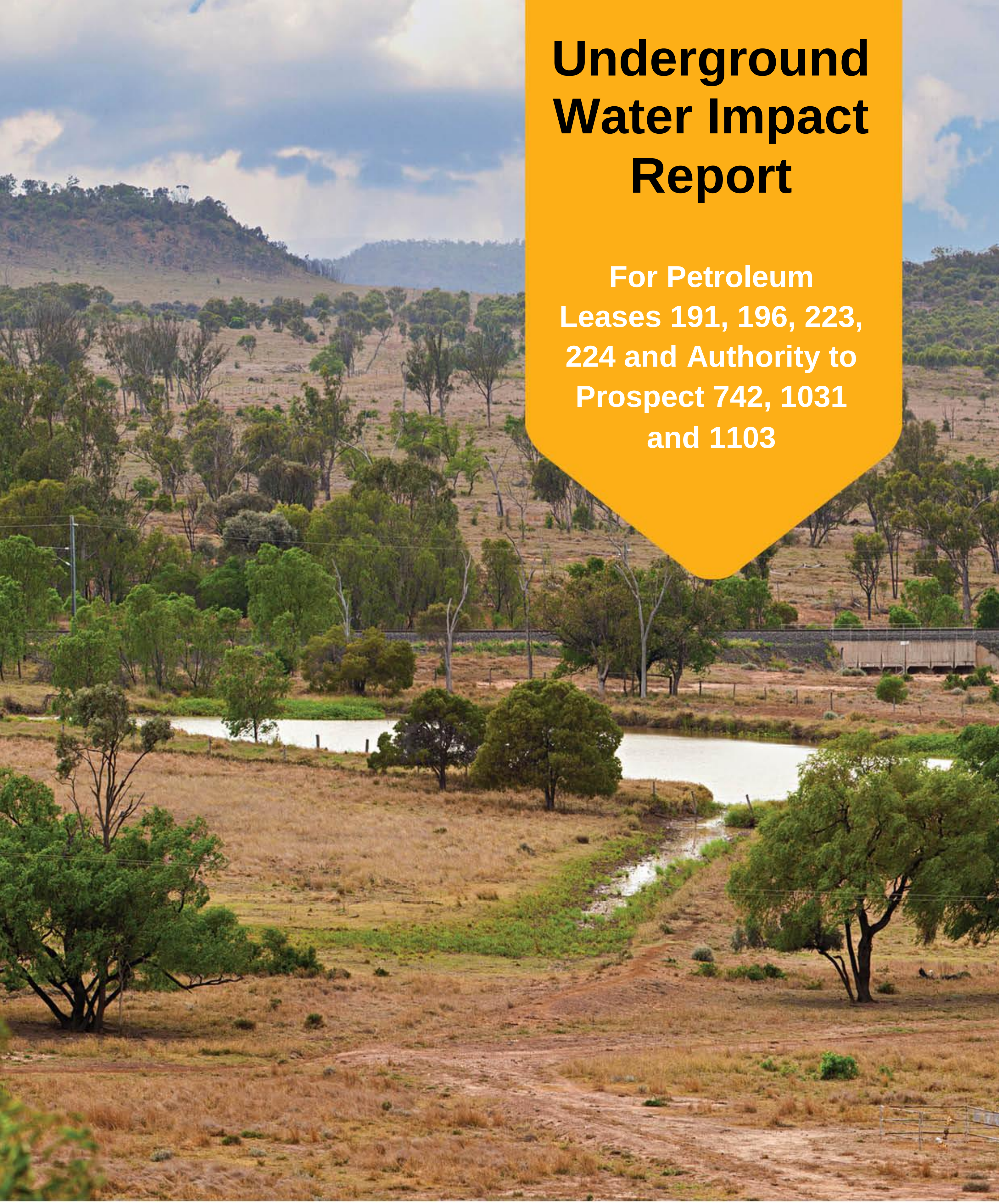

Underground Water Impact Report

For Petroleum Leases 191, 196, 223, 224 and Authority to Prospect 742, 1031 and 1103

arrow energy
go further

4 April 2019

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EXECUTIVE SUMMARY

This Underground Water Impact Report (UWIR) provides information on the potential decline in water levels in aquifers within the Project Area as a result of the taking of water during production of coal seam gas (CSG) and production testing. The Project Area comprises Petroleum Leases (PLs) 191, 196, 223, 224 and Authorities to Prospect (ATPs) 1103, 1031, and 742.

A conceptual hydrogeological model was developed as part of the UWIR and includes model predictions of potential depressurisation impacts on groundwater resources as a result of CSG production. The predictions for the UWIR were made using the latest 2018 groundwater model.

This 2019 Bowen UWIR includes:

- the quantity of water taken because of the exercise of any previous relevant underground water rights;
- the quantity of water estimated to be taken because of the exercise of any relevant underground water rights over the next three years;
- an updated description of aquifers potentially affected (informed by information collected since the publication of the previous UWIRs) including how the aquifer interacts with other aquifers;
- the predicted water level decline as a result of the taking of water and a description of the methods and techniques used to make the prediction;
- information on water bores that may be impacted by a water level decline in excess of the bore trigger threshold; and
- a program for conducting an annual review of the predictions.
- the outcome of the Australian Groundwater and Environmental Consultants (AGE) Model developed to determine impacts from the proposed development scenarios.

Historical water production from the Project Area was 5293ML up to end 2018. In the next 3 years an additional 634ML is forecast to be produced from the MGP (PLs 191, 196 and 224) and 375ML from Red Hill Central. The production from Mavis Downs operations, coming online in 2021, has been forecasted to be in the order of 66.1ML.

The validity of the existing conceptual hydrogeological model was reviewed in light of new data from site (including from implementation of the Water Monitoring Strategy described in the previous UWIRs). It was concluded that:

- Data obtained to date is in support of the existing conceptual hydrogeological model, and
- The 2018 groundwater model is considered to be suitable for predicting depressurisation impacts as a result of CSG operations for the Project Areas as part of this UWIR.

The 2018 groundwater model developed as part of this UWIR simulates historical and forecast production as well as historical production testing. The 2018 groundwater model has been utilised to predict water level decline in aquifers as a result of the taking of water during production of CSG and production testing. This includes identification of Immediately Affected Areas (IAAs; where the predicted drawdown within the next three years exceeds the bore trigger threshold) and the Long-term Affected Areas (LAAs; where the predicted drawdown exceeds the bore trigger threshold at any time).

Key findings are:

- Within PLs 191, 196, and 224 an IAA exists for the Moranbah Coal Measures associated with production of CSG. There are no existing or useable landholder bores in this IAA.
- Within ATPs 1103 and 1031 there are small areas of IAA for the Moranbah Coal Measures and Rangal Coal Measures associated with proposed production testing in these tenures. There are no existing or useable bores located within these IAAs.
- There are no IAAs in any of the other aquifers (including Alluvial and Tertiary aquifers) modelled within the project area.

A water monitoring strategy has been prepared. The strategy proposes the installation and monitoring of a total of 43 groundwater monitoring bores. The installation of 16 of these groundwater monitoring bores, located on PLs 191, 196, 223 and 224 has been completed and groundwater monitoring has been ongoing within the bores. An additional 27 bores are proposed for groundwater monitoring of potential future impacts associated with the proposed Bowen Gas Project.

This report will be reviewed annually. The review will consider:

- new hydrogeological data that significantly alters the conceptual model;
- whether new production testing or production has been undertaken or is planned; and
- whether the predictions made have materially changed.

1 INTRODUCTION

1.1 Preamble

Pursuant to s. 370(3)(b) of the *Water Act 2000*, the chief executive of the Department of the Environment and Science (DES) directed Arrow Energy Pty. Ltd (Arrow) to submit a single Underground Water Impact Report (UWIR) for Petroleum Leases (PL) 191, 196, 223, and 224 and Authorities to Prospect (ATP) 1103, 1031, 831 and 742. The 2016 Bowen UWIR was approved with conditions by the DES, and took effect on 28 October 2016 (Reference 101/0017988-002).

This report forms the 2019 Bowen UWIR and provides information on the potential decline in water levels in aquifers due to the taking of water during coal seam gas (CSG) production and CSG production testing activities in Arrow's Bowen Basin tenure (detailed above), as required by the Water Act 2000. The relinquishment of ATP 831 at the end October 2018 requires a separate final report to be submitted to the chief executive and has therefore been excluded from this 2019 UWIR submission.

The Registered Holders of the tenures covered in this report are presented in the table below.

Table 1: Arrow's Tenements, Registered Holder details

Tenure	Registered Holder
PL191, PL196, PL223 and PL224	AGL Energy Limited ACN 115 061 375 (50%), CH4 Pty Ltd ACN 092 501 016 (35%) Arrow CSG (ATP 364) Pty Ltd ACN 092 970 557 (15%)
PL486	CH4 Pty Ltd - 70% Arrow CSG (ATP364) Pty Ltd - 30%
ATP 742	CH4 Pty Ltd ACN 092 501 016 (100%)
ATP 1031	Bow CSG Pty Ltd ACN 117156742 (100%)
ATP 1103	AGL Energy Limited ACN 115 061 375 (99%), CH4 Pty Ltd ACN 092 501 016 (0.7%) Arrow CSG (ATP 364) Pty Ltd ACN 092 970 557 (0.3%)

1.2 Project Area

Arrow's Bowen Basin tenure is the subject of both production wells (in PLs) and production testing activities (in ATPs) for CSG. The spatial distribution of Arrow's tenure in the Bowen Basin is shown in Figure 1 and spans the area, from north to south, around the towns of Glenden, Moranbah, Dysart, Middlemount, Saraji, Norwich, Essex and Dingo The Project Area includes:

- The Moranbah Gas Project (MGP) area (Arrow's existing production field) comprising PLs 191, 196, 223 and 224 and the following production between 2003 and 2018:
    - approximately 744 production testing and production wells distributed over 49,225 hectares,
    - an existing gathering system consisting of approximately 188 kilometres of easements containing gas and water gathering lines from the well heads to relevant gas compression and water storage facilities, and
    - 5 approved compressor facilities including the Moranbah Gas Processing Facility (MGPF) and the Node 1, 2, 3 and 4 compressor stations.

- The Bowen Gas Project (BGP) within which exploration and production testing has been undertaken comprise of ATPs 1103, 1031, and 742 and including:
    - Exploration and Testing within:
        - ATP 742 - including 3 wells used for production tests between 2015 and 2018;
        - ATP 1031 - including 6 wells used for production tests between 2012 and 2015;
        - ATP1103 - including 98 wells used for production testing wells between 2008 and 2015, 19 wells between 2015 and 2017, 11 wells in 2017 and 8 wells in 2018.
    - Future proposed development including:
        - Red Hill Central (PL486 within ATP1103) - including 31 wells to be used for production between 2019 to 2025
        - Mavis Downs (within ATP 1103) – including 17 production wells to be used for production between 2021 to 2030,
        - The remainder of the field development plan (FDP) presented in the 2016 Bowen UWIR (within ATPs1103, ATP742 and ATP1031) to include 1360 production wells between 2030 and 2060

The MGP and the BGP Areas are collectively referred to as the Project Area and shown in Figure 1.

