to the UWIR 2019, in the short and in the long term**



## 3.4 Monitoring ground motion

As part of project approval conditions, tenure holders are required to monitor and assess changes in ground motion in relation to specified triggers. Monitoring is undertaken at two scales – regional and tenement. The following section provides a brief summary of monitoring underway in the Surat CMA. Data and findings from these assessments will be integrated into the assessment of subsidence for the UWIR 2021.

As stated previously, ground movement is caused by a combination of factors such as the tectonic and seismic action, shrinking or swelling of high clay-content soils due to changes in saturation, groundwater development and compaction from CSG depressurisation. In these circumstances, there is no direct way of measuring or monitoring CSG-induced surface subsidence. Monitoring provides ground movement measurement over time. This then has to be unpacked using various interpretation techniques to separate out signals from CSG-induced depressurisation.

### 3.4.1 Regional

At a regional scale, the following monitoring is currently underway:

- Remote sensing of ground motion is monitored using Interferometric Synthetic Aperture Radar (InSAR) technology. An initial baseline survey was completed in 2011. Subsequent captures occurred in 2012-2014 and 2015-2017. Industry is working with UQ to analyse and understand observed changes.
- Geoscience Australia, Origin Energy and QGC have established a network of geodetic markers. Around 140 locations are established with additional locations currently under construction by other tenure holders. The locations of points in the vicinity of the Condamine Alluvium are shown in Figure 3-4.

In general terms, the difference between measurements within a time series indicates ground motion. As discussed in section 3.1.2, further evaluation of the potential influences on ground motion is then necessary to determine a CSG impact from other influences.

### 3.4.2 Local

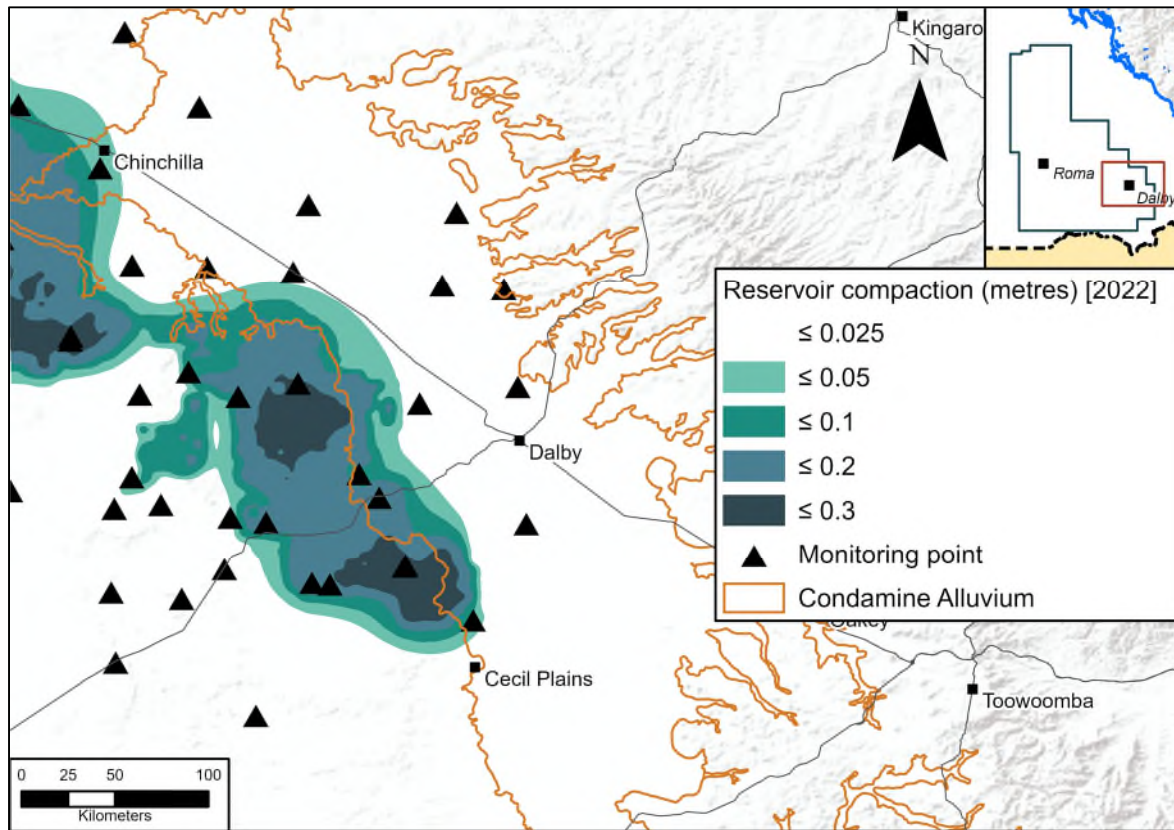
At a more local tenement scale, a range of monitoring methods are currently applied. A summary of the main approaches is as follows:

- Tiltmeters – these measure oblique ground movement and are designed to accurately measure inclination at the millimetre scale.
- Extensometer – subsurface geotechnical devices used to measure small changes across the length over which they are anchored. By measuring the change in length of the formation, the extensometer will directly measure the amount of compression/compaction that has occurred within the measured unit.
- Light Detection and Ranging (LiDAR) – within cropping lands, in a similar way to how InSAR is being applied, some tenure holders are using multiple LiDAR captures to assess ground motion at a farm and paddock scale.

### 3.4.3 Next steps

OGIA is required to assess the potential for impacts resulting from subsidence on environmental values for the UWIR 2021. From this point, OGIA will collate the necessary ground-based monitoring

data from industry and work in collaboration with other organisation, such as UQ and Geoscience Australia, in relation to remotely acquired data (InSAR), general monitoring and analysis. This will support a more comprehensive picture of surface motion trends and potential subsidence. In parallel, OGIA is planning additional workshops with stakeholders in the Condamine Alluvium to develop a common understanding on monitoring, and to further refine consequence for the risk assessment to be presented in the UWIR 2021.



**Figure 3-4 Locations of ground motion monitoring infrastructure**

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## Appendix A

**Table A-1 Hydrochemistry summary for aquifers in the Surat CMA (prior to 2005)**

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Alluvium	1	2,214	1,010	46	37	219	1	402	273	31	0.23	1.72	6
	2	36	2,630	59	78	711	3	799	896	82	1.04	1.42	20
	3	234	3,733	109	129	1,052	2	491	1,791	159	0.40	0.92	18
	4	51	7,941	279	392	2,099	3	401	4,397	371	0.33	0.75	20
	5	9	16,686	950	839	3,950	3	1,136	9,199	609	0.25	0.66	23
Main Range Volcanics	1	1,630	861	59	63	117	2	357	248	15	0.20	1.13	4
	2	3	2,321	29	47	675	6	800	733	31	0.88	2.26	37
	3	20	3,413	214	216	689	5	376	1,765	149	0.41	0.64	10
	4	2	7,383	776	830	635	0	776	4,070	296	0.58	0.24	4
	5	1	26,581	830	760	8,100	56	285	15,000	1,550	0.30	0.83	49
Upper Cretaceous formations	1	25	1,022	19	12	294	2	388	252	54	0.34	2.89	15
	2	5	2,798	57	48	789	7	949	802	146	0.22	1.55	19
	3	11	3,991	103	67	1,285	7	361	1,969	198	0.31	1.02	25
	4	21	8,835	418	256	2,518	27	168	4,844	602	0.24	0.81	26
	5	32	21,180	1,042	861	5,624	54	203	11,649	1,746	0.36	0.75	31
Wallumbilla Formation	1	16	1,408	11	10	416	3	670	272	24	1.04	3.73	46
	2	1	1,907	3	0	537	0	1,287	75	0	5.00	11.04	84
	4	3	11,252	457	398	3,114	18	122	5,590	1,552	0.14	0.87	28
	5	6	21,408	1,112	774	5,825	28	136	12,170	1,364	0.20	0.74	33

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Bungil Formation	1	58	1,584	15	6	481	1	737	329	15	1.39	3.52	61
	2	23	1,977	4	2	594	1	1,081	287	4	2.65	6.75	76
	3	15	3,675	77	15	1,284	3	241	1,872	183	0.55	1.08	43
	4	3	9,306	259	267	2,770	14	438	4,987	571	0.60	0.87	33
	5	3	21,380	1,444	558	5,853	20	114	12,449	941	0.21	0.75	34
Mooga Sandstone	1	140	1,451	9	3	443	1	719	251	24	1.37	3.93	60
	2	30	1,890	3	1	555	1	1,151	173	2	3.01	6.59	74
	3	12	4,176	106	104	1,299	1	207	2,028	431	0.15	1.02	46
	4	6	8,229	366	228	2,381	1	168	4,375	711	0.43	0.91	41
	5	2	27,974	1,890	1,030	7,282	0	14	17,053	704	1.10	0.63	32
Orallo Formation	1	95	1,199	7	2	361	1	618	185	24	1.16	5.41	51
	2	24	1,829	2	1	533	2	1,138	145	4	3.89	7.83	84
	3	10	3,133	67	20	1,067	2	345	1,547	85	0.37	1.07	37
	4	8	9,075	333	157	2,885	6	193	4,942	559	0.22	0.92	53
	5	3	18,371	883	559	5,189	24	325	10,300	1,089	0.56	0.80	35
Gubberamunda Sandstone	1	93	1,151	13	4	338	2	577	189	28	0.64	3.97	48
	2	7	1,958	3	1	574	1	1,194	179	2	2.91	6.52	81
	3	2	5,005	85	121	1,614	0	304	2,497	384	0.65	1.00	27
	4	2	9,419	534	116	2,840	11	172	5,100	645	0.55	0.85	29
Westbourne Formation	1	11	674	12	4	199	3	272	158	26	0.35	3.15	24
	4	4	10,737	376	151	3,493	26	107	6,325	259	0.65	0.85	39
	5	1	13,890	370	340	4,450	28	59	8,600	42	0.70	0.80	40
Springbok Sandstone	1	38	1,324	28	15	405	4	347	505	21	0.46	1.63	23

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
	2	2	2,837	30	14	884	0	1,114	786	7	2.05	2.05	59
	3	11	3,861	164	101	1,120	4	282	2,136	54	0.37	0.85	24
	4	7	6,900	156	84	2,364	1	286	3,947	61	0.42	0.92	48
Walloon Coal Measures, non-CSG	1	322	1,247	45	34	314	2	445	381	26	0.36	1.70	15
	2	38	2,894	23	18	899	1	1,178	742	30	2.13	2.42	68
	3	87	4,210	80	58	1,393	4	499	2,102	72	0.68	1.02	53
	4	65	8,434	197	146	2,813	9	352	4,764	154	0.54	0.92	57
	5	12	16,391	659	500	4,850	13	262	9,775	332	0.32	0.76	69
Walloon Coal Measures, CSG	2	3	3,831	4	2	1,397	5	1,340	1,083	1	0.05	1.99	148
	3	10	4,449	10	4	1,630	8	811	1,985	1	0.83	1.29	112
	4	8	6,885	55	20	2,489	13	388	3,915	5	0.79	0.99	83
Hutton Sandstone	1	532	1,197	50	39	288	3	399	397	22	0.38	1.54	15
	2	25	2,784	77	116	666	2	995	880	47	1.16	1.97	39
	3	88	3,769	162	160	975	6	422	1,927	117	0.41	0.81	22
	4	23	7,981	218	283	2,360	6	543	4,377	193	0.60	0.84	32
	5	1	15,327	209	273	5,370	0	160	9,121	195	0.01	0.91	57
Evergreen Formation	1	95	615	29	14	144	3	260	151	14	0.45	3.27	10
	2	2	3,620	111	96	810	15	2,031	534	23	0.75	4.22	16
	3	5	3,856	250	216	827	3	453	2,003	103	0.25	0.66	10
	4	5	9,741	810	178	2,583	1	330	5,521	318	0.53	0.72	25
	5	1	14,684	461	491	4,443	0	132	8,353	805	0.01	0.82	34
Precipice Sandstone	1	111	227	7	2	58	2	117	39	2	0.25	5.31	7
Moolayember Formation	1	40	1,068	30	29	284	5	337	360	23	0.49	1.62	13

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
	3	8	4,843	123	115	1,532	3	428	2,614	28	0.31	0.92	26
	4	6	7,740	231	159	2,475	4	356	4,413	102	0.33	0.86	34
	5	1	14,195	600	690	3,964	0	238	8,680	22	0.50	0.70	26
Clematis Sandstone	1	147	497	24	20	80	11	290	61	10	0.17	2.21	3
Rewan Group	1	10	1,209	26	51	299	2	362	366	102	0.44	1.77	11
	2	1	2,762	85	115	630	6	870	750	305	0.50	1.29	10
	3	2	4,242	168	378	799	12	359	2,387	140	0.13	0.65	12
	4	7	8,032	359	188	2,484	6	179	4,803	13	0.26	0.81	29
	5	2	16,668	1,150	821	3,933	6	218	9,990	551	0.30	0.63	26
Undivided Permian Upper	1	14	1,407	60	52	292	3	667	302	31	0.36	1.78	7
	2	1	2,461	43	27	700	4	1,100	570	17	0.30	1.89	21
	3	1	3,988	99	42	1,300	2	290	2,250	5	0.30	0.89	27
	4	2	7,683	140	337	2,154	10	755	3,862	425	0.76	0.86	22
Bandanna Formation, non-CSG	1	7	1,050	37	40	221	2	545	185	20	0.28	4.20	7
	2	2	2,890	21	24	974	3	760	1,095	12	1.00	1.39	68
	4	2	6,556	395	176	1,851	0	135	3,980	21	0.35	0.72	20
Basement	1	11	1,456	93	69	308	5	275	642	64	0.42	0.97	7
	2	1	2,366	40	50	674	0	817	785	0	0.01	1.32	17
	3	6	4,458	213	122	1,226	21	386	2,247	243	0.43	0.84	19

**Notes:**

KCA-Class = K-means statistical cluster analysis class, TDS = total dissolved solids, Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO<sub>3</sub> = bicarbonate, Cl = chloride, SO<sub>4</sub> = sulphate, F = fluorite, SAR = sodium adsorption ratio.