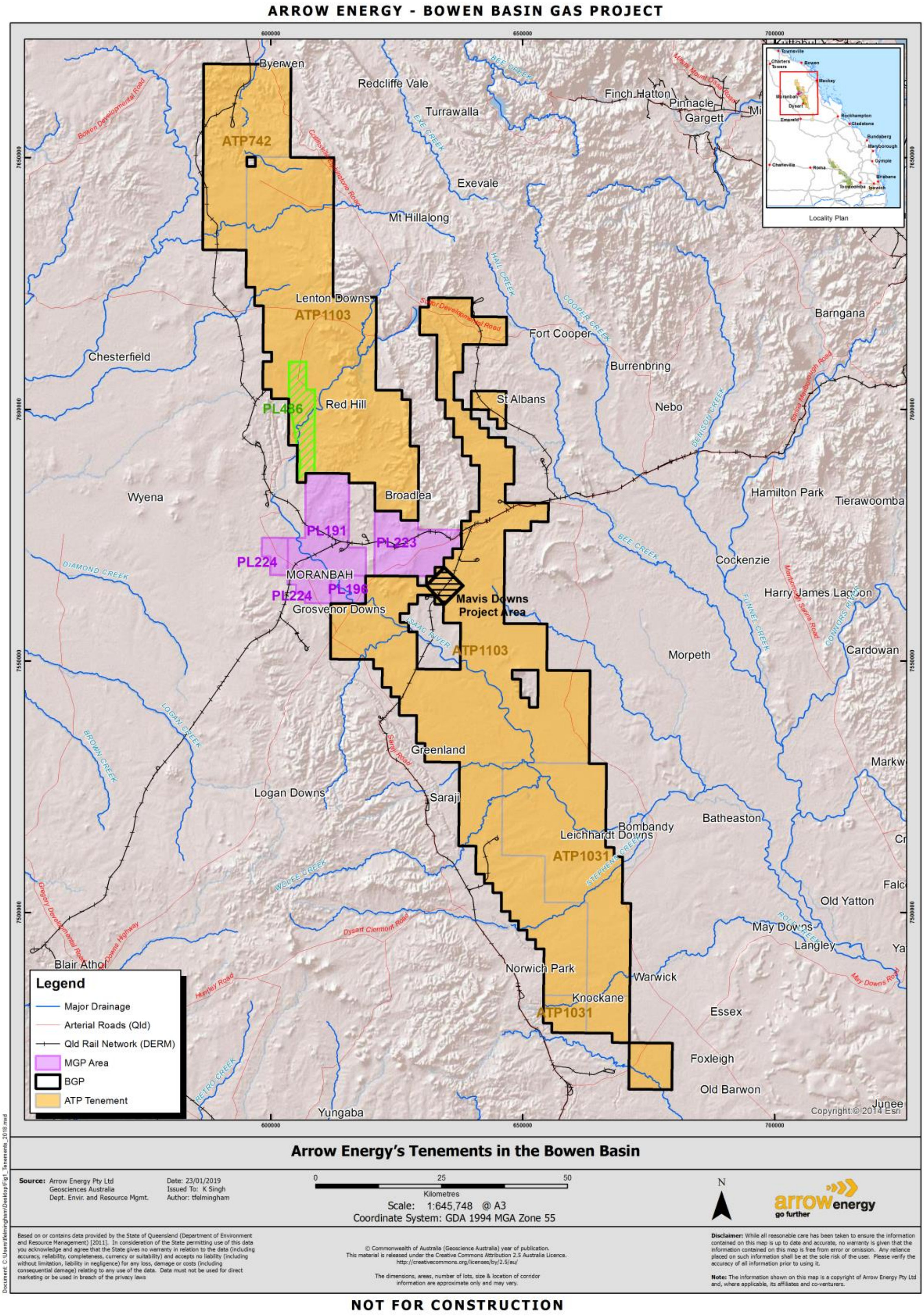


Figure 1: Arrow Energy's Tenements in the Bowen Basin

1.3 Requirement for a UWIR

1.3.1 *Cumulative Management Areas*

The chief executive of DES may declare a cumulative management area (CMA) in areas of concentrated CSG development where the impacts on water levels caused by individual petroleum and gas projects can overlap. In Queensland, the Surat CMA has been declared in the area of planned concentrated CSG development within the Surat basin.

Arrow's operations/project in the Bowen Basin falls outside of the Surat CMA, and under the Water Act (QLD) 2000, there is a requirement to prepare an UWIR. This requirement is addressed by this report.

1.3.2 *This UWIR*

This report forms the UWIR for Arrow's CSG activities in the Bowen Basin, including production and production testing wells, contained within the bounds of the combined tenure.

The purpose of this report is to address Chapter 3, and in particular, s376 of the Water Act (Qld) 2000 which stipulates that the UWIR must include:

a) For the area to which the report relates –
   i. The quantity of water produced or taken from the area because of the exercise of any previous relevant underground water rights; and
   ii. An estimate of the quantity of water to be produced or taken because of the exercise of the relevant underground water rights for a 3 year period starting on the consultation day for the report;

b) For each aquifer affected, or likely to be affected, by the exercise of the relevant underground water rights–
   i. A description of the aquifer; and
   ii. An analysis of the movement of underground water to and from the aquifer, including how the aquifer interacts with other aquifers; and
   iii. An analysis of the trends in water level change for the aquifer because of the exercise of the rights mentioned in paragraph (a)(i); and
   iv. A map showing the area of the aquifer where the water level is predicted to decline, because of the taking of the quantities of water mentioned in paragraph (a), by more than the bore trigger threshold within 3 years after the consultation day for the report; and
   v. A map showing the area of the aquifer where the water level is predicted to decline, because of the exercise of relevant underground water rights, by more than the bore trigger threshold at any time;

c) A description of the methods and techniques used to obtain the information and predictions under paragraph (b);

d) A summary of information about all water bores in the area shown on a map mentioned in paragraph (b)(iv), including the number of bores, and the location and authorised use or purpose of each bore;

e) A program for –
   i. Conducting an annual review of the accuracy of each map prepared under paragraph (b)(iv) and (v); and
   ii. Giving the chief executive a summary of the outcome of each review, including statement of whether there has been a material change in the information or predictions used to prepare the maps;

f) A water monitoring strategy;

g) A spring impact management strategy;

h) if the responsible entity is the office—
   i. a proposed responsible tenure holder for each report obligation mentioned in the report; and

    ii. for each immediately affected area—the proposed responsible tenure holder or holders who must comply with any make good obligations for water bores within the immediately affected area;.

i) Other information or matters prescribed under a regulation.

1.4 Legislation

The primary legislative requirements for the management and development of groundwater for Arrow's Bowen Basin activities are summarised below.

1.4.1 *Petroleum and Gas (Production and Safety) Act 2004 and Petroleum Act 1923*

The *Petroleum and Gas (Production and Safety) Act 2004* (P&G Act, 2004) and the *Petroleum Act 1923* regulate coal seam gas activities and also govern groundwater management in relation to CSG development. Under the P&G Act, the petroleum tenure holder may take or interfere with water if taking or interference happens during the course of, or results from, the carrying out of another authorised activity for the tenure. These rights are subject to the tenure holder complying with the holder's underground water obligations (defined in the *Water Act 2000*).

1.4.2 *Water Act 2000*

Chapter 3 of the *Water Act 2000* provides for the management of impacts on underground water caused by the exercise of underground water rights by petroleum tenure holders. This is achieved primarily by:

- providing a regulatory framework to:
    - require petroleum tenure holders to monitor and assess the impact of the exercise of underground water rights on water bores and to enter into 'make good' agreements with the owners of the bores;
    - requires the preparation of UWIRs that establish underground water obligations, including obligations to monitor and manage impacts on aquifers and springs;
    - manage the cumulative impacts from 2 or more petroleum tenure holders' underground water rights on underground water; and
- giving the chief executive and the office functions and powers for managing underground water.

If a water bore has an impaired capacity as a result of CSG activities, an agreement will be negotiated with the owner of the bore about the following:

- The reason for the bore's impaired capacity.
- The measures the holder will take to ensure the bore owner has access to a reasonable quantity and quality of water for the authorised use and purpose of the bore;
- Any monetary or non-monetary compensation payable to the bore owner for impact on the bore.

If an agreement relating to a water bore is made the agreement is taken to be a 'make good' agreement for the bore.

An UWIR will identify whether an 'immediately affected area' will result from CSG activities. An immediately affected area is defined as an area where the predicted decline in water levels within 3 years is at least:

- 5 m for a consolidated aquifer.
- 2 m for an unconsolidated aquifer.
- 0.2 m for a spring.

UWIRs are published to enable comments from bore owners within the area. Submissions made by bore owners will be summarised by Arrow, addressed as appropriate and provided to the DES. UWIRs are submitted for approval by DES. The OGIA may also advise DES about the adequacy of these reports.

The DES will maintain a database of information collected under monitoring plans carried out by petroleum tenure holders in accordance with approved UWIRs. The database will also incorporate bore baseline data collected by petroleum tenure holders.

1.5 Summary of Methods

This UWIR builds on information presented in the:

- UWIR for PLs 191, 196, 223, 224 (Arrow Energy, 2012a);
- UWIR for ATP 1103 (Arrow Energy, 2012b);
- Bowen Gas Project Environmental Impact Statement (EIS) (Arrow Energy, 2012c);
- UWIR for ATP 1031 (Arrow Energy, 2014a);
- Bowen Gas Project Supplementary Report to the EIS (Arrow Energy, 2014b);and
- UWIR for PL 191, 196, 223, 224 and ATP 644, 831, 742, 1031 and 1103 (Arrow Energy 2016)
- 2017 and 2018 Annual Reviews of the UWIR's for PL 191, 196, 223, 224 and ATP 644, 831, 742, 1031 and 1103

Since the development of the previous UWIRs for PLs 191, 196, 223, 224 and ATPs, 831, 742, 1103 and 1031, the conceptual understanding of groundwater occurrence and processes in the Project Area has been updated based on the collection and interpretation of the new data from site.

An assessment of impacts to groundwater from the aforementioned FDP was then undertaken based on the following tasks:

- Task 1: Review and analysis of site specific monitoring and assessment data
- Task 2: Hydrogeological assessment and conceptualisation
- Task 3: Numerical and Analytical groundwater model development for making predictions of groundwater impacts
- Task 4: Identification of potential impacts on groundwater
- Task 5: Review of the Water Monitoring Strategy (WMS) and Spring Impact Management Strategy (SIMP)

The continual improvement in understanding of the Bowen basin was incorporated into the 2018 groundwater model through a new mesh that allowed better discretisation of individual coal seams, representation of in-seam wells and inclusion of more hydraulic calibration data. This model was used to simulate the impacts of an updated FDP for the BGP in this UWIR.

A summary of the reporting requirements as stipulated in the Water Act 2000 for this UWIR and relevant sections of this report in which they have been addressed is included in Table 2 below.

Table 2: *Water Act 2000* reporting requirements for this UWIR

UWIR reporting requirement	**Report Section**
s376 a) For the area to which the report relates – i. The quantity of water produced or taken from the area because of the exercise of any previous relevant underground water rights; and	Section 2
ii. An estimate of the quantity of water to be produced or taken because of the exercise of the relevant underground water rights for a 3 year period starting on the consultation day for the report;	Section 2
b) For each aquifer affected, or likely to be affected, by the exercise of the relevant underground water rights– i. A description of the aquifer; and	Section 3
ii. An analysis of the movement of underground water to and from the aquifer, including how the aquifer interacts with other aquifers; and	Section 3, Section 4
iii. An analysis of the trends in water level change for the aquifer because of the exercise of the rights mentioned in paragraph (a)(i); and	Section 4
iv. A map showing the area of the aquifer where the water level is predicted to decline, because of the taking of the quantities of water mentioned in paragraph (a), by more than the bore trigger threshold within 3 years after the consultation day for the report; and	Section 7
v. A map showing the area of the aquifer where the water level is predicted to decline, because of the exercise of relevant underground water rights, by more than the bore trigger threshold at any time;	Section 7
c) A description of the methods and techniques used to obtain the information and predictions under paragraph (b);	Section 1, Section 4, Section 7
d) A summary of information about all water bores in the area shown on a map mentioned in paragraph (b)(iv), including the number of bores, and the location and authorised use or purpose of each bore;	Section 7
e) A program for – i. Conducting an annual review of the accuracy of each map prepared under paragraph (b)(iv) and (v); and	Section 10
ii. Giving the chief executive a summary of the outcome of each review, including statement of whether there has been a material change in the information or	Section 6, Section 7

UWIR reporting requirement	Report Section
predictions used to prepare the maps;	
f) A water monitoring strategy;	Section 8
g) A spring impact management strategy;	Not applicable to the Project Area. Refer to Section 9
h) If the responsible entity is the commission – i. A proposed responsible tenure holder for each report obligation mentioned in the report; and	Not applicable to the Project Area
ii. For each immediately affected area (IAA) – the proposed responsible tenure holder or holders who must comply with any make good obligations for water bores within the IAA;	Not applicable to the Project Area
i) Other information or matters prescribed under a regulation.	No matters identified
s378 1(a) Water Monitoring Strategy i. Strategy for monitoring the quantity of water produced	Section 8, Section 4
ii. Strategy for monitoring changes in water level	
b) Rationale for the strategy	
c) Timetable for implementing the strategy	
d) Program for reporting the implementation of the strategy	
2 Strategy must include:	
a) The parameters to be measured	
b) Locations for taking the measurements	
c) Frequency of the measurements	
3 A program for a baseline assessment for each bore that is:	
a) Outside the tenure, within an immediately or long term affected area b) within the area shown on the map prepared under section 376(b)(v)	

2 EXISTING AND FORECAST WATER PRODUCTION

Historical water production data since the last UWIR has been compiled for the production and production testing wells to provide an indication of the quantity of water taken and allow for comparison against the modelled historical and forecast volumes for the Project Area.

The volumes of water produced from the wells were measured using progressive cavity pumps (PCPs) in the gas production and production testing (appraisal) wells. These pumps work by rotating an eccentric screw which pushes the inflowing water in the well upwards. Consequently, the pumping rate (expressed as a volume/time)is proportional (based on an 'efficiency factor') to the rate of rotation of the pump i.e. there is a direct correlation between a given number of revolutions per minute (rpm) and a corresponding pumping rate. A flow test is undertaken to calculate the volume of water produced from the PCPs i.e. the pump rate and time for a known volume of water to be pumped is used to calculate the 'efficiency factor'. This is applied to a record of the pumps operating rpm to calculate the volume of water pumped. Flow tests are undertaken regularly to maintain the accuracy of the flow calculation. In addition, the total volume of water pumped into the dam constructed to hold the pilot test water is used as a check on this calculation.

Forecasts of water production were collated for the Project Area. Production data are provided for each tenure in the following sections.

2.1 Existing Water Production Summary – MGP Area

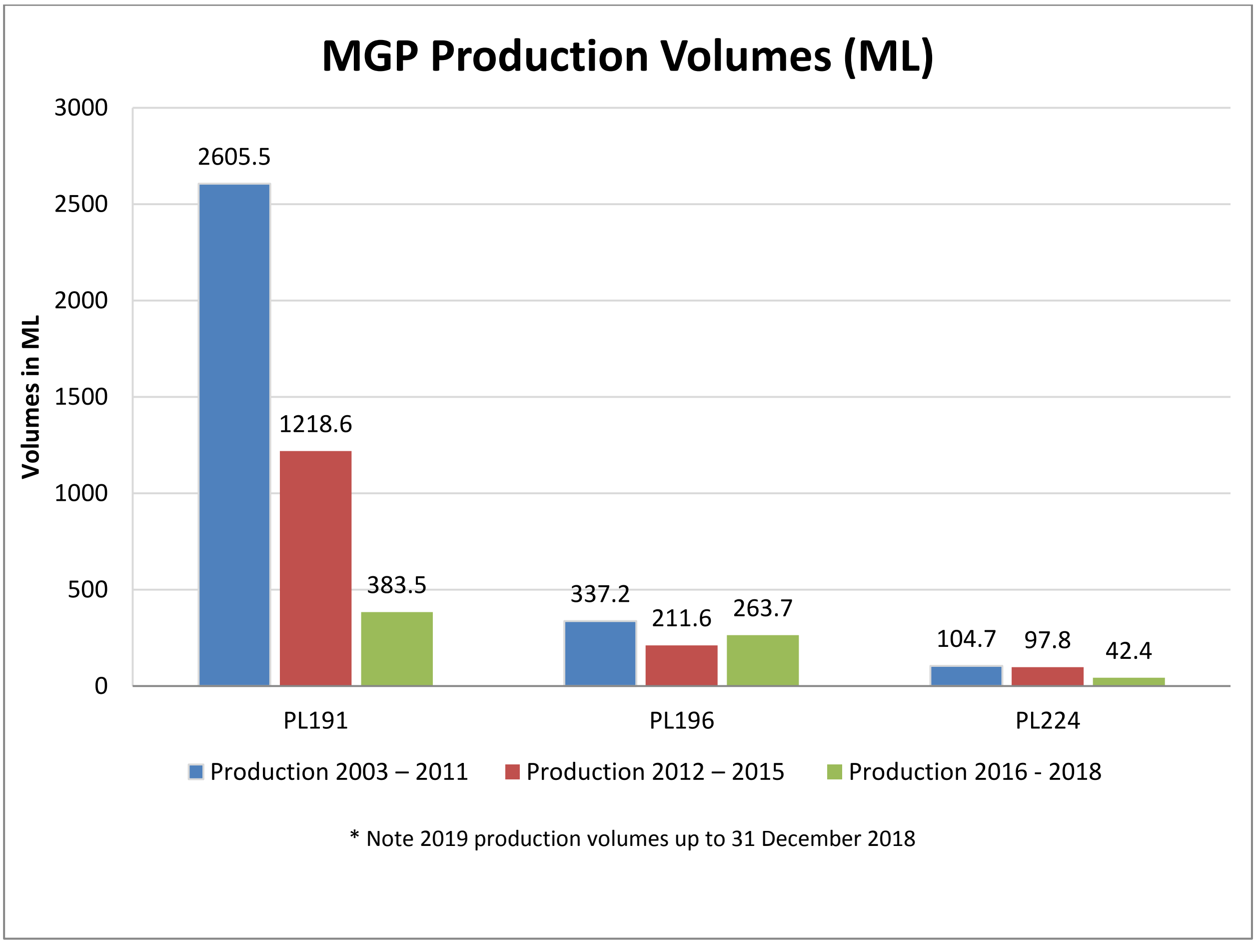
The total volume of water taken from each PL for the period of 1 January 2016 to 31st December 2018 (hereafter referred to as the 'UWIR reporting period) in the MGP Area during production and production testing is presented in Table 3 along with historical water production rates. It should be noted that whilst PLs 191, 196, 223 and 224 make up the MGP, production has only been undertaken in PLs 191, 196 and 224.

Table 3: Historical water production and production testing data

Tenure	Formation	Production 2003 – 2011	Production 2012 – 2015	Production 2016 - 2018	Production Testing 2003 – 2011	Production Testing 2012 – 2015	Production Testing 2016 – 2018
		Volume (ML)	Volume (ML)	Volume (ML)	Volume (ML)	Volume (ML)	Volume (ML)
PL191	GM Seam	1439.4	697.9	230.2	0	0	0
	P Seam	1038.5	421.2	117.4	0	0	0
	Q Seam	22.2	0	6.3	0	0	2.7
	Moranbah Coal Measures (GM, P, GML, Q Seams)	105.4	99.5	29.6	4.5	30.2	0
	Fort Cooper Coal Measures and Moranbah Coal Measures	0	0	0	29	0	0
PL196	GM Seam	77.9	73.1	39.2	0	0	0
	P Seam	127	14.4	0.0	0	0	0
	Moranbah Coal Measures (GM, P, GML, Q Seams)	132.3	124.1	224.5	0	0	0
PL223	FG1 Seam	0	0	0	2.8	0	0
	Rangal Coal Measures	0	0	0	0	0.4	0
PL224	GM Seam	55.9	42.8	13.6	0	0	0
	P Seam	6.6	12.1	3.2	0	0	0
	Moranbah Coal Measures (GM, P, GML, Q Seams)	42.2	42.9	25.7	0	0	0
CUMULATIVE TOTAL		**3047.4**	**1528.0**	**689.7**	**36.3**	**30.6**	**2.7**

As indicated in Table 3, the water production in the UWIR reporting period totalled 689.7ML from production and 2.7ML from production testing. This is less that the previously (in the 2016 UWIR) forecast production for the period 2016 to 2018 of 762ML.

The water production data has been plotted in Figure 2 to illustrate the proportion of water extracted historically from the petroleum leases that make up the MGP. As indicated in Table 3 and graphically presented in Figure 2, the water production volumes in the PL's have steadily decreased over the reporting period with the exception of PL196, increasing by 39ML.



* Note 2019 production volumes up to 31 December 2018

Figure 2: Water produced from production wells on PL191, PL196 and PL224

2.2 Forecast Water Production – MGP Area

The methodology for forecasting water production for the MGP is based on a Decline Curve Analysis (DCA). DCA uses historical production from existing wells to produce a type curve used to forecast water production in proposed wells. DCA involves matching the profile of water production with an empirical set of equations. These equations predict the long term behaviour of the well. They are widely used in the coal seam gas industry as wells of all types tend to follow these trends. This has proven a reliable method in both gas and water production prediction in the project area given the nature of the production trend. The accuracy of the prediction is subject to uncertainties in the measurement and reporting of the historical water rates.

A forecast of the quantity of water to be produced for the next 3 years (2019-2021 inclusive) has been prepared for the MGP (PL191, PL196 and PL224). In addition to this, a modelled forecast of production has been provided up until 2025.

Field development of PLs 191, 196 and 224 are on-going and any updates to the forecast production will be incorporated into future annual review reporting.

The MGP water production forecast for the next 3 years (UWIR reporting interval) commencing 01/01/2019 totals 634 ML and the water production forecast from 2019 to 2025 totals 1387.5 ML. The MGP is forecast to remain operational until end 2025. No future production testing has been earmarked for the MGP.

Table 4: Forecast water production data for the MGP

Year	Total Forecast Water production (ML)
2019	218.5
2020	211.5
2021	203.8
2022	197.2
2023	191.0
2024	185.7
2025	179.7
Total	**1387.5**

2.3 Water Production Summary – BGP Area

Historical water production data for the production testing wells on ATP 742, 1031 and 1103 is summarised in Table 5 to Table 7. The production testing cumulative volume of water over the period totals approximately 326.13 ML of water.

2.3.1.1 ATP 742

Water production testing data is presented in Table 5. No production testing has been carried out since 31 Dec 2017.

Table 5: Summary of Production Testing in ATP 742

Well Name	Date Start	Date End	Total days of water production	Average Flow kL/day	Cumulative Flow (ML)	Target Formation
CE010V	09-Apr-15	31-Dec-17	457	7.428	1.103	Moranbah Coal Measures
Newlands 10	15-Jun-15	31-Dec-17	599	8.318	1.583	Moranbah Coal Measures
Byerwen 3	09-Feb-15	21-Dec-16	616	0.766	0.206	Moranbah Coal Measures
Total (ML)					**2.892**	

2.3.2 *ATP 1031*

Water production testing data is presented in Table 6. No production testing has been carried out since 19 June 2015 i.e. in the current UWIR reporting period.

Table 6: Summary of Production Testing in ATP 1031

Well Name	Date Start	Date End	Total days of water production	Average Flow kL/day	Cumulative Flow (ML)	Target Formation
PY031	29-Jul-13	25-Sep-14	27	3.700	1.390	Rangal Coal Measures
VM010V	07-Nov-13	02-Nov-14	354	30.830	7.830	Rangal Coal Measures
VM011V	07-Nov-13	14-Nov-14	365	15.480	5.650	Rangal Coal Measures
PY030	20-Dec-12	06-Dec-14	38	1.030	0.550	Rangal Coal Measures
PY012A	10-Jun-15	19-Jun-15	7	0.360	0.003	Rangal Coal Measures
PY011A	13-Jun-15	19-Jun-15	1	0.140	0.00014	Rangal Coal Measures
Cumulative Total (ML)					**15.423**	

2.3.3 *ATP 1103*

The review of production testing undertaken on ATP 1103 is summarised below in Table 7and includes actual production testing volumes up to 31st December 2018.

Table 7: Summary of Production Testing in ATP 1103

Bore Name	Date Start	Date End	Average Flow kL/day	Cumulative Flow (ML)	Target Formation
HY001	29-Nov-08	23-Apr-09	1.801	0.243	Rangal Coal Measures
MB05V	12-Nov-08	10-Jul-09	0.438	0.122	Moranbah Coal Measures
MB04V	12-Nov-08	26-Aug-09	0.148	0.0411	Moranbah Coal Measures
MB06	12-Nov-08	26-Aug-09	0.245	0.068	Moranbah Coal Measures
MB07V	12-Nov-08	27-Aug-09	0.118	0.032	Moranbah Coal Measures
MB03V	12-Nov-08	27-Aug-09	0.213	0.059	Moranbah Coal Measures
HY01	23-Apr-09	28-Aug-09	1.906	0.244	Rangal Coal Measures
HY02	18-Nov-08	28-Aug-09	0.498	0.136	Rangal Coal Measures
SRJ001	29-Jun-09	3-Mar-10	23.183	6.653	Moranbah Coal Measures
SRJ002	29-Jun-09	4-Mar-10	20.525	5.911	Moranbah Coal Measures
SRJ003	29-Jun-09	4-Mar-10	45.644	12.186	Moranbah Coal Measures
RHGU020	26-Aug-09	24-Apr-10	3.669	0.88	Moranbah Coal Measures
RHGU019	26-Aug-09	19-Jul-10	2.073	0.665	Moranbah Coal Measures
LW006	3-Aug-09	6-Aug-10	23.68	4.973	Moranbah Coal Measures
LW007	3-Aug-09	14-Aug-10	32.96	8.337	Moranbah Coal Measures
LW005	3-Aug-09	15-Aug-10	24.65	6.77	Moranbah Coal Measures
COX10	4-Nov-09	4-Oct-10	16.223	3.342	Rangal Coal Measures
RHGU001	12-Nov-08	8-Oct-10	7.19	5.529	Moranbah Coal Measures
RHGU002	14-Dec-08	1-Nov-10	20.363	15.008	Moranbah Coal Measures
RH014GL1	29-Dec-08	3-Nov-10	4.297	3.081	Moranbah Coal Measures
COX016	19-May-10	25-Jan-11	7.467	1.067	Rangal Coal Measures
RH013GL1	19-Mar-09	30-Jan-11	0.834	0.566	Moranbah Coal Measures
WW019	22-Dec-09	31-Jan-11	1.79	0.816	Moranbah Coal Measures
WW020	19-Dec-09	31-Jan-11	3.522	1.641	Moranbah Coal Measures
WW023	24-Aug-10	31-Jan-11	3.052	0.656	Fort Cooper Coal Measures