Table A-2 Hydrochemistry summary for aquifers in the Surat CMA (2005 to 2018)

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Alluvium (Condamine)	1	338	999	44	36	224	2	381	274	38	0.16	1.69	6
	2	6	2,779	23	109	787	2	728	984	147	0.19	1.23	16
	3	29	3,773	191	154	925	4	474	1,850	174	0.39	0.79	13
	4	38	8,949	651	417	2,026	6	494	5,121	233	0.83	0.63	17
	5	3	15,368	835	945	3,533	6	301	8,860	887	0.77	0.62	20
Main Range Volcanics	1	89	821	57	54	122	2	343	227	16	0.25	1.42	7
	2	1	3,094	33	4	980	25	950	1,100	1	0.80	1.37	43
	3	1	4,477	436	520	418	9	788	2,220	86	0.02	0.29	3
	4	2	9,881	354	560	2,515	6	627	5,445	375	0.40	0.72	19
Upper Cretaceous formations	1	1	507	7	5	140	7	244	80	24	0.46	2.70	10
	3	1	3,592	100	71	1,100	16	413	1,640	252	0.40	1.03	20
	4	5	9,776	296	271	2,888	34	507	5,092	689	0.28	0.89	29
	5	2	17,694	720	747	4,775	14	251	10,250	938	0.08	0.72	30
Wallumbilla Formation	1	4	1,677	3	1	545	2	746	365	13	2.83	3.02	71
	5	1	17,471	507	1,160	3,680	16	228	7,930	3,950	0.01	0.72	20
Bungil Formation	1	28	1,549	14	5	509	3	569	409	39	0.37	3.74	47
	2	2	1,844	2	1	522	2	1,219	96	1	2.75	8.45	88
	3	10	3,260	35	11	1,183	4	283	1,720	23	0.20	1.07	50
Mooga Sandstone	1	71	1,454	13	6	469	3	544	361	57	0.74	2.86	49
	2	1	2,740	22	12	880	6	500	1,100	220	0.10	1.23	37
	3	7	3,835	143	69	1,172	12	199	1,667	572	0.14	1.08	25

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Orallo Formation	1	50	1,227	12	3	397	2	474	291	47	0.35	2.75	44
	2	2	2,158	7	7	719	3	935	482	5	2.15	4.07	63
	3	1	4,007	95	36	1,420	11	107	2,150	188	0.10	1.02	31
	4	2	8,558	134	161	2,795	16	463	4,465	525	0.05	0.97	40
Gubberamunda Sandstone	1	243	1,026	8	3	327	3	455	205	24	0.36	3.33	41
	2	12	2,578	19	10	869	6	744	870	59	0.18	1.76	45
	3	7	3,394	19	9	1,253	6	368	1,724	15	0.31	1.15	75
	4	2	7,904	282	64	2,680	26	202	4,650	1	0.13	0.93	45
	5	1	14,505	360	330	5,000	35	220	8,300	260	0.10	0.93	46
Westbourne Formation	1	13	1,421	12	4	479	2	413	480	29	1.88	1.89	50
	4	1	12,138	163	50	4,460	18	444	6,840	163	0.20	1.01	78
	5	8	17,331	456	373	5,456	30	444	9,910	661	0.10	0.85	46
Springbok Sandstone	1	113	1,618	13	6	531	13	512	506	36	1.50	2.48	66
	2	16	2,501	5	1	890	4	777	821	1	2.23	1.87	99
	3	46	3,832	45	12	1,372	7	278	2,095	22	1.02	1.04	75
	4	11	8,139	212	103	2,737	16	183	4,809	78	0.55	0.88	54
	5	6	19,163	317	395	6,082	438	283	11,195	454	0.23	0.83	61
Walloon Coal Measures, non-CSG	1	37	1,171	34	24	315	11	372	380	34	0.57	1.57	21
	2	23	2,732	4	2	897	9	1,148	667	2	2.66	2.98	100
	3	17	4,387	25	13	1,545	8	885	1,896	14	1.47	1.31	97
	4	14	8,863	314	155	2,784	13	276	5,152	169	0.74	0.85	63
	5	9	16,729	476	525	5,077	26	256	10,223	146	0.23	0.76	41

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Walloon Coal Measures, CSG	1	207	1,612	3	0	536	12	609	442	6	3.05	2.56	88
	2	3,109	3,049	5	1	997	11	1,389	640	4	3.16	2.85	114
	3	1,577	4,838	12	4	1,701	19	1,118	1,980	3	1.69	1.37	116
	4	592	7,431	36	11	2,641	36	803	3,903	1	1.26	1.06	108
	5	18	17,036	255	90	5,891	454	302	10,034	10	0.66	0.91	91
Hutton Sandstone	1	166	994	16	4	308	8	372	263	21	0.84	2.60	33
	2	65	2,527	4	1	798	16	1,289	399	14	5.63	4.12	108
	3	8	3,169	43	6	1,152	10	401	1,505	52	0.52	1.19	55
	4	1	7,146	170	8	2,520	7	53	4,360	28	0.10	0.89	51
	5	1	23,728	345	473	7,700	79	741	14,000	390	0.24	0.85	63
Evergreen Formation	1	18	921	69	35	185	6	231	361	34	0.18	1.40	7
	2	6	2,279	5	1	717	8	1,253	292	1	2.42	4.10	124
	3	1	4,782	16	6	1,680	7	819	2,250	1	3.40	1.15	91
Precipice Sandstone	1	121	265	5	2	72	7	139	35	4	0.41	4.19	10
	2	13	2,727	9	3	781	38	1,661	222	8	4.62	6.22	62
	3	6	6,209	104	46	1,892	190	2,084	1,800	94	0.40	1.63	39
Moolayember Formation	1	1	157	1	0	43	2	100	10	1	0.50	6.63	12
Clematis Sandstone	1	35	563	33	29	82	11	345	49	15	0.25	2.69	3
Bandanna Formation, non-CSG	1	8	1,204	2	1	371	1	743	83	1	1.60	11.42	53
	2	5	2,722	5	1	913	2	1,036	761	1	2.60	1.85	100
	3	2	5,915	17	1	2,068	4	1,615	2,205	1	5.00	1.44	132
	1	138	1,381	2	0	435	4	797	132	9	1.93	8.30	141

Formations	KCA-Class	Number of samples	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO <sub>3</sub> (mg/L)	Cl (mg/L)	SO <sub>4</sub> (mg/L)	F (mg/L)	Na:Cl ratio	SAR
Bandanna Formation, CSG	2	180	2,813	3	1	933	12	1,241	614	5	3.65	3.07	145
	3	145	5,635	12	3	1,895	33	1,814	1,872	3	2.85	1.58	161
	4	64	10,312	18	5	3,542	43	2,495	4,204	3	2.05	1.32	207

**Notes:**

KCA-Class = K-means statistical cluster analysis class, TDS = total dissolved solids, Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO<sub>3</sub> = bicarbonate, Cl = chloride, SO<sub>4</sub> = sulphate, F = fluorite, SAR = sodium adsorption ratio.

## Appendix B

### B.1 Technical summary

The following sections provide a summary of the methodology for the calculation of compaction, slope and changes in aspect presented in section 3.3.

#### Reservoir compaction

Reservoir compaction was calculated utilising geomechanical rock properties and modelled drawdown for those formations which are depressurised for Coal Seam Gas production. For this calculation, the following information is integrated to provide an estimate of compaction:

- Lithological proportion of the Walloon Coal Measures were derived from downhole geophysical logs
- Rock elastic properties (Young's modulus) were calculated per lithology and applied to the Walloon Coal Measures layer thicknesses at each location to obtain a bulk Young's modulus
- Drawdown in the Walloon Coal Measures was extracted from the UWIR2019 groundwater model at each of the three statutory timeframes – prior to 2019, the short and long term.

#### Slope and aspect

Change to slope and aspect were calculated as follows:

- Compaction within the reservoir was calculated accounting for the elasticity of the coal measures and the pressure reduction within those layers
- A recalculated ground surface for each year is estimated by subtracting the compaction estimated for that year from a reference elevation (1-second digital elevation model (DEM) captured in the year 2000 at ~30x x 30 m resolution)
- For each year, a change in slope and aspect is calculated with reference to the baseline period.

The above approach applies a simple method to estimate the potential influence of compaction on surface movement and changes in slope. It is likely that, in some areas, baseline slope and aspect characteristics are not entirely represented through the use of the 1-second DEM. However, this approach was considered appropriate to identify areas of high and low risk.

### B.2 Workshop outcomes

There are limited studies on the impact of subsidence on surface infrastructure and the environment (Wu, Jia & Wu 2019). To better understand the potential consequences of subsidence in the Surat CMA, OGIA collaborated with the GasFields Commission Queensland to hold a workshop in November 2020 with irrigators in the western Condamine Alluvium.

Across the group of stakeholders, there were varied perspectives on the potential for impacts from subsidence. This most likely reflects the variance in site specific conditions, such as landscape position, soils, infrastructure and farming approaches on individual farms. The following is a summary of the observations from the workshop:

- *Farming systems* – in terms of perceived consequences of subsidence, there was minimal differentiation between farming systems (furrow, overhead and dryland).

- *Initial surface gradients* – farms located lower in the catchment typically have lower surface gradients and are therefore more susceptible to change in gradient. There was a consistent view that an understanding of background/baseline conditions is required.
- *Surface water flow directions* – depending upon the magnitude of change, there was a consistent view that increased velocity of surface flows resulted in erosion of the soil profile; redirection of surface flows may affect capture of overland flows; possible adverse impacts on pipes and the effectiveness of water distribution channels.
- *Crop yields* – the potential for lower crop yield due to uneven distribution of soil moisture and susceptibility of some crops (e.g. mung beans) to disease associated with waterlogging.
- *Farm maintenance* – there were concerns that subsidence would lead to increased costs due to the need for more frequent laser levelling; increased traffic resulting in soil compaction and lower crop yields; and disruption to the farming cycle because of greater time demands for managing the ground surface.

The workshop highlighted that the key information requirements for understanding the potential consequences of subsidence on cropping land are the degree and rate of changes to slope and changes in direction of surface flows.

**Appendix E – Assessment of Connectivity of the Condamine Alluvium with the  
Walloon Coal Measures (CSIRO, 2021)**



# Assessment of Connectivity of the Condamine Alluvium with the Walloon Coal Measures

An environmental tracer pilot study on two depth profiles using noble gases and conventional tracers to gain critical information on hydraulic connectivity

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St. John Herbert

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## Executive summary

Most of the current and planned development area of Walloon Coal Measures (WCM) underlying the central Condamine Alluvium (CA) are held by Arrow Energy. De-pressurization to produce coal seam gas (CSG) has generated public concerns about possible CSG fluxes from the WCM to the CA or fluxes of shallow groundwater from the alluvium to the WCM with the alluvium becoming depleted by the de-pressurization. While prior field studies and modelling by OGIA and Arrow Energy have shown that the potential risk from this is very low, Arrow Energy approached CSIRO to trial noble gas isotopes as a further tool in assessing this risk. This report about the Condamine Alluvium and the underlying Walloon Coal Measures is a first successful feasibility study in Australia using noble gases and their complete set of stable isotopes, in particular helium (He) and its isotopes  $^3\text{He}$  and  $^4\text{He}$ , conventional isotopes and hydrochemistry (multiple lines of evidence) to investigate inter-aquifer connectivity.