Bore Name	Date Start	Date End	Average Flow kL/day	Cumulative Flow (ML)	Target Formation
SC006LC	28-Sep-09	31-Jan-11	3.034	1.541	Rangal Coal Measures
RHGM008	11-Nov-08	1-Feb-11	4.182	3.358	Moranbah Coal Measures
RHGM009	11-Nov-08	1-Feb-11	2.165	1.791	Moranbah Coal Measures
SC007LC	30-Sep-09	9-Feb-11	1.654	0.889	Rangal Coal Measures
SC008LC	28-Sep-09	24-Mar-11	2.461	1.299	Rangal Coal Measures
RHGU003	11-Nov-08	24-Feb-11	5.248	4.009	Moranbah Coal Measures
RH015GL1	29-Dec-08	24-Mar-11	4.877	3.823	Moranbah Coal Measures
KC008	3-Jul-10	24-Mar-11	4.792	1.509	Rangal Coal Measures
KC009	2-Jul-10	24-Mar-11	0.528	0.134	Rangal Coal Measures
WW018	12-Dec-09	31-Mar-11	16.262	7.659	Moranbah Coal Measures
WW021	28-Aug-10	24-Apr-11	12.875	2.678	Fort Cooper Coal Measures
COX11	4-Nov-09	24-May-11	7.051	3.032	Rangal Coal Measures
SRJ020	10-May-10	24-May-11	1.562	0.834	Moranbah Coal Measures
COX018	21-Apr-10	24-May-11	10.427	3.659	Rangal Coal Measures
RHGM007	11-Nov-08	2-Jun-11	2.987	2.643	Moranbah Coal Measures
SRJ021	25-May-10	12-Jun-11	2.434	1.273	Moranbah Coal Measures
RH023GL	9-Apr-10	4-Aug-11	4.503	2.075	Moranbah Coal Measures
RH027GU	18-Apr-10	11-Aug-11	5.788	3.131	Moranbah Coal Measures
SRJ019	10-May-10	6-Sep-11	1.155	0.63	Moranbah Coal Measures
RH022GL	9-Apr-10	16-Sep-11	5.943	3.411	Moranbah Coal Measures
RH024GL	9-Apr-10	16-Sep-11	1.709	0.977	Moranbah Coal Measures
RH025GU	10-Apr-10	3-Oct-11	4.928	2.651	Moranbah Coal Measures
RHGM35	1-Sep-11	15-Nov-11	4.191	0.318	Moranbah Coal Measures
RHGM035	14-Oct-09	24-Jan-12	6.297	5.219	Moranbah Coal Measures
COX019	10-Jun-10	23-Jun-12	4.922	2.912	Rangal Coal Measures
COX020	9-Jun-10	30-Jun-12	5.209	3.089	Rangal Coal Measures
COX021	10-Jun-10	23-Jun-12	5.364	3.261	Rangal Coal Measures
RH014	27-Apr-12	11-Sep-12	6.378	0.739	Moranbah Coal Measures
RH026GU	18-Apr-10	20-Dec-12	5.422	5.29	Moranbah Coal Measures
WW015F	19-Apr-12	16-Feb-13	4.517	1.151	Fort Cooper Coal Measures
PD141V	16-Feb-13	15-Mar-13	2.928	0.079	Moranbah Coal Measures
WW016F	19-Apr-12	15-Apr-13	2.721	0.821	Fort Cooper Coal Measures
RH031F	29-Oct-11	16-Apr-13	5.693	1.837	Fort Cooper Coal Measures
RH033F	1-Nov-11	16-Apr-13	2.461	0.936	Fort Cooper Coal Measures
RH028F	17-Nov-11	21-Apr-13	6.152	1.925	Moranbah Coal Measures
RH030F	16-Nov-11	25-May-13	1.896	0.544	Moranbah Coal Measures
CX014V	24-Jul-13	11-Nov-13	3.934	0.436	Rangal Coal Measures
RH080A	4-Jul-13	8-Jan-14	1.062	0.118	Moranbah Coal Measures
CX013V	24-Jul-13	31-Mar-14	6.426	1.088	Rangal Coal Measures
NP041V	6-Dec-13	29-Jun-14	3.947	0.572	Moranbah Coal Measures
OD011F	5-Aug-13	8-Jul-14	2.896	0.988	Rangal Coal Measures
OD012F	5-Aug-13	8-Jul-14	1.175	0.41	Rangal Coal Measures
PD131V	8-Jul-13	12-Jul-14	5.528	1.631	Moranbah Coal Measures
OD021F	18-Mar-13	11-Aug-14	0.849	0.487	Rangal Coal Measures
OD022F	16-Mar-13	11-Aug-14	0.964	0.57	Rangal Coal Measures
EF032V	17-Aug-13	30-Aug-14	3.161	1.161	Rangal Coal Measures
WB010LCV	31-May-13	25-Sep-14	9.359	4.442	Rangal Coal Measures
EF031V	15-Sep-13	15-Oct-14	16.387	6.536	Rangal Coal Measures
PD091V	1-Jun-13	3-Nov-14	13.852	7.039	Moranbah Coal Measures
WB011LCV	30-May-13	26-Nov-14	1.007	0.543	Rangal Coal Measures
PD100V	10-Jun-14	31-Dec-16	10.812	3.836	Moranbah Coal Measures

Bore Name	Date Start	Date End	Average Flow kL/day	Cumulative Flow (ML)	Target Formation
PD130V	8-Jul-13	11-Feb-15	13.072	6.575	Moranbah Coal Measures
PD140V	15-Feb-13	19-Feb-15	5.386	3.899	Moranbah Coal Measures
NP040A	6-Dec-13	15-Jun-15	5.506	1.53	Moranbah Coal Measures
PD111V	11-Jun-14	31-Dec-17	17.246	5.201	Moranbah Coal Measures
CX101	7-Nov-13	18-Aug-15	4.944	2.536	Rangal Coal Measures
MD040V	29-Sep-13	23-Aug-15	9.502	5.178	Rangal Coal Measures
MD041V	30-Sep-13	17-Sep-15	11.379	6.463	Rangal Coal Measures
EF061V	15-Apr-14	31-Dec-16	0.941	0.377	Rangal Coal Measures
PD122V	22-Jun-13	31-Dec-16	36.426	11.124	Moranbah Coal Measures
CX100	4-Nov-13	31-Oct-15	6.352	2.648	Rangal Coal Measures
EF060V	4-May-14	31-Dec-16	3.575	1.501	Rangal Coal Measures
PD120V	22-Jun-13	31-Dec-16	22.853	10.173	Moranbah Coal Measures
RH051F	10-Sep-13	12-Sep-18	12.922	2.293	Moranbah Coal Measures
CX090V	21-Jul-14	31-Dec-16	16.084	6.046	Rangal Coal Measures
CX091V	15-May-14	31-Dec-16	11.005	2.232	Rangal Coal Measures
PD101V	22-Jun-14	31-Dec-16	4.374	1.786	Moranbah Coal Measures
PD110V	9-Jun-14	31-Dec-17	17.947	6.119	Moranbah Coal Measures
RH050F	10-Sep-13	31-Dec-17	15.777	1.980	Moranbah Coal Measures
RH052F	10-Sep-13	31-Dec-17	12.253	2.134	Moranbah Coal Measures
RH100A	28-May-18	28-Jun-18	2.000	0.002	Moranbah Coal Measures
RH098A	28-May-18	06-Aug-18	3.667	0.120	Moranbah Coal Measures
RH099A	28-May-18	20-Aug-18	4.857	0.395	Moranbah Coal Measures
RH060F	01-Jan-18	27-May-18	0.190	0.019	Moranbah Coal Measures
RH061F	20-Nov-15	31-Dec-17	6.640	0.939	Moranbah Coal Measures
RH062F	20-Nov-15	27-May-18	5.291	0.601	Moranbah Coal Measures
PD032F	01-Apr-15	31-Dec-17	5.040	0.974	Moranbah Coal Measures
PD033F	01-Apr-15	31-Dec-17	11.030	1.540	Moranbah Coal Measures
PD034F	01-Apr-15	31-Dec-17	7.286	0.362	Moranbah Coal Measures
Cumulative Total (ML)				**307.815**	

* Numbers have been updated to reflect the latest data

The table above provides the extraction volumes from the 104 individual production testing wells and include an additional 3 new production testing wells (Redhill Area) have been brought online and production was discontinued in 13 wells.

2.4 Forecast Appraisal Program in BGP Area

No new production testing has been planned for ATP 742 and 1031. Additional production testing is being considered for ATP 1103, subject to additional geological appraisal and evaluation. However, proposed locations and schedules for production testing, should it proceed, have not yet been determined. Forecasts for future production testing volumes can therefore not be provided.

The extent of impact for production testing has been assessed based on both the performance of historical production tests and simulation of historical production testing.

The production test with the greatest water production recorded was from the production testing wells in the Peak Downs area (reported as the Peak Downs IAA area in 2018 Annual Review) which reported a total of 26.7ML water production between 2013 and 2015. The simulation (2016 UWIR) indicated the 5 m drawdown contour extended up to 1 km from this production test. Actual water production from each production testing well in the annual review data capture period will be compared to the Peak Downs IAA site. If actual water production in the production testing well in the annual review data capture period is equal to or less than the Peak Downs IAA site, then it will be assumed that any resultant IAA would be equal to or less than the Peak Downs IAA site. If water production in the production testing well in the annual review data capture period is greater than the Peak Downs IAA site, then a review of the 1m drawdown contour will be undertaken to identify any existing or abandoned but useable landholder water supply bores that may be at risk of impact.

The impact of any future water production as part of production testing will be reviewed as part of the annual review in accordance with this methodology.

2.5 Bowen Gas Project

Arrow's proposed BGP involves a phased expansion of Arrow's CSG production in the Bowen Basin. It comprises an update of development plans in the same general areas (i.e. within tenements ATP742, ATP1103, and ATP1031) from those presented in the Supplementary Report to the Environmental Impact Statement (SREIS) with the addition of development in Mavis Downs (also located within ATP1103). The project, as described in the 2016 Bowen UWIR, included development in 3 phases (1, 2 and 3). The groundwater modelling undertaken for the 2016 Bowen UWIR simulated phase 1, 2 and 3 of the BGP (with associated water production of 116 GL) occurring over 30 years commencing 2019 (and continuing to 2049). This production has been revised and the 2019 Bowen UWIR is based on an updated FDP as follows:

- Red Hill Central (PL486 within ATP 1103) commencing 2019
- Mavis Downs (within ATP1103) commencing 2021
- The remainder of the field development plan (FDP) area presented in the 2016 Bowen UWIR (ATP1103, ATP742 and ATP1031) commencing 2030

A forecast of the quantity of water to be produced against respective project timelines for the BGP FDP has been prepared and discussed below:

- Red Hill Central lies within the footprint of BGP development case and is located approximately 30 km north of the township of Moranbah, and borders the MGP area to the south. Water production from Red Hill Central is currently forecast to occur from 2019 to 2025, with a total of 875 ML of water to be produced.
- The Mavis Downs development is located to the south of PL223 in a comparatively mature area in ATP 1103, approximately 24 km east of the township of Moranbah. This development borders the MGP to the west. Mavis Downs production is currently forecast to occur from 2021 to 2030, with a total of 673 ML of water to be produced.
- Production from the remainder of the FDP area, tentatively planned from 2030 to 2060, will comprise 1,360 wells and total water production of 80.7 GL.

Table 8: FDP Comparison

Table 8: FDP Comparison

FDP		Number of wells	Water production		Timing	
			Total (GL)	Peak (GL)	Start	End
SREIS BGP FDP		4000	153	10.4	2019	2049
BGP FDP	Red Hill Central	31	0.88	0.16	2019	2025
	Mavis Downs	17	0.67	0.097	2021	2030
	Remainder of the FDP	1360	80.7	3.80	2030	2060
	Total	**1408**	**82.25**	**4.057**	**2019**	**2060**

Figure 3 below shows the forecast water production as per the FDP.

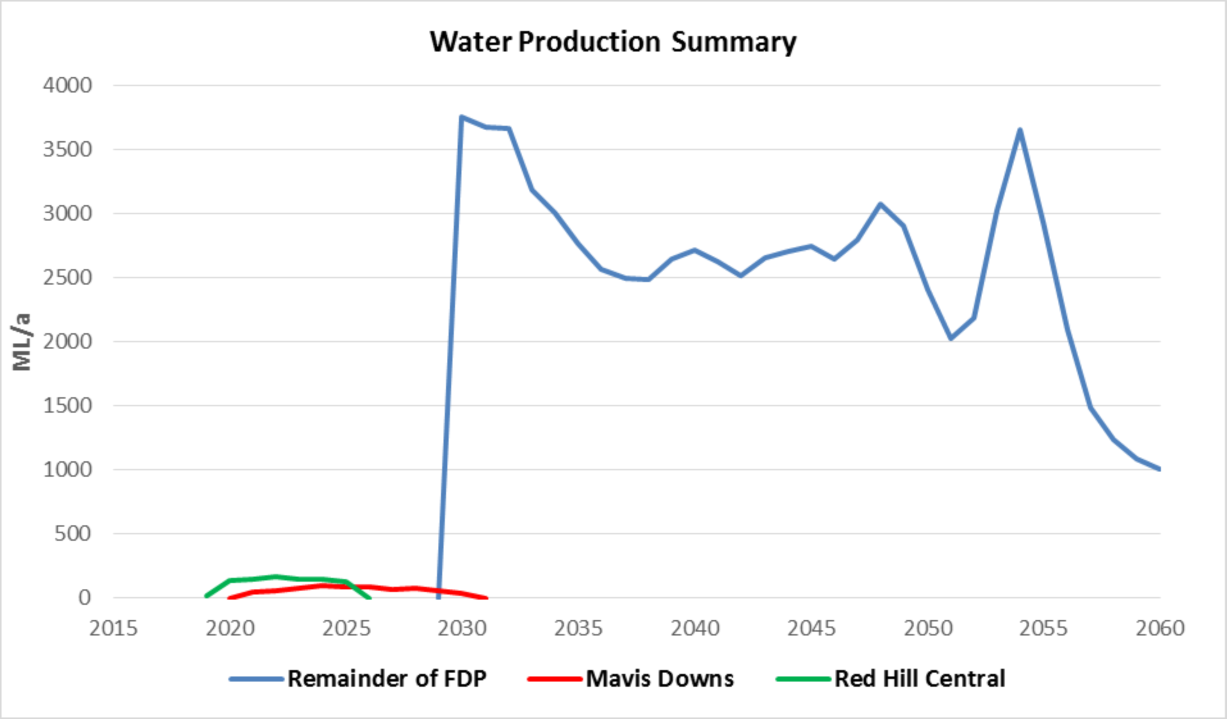


Figure 3: BGP FDP Water Production

3 EXISTING CONCEPTUAL MODEL

The conceptual hydrogeological model was described in the previous UWIRs for PLs 191, 196, 223, 224 (Arrow Energy, 2012a), ATPs 1103 (Arrow Energy, 2012b), 1031 (Arrow Energy, 2014a) and the 2016 UWIR. This was based predominantly on a desktop review of available groundwater related data including data from neighbouring coal mines, hydrogeological reports and records obtained from the DES and DNRME.