Two depth profiles consisting each of three to four nested bores covering sampling depths from the shallow CA down to the underlying WCM were investigated, in a multi-tracer study using hydrochemistry, a standard suite of environmental tracers ( $^2\text{H}$ ,  $^{18}\text{O}$ ,  $^3\text{H}$ ,  $^{13}\text{C}$ ,  $^{14}\text{C}$ ) and noble gases (He, Ne, Ar, Kr, Xe). The investigation aimed at qualitatively detecting possible groundwater fluxes between the shallow alluvium and the WCM, and the direction of such fluxes.

The findings of this pilot study demonstrate that one out of the two helium depth profiles (Lone Pine) can confirm the stagnant nature of groundwater within the WCM, quantifying vertical advective groundwater velocities as smaller than 1mm/year. These very small fluxes indicate a low hydraulic connectivity between WCM and CA, which agrees with independent assessments from pump tests, hydrochemistry, and geologic modelling. The other profile (Daandine) sampled transition zone and CA and indicated the dominance of horizontal flow. This study provides evidence for the need for optimizing sampling conditions and demonstrate the advantages of using multiple lines of evidence from hydrogeology, hydrochemistry, and the application of conventional tracers to confirm the noble gas findings. Better vertical resolution of each depth profile and samples from deeper within the WCM or the GAB formations below are desirable. Furthermore, the results are a snapshot in time. A continuous monitoring of higher resolution depth profiles in subsequent sampling campaigns is desirable to detect changes in vertical groundwater movement as manifested by changes in the vertical concentration patterns.

Now proof of concept has been achieved, should future studies be considered – either local or wider in scope, the following recommendations are made with respect to sampling programs:

- A total of ten to 15 discrete sampling depths per depth profile through the alluvial and GAB sequence;
- A lateral sample density consistent with the heterogeneity shown in initial sampling and the problem statement being assessed;
- A time series of sampling to detect changes in vertical groundwater movement as manifested by changes in the vertical concentration of Helium at a frequency required for the problem statement being assessed.



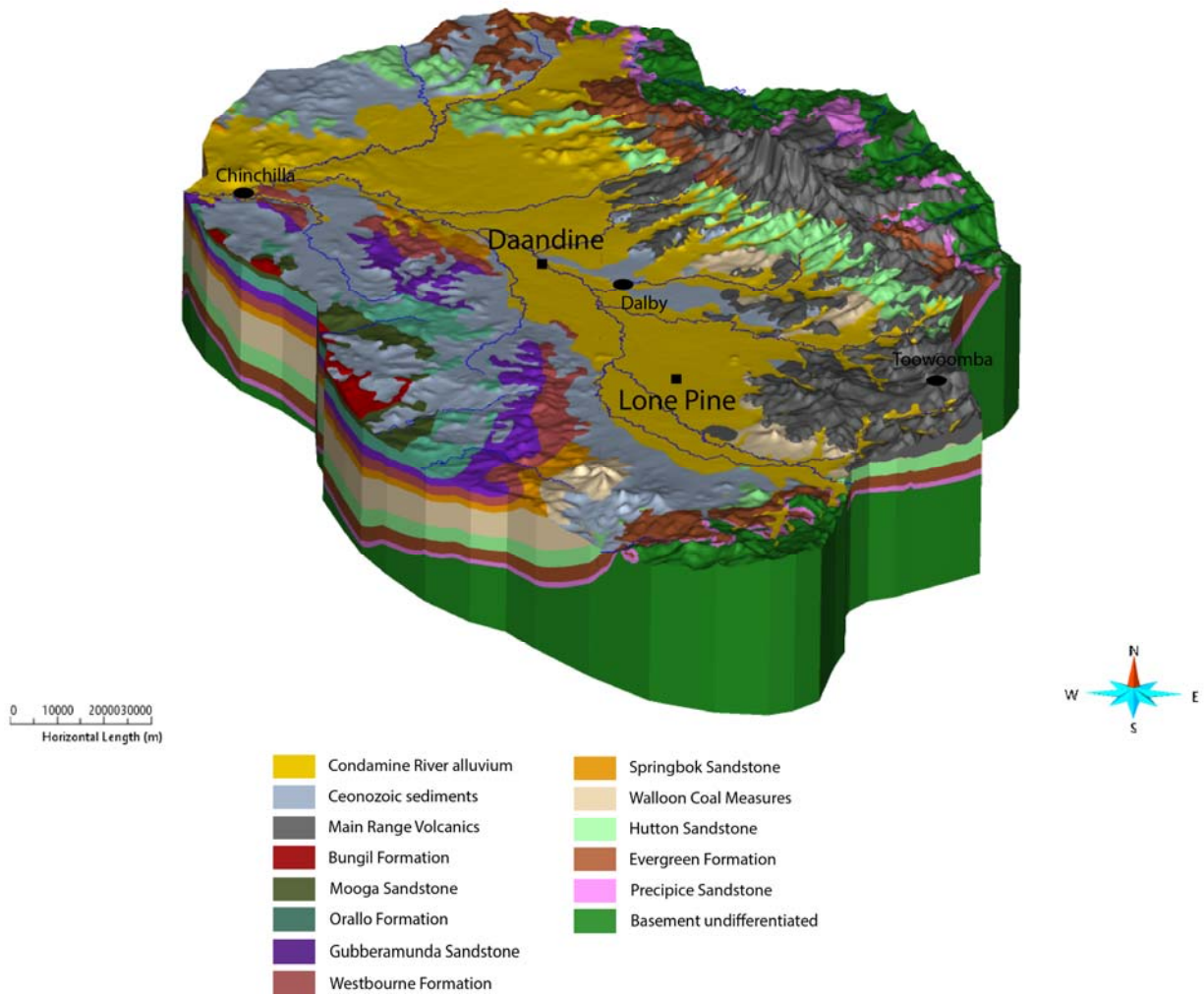
# 1 Introduction and hydrogeological setting

Arrow Energy requested CSIRO to undertake a pilot study into the use of helium (He) isotopes for gaining critical information on hydraulic connectivity of the Condamine Alluvium (CA) with the underlying Walloon Coal Measures (WCM) in their Surat Basin Coal Seam Gas production fields in Queensland. The work presented here summarises the results of a pilot study which involved two well nests in the centre of the Condamine Alluvium. A combination of several lines of evidence (sedimentology, 3D geological models, hydrochemistry, environmental tracers and noble gas isotopes) was applied to investigate, and if possible, quantify the magnitude of the vertical groundwater exchange (i.e. the advective groundwater velocity) between CA and WCM at these two depth profiles.

The two depth profiles are shown together with a three-dimensional geological model of the area in Figure 1. The two depth profiles which are investigated here are Daandine and Lone Pine. Each site consists of a well nest with different bores and screens targeting different sub-aquifers of the Condamine Alluvium and the underlying Walloon Coal Measures, with some bores also screened in the transition zone (Figure 2 & Figure 3). A detailed description of the hydrogeology and pump tests conducted on these two sites can be found in OGIA (2016). The horizontal distance between the two depth profiles is ca 56 km while the depth of the deepest screen is 85 m for Daandine and 136 m for Lone Pine. Also, the general hydrogeological setting of the two profiles is different (e.g. distance to the Condamine River, proximity to potential WCM recharge areas, etc.). Therefore, the two profiles need to be discussed separately and cannot be combined into one depth profile or aim to assess regional hydrological processes.

Figure 2 shows that screens in the Daandine profile, covering depths between 45 m and 85 m, are situated in the Condamine Alluvium and the transition zone, with only the deepest well (Daandine 164) truly screened in the Walloon Coal Measures. In contrast, the screens in the Lone Pine profile (Figure 3) cover depths between 82 m and 136 m and are situated in the transition zone and the Walloon Coal Measures. The Daandine profile therefore primarily assesses the alluvium and transition zone, whereas the Lone Pine profile assesses different depths in the WCM. Both profiles would benefit from more available screens, as a sampling resolution of only three (Lone Pine) or four depths (Daandine) is only just sufficient to assess vertical hydraulic connectivity using tracers. The optimum vertical resolution would consist of ten to 15 short screens at different depths between the groundwater table of the alluvium and the deepest part of the Walloon Coal Measures, and to sample also the formation underlying the WCM to quantify fluxes from below. Only this way the lower boundary condition can be well quantified and horizontal fluxes can be sufficiently separated from vertical ones.





**Figure 1 Three-dimensional hydrogeology model of the Condamine Alluvium.**  
 The two depth profiles investigated here, Daandine and Lone Pine, are situated ca. 50 km apart from each other in the centre of the Condamine River Alluvium.

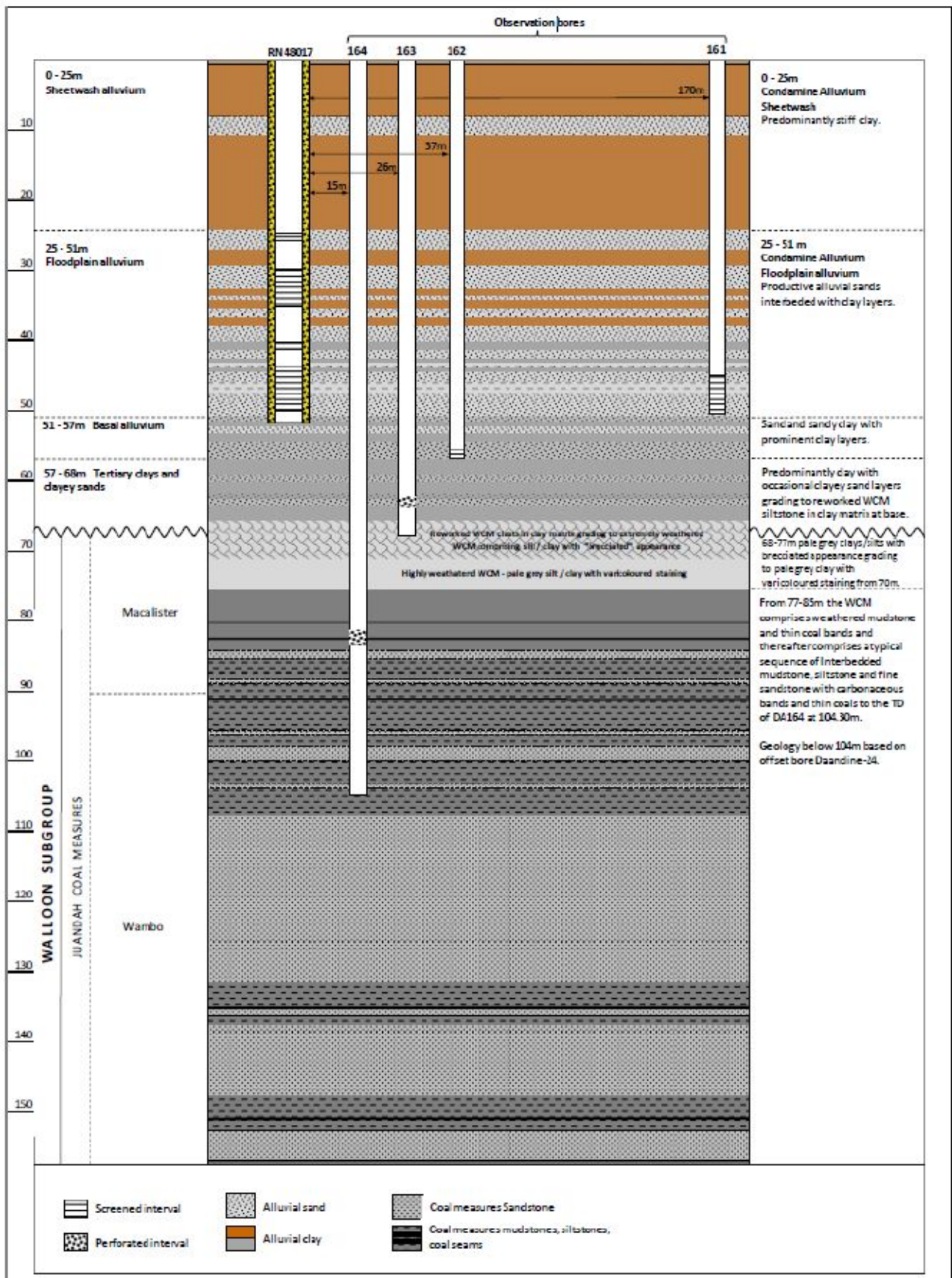


Figure 2 Screens at the Daandine well nest (from Jacobs (2015a), provided by Arrow Energy). Sampled wells here are D161, D162, D163, D164. The nearby observation bore RN48017 was not suitable to sample for environmental tracers since it had screens in various formations resulting in a mixed sample.