Since then an EIS (Arrow Energy, 2012c) and SREIS (Arrow Energy 2014b) were prepared for the BGP. The geological and hydrogeological setting of the Project Area was described in detail in the Bowen Gas Project EIS and SREIS groundwater chapters. A summary of the conceptual hydrogeological model (Figure 9), including geology and aquifers is provided in the following sections.

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3.1 Geological Summary

The Bowen Basin covers an area of approximately 200,000 km^2, and spans over 600 km from Collinsville in the north to Rolleston in the south. It contains a sedimentary sequence of Permo-Triassic clastics, which attain a maximum thickness of 9,000 m in the depocentre of the Taroom Trough.

Deposition in the Bowen Basin commenced during an Early Permian extensional phase, with fluvial and lacustrine sediments and volcanics being deposited in a series of half-grabens in the east while in the west a thick succession of coals and non-marine clastics were deposited. Following rifting there was a thermal subsidence (sag) phase extending from the Early to Late Permian, during which a basin-wide transgression allowed deposition of deltaic and shallow marine, predominantly clastic sediments as well as extensive coal measures. Foreland loading of the basin spread from east to west during the Late Permian, resulting in accelerated subsidence, which allowed the deposition of very thick successions of Late Permian marine and fluvial clastics, again with coal and Early to Middle Triassic fluvial and lacustrine clastics. Sedimentation in the basin was terminated by the Middle to Late Triassic (Geoscience Australia 2008).

The surface geology mapped across the Project Area is diverse (Figure 4). Approximately half of the Project area is covered by Late Tertiary and Quaternary unconsolidated sediments. This cover includes the Isaac River alluvial sediments, with thicknesses of 10 to 50 m along the Isaac River. The characteristics of the superficial Quaternary alluvium reflect the nature of the source rocks, weathering, transport, and depositional conditions. Poorly sorted clay, silt, sand and gravel represent floodplain alluvium: locally mottled, poorly consolidated sand, silt, clay and minor gravel, generally dissected by high-level alluvial deposits reflect present stream valleys.

The Tertiary sediment cover includes thick, clay-rich laterite, a result of the laterisation of Permian units during the Tertiary period. In addition, Tertiary aged infill includes palaeochannel deposits and basalt flows provide surficial cover across the Project area. The major Tertiary formations mapped in the Project area include the Duaringa and Suttor formations.

Outcrops of consolidated formations are confined mainly to the northern portion of the Project area. The consolidated formations represented in surface outcrops include: the Late Permian Blackwater Group (Fort Cooper Coal Measures, Moranbah Coal Measures and Rangal Coal Measures) in the northernmost and north-eastern portion of the Project area; the mid-Triassic Moolayember Formation and Clematis Sandstone in the north-central portion of the Project area, and the Early Triassic Rewan Group can be found the northern portion of the Project area.

The stratigraphy of the Bowen Basin is summarised in Table 9. The Late Permian Blackwater Group comprises (from oldest to youngest) the Moranbah Coal Measures (MCM), the Fort Cooper Coal Measures (FCCM), and the Rangal Coal Measures (RCM).

Table 9: Regional Stratigraphy Bowen Basin

Quaternary	Alluvium Alluvium, colluvium and other sediments in floodplains, alluvial fans, and high terraces				Clay, silts, sand, gravel, floodplain alluvium
Tertiary	Suttor Formation				Clay, silt, sand, gravel, colluvium, fluvial and lacustrine deposits including cross-bedded quartz sandstone, conglomerate, claystone
	Basalt				Olivine rich weathered basaltic sands, weathered basalt, and fresh basalt flows
	Duaringa Formation				Mudstone, sandstone, conglomerate, siltstone, oil shale, lignite and basalt
Triassic	Mimosa Group		Moolayember Formation		Mudstone, lithic sandstone, interbedded siltstone, mudstone, sandstone and thin coal seams.
			Clematis Sandstone		Cross-bedded quartz sandstone, some quartz conglomerate and minor red-brown mudstone.
			Rewan Formation		Green lithic sandstone, pebble conglomerate, red and green mudstone
Permian	Late	Blackwater Group	Rangal Coal Measures		Coal seams, carbonaceous shale and mudstone, tuff, siltstone and mudstone
			Fort Cooper Coal Measures	Burngrove Formation	Coal, brown and green sandstone, conglomerate, carbonaceous shale, tuff
				Fairhill Formation	Labile sandstone, quartzose sublabile sandstone, siltstone, mudstone, calcareous and tuffaceous sandstone, volcanic conglomerate, carbonaceous mudstone, coal
			Moranbah Coal Measures	MacMillan Formation	Quartzose to sublabile, locally argillaceous sandstone, siltstone, mudstone, carbonaceous mudstone and coal
				German Creek Formation	
	Early to Middle	Back Creek Group			Quartzose to lithic sandstone, siltstone, carbonaceous shale, minor coal and sandy coquinite

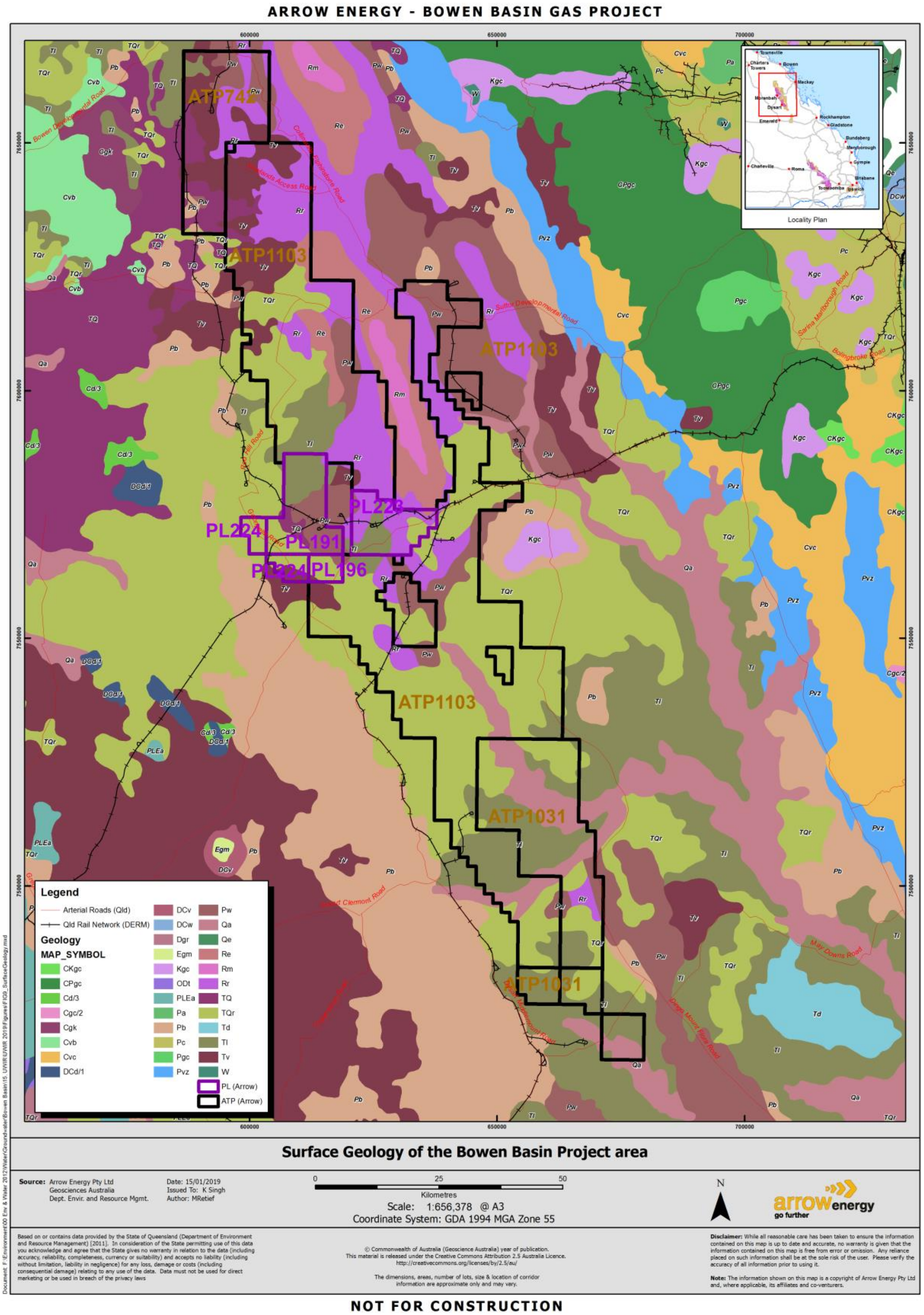


Figure 4: Surface Geology of the Bowen Basin

3.1.1 *Target Geological Formations*

The principal target within the Project Area has traditionally been the MCM. Production testing has also targeted the RCM. Testing of the FCCM has shown net coal thicknesses of coal of up to 50 metres, some with high methane content.

3.1.1.1 Moranbah Coal Measure Targets

The MCM form part of the Late Permian "Group III" coals deposited in the third and final phase of the formation of the Bowen Basin. The MCM consist of coals, sandstones, siltstones and mudstones and average from 250 m to 300 m in thickness. They are characterised by several laterally persistent, relatively thick coal seams interspersed with several thin minor seams. The predominant target seams in order of importance are the GM, P and QA2 seams. The typical thicknesses of these seams are:

- The Q seam is split into three main plies, the QA1 (3.5 m thick), QA2 (3 m thick), and QB (1.75 m thick).
- The P seam is the second most targeted source of coal seam methane within the MGP Area. The P seam consists of 3 plies, the GR (3 m thick), PL1 (1.5 m thick), PL2 (0.5 m thick) and averages about 5 m in total thickness.
- The GM seam is the primary target seam within the Project Area. The seam averages 5 m in thickness but thins towards the southeast as a result of seam splitting.
- The Goonyella Middle Lower (GML) seam also forms part of the MCM and in relatively small local pockets, the seam can reach thicknesses of up to 6.5 m.

3.1.1.2 Fort Cooper Coal Measure Targets

The FCCM conformably overlies the MCM and are approximately 400 m thick. Along with the coal seams, sediments of the FCCM include green lithic sandstone, conglomerate, mudstone, carbonaceous, shale, coal, and thin beds of greyish white cherty tuff containing abundant leaf impressions (Jensen, 1968). The FCCM are characterised by up to seven formations (6 – 60 m thick) rich in carbonaceous mud and thin coal seams, and its distinctive tuff beds. These formations are interbedded with 10 m to 30 m thick siltstone and sandstone sequences. The potential target seam of the FCCM is the Girrah Seam. This seam marks the roof of the FCCM (Burngrove Formation) and is one of the few identifiable horizons. The seam is approximately 30 m in thickness with numerous stone bands and a notable radioactive tuff band.

3.1.1.3 Rangal Coal Measure Targets

The final phase of coal deposition in the Bowen Basin in the Late Permian resulted in the formation of Group IV coals. These include, from north to south, the Rangal Coal Measures, Baralaba Coal Measures and the Bandanna Formation. The coals in this group are the most diverse in terms of quality, and also the most widely distributed within the basin. Group IV coals were deposited under fluviatile, lacustrine and paludal conditions (Mutton, A. J. 2003) and comprise sandstones, calcareous sandstone, carbonaceous shale, mudstone, coal, volcano-clastics (tuff), and concretionary limestone.