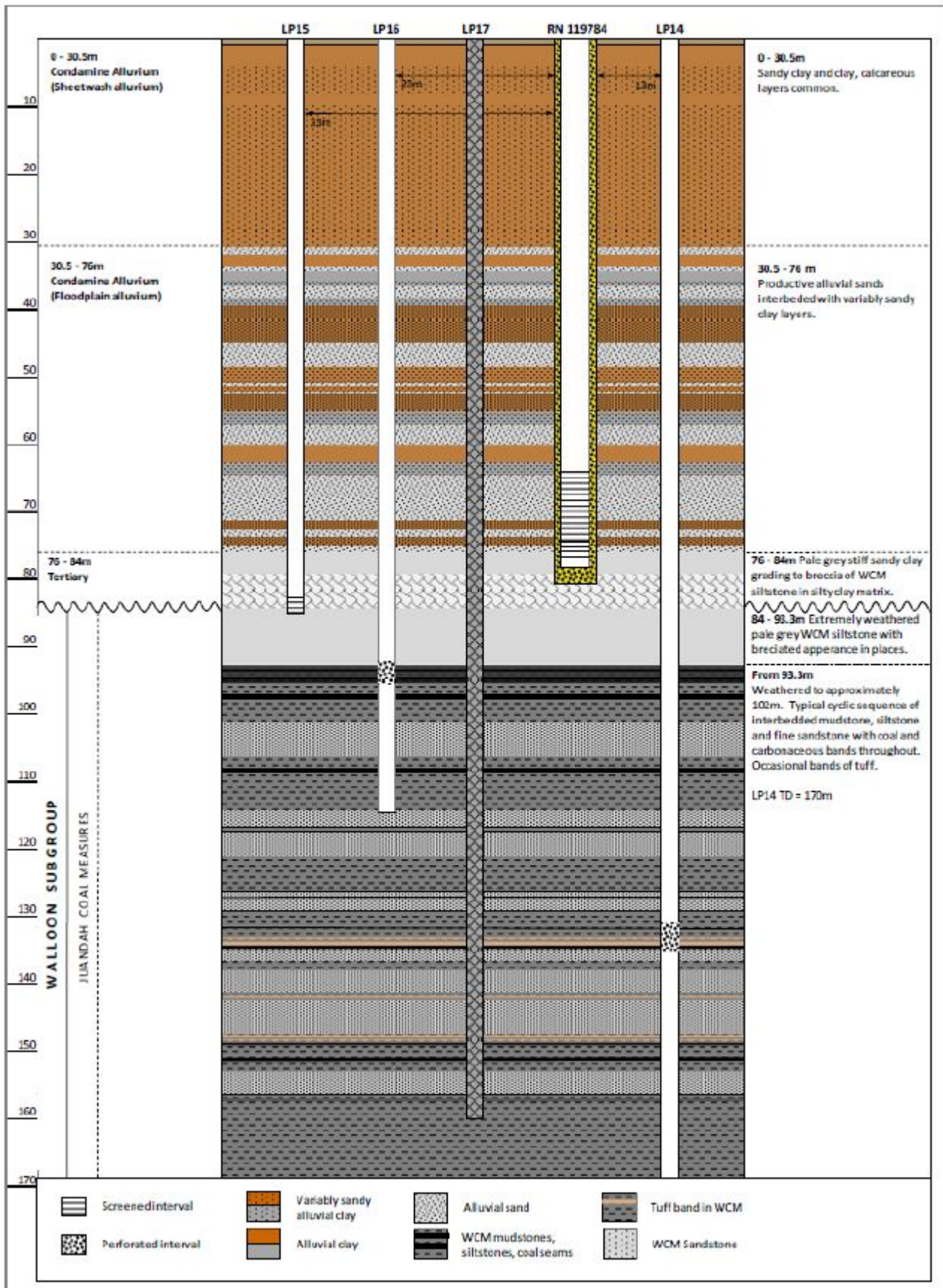


Figure 3 Screens at the Lone Pine well nest (from Jacobs (2015b), provided by Arrow Energy). Sampled wells here are LP14, LP15 and LP16. The nearby observation bore RN119784 was not available for sampling, LP17 is backfilled.

## 2 Field Sampling Methods

The sampling of bores at sites took place on November 3 to 5 2020 by the Queensland team of CSIRO (Matthias Raiber & Jorge Martinez). Due to COVID restrictions dedicated technologies operated by the Adelaide team for taking noble gas samples from bores known to have high supersaturation of gases were not available (Banks et al., 2017) and effervescence in some samples was observed. This is important because it can influence the results of noble gas concentrations, as discussed in the Results section.

### 2.1 Sample Collection

Groundwater samples were collected from seven bores (Table 1) at the two sites (Daandine and Lone Pine) within the Condamine River catchment. Samples were taken from the alluvial aquifer, transition zone and the WCM using low flow sampling techniques (with both dedicated pumps permanently installed in the bore holes and “mobile” pumps submersed into the bore hole for this sampling campaign). The pumps were placed close to the screened interval (for some bores a drop tube was attached to the pump for this purpose). Low-flow rates commonly ranging between 100 and 500 mL/min was achieved by deploying a submersible stainless-steel bladder pump connected to disposable non-Teflon tubing for each well to minimise risks of cross-contamination. Despite efforts in the field to avoid degassing, three samples showed considerable effervescence during sampling, which influences the interpretation of noble gas results. These samples are from Daandine-162 (Condamine Alluvium), Daandine 164 (WCM) and Lone Pine 14 (WCM, deepest screen).

Field electrical conductivity (EC), pH, oxidation–reduction potential (ORP), temperature and dissolved oxygen (DO) were continuously monitored using a multi-parameter probe (YSI) and recorded during pumping in a flow-through cell using a field calibrated water quality meter.

**Table 1 Sampling overview**

BORE NAME AND AQUIFER	SAMPLING DATE	INITIAL WATER LEVEL [M]	PUMP DEPTH [M]
Daandine-164 (WCM)	3/11/2020	20.35	40 + 44 m drop tube
Daandine-162 (alluvium)	4/11/2020	18.96	45
Daandine-163 (transition zone)	4/11/2020	17.86	50
Daandine-161 (alluvium)	4/11/2020	17.59	40 +5 m drop tube
LonePine-14 (deep WCM)	5/11/2020	not available	49
LonePine-16 (shallower WCM)	5/11/2020	not available	58
LonePine-15 (transition zone)	5/11/2020	56.50	70 + 15 m drop tube

At each location (screen) sub-samples of groundwater were taken for stable isotopes (two 100ml McCartney bottles each filled without headspace), a 0.45 µm syringe filtrated sample in 100 ml plastic bottle for anions and a 0.45 µm syringe filtrated and acidified 100 ml bottle for major cations, a tritium and radiocarbon sample each (1L untreated water in PE bottle), a radon sample (Leaney and Herczeg, 2006), an unfiltrated sample (125ml plastic bottle) for Sr isotopes and several headspace vials for methane analysis. Noble gas samples were taken establishing a gas-tight connection to the pump outlet to avoid any contact with ambient air and closing three copper tubes for stable noble gas analysis with dedicated steel pinch-off clamps as described in Suckow et al. (2019).

## 3 Analytical Methods

Samples were dispatched directly after sampling to the relevant laboratories and this section describes which laboratory measured which parameter and the methodology applied. All data handling was done with the CSIRO version of the laboratory information system LabData (Suckow and Dumke, 2001), where the data set has identifier “Set 434”.

### 3.1 Hydrochemistry and conventional tracers

Anions and major cation concentrations were determined at CSIRO Waite Campus, Adelaide. Filtered (0.45 µm) samples were analysed for major and minor cations (Ca, K, Mg, Na, S, Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, Se, Si, Sr, Zn) by inductively coupled plasma optical emission spectrometry (ICP-OES), trace metals (Li, Mn, Fe, Sr, Ba) by inductively coupled plasma mass spectrometry (ICP-MS), alkalinity by automatic titration and anions (F, Cl, Br, NO<sub>3</sub>, SO<sub>4</sub>) by ion chromatography.

The analysis of tritium (<sup>3</sup>H), δ<sup>13</sup>C, and <sup>14</sup>C occurred at the Australian Nuclear Science and Technology Organization (ANSTO), Lucas Heights. Measurement of δ<sup>2</sup>H and δ<sup>18</sup>O was intended to be done with dual inlet mass spectrometry. However, since the facility at ANSTO was not operational at the time, samples were sent from ANSTO to the Australian National University (ANU) using Infrared Laser Cavity Ringdown Spectroscopy (ILCRS) (Picarro). The analysis of δ<sup>2</sup>H and δ<sup>18</sup>O by ILCRS can be influenced by organics in samples as observed for Daandine-164.

Samples to be measured for δ<sup>13</sup>C and <sup>14</sup>C by accelerator mass spectrometry (AMS) at ANSTO were prepared by converting total dissolved inorganic carbon (DIC) to carbon dioxide (CO<sub>2</sub>) by acidifying the samples with phosphoric acid (H<sub>3</sub>PO<sub>4</sub>) and extracting the liberated CO<sub>2</sub> gas using a custom-built extraction line. The CO<sub>2</sub> sample was then heated in a sealed glass tube, containing baked copper oxide (CuO) and metallic silver (Ag) and copper (Cu) wire at 600°C for 2 h – to remove any sulphur compounds that may have been liberated – and followed by graphitisation. Measurement of δ<sup>13</sup>C was intended to happen on this CO<sub>2</sub> fraction allowing a direct comparison of <sup>13</sup>C and <sup>14</sup>C on the same aliquot. Unfortunately amounts of CO<sub>2</sub> were too low in two samples (Daandine-162 & Daandine-163) for this additional measurement of δ<sup>13</sup>C. Samples for tritium were analysed at the tritium laboratory at ANSTO, Lucas Heights, by electrolytic enrichment and subsequent liquid scintillation counting. One sample (Daandine-162) was lost during handling and preparation.

### 3.2 Noble gases

Samples for radon analysis were transported immediately from the field to the CSIRO Environmental Tracer Laboratory (ETL) at the Waite Campus, SA where analysis took place within two weeks after sampling. Samples for <sup>222</sup>Rn analysis (scintillation with mineral oil scintillant from the PET method (Leaney and Herczeg, 2006)) were measured with ten intercalated cycles and a total of 300 min counting time per sample on a Quantulus Liquid Scintillation Counter (LSC) with an analytic precision of 5% and an overall detection limit of 0.01 Bq/L.

Measurement of copper tube samples for He, Ne, Ar, Kr, and Xe noble gas isotope analysis occurred at CSIRO Environmental Tracer Laboratory (ETL) at the Waite Campus, SA. Dissolved gasses were first separated from water using an offline extraction system. The resulting gas subsamples were analysed on a fully automated facility; this includes drying of all gases, separation of noble gases from reactive gases using a variety of reactive getter<sup>1</sup> systems, separation of the noble gases by cryogenic techniques and measurement of gas amounts and their isotopic composition using a spinning rotor gauge, quadrupole mass spectrometers and a high-resolution Helix MC Plus noble gas mass spectrometer (Suckow et al., 2019). This set of samples is the first one where all stable noble gas isotopes were determined for all elements (He, Ne, Ar, Kr, and Xe). Reproducibility for this set, determined from duplicate measurements of copper tubes, is better than  $\pm 5\%$  for the noble gas concentrations. For the isotope ratio measurements, it is 10% for  $^3\text{He}/^4\text{He}$ , 2% for the krypton isotopes ( $^{80}\text{Kr}$ ,  $^{82}\text{Kr}$ ,  $^{83}\text{Kr}$ ,  $^{84}\text{Kr}$ ,  $^{86}\text{Kr}$ ) and better than 1% for the main isotopes of neon ( $^{20}\text{Ne}$ ,  $^{21}\text{Ne}$ ,  $^{22}\text{Ne}$ ), argon ( $^{36}\text{Ar}$ ,  $^{38}\text{Ar}$ ,  $^{40}\text{Ar}$ ) and xenon ( $^{128}\text{Xe}$ ,  $^{129}\text{Xe}$ ,  $^{131}\text{Xe}$ ,  $^{132}\text{Xe}$ ,  $^{134}\text{Xe}$ ,  $^{136}\text{Xe}$ ).

Isotope ratios are given as dimensionless atomic ratios. All noble gas concentrations are given in cubic centimetre of gas per gram (cc(STP)/g; where STP stands for Standard Temperature and Pressure and the gram are related to the weight of the sample). Post processing of radon and noble gas measurements as well as lumped parameter and diffusion modelling was done using the LabData laboratory information management and database system (Suckow and Dumke, 2001) where samples for this project are handled under the identifier Set 434.

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<sup>1</sup> Getters are chemical reactors that can be applied in ultra-high vacuum systems to remove all reactive gases such as N<sub>2</sub>, O<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>...

## 4 Results

The key results of this study are derived from the helium concentrations and from the helium isotopes  $^3\text{He}/^4\text{He}$ . However, helium and other noble gas measurements rarely stand completely alone and need to be interpreted in the context of all other environmental tracers and the hydrochemistry and hydrogeology. This chapter presents the measurement results from the environmental tracer measurements and of selected hydrochemical parameters.

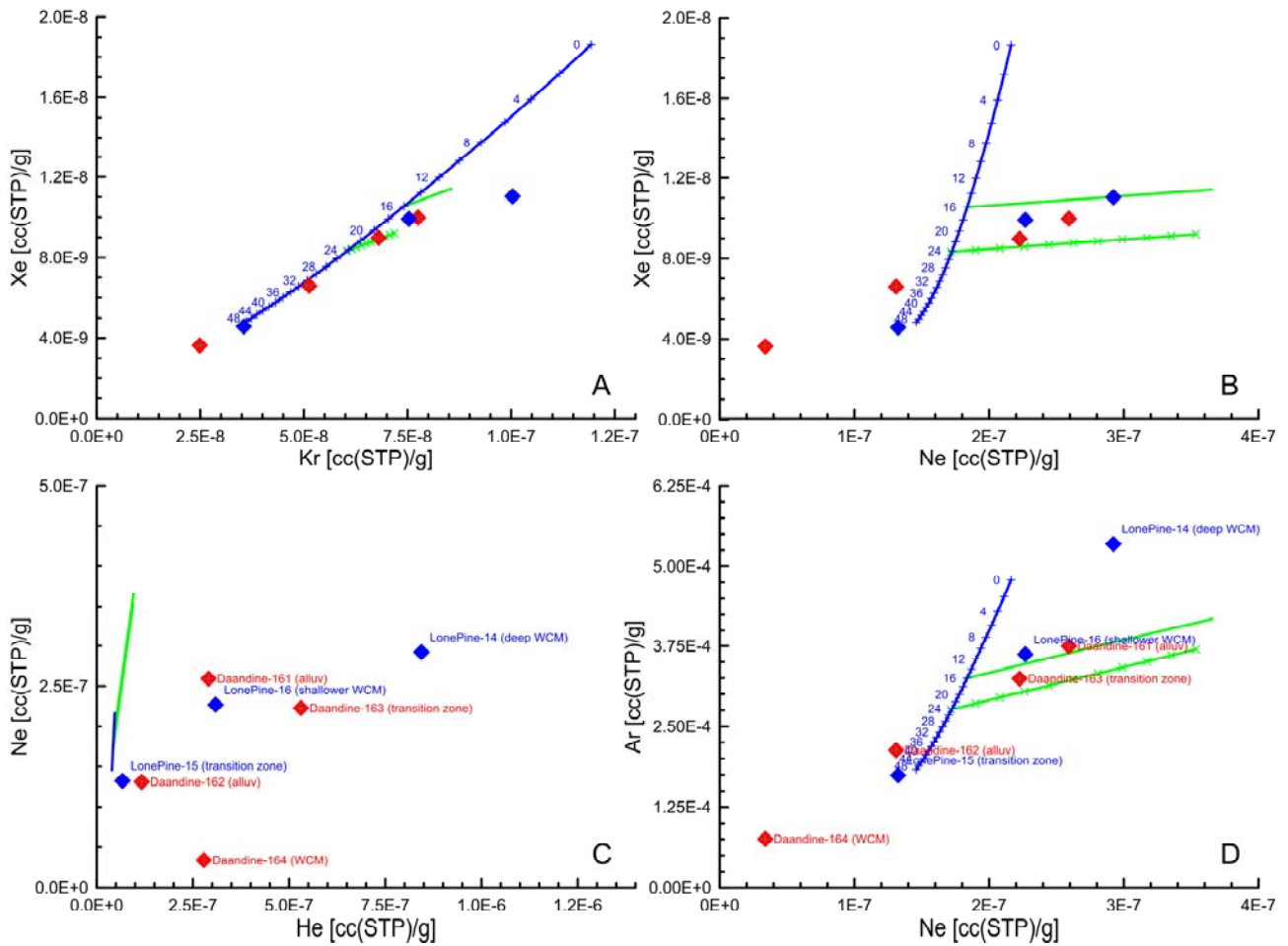
### 4.1 Noble gases

Noble gases contain different kinds of information: concentrations of neon, argon, krypton and xenon can give information on infiltration conditions such as recharge temperature and how much excess air was trapped during infiltration (which is an indication of groundwater level variations during recharge). They can also provide critical information about the sampling conditions and whether this was successful or influenced by gas losses. The latter can be caused by effervescence during sampling or as a natural process involving stripping out noble gases in the aquifer by other gases such as methane.

#### 4.1.1 Noble gas concentrations

Noble gas (NG) results are presented as cross-plots of one element against another in Figure 4. The blue lines and numbers in these plots represent solubility equilibrium of the noble gases with the atmosphere at different temperatures. Since the solubility of noble gases decreases with increasing temperature, low temperatures on these lines are on the top right and high temperatures at the bottom left. A common process occurring during infiltration is the addition of noble gases to concentrations above solubility equilibrium (to the right of the blue curves) by the complete or partial dissolution of air bubbles during infiltration. This additional amount of noble gases is known as “excess air” (Heaton and Vogel, 1981) and characterised by the green lines in Figure 4. These green lines start at characteristic infiltration temperatures on the blue line and then add up to 10cc/kg of the respective noble gases in the ratio found in air. From plots A, B and D in Figure 4 it can be seen that samples from Lone Pine 16, Daandine 161 and Daandine 163 fall into the expected space of infiltration temperatures between 16°C and 24°C with additional excess air between 3 and 6cc/kg. The sample from Lone Pine 14 deviates from this pattern towards much higher excess air and the Ar concentration even exceeds the value for solubility equilibrium at 0°C. This means that this sample is probably influenced by an additional, non-natural amount of excess air. We suspect this is the result from a leaky bladder, since the samples were taken using a bladder pump driven with compressed air. Furthermore, three samples show noble gas concentrations below and to the left of the blue line (Daandine-162, Daandine-164 and Lone Pine 15). This indicates gas loss. The process may either be due to effervescence during sampling or can in principle also happen in the aquifer itself if hydrostatic pressure drops to below solubility equilibrium for one of the major dissolved gas components – the most probable here being methane.





**Figure 4** Noble gas cross plots of samples collected at the two sites.

The blue lines and numbers represent solubility equilibrium of noble gases with the atmosphere at different temperatures. Green lines show additional amount of up to 10cc/kg noble gases known as “excess air”. Helium is up to a factor of 20 higher than solubility equilibrium (C). All other NG are close to or below solubility equilibrium, the latter indicating degassing in the aquifer or effervescence during sampling.

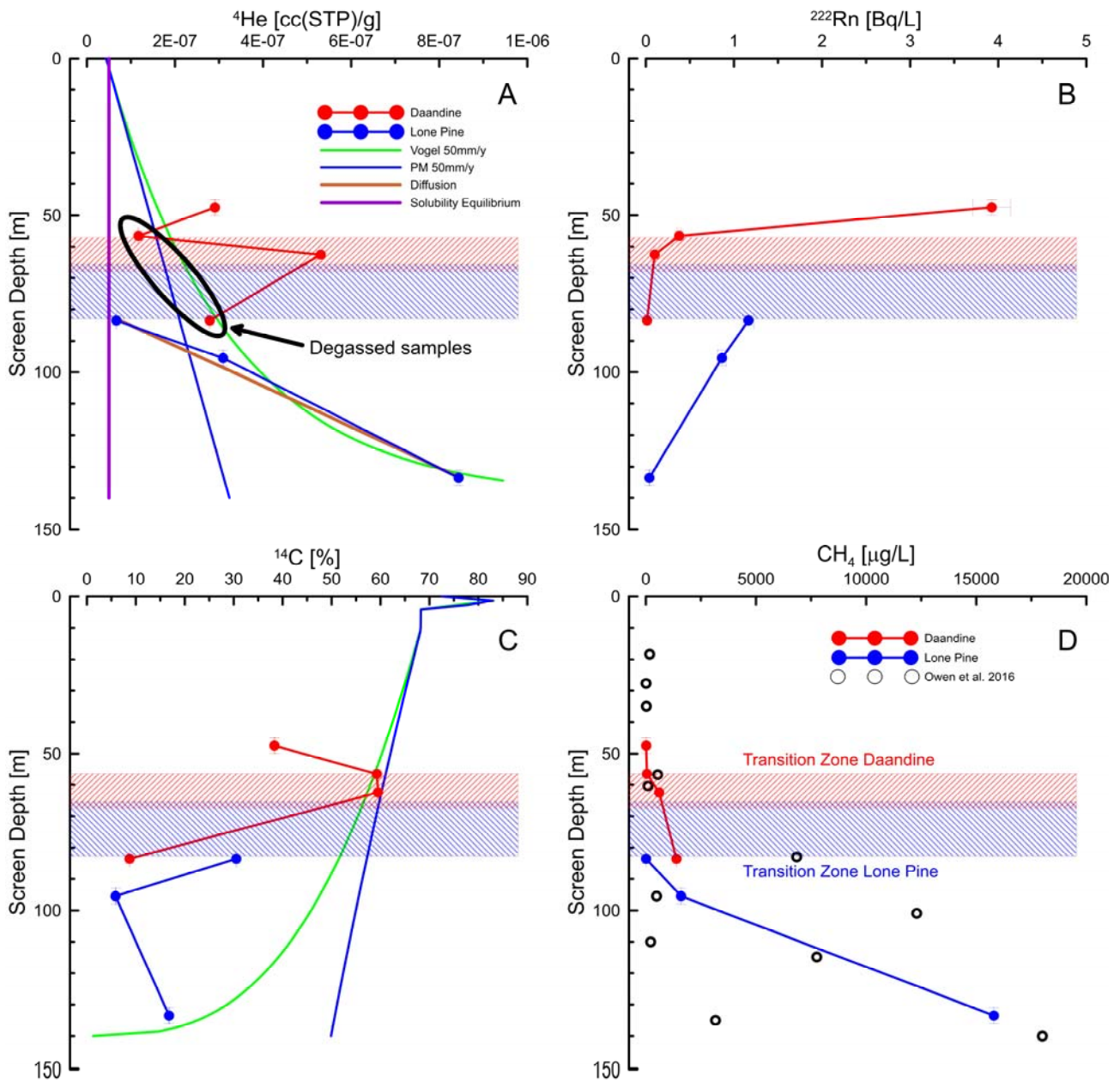
The most important noble gas for this study, helium, in all samples shows concentrations above solubility equilibrium (Figure 4 C, indicated by measurements all lying to the right of the blue and green lines) of up to a factor of 20. This is expected for old groundwater, since helium is produced in the underground from the decay of uranium and thorium contained in aquifer rocks. Since deeper waters normally tend to be older, this helium concentration needs further investigation as function of depth in the aquifer.

Depth profiles of helium (<sup>4</sup>He), radon (<sup>222</sup>Rn), radiocarbon (<sup>14</sup>C) and methane (CH<sub>4</sub>) are shown in Figure 5 A-D. The latter two are not noble gases but are included here as comparative age (<sup>14</sup>C) and context (CH<sub>4</sub>) information. The transition zones between alluvium and WCM are indicated as rectangles in red for the Daandine profile and in blue for the Lone Pine profile. All measurements in red above this rectangle are from the alluvium in Daandine, all measurements in blue below the blue rectangle are from the WCM in Lone Pine. The violet vertical line in Figure 5 shows the solubility equilibrium of helium (corresponding to the blue line in Figure 4 C). The blue and green lines in Figure 5 A and C describe the expected development if the profiles were situated in an



infiltration area according to a piston flow model (blue line) or a model aquifer with homogeneous infiltration and impervious lower boundary as described in Vogel (1967). For a piston flow infiltration  $^4\text{He}$  increases linear with depth due to water moving purely vertically, increasing in age, and helium being produced at a constant rate. In a Vogel aquifer the water “age” at the lower boundary is mathematically infinite, leading to higher helium concentrations (Vogel, 1967). Similarly, radiocarbon ( $^{14}\text{C}$ ) concentrations decrease owing to radioactive decay and the theoretical blue and green lines describe the decrease in concentration with depth for the same theoretical models as before. It is obvious that neither the measured helium nor the radiocarbon concentration depth profiles show any resemblance to these theoretical models, therefore excluding a purely vertical downward movement at the two sites. Helium concentrations in Daandine show no regular profile with depth. This may indicate that in the alluvium the He concentrations may be dominated by horizontal advection rather than vertical. However, the two samples with the lowest helium concentrations are also the ones with observed gas loss from effervescence during sampling. A reconstruction of the original in-situ gas concentrations is therefore not possible. The helium depth profile in Lone Pine is monotonous with depth and its interpretation will be discussed in detail in section 5.2 on page 18.