Figure 5 to Figure 8 provide schematic cross-sections through each of the Arrow tenure (Petroleum Leases 191, 196, 223, 224 and, ATP 742, 1031 And 1103), presented as 5 southwest to northeast orientated sections from the northern-most tenure to the southernmost. Each cross section was generated from the Arrow geological model using Petrel^{TM}. The model has been prepared from the latest geological information (incorporating the most recent gas well exploration and testing drilling information, mine drilling and water user data).

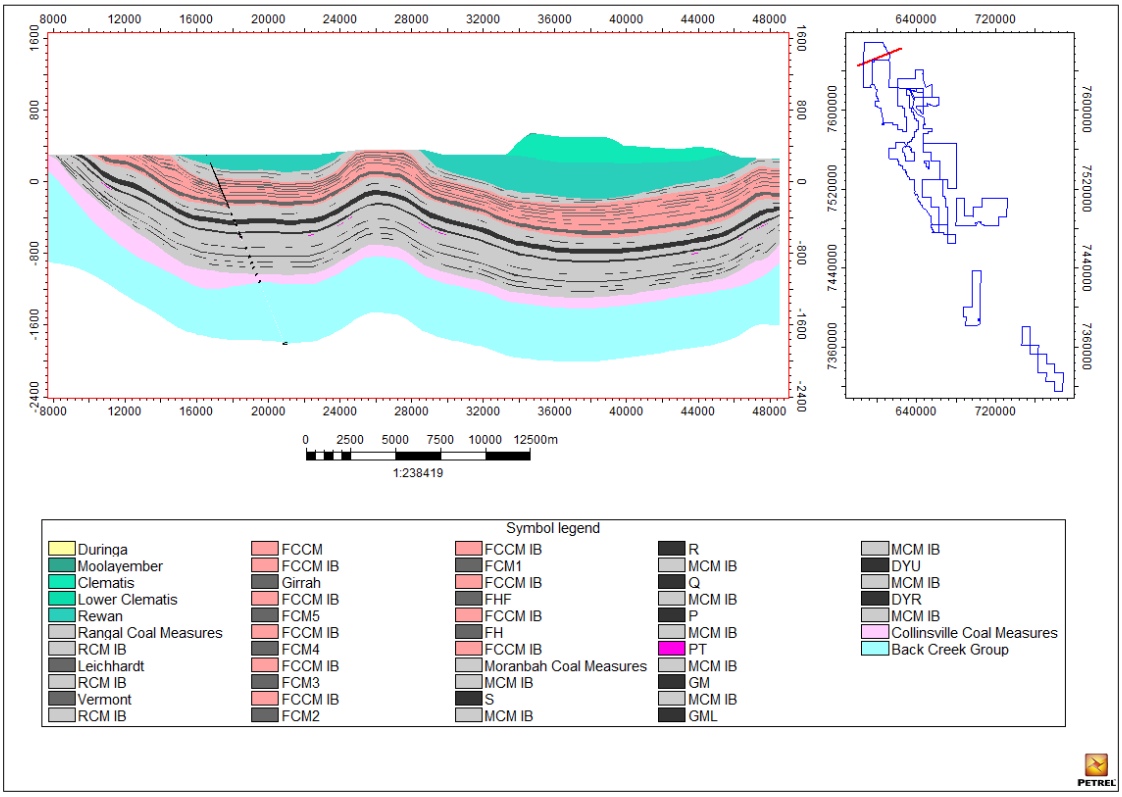


Figure 5 : Stratigraphy underlying ATP 742

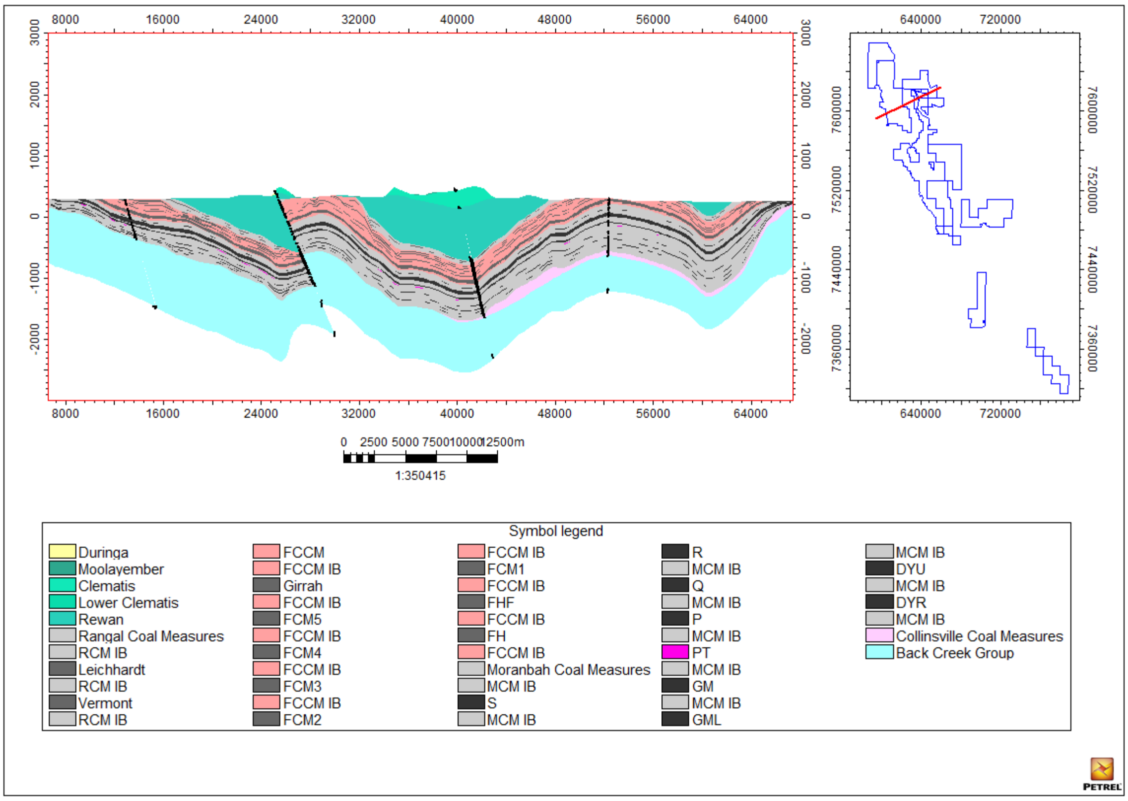


Figure 6 : Stratigraphy underlying northern ATP 1103

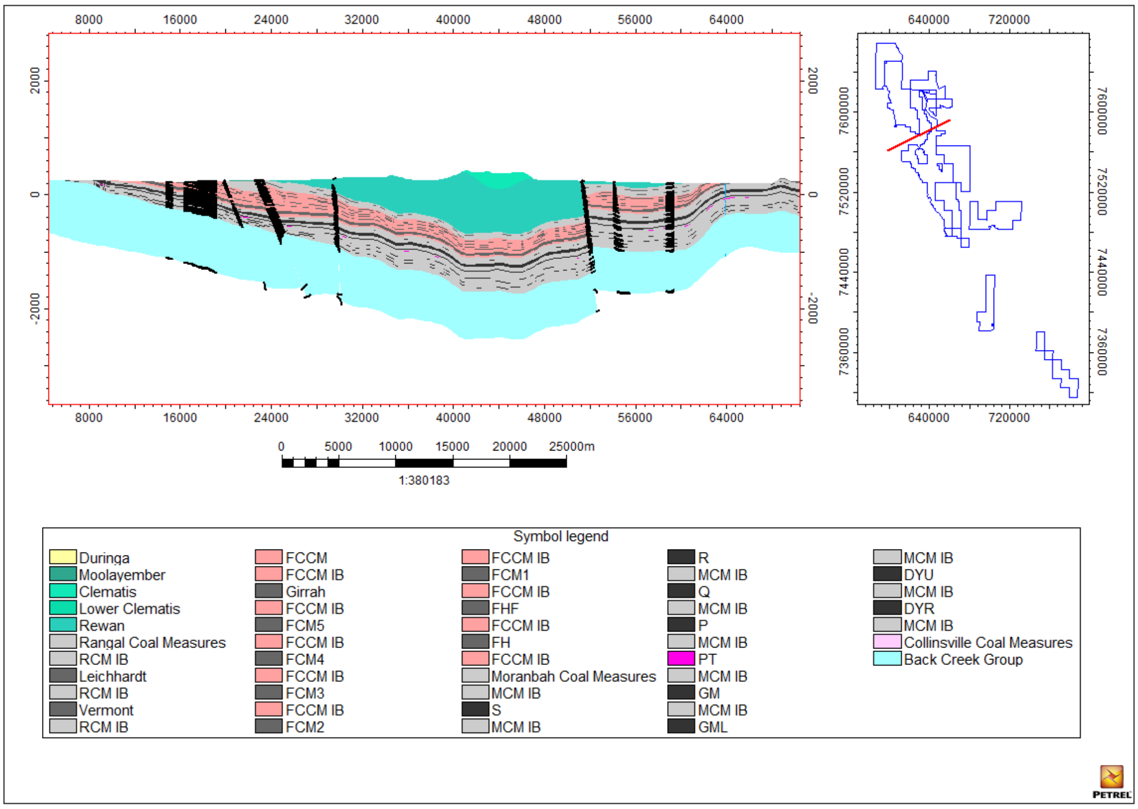


Figure 7 : Stratigraphy underlying MGP Area

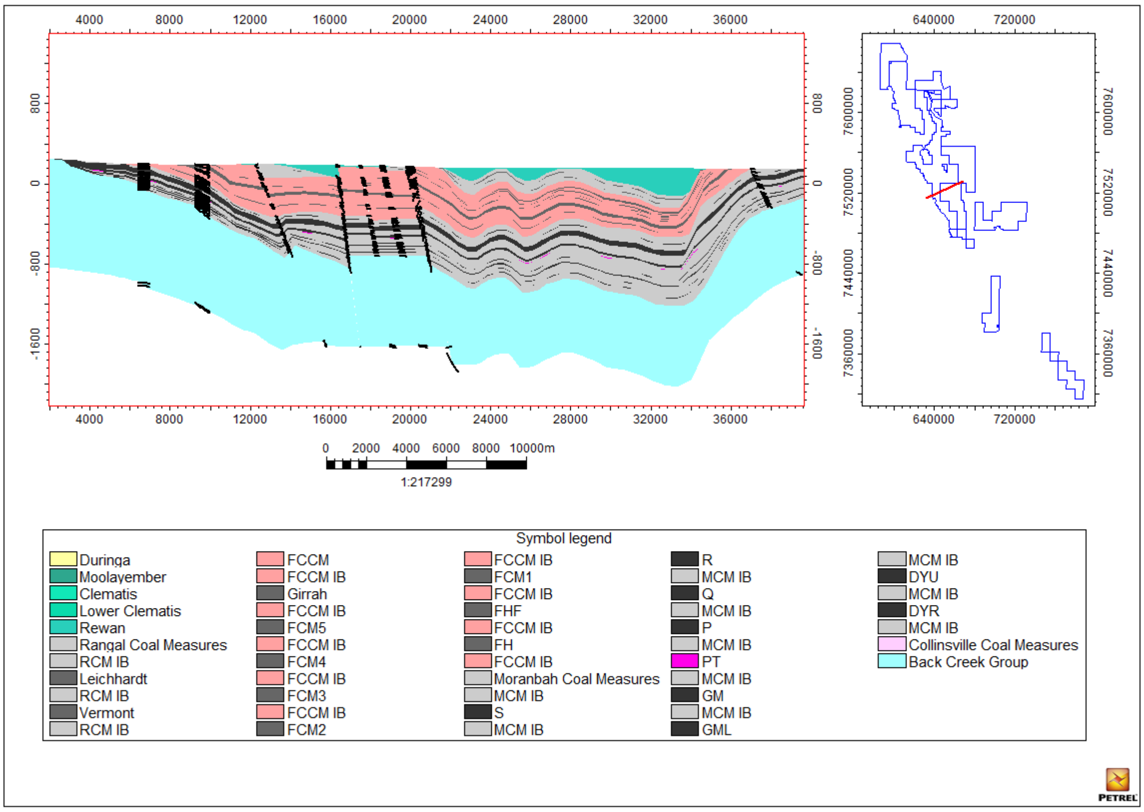


Figure 8 : Stratigraphy underlying ATP 1031

3.2 Conceptual Hydrogeological Model

The hydrostratigraphy of the Bowen Basin is summarised in the following table.

Table 10: Hydrostratigraphy of the Bowen Basin

Age	Stratigraphic Unit		Lithology	Typical thickness (m)	Aquifer Type
Quaternary	Alluvium	🟧	Clay, silts, sand, gravel, floodplain alluvium	15-35	Unconfined (resource aquifer)
Tertiary	Suttor Formation	🟫	Clay, silt, sand, gravel, colluvium, fluvial and lacustrine deposits including cross-bedded quartz sandstone, conglomerate, claystone	0-120	Aquitard
	Basalt	🟧	Olivine-rich weathered basalt remnants, moderately weathered and fresh basalts	0-80	Unconfined (resource aquifer); fractured rock aquifer
	Duaringa Formation	🟫	Mudstone, sandstone, conglomerate, siltstone, oil shale, lignite and basalt	0-50	Aquitard
Triassic	Moolayember Formation	🟫	Mudstone, lithic sandstone, interbedded siltstone, mudstone, sandstone and thin coal seams.	0-200	Confining unit - GAB
	Clematis Sandstone	🟧	Cross-bedded quartz sandstone, some quartz conglomerate, minor reddish brown mudstone	0-300	Confined GAB aquifer
	Rewan Formation	🟫	Green lithic sandstone, pebble conglomerate, red and green mudstone, siltstone	200-800	Confining unit
Late Permian	Rangal Coal Measures (RCM) and equivalents	⬛	Coal seams, carbonaceous shale and mudstone, tuff, siltstone and mudstone	25-200	Confined aquifer (coal) and confining unit (interburden)
	Fort Cooper Coal Measures (FCCM) and equivalents	🟫 ⬛ 🟫	Coal, brown and green sandstone, conglomerate, carbonaceous shale, tuff	100-600	Confined aquifer (coal) and confining unit (interburden)
	Moranbah Coal Measures (MCM)	⬛	Coal, sandstone, siltstone, mudstone, carbonaceous mudstone	100-700	Confined aquifer (coal) and confining unit (interburden)
Middle Permian	Back Creek Group	🟫	Sandstone, siltstone, carbonaceous shale, minor coal and sandy coquinite	400-1200	Confining unit

These cross sections in Figure 5 to Figure 8 show the key aquifer layers present at each section location, namely, the coal aquifers. The interburden aquitards and shallower Triassic and Tertiary hydrological units are also presented.

The occurrence and continuity of the above mentioned aquifers is highly dependent on the spatial distribution of the corresponding geological units.

The conceptual representation of the hydrogeology and hydrogeological processes as assessed in the EIS (Arrow Energy, 2012c) is shown in Figure 9.

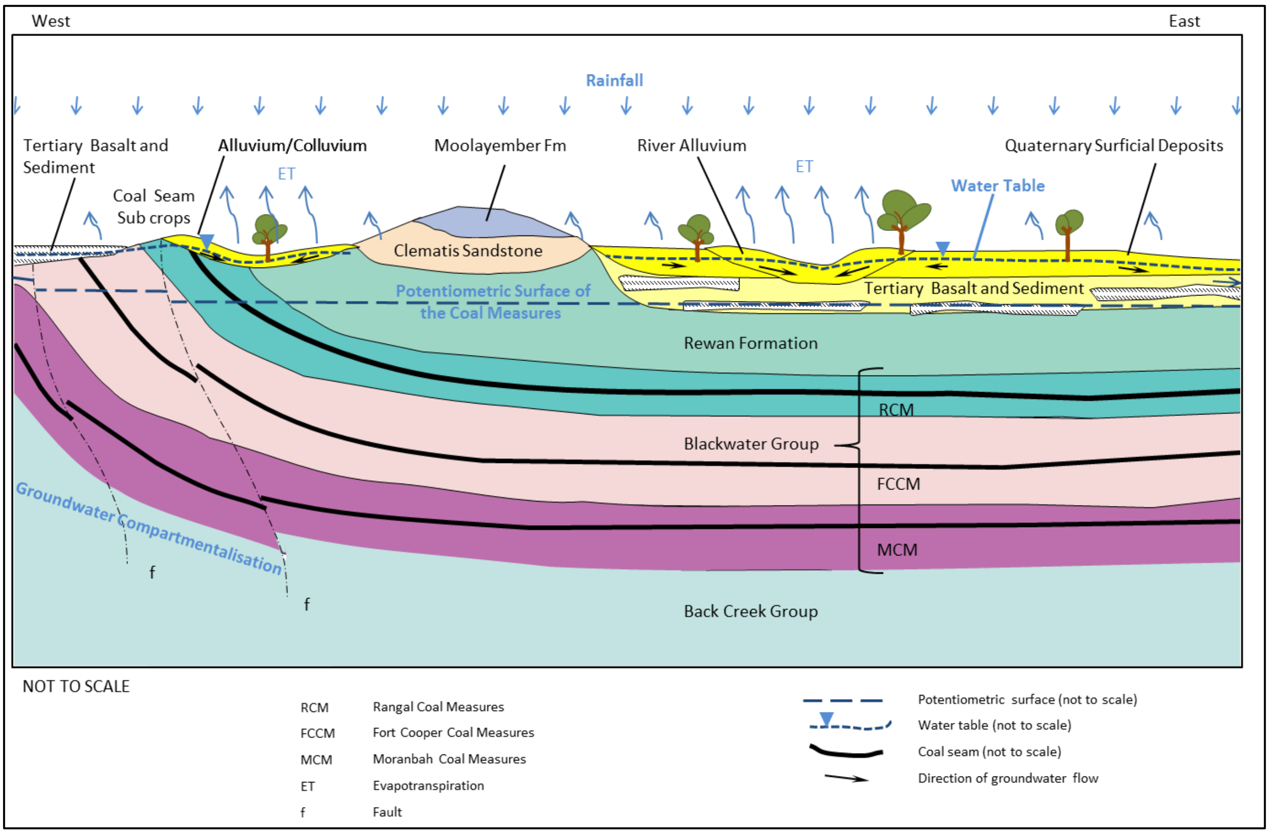


Figure 9: Conceptual Hydrogeological Model (Arrow Energy, 2012c)

A summary of the existing understanding of the hydrogeological setting as conceptualised in Figure 9 is provided in the following sections.

3.2.1 *Quaternary Alluvium Aquifers*

Quaternary alluvium aquifers (alluvium aquifers) form the shallow most aquifers in the Project Area and are generally associated with creek and river systems. The alluvium aquifers typically occupy an area within the river valley which is generally about 500 m wide. Due to the semi-arid climate, the ephemeral nature of the stream flow, and discontinuity of the more permeable gravel and sand layers, the groundwater resources in the Quaternary alluvium in the Project Area are not abundant and groundwater only occurs in isolated areas.

Key aquifer characteristics are:

- Groundwater levels fluctuate between 6 to 10 meters below ground level (mbgl);
- May not be fully saturated all year;
- Are of variable permeability being characterised by relatively high permeability river bed sands and relatively low permeability river bank sediments;
- Recharge mainly through direct infiltration of rainfall, overland flow and surface water flow;
- Discharge is generally through evapotranspiration from vegetation, infiltration and recharge to underlying older formations;
- Groundwater quality is highly variable ranging from brackish to saline;
- Groundwater use is erratic, and no significant extraction areas are recognised from the alluvium aquifers in the Project Area.

3.2.2 *Tertiary Sediment Aquifers*

The undifferentiated Tertiary sediments and Suttor Formation occurs extensively throughout the northern portion of the Bowen Basin, although outcrops are not continuous, and much of the Tertiary sequence is concealed by younger, overlying Quaternary alluvium and colluvium. The Tertiary sediments generally consist of lenses of palaeochannel gravels and sands separated by sandy silts, sandy clays and clays. Potential for groundwater exists within the more permeable sand and gravel sections of the Tertiary sediments.

Key aquifer characteristics are:

- The average groundwater level around 52 mbgl;
- Lenses of saturated sand and gravel are limited in extent and separated by sandy silts and clays;
- Highly variable in permeability and porosity and limited in lateral and vertical extent;
- Recharge mainly through direct infiltration of rainfall, overland flow in outcrop areas and vertical seepage from overlying Quaternary alluvium;
- Discharge is generally through evapotranspiration from vegetation, infiltration and recharge to underlying older formations;
- Groundwater quality is classed as fresh to brackish;
- Groundwater use is sparse, and no significant extraction areas are recognised from the Tertiary sediment aquifers in the Project Area.

3.2.3 *Tertiary Basalt Aquifers*

The spatial distribution of the Tertiary basalt is sporadic within the Bowen Basin. The largest mass occurs to the west of Dysart with several other masses occurring near Moranbah, west of Nebo and northeast of Middlemount (Pearce .B, Hansen .J, 2006a). Groundwater is principally stored and transmitted in the fractures, joints and other discontinuities within the rock mass.

Key aquifer characteristics are:

- Groundwater levels range between 17 to 38 mbgl;
- Vesicular basalt acts as localised, discontinuous aquifers;
- Permeability and porosity is highly variable depending on degree of weathering and interconnectedness of jointing and/or fracturing;
- Recharge mainly through direct infiltration of rainfall, overland flow and surface water flow in rock outcrop areas where no substantial clay barriers exist in the shallow subsurface and vertical seepage from overlying aquifers;
- Discharge is generally through flow into adjacent or underlying older formations and evapotranspiration;
- Groundwater quality is variable ranging from brackish to saline;
- Considered unlikely to represent a significant groundwater supply given the isolated and sporadic occurrence of groundwater and highly variable permeability and porosity.

3.2.4 *Triassic Aquifers*

The Triassic aquifer refers to the Clematis Sandstone. The Moolayember Formation is a recognised aquitard generally overlying and confining parts of the Clematis Sandstone. The distribution of the Clematis Sandstone and Moolayember Formation has mostly eroded but a few remnants occur as outcrops in the north. These two formations form part of the basal section of GAB recharge beds (Pearce .B, Hansen .J, 2006a). The Triassic Rewan Formation is considered to be a regional-scale confining unit (aquitard) along most of the central axis of the Bowen Basin but is absent from the east and west flanks of the basin.

Key aquifer characteristics are:

- Rewan Formation:
    - The Rewan Formation average groundwater level at 24.77 mbgl;
    - Highly variable in permeability and porosity and limited in lateral and vertical extent;
    - Groundwater quality collected from the one monitoring bore in the Rewan Formation classed the groundwater as saline;
    - Recharge is localised and mainly through direct infiltration of rainfall, overland flow and surface water flow in outcrop areas;
    - Discharge is localised and generally via through flow into adjacent or underlying older formations and evapotranspiration;
    - Groundwater use in the Project Area is unknown and given the limited extent of this aquifer, groundwater supply is likely to be isolated;
- Clematis Sandstone:
    - The average groundwater level is around 52 mbgl;
    - Highly variable in permeability and porosity and limited in lateral and vertical extent;

    - Clematis Sandstone aquifer has a localised presence to only a few small outcrops in the Project Area;
    - The Clematis Sandstone aquifer has moderate to good permeability;
    - Recharge is localised and mainly through direct infiltration of rainfall, overland flow and surface water flow in outcrop areas;
    - Discharge is localised and generally via through flow into adjacent or underlying older formations and evapotranspiration;
    - Groundwater use targeting the sandstone is unknown.

3.2.5 *Permian Aquifers*

The two dominant Permian formations within the Project Area are the Blackwater Group and the Back Creek Group. The coal seams of the Blackwater Group are the more permeable units within the Permian sequences. The coal seams are continuous across the Project Area and constitute the most extensive aquifers. These seams have been extensively mined along the western margin of the Bowen Basin. The Back Creek Group is a confining unit however shallow unconfined groundwater has been known to occur in outcrops/subcrop areas.

Key aquifer characteristics are:

- Blackwater Group:
    - The recorded pressures associated with the Back Creek Group indicate artesian groundwater pressures
    - Low to moderately permeable coal seams;
    - Recharge is limited and generally via direct infiltration of rainfall and overland flow as well as downward seepage from overlying aquifers where no clay barriers exist in outcropping/ subcropping areas;
    - Discharge is generally through flow into adjacent (outcropping or sub-cropping coal seams) aquifers or seepage into underlying aquifers (via structural discontinuities) and groundwater extraction (CSG, incidental mine gas management, and mine dewatering activities);
    - Groundwater quality is generally poor, however varies from being fresh to saline
    - Groundwater resources associated with the Blackwater Group are typically contained in porous sandstones and fractured shale and siltstones
    - Confined by low permeability overburden and interburden as well as the overlying Rewan Formation where it exists
- Back Creek Group
    - Low to moderately permeable coal seams Recharge is limited and generally via direct infiltration of rainfall and overland flow as well as downward seepage from overlying aquifers where no clay barriers exist in outcropping/ subcropping areas;
    - Discharge is generally through flow into adjacent (outcropping or sub-cropping coal seams) aquifers or seepage into underlying aquifers (via structural discontinuities) and groundwater extraction (CSG, incidental mine gas management, and mine dewatering activities);
    - Confined by low permeability overburden and interburden as well as the overlying Rewan Formation where it exists;
    - Groundwater quality is generally poor, however varies from being fresh to saline.

4 ARROW MONITORING RESULTS

Groundwater monitoring has been undertaken by Arrow in accordance with the UWIR WMS groundwater monitoring network located in the MGP Area. The locations of these bores are shown in Figure 10. This site specific data is presented in more detail in the following sections and new data (groundwater levels and water quality) provide an update to the current understanding of the conceptual hydrogeological model.

4.1 Groundwater Levels

4.1.1 *Shallow UWIR Monitoring Data Summary*

Groundwater level monitoring has been undertaken in the following shallow groundwater monitoring bores which form part of the UWIR groundwater monitoring network for the MGP Area.