The radon ( $^{222}\text{Rn}$ ) concentrations in samples can be found in Figure 5 B and were observed to decrease monotonous with depth.  $^{222}\text{Rn}$  is produced by the decay of  $^{226}\text{Ra}$  in the aquifer and since it has a half-life of only 3.8 days, its production in the aquifer is very close (around one meter) around the screened interval over the last four weeks before sampling. The observation that radon and helium concentrations are not correlated (in Lone Pine even anti-correlated, Figure 5 A & B) indicates that the helium concentrations are much “older” and not related to the close vicinity of the screen. This is important for the subsequent interpretation of the helium depth profile of Lone Pine (Section 5). Methane concentrations increase monotonously with depth and are in agreement with earlier findings in the Condamine alluvium, as indicated by the open black circles in Figure 5 D, which are taken from the dataset in Owen et al. (2016).



**Figure 5** Depth profiles of  $^4\text{He}$  (A),  $^{222}\text{Rn}$  (B),  $^{14}\text{C}$  (C), and  $\text{CH}_4$  (D) concentrations at the two sites. Helium concentration increases with depth in Lone Pine but not in Daandine, which may be due to the two samples with lower concentration being degassed.  $^{222}\text{Rn}$  decreases with depth demonstrating that  $^4\text{He}$  and  $^{222}\text{Rn}$  are not correlated and that  $^4\text{He}$  is not produced in the vicinity of the wells.  $\text{CH}_4$  increases with depth, in agreement with earlier findings.  $^{14}\text{C}$  is for both sites not correlated with depth, indicating the influence from fossil carbon (see text).

#### 4.1.2 Noble gas isotopes

The dataset presented here is the first ever reported from the CSIRO noble gas laboratory comprising the full suite of stable noble gas isotopes. The most important isotope combinations are shown in Figure 6 A-D. The black crosses in Figures B, C and D indicate a measurement precision of 1% for these isotopes around the isotopic composition of air. Figure 6 B-D demonstrates that the isotopes of neon, argon and xenon show no radiogenic or primordial component in the samples of this study, since they lie inside the uncertainty margins given by the

black crosses. This was also not expected since radiogenic isotopic signatures in these noble gases are discernible only after residence times of the fluids exceeding one million years. Radiogenic helium (formed as a result of radioactive decay of naturally occurring U and Th), however, is clearly present in both Daandine and Lone Pine in Figure 6 A, since the measured values deviate from the air composition. In this figure the crossing point between the orange, red, black, blue and green lines correspond to the atmospheric isotopic composition of helium having a  $^3\text{He}/^4\text{He}$  ratio of  $1.36 \cdot 10^{-6}$  (y-axis) and the Ne/He ratio of atmospheric air (3.8-4.6 on x-axis, depending on temperature). The solid black and light blue dashed line correspond to solubility equilibrium at different temperatures and varying amounts of excess air and are the equivalent to the blue and green lines in Figure 4 C. The radioactive decay of tritium produces only  $^3\text{He}$  (tritiogenic helium) and in negligible amounts compared to the total helium concentrations. Therefore, it leaves the Ne/He ratio unchanged and only changes the  $^3\text{He}/^4\text{He}$  ratio, leading to the vertical orange line in Figure 6 A. The red line in Figure 6 A corresponds to the addition of radiogenic helium, which is mainly  $^4\text{He}$  from the alpha particles of the decay of U and Th and typically has an isotopic ratio of  $^3\text{He}/^4\text{He}$  of  $10^{-7}$  to  $10^{-8}$  (defined as the crossing point of the red line with the y-axis which is at  $10^{-7}$  in Figure 6 A). If there is a combination of both tritiogenic helium and radiogenic helium, the samples would follow the blue or green line, which is the piston flow model and the exponential model and equivalent to the blue and green lines in Figure 5 A and C. The position of the blue “tritium peak” in this case is defined by the rate of radiogenic helium production and any sample left of the tritium peak on the blue or green line originates from times earlier than 1963. It is evident that the samples of Lone Pine fall along the line of radiogenic helium and show a slight elevation of the  $^3\text{He}/^4\text{He}$  ratio that can be explained from tritium decay in the water having pre-bomb tritium concentrations. Interestingly and unexpectedly, the samples from Daandine show higher  $^3\text{He}/^4\text{He}$  ratios. This can only be explained by an admixture of primordial helium from the mantle. Such primordial admixtures point towards the influence of old volcanics or volcanic intrusions and further support the findings from the depth profiles in Figure 5 discussed earlier. Main Range Volcanics crop out in the east of the Condamine River catchment (Figure 1) and waters having this helium signature may have been transported into the Daandine profile by horizontal flow within the sediment layers of the alluvium. A more detailed assessment into the origin of this primordial component needs a detailed mapping of this  $^3\text{He}/^4\text{He}$  isotopic signature within the sediments of the alluvium which is beyond the scope of the present study. This can be of further interest since such waters are often geothermally influenced, which is an energy resource and sometimes also used for spa waters.

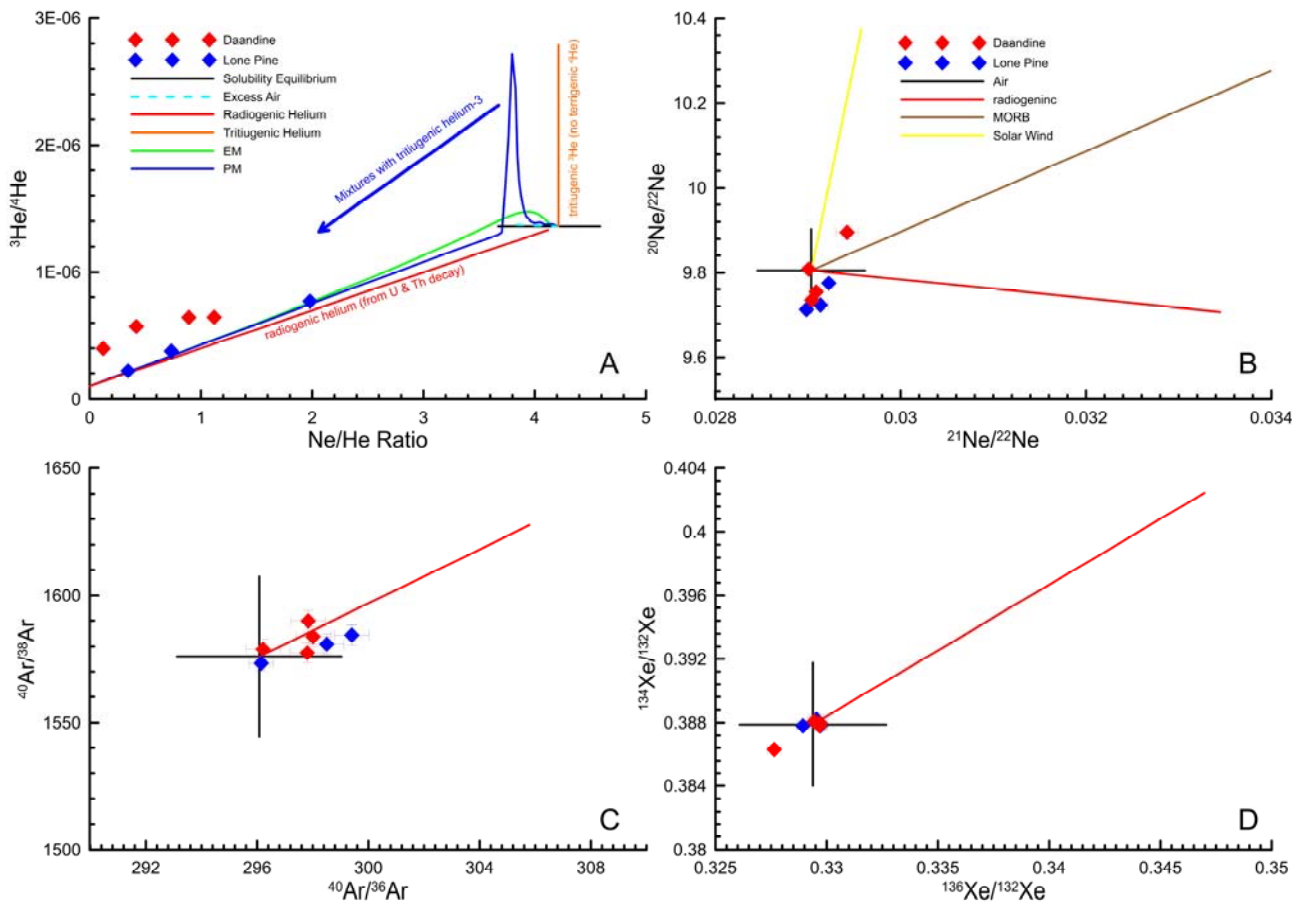
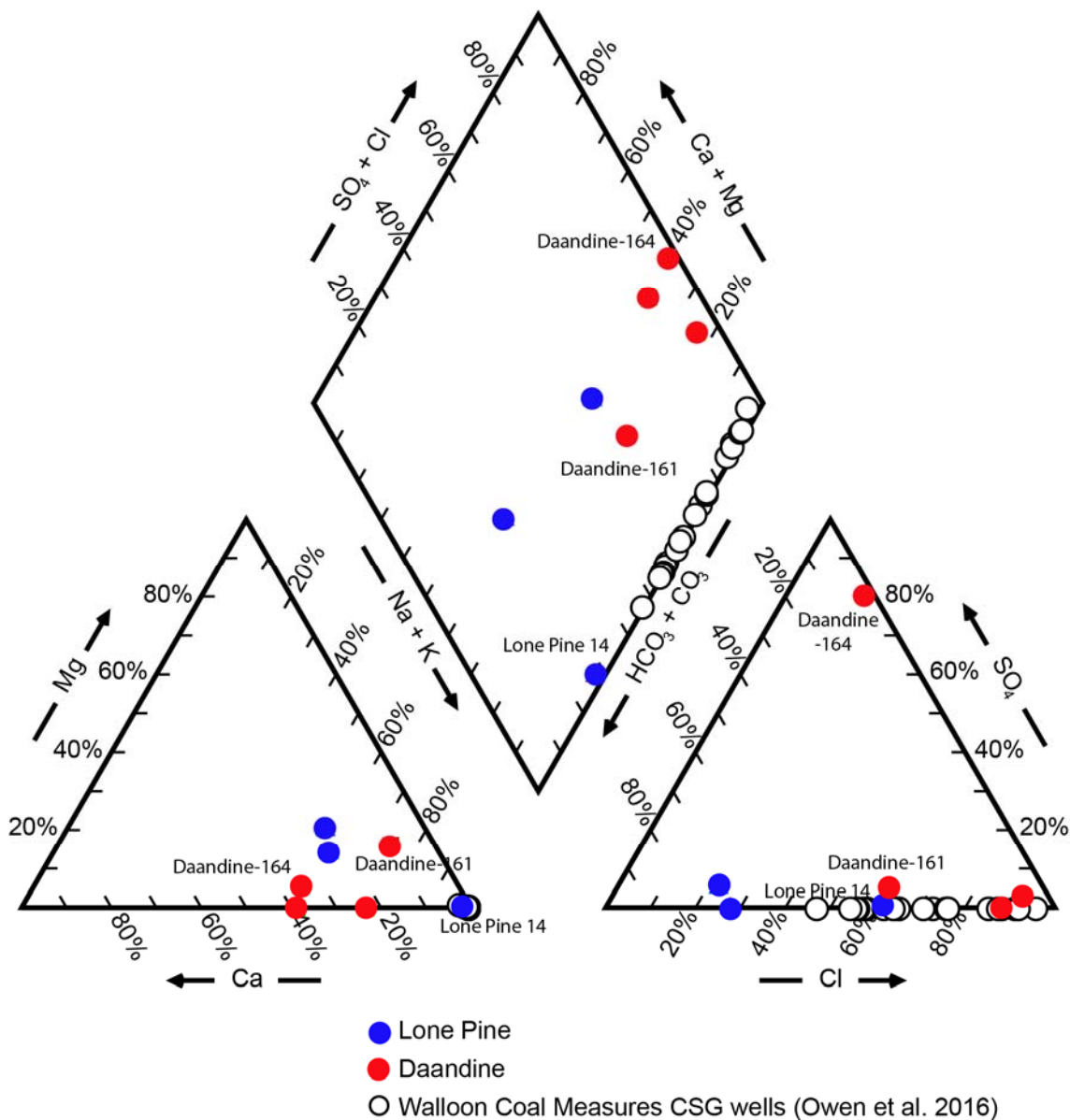


Figure 6 Noble gas isotopic composition for He (A), Ne (B), Ar (C), Xe (D). Lines of atmospheric isotope compositions are in black, those from radiogenic production in red. For further explanation see text.

## 4.2 Hydrochemistry

### 4.2.1 Major anions and cations

A Piper plot of separate major cations and anions in groundwater samples from the Daandine and Lone Pine nested bore sites can be found in Figure 7.



**Figure 7 Piper plot showing ion ratios at Lone Pine and Daandine nested bore sites and from Walloon Coal Measures CSG wells (Owen et al., 2016).**

At the Lone Pine site, multiple patterns in the groundwater samples can be observed:

In general, the three samples from Lone Pine are distinct with regards to their major ion compositions (Figure 7). Lone Pine 14 (the deepest bore screened in the WCM) shows similarities to coal seam gas wells in the WCM observed by Owens et al (2016), such as the lower concentrations of Ca, Mg and  $\text{SO}_4$ , higher F concentrations and a dominance of  $\text{HCO}_3$  over Cl. These ion characteristics in LP14 are not observed in Lone Pine 16 (shallower WCM) and Lone Pine 15 (transition zone). The samples from the shallower part of the WCM and the transition zone are also clearly separated on the Piper plot, with the shallower WCM groundwater dominated by Na-Cl compared to the dominance of  $\text{HCO}_3$  over Cl at the bore in the transition zone. At these three sites, as expected there is also a decrease of  $\text{CH}_4$  concentrations from the deeper to the shallower bores, with no  $\text{CH}_4$  above the reporting limit (10  $\mu\text{g/L}$ ) observed at the bore in the transition zone.

At the Daandine nested bore site, the groundwater sample from Daandine-164 (screened in the deeper parts of the WCM) had very high  $\text{SO}_4$  and high K concentrations (that result in a large charge imbalance) and is likely due to contamination with drilling muds (Figure 8). This suggests that analytical results for other parameters for this groundwater bore may also not be reliable.

The shallower alluvial bore at the Daandine nested bore site (Daandine 161) shows a clear hydrochemical separation compared to groundwater from all other bores at this site (Figure 7). This sample had lower EC and higher  $\text{HCO}_3^-$  concentration compared to the groundwater samples collected from the deeper bores. The Daandine 161 sample also had a very low concentration of  $\text{CH}_4$  (12  $\mu\text{g/L}$ ), just above the limit of reporting. Although distinct from Daandine 161, Daandine 162 (alluvium) and Daandine 163 (transition zone) have a relatively similar major ion chemistry with lower  $\text{HCO}_3^-$  concentrations, higher Cl and lower Mg concentrations compared to Daandine 161, and samples from both groundwater bores have a very different major ion chemistry compared to groundwaters from CSG wells (Figure 7).

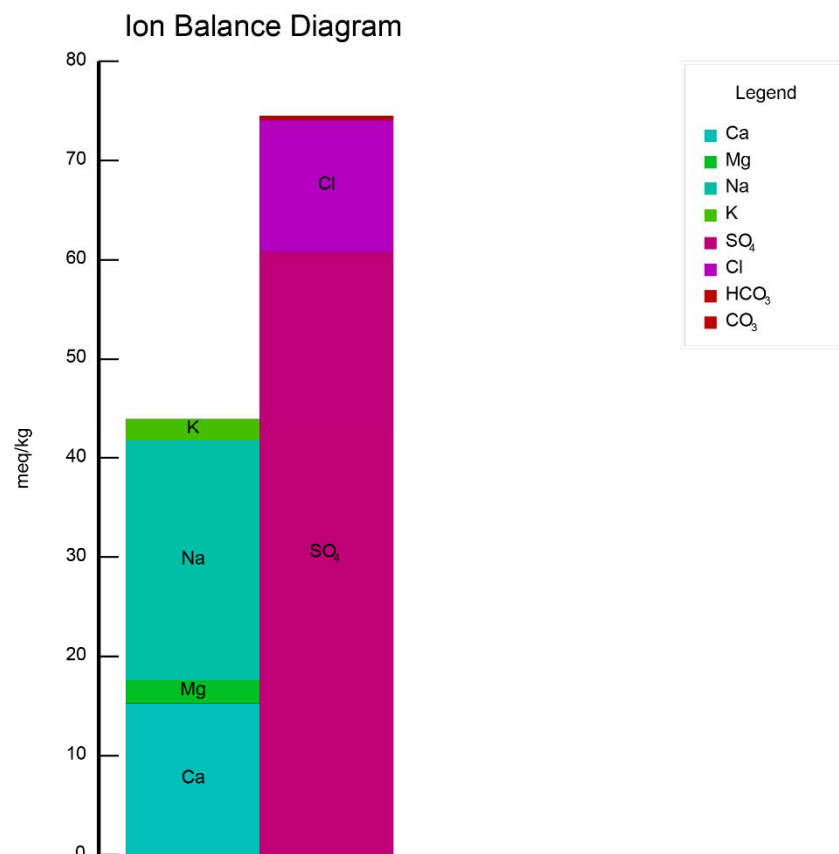


Figure 8 Ion balance of Daandine-164, showing excess of  $\text{SO}_4$ .

#### 4.2.2 Minor elements

In the study by Owen et al. (2015), the authors suggested Li concentrations and the ratios of Li to Cl and Li to Na within the Condamine River catchment are distinct in the coal-bearing and sedimentary bedrock aquifers ( $>0.0001$ ) and groundwaters in alluvial and basalt aquifers ( $<0.0001$ ). A groundwater sample from alluvial bore Daandine-161 contained very low Li concentration (1.62  $\mu\text{g/L}$ ) compared to other samples measured during this study (concentrations range from 1.62 to 129.16  $\mu\text{g/L}$ ) and low Li/Cl ( $4 \cdot 10^{-6}$ ) and Li/Na ratios ( $5 \cdot 10^{-6}$ ), whereas alluvial bore Daandine-162 has the highest Li concentration (274  $\mu\text{g/L}$ ) measured in any groundwater sample at the two sites and with a Li/Cl ratio ( $4 \cdot 10^{-4}$ ) similar to those of WCM groundwaters reported by Owen et al. (2015). Daandine-162 also had an alkaline pH of  $\sim 10.7$ , in a similar range as the pH of Daandine-163 ( $>11$ ), and has elevated concentrations of other minor ions such as Ba (0.48  $\text{mg/L}$ ) and Sr (3.76  $\text{mg/L}$ ) compared to groundwater samples from other bores at the Daandine nested bore site (Ba concentrations range from 0.06 to 0.48  $\text{mg/L}$  and Sr ranges from 1.12 to 3.76  $\text{mg/L}$  for all Daandine bores). This may indicate that there is some level of connectivity between the alluvium and the transition zone.

### 4.3 Conventional tracers

While the noble gases and their isotopes were the main tool of this study, they always benefit from additional lines of evidence from the more conventional tracers  $^2\text{H}$ ,  $^{18}\text{O}$ ,  $^3\text{H}$ ,  $^{13}\text{C}$ ,  $^{14}\text{C}$  (and hydrochemistry as discussed in the last section). The main value of putting conventional tracers (and other lines of evidence) into the picture is that contradictions may show up that reveal too simplistic interpretations or that they lead to a more robust conceptualisation if no such contradictions occur (Iverach et al., 2017; Iverach et al., 2015; Scheiber et al., 2020).

Figure 9 shows the results of these tracers in bores samples in conventional cross-plots. The stable isotopes of water in the common meteoric water line plot can be found in Figure 9 A. With one exception the bore samples from both sites lie on the meteoric water line (black line), towards the more negative end of the rain values of Toowoomba (Crosbie et al., 2012), which is shown for comparison as grey crosses. The more negative stable isotope values are expected, as the Condamine Alluvium lies further inland than Toowoomba, leading to more negative stable isotopic values due to the “continental effect” (Sonntag et al., 1983; Winnick et al., 2014). The values measured in this study agree well with the findings by Owen et al. (2016) from the broader Condamine Alluvium (Owen et al., 2016), given as open grey circles. The only outlier is the sample from the WCM screen Daandine-164, which was also described as an outlier in hydrochemistry characterisation (i.e. elevated  $\text{SO}_4$  content, see last section). This is may be due to presence of remnants of the drilling fluid with organic compounds strongly influencing the isotopic measurement by Cavity Ring-Down spectroscopy.

The radiocarbon ( $^{14}\text{C}$ ) cross-plot with tritium is presented in Figure 9 B. The blue and green lines on the plot show the piston flow model (PM) and exponential mixing model (EM). This plot also presents the binary mixture (BMM) of old and young water (red line). Except for two bore samples, all samples are at the detection limit of tritium, indicating recharge before 1963. The two samples from the transition zone indicate a small admixture (<10%) of young water to the bulk of tritium-free water.

The cross-plots of  $^{14}\text{C}$  and Total Dissolved Inorganic Carbon (TDIC) is shown in Figure 9 C. Here  $^{14}\text{C}$  in % is in reality a ratio  $^{14}\text{C}/\text{C}$ , which is why radiocarbon expressed as absolute  $^{14}\text{C}$  atoms in water versus this ratio is again shown in Figure 9 D. These plots demonstrate the carbonate system in these aquifers has been overprinted by the addition of “fossil” (and  $^{14}\text{C}$ -free) carbon from the oxidation of coal seam gas. This is evident by some of the samples that plot along one version of the Phillips model (grey line in Figure 9 C&D) which describes how additional  $^{14}\text{C}$  free carbon changes these concentrations (Phillips, 2013). This effect is important because it precludes interpretation of the radiocarbon values in terms of a straightforward groundwater “age” – these would be too old since they don’t take this addition of fossil carbon into account. The lowest radiocarbon value measured is 5.85%, yet another indication that the bulk of the groundwater is not older than 20ky, which confirms the finding from the helium concentrations and noble gas isotopes discussed earlier. For a more detailed chemical and isotopic interpretation of the hydrochemical processes disturbing the radiocarbon age information in these groundwaters, further data along the potential flow paths are necessary, including  $^{13}\text{C}$ . For this interpretation additional information on the time scales between  $^{14}\text{C}$  and tritium is needed using an isotope tracer such as  $^{39}\text{Ar}$ .



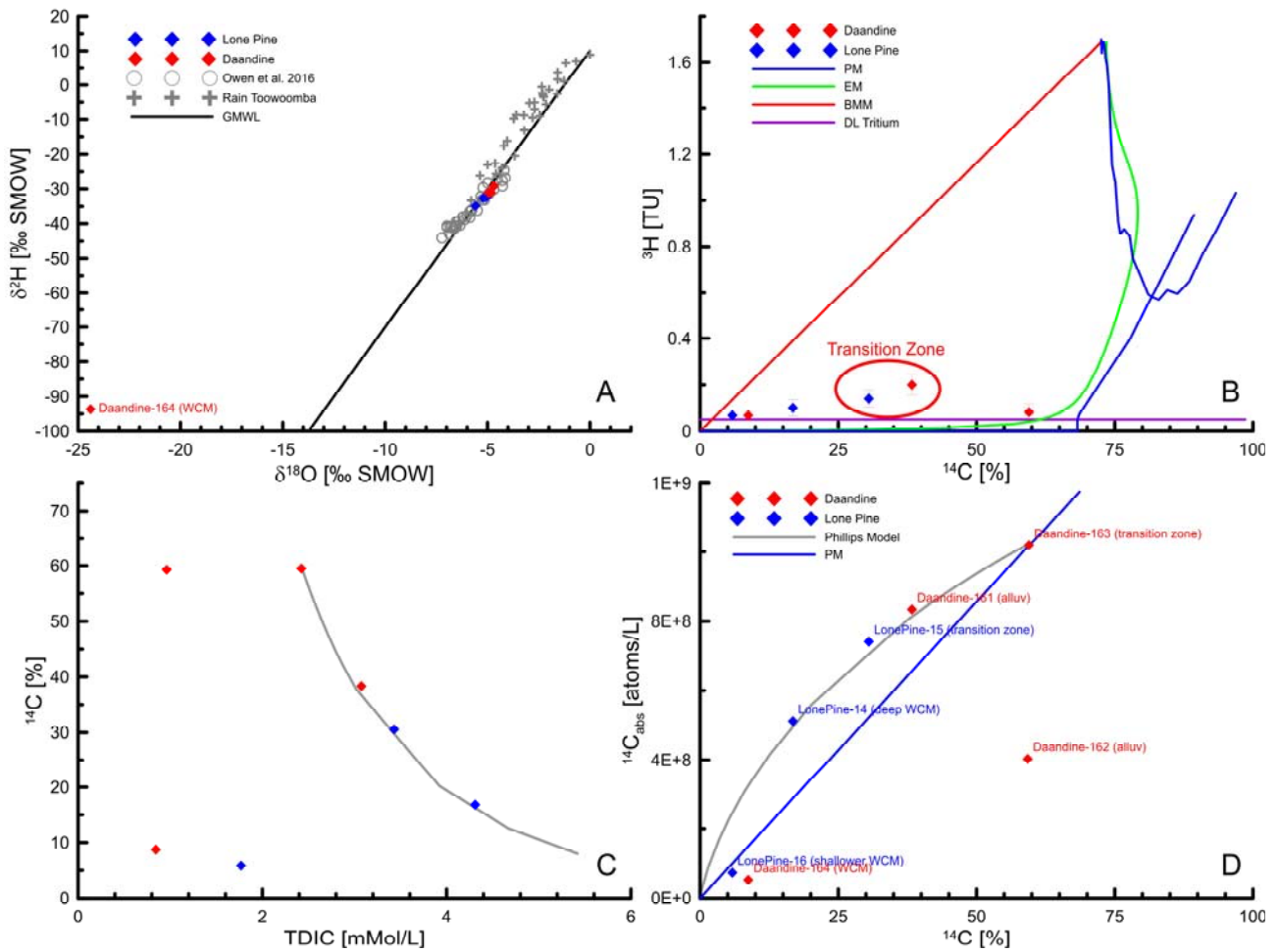


Figure 9 Conventional tracer cross-plots for bore samples collected at sites.

Stable Isotopes of water ( $^2\text{H}$  &  $^{18}\text{O}$ ) (A),  $^3\text{H}$  versus  $^{14}\text{C}$  (B),  $^{14}\text{C}$  versus Total Dissolved Inorganic Carbon (TDIC) (C),  $^{14}\text{C}$  in % versus  $^{14}\text{C}$  as absolute number of atoms per litre (D). For further explanation see text.

## 5 Interpretation

### 5.1 Lines of evidence from noble gases, conventional tracers and hydrochemistry

The hydrochemical results (section 4.2) show the expected distinction between waters from the WCM and the Condamine Alluvium, with mixtures and possibly horizontal fluxes occurring in the alluvium and the transition zones. These findings are confirmed by the conventional tracers (section 4.3), giving further evidence that the bulk of the water is older than the anthropogenic influence after 1963 but younger than a couple of ten thousand years. The tracer and hydrochemistry depth profile in the alluvium from Daandine indicates that the alluvium is dominated by horizontal flow which agrees with the general hydrogeological model. This can be investigated in detail only by further depth profiles in the alluvium. The helium depth profile from the transition zone to the WCM in Lone Pine site, however, can be interpreted as a profile with nearly no advection (i.e., flowing groundwater) with transport of tracers dominated by molecular diffusion (driven only by a concentration gradient, not a hydraulic gradient), as described in the next section.

### 5.2 Interpretation of the Lone Pine helium depth profile

We interpret the depth profile in Lone Pine bore using the uppermost helium concentration – which is close to solubility equilibrium – and the bottom helium concentration – which is the highest helium concentration observed in this study – as boundary conditions for a one-dimensional diffusion-advection model. This model is shown in Figure 10, assuming several possibilities for the vertical groundwater advection velocity.

The black line describes the absence of any advection, when the profile is dominated by pure diffusion. The green lines demonstrate very small upward advective velocities of 0.5mm/y (light green) and 1mm/y (olive green). It is evident how the straight diffusive profile is bent upward into a curved shape by the advection, and that upward advection of more than 1mm/y is not in agreement with the intermediate measured concentration. Figure 10 also demonstrates that the intermediate concentration is not in agreement with any downward advection (e.g., caused by the de-pressurization from coal seam gas production), even not small values of 0.5mm/y or 1mm/y.

### 5.3 Limitations of this Interpretation

There are several limitations to the interpretation presented here, which can be addressed in future studies. These limitations result from knowledge gaps due to i) unknown porosity, ii) depth resolution and iii) limited total depth of the profiles, iv) time resolution and v) the local nature of the study presented here.

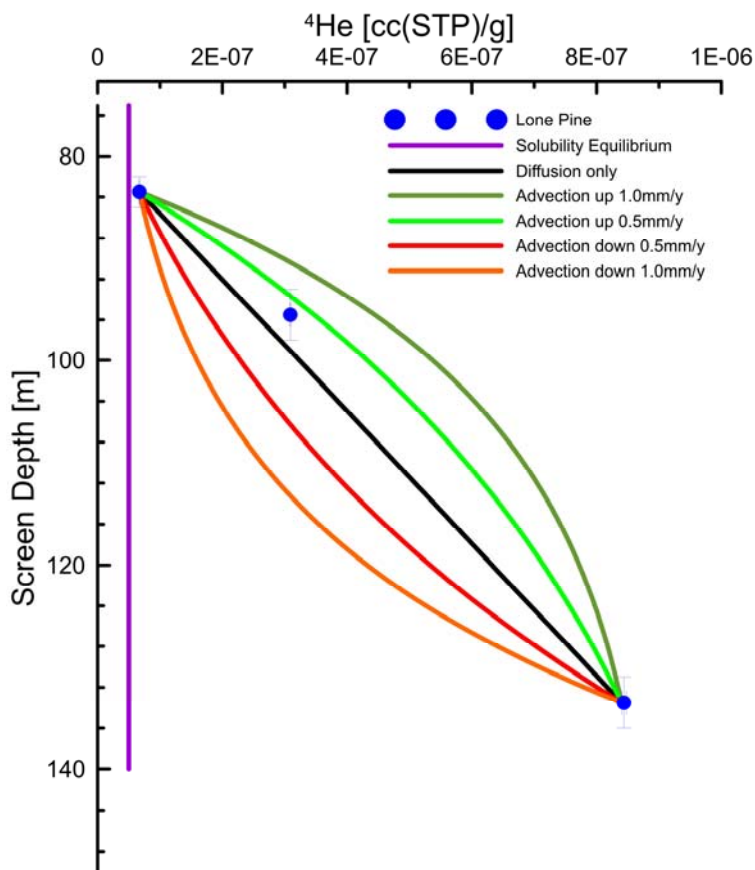


Figure 10 Modelling of the helium depth profile at Lone Pine.

The vertical violet line is the concentration of helium at solubility equilibrium with the atmosphere (background value). Advection-Diffusion profiles assume that the measured helium concentration at the top and the bottom of the profile are boundary conditions. The black line shows pure diffusion with negligible advection, the red and orange line show a small downward, the light and dark green lines small upward advection. The measurement at intermediate depth is commensurable with a vertical upward advection within the WCM of between 0mm/y and 0.5mm/y.

*Unknown porosity:* It is necessary to emphasize that the velocities used in the presented advection-diffusion model (Figure 10) are distance or porewater velocities (Darcy velocity divided by porosity). To convert them into the Darcy velocity (that is: a volumetric water flux per cross-sectional area) they must be multiplied by the *a priori* unknown porosity – which in any case is a number smaller than one, so the Darcy velocity is smaller than the values given in Figure 10.

*Limited depth resolution and total depth:* The number of measurements per depth profile in this study is the absolute minimum for an interpretation. Interpretation has been done using *only one* intermediate depth between the two measurements at the top and bottom of the profile to define the boundary conditions. For solving the advection diffusion equation along a depth profile typically ten depths would be desirable to obtain a more robust interpretation. The helium concentration at the top is the concentration in solubility equilibrium with the atmosphere and can therefore not be lower. The concentration at the bottom, however, is just the highest helium concentration measured. It may well be, is even very probable, that the helium concentration further down in the WCM is much higher. It is therefore desirable to measure a depth profile through the whole of the Walloon Coal Measures, to understand whether the helium is produced in situ in a stagnant pore water body or, more probably, enters the WCM from below as basal flux

– these two possibilities would be discernible from the shape of the diffusive profile (Osenbrück et al., 1998; Rübél et al., 2002). Only a full depth profile through the WCM can elucidate whether the diffusive profile prevails over the whole depth of the WCM or whether there are intermediate horizons which are dominated by horizontal flux (as interpreted for the alluvium and transition zone in the Daandine profile).

*Temporal resolution:* Furthermore, the depth profile measured here is a snapshot in time. Like Astronomy being a picture of the past because the light needs many years from far away objects to reach our telescopes, also tracer profiles need a long time to establish. The time constant to establish a diffusion profile of thickness  $d$  with two different concentrations at the boundaries is  $t=d^2/D$  (Crank, 1979). The vertical distance between LP15 and LP14 is 50m and in free water the diffusion constant  $D$  of helium is  $5.7 \cdot 10^{-9} \text{m}^2/\text{s}$ . A diffusion profile over this distance therefore needs several ten thousand years to establish, likely even longer since the diffusion in sediment is smaller due to tortuosity. It is therefore possible to conclude from a diffusive profile in the WCM, that *before human influence* there was no (or less than 1mm/year) natural vertical advection in the WCM at this location. Any influence of de-watering, however, would change this profile with time and this change would only be visible as a change in the concentration-depth profile over time. An induced downward advection will cause helium with solubility equilibrium concentration to move from the Condamine Alluvium through the transition zone into the Walloon Coal Measures. An induced upward advection (e.g. induced by pumping of irrigation bores from the CA) would transport water with higher helium concentrations from the WCM into the transition zone and the Condamine Alluvium. Smith et al. (2019) describe such time-varying diffusion profiles for the case of the Gunnedah Basin in NSW. It is therefore recommended to repeat the measurements presented here with higher depth resolution of 10-15 screens distributed over the whole depth from the groundwater surface in the Condamine Alluvium to the base of the WCM after three years and if no change is detected after longer time periods.

*Locality of the studies:* The depth profile in Lone Pine and any vertical advective velocity deduced from it is valid only for this single location. To obtain a similar result regarding the connectivity between the WCM and the Condamine Alluvium for the whole area of the Condamine River catchment where the CA overlies the WCM, more such depth profiles are necessary, spread throughout the alluvium and with a greater depth resolution. For instance in a first step more bores can be added to the existing well nests, above and between the existing ones in Lone Pine and extending to greater depth in both locations; then new well nests can be established in areas that are regarded as “critical” (or of special public interest) concerning the vertical connectivity; a final goal would be reaching sufficient coverage of the Condamine River Catchment to get a 3D-picture of groundwater flow.

The study presented here can only be interpreted as a first feasibility study demonstrating the value of the method in general.

## 6 Conclusion

The work presented here is a first and successful feasibility study to use depth profiles of helium concentrations to assess the degree of connectivity between the WCM and the Condamine Alluvium. It demonstrates the value of an integrated multi-tracer approach to quantify vertical advective velocities in groundwater between these two strata. It also demonstrates how advective distance velocities over a depth of 50 m can be demonstrated to be smaller than a millimetre per year using helium depth profiles.

The present work also showed how future studies using these isotope systems can further be improved by:

1. Sampling for noble gases (and dissolved gases in general) needs to be improved to avoid effervescence, using established but more elaborate techniques such as described in Banks et al. (2017) and/or rotary submersible pumps such as the MP-1, avoiding the use of compressed air-driven bladder pumps.
2. Thorough pumping after the installation of sampling wells is needed to remove contamination in samples due to drilling fluids.
3. Improved accuracy in model fits through higher depth resolution and a higher maximum depth is necessary, with an optimum target of in total 10-15 different depths from the groundwater surface in the Condamine Alluvium to the base of the WCM.
4. The influence of de-pressurization can cause a change in the concentration depth profiles; therefore, it is recommended to repeat these measurements in regular intervals as soon as the infrastructure is established. A data worth analysis can be used to determine optimized time intervals.
5. Each depth profile can only be interpreted as local information. An assessment of connectivity for the whole area of the Condamine Alluvium needs more such depth profiles covering the area. These can be strategically developed at sites where leaks between the formations are suspected.
6. The study demonstrated the presence and dominance of horizontal flow in the Condamine Alluvium and the weakness of using radiocarbon as groundwater age tracer in this hydrochemical setting. If further confidence in horizontal flow directions and velocities within the Condamine Alluvium are desired, e.g. for a future calibration of numerical flow and transport models, it is recommended to integrate a tracer that will not be altered by hydrochemical processes and assesses the time scale of centuries, such as  $^{39}\text{Ar}$ .

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