- Monitoring since June 2012 for bores M339W, M225W, M340W, M230W, M250W, M224W, M222W; and
- Monitoring since March 2016 for bores AN020F (replaced AN021F).

A summary of these bores are presented in Table 11 below indicating horizons targeted across the screened intervals. The Table 11 presents the range in the static water levels (SWL), maximum and minimum levels, recorded over the 2012 to 2018 period. The exception is bore AN020F, where water level recording commenced in 2016, as a replacement for AN021F. The locations of the monitoring wells are presented in Figure 10.

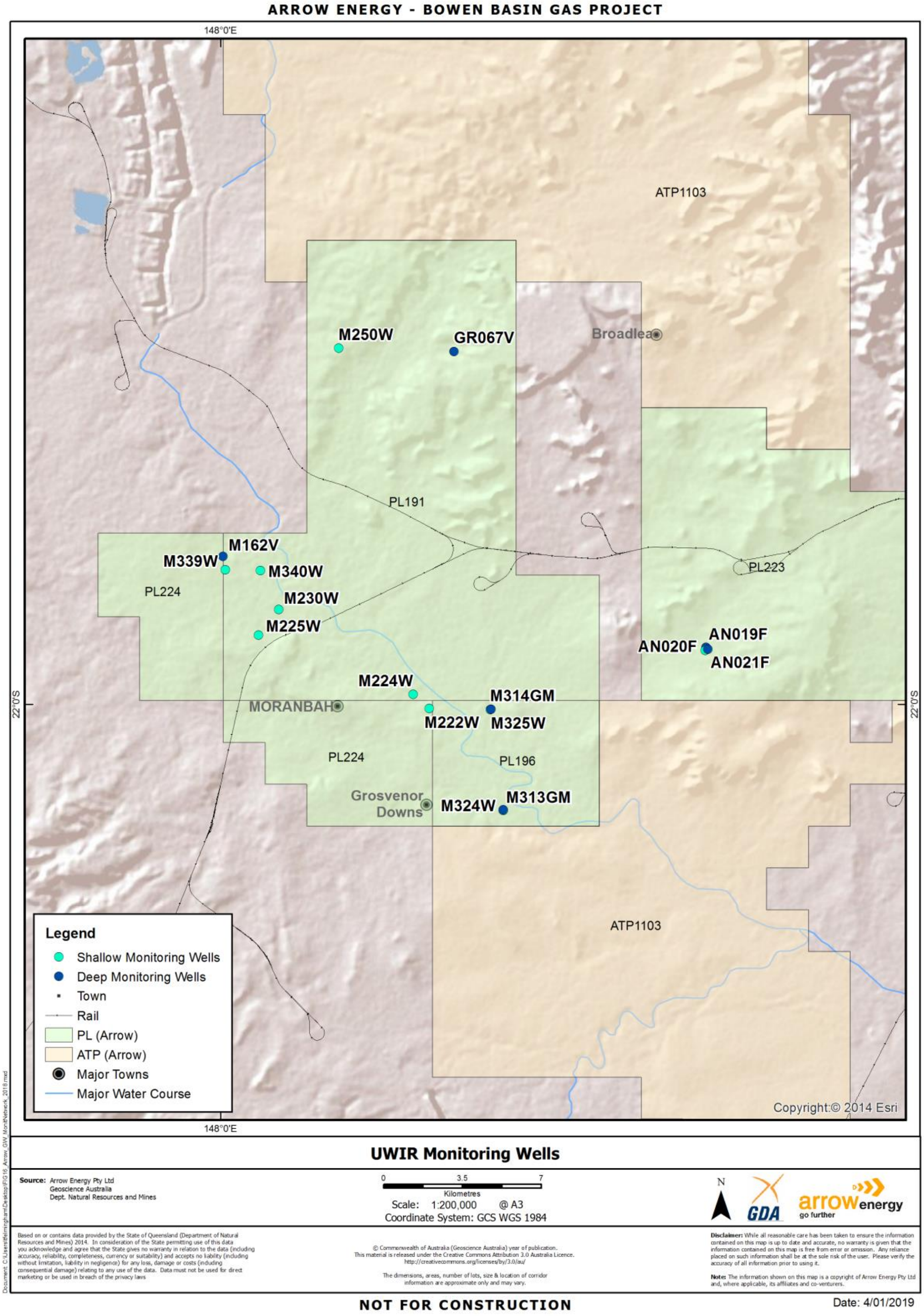
Table 11: Shallow Groundwater Monitoring Bores

Bore ID	Total Constructed Depth (m)	Screen Interval (mbgl)	SWL Minimum (mbgl)	SWL Maximum (mbgl)	Screened Formation
M339W	41.00	35.0 – 41.0	37.73	37.89	Weathered Tertiary Basalt
M225W	34.00	23.0 – 34.0	22.18	23.63	Weathered Tertiary Basalt
M340W	27.30	19.3 – 27.3	18.46	24.40	Weathered Tertiary Basalt
M230W	32.00	29.0 – 32.0	15.71	16.70	Weathered Tertiary Basalt
M250W	56.50	44.5 – 56.5	51.83	51.94	Sand (Tertiary alluvium)
M224W	17.50	6.5 - 15.5	8.29	10.15	Sand and clay (Quaternary Alluvium)
M222W	30.20	20.0 – 26.0	18.18	22.07	Weathered Fort Cooper Coal Measures
AN020F	77.00	70.0 – 72.0	24.59	26.02	Rewan Formation
AN021F	27.00	20.0 – 22.0	Dry	Dry	Tertiary Formation

The groundwater level monitoring results are shown in Appendix A. The groundwater level changes are due to natural fluctuations with the exception of M224W, which is discussed in more detail later in this section. The range of the water levels as tabulated above for the Formations are summarised below:

- Quaternary Alluvium – levels fluctuated between 8.29 to 10.15 mbgl
- Tertiary Alluvium – levels fluctuated between 51.83 to 51.94 mbgl
- Weathered Tertiary Basalt – levels fluctuated between 15.71 to 37.89 mbgl
- Rewan Formation - levels fluctuated between 24.59 to 26.02 mbgl
- Weathered Fort Cooper Coal Measures - levels fluctuated between 18.18 to 22.07 mbgl

The groundwater levels recorded over the 2012 to 2018 period are presented against the rainfall (in Figure 11) and river levels changes (in Figure 12).



Source: Arrow Energy Pty Ltd
Geoscience Australia
Dept. Natural Resources and Mines

Scale: 1:200,000 @ A3
Coordinate System: GCS WGS 1984

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The dimensions, areas, number of lots, size & location of corridor information are approximate only and may vary.

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Date: 4/01/2019

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Figure 10: MGP and UWIR Groundwater Monitoring Network

Table 12: Shallow Monitoring bores pressure data

Bore ID *(Screened Formation)	Total Constructed Depth (m)	Pressure difference over monitoring period June 2012 to June 2018 (m)	Comments on groundwater pressures
M339W (WTB)	41.00	-0.094	Rise in water levels over reporting period
M225W (WTB)	34.00	-1.452	Rise in water levels over reporting period
M340W (WTB)	27.30	4.589	Water levels dropped below bore completed depth – see discussion below
M230W (WTB)	32.00	0.281	Drop in water levels over reporting period
M250W (TA)	56.50	-0.002	Very small change in water level over reporting cycle
M224W (QA)	17.50	1.595	Water level fluctuations with possible hydraulic link to Isaac river
M222W (WFCCM)	30.20	-3.886	Rise in water level over reporting period
AN020F (RF)	77.00	-0.240	Rise in water levels over reporting period

* *WTB – Weathered Tertiary Basalt, TA – Tertiary Alluvium, QA – Quaternary Alluvium, WFCCM – Weathered Fort Cooper Coal Measures, RF – Rewan Formation*

(-) – negative indicates pressure recovery

A review of the groundwater levels in bore M224W, installed in the Quaternary Alluvium and within 300 m of the Isaac River was compared against data obtained from the Isaac River stream gauge (130414A). The graphically presented river level data (Figure 12) indicates a gradual decline in flow periods from mid-2013 to the end of 2014 and an increase in flow periods linked to rainfall events into 2018. The only shallow monitoring bore indicating a possible hydraulic link to the river level fluctuations, is bore M224W. The conceptual hydrogeological model reports to linkage between rainfall events and river level flow periods to groundwater levels. The current data set does however not indicate a strong link and the outcome is still inconclusive. Insufficient data available to suggest and allow changes to the current conceptual model.

The groundwater levels in the monitoring bores completed into the weathered tertiary basalt (M339W, M225W, M340W and M230W) and located in close proximity to the Isaac river, no direct hydraulic connection to the Isaac river fluctuations. The water level in monitoring bore M339W has been very stable of the last 7 years. The water level in M225W has continued to recover and M230W has gradually dropped over the last 4 years, not in sequence to the river fluctuations. The water level in M340W has dropped below the completed depth of the monitoring bore due to the impact of the underground mining directly below the area.

The graphically presented groundwater levels for shallow monitoring bores M250W and AN020F (installed in the Tertiary Alluvium and Rewan Formation) are higher due to the respective surface elevation at the bore locations, being approximately 50 to 60m and 30 to 40m above the monitoring bores in the proximity of the Isaac River. The two monitoring bores are located approximately 10 to 15 km to the north and east of the other groundwater monitoring sites and over 8km from the Isaac river. The monitoring bore AN020F acts as a replacement for AN021F, installed in the Tertiary Formation, but has been dry since installation.

No decline in groundwater levels greater than the bore trigger threshold has been observed (excluding M340W discussed above) and there is no apparent influence of CSG production to the Quaternary alluvium, weathered Tertiary basalt, Tertiary sediment and weathered Fort Cooper Coal Measures (FCCM) aquifers where these bores are installed

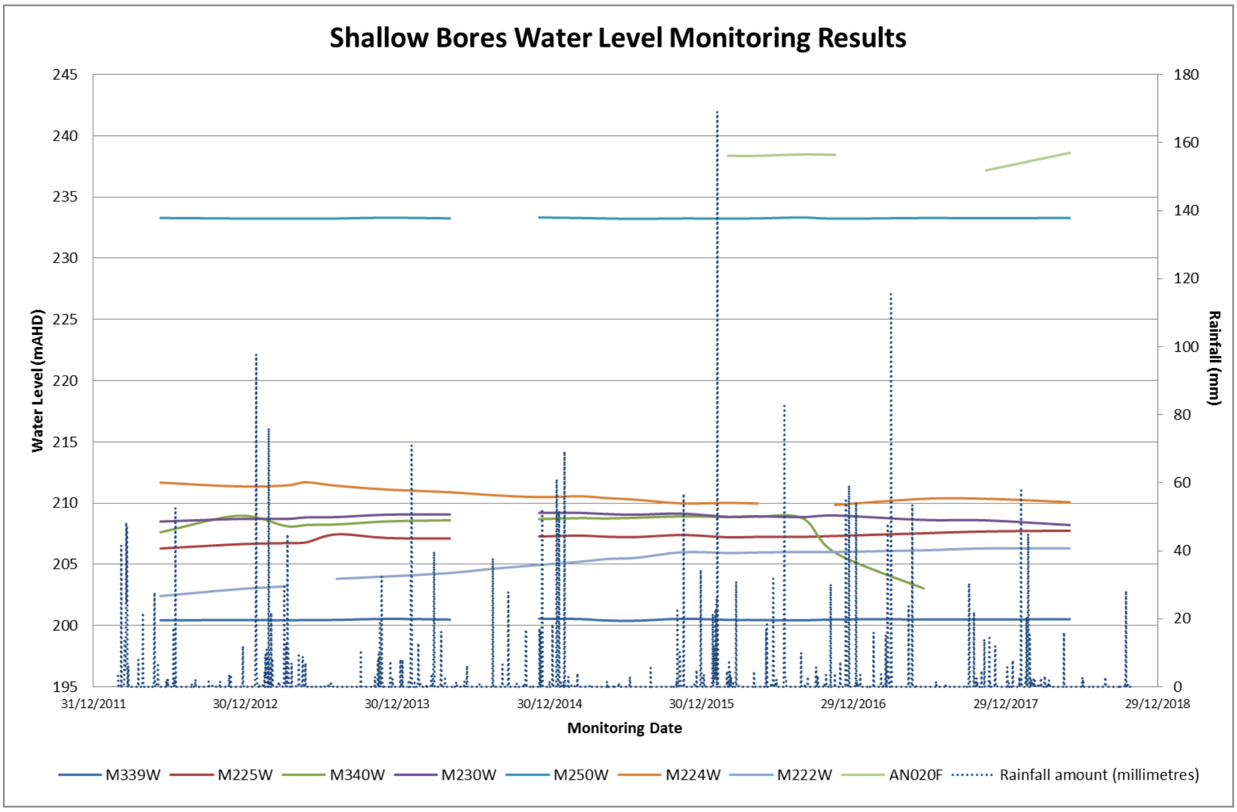

Figure 11: UWIR Shallow Bores Water Levels vs Rainfall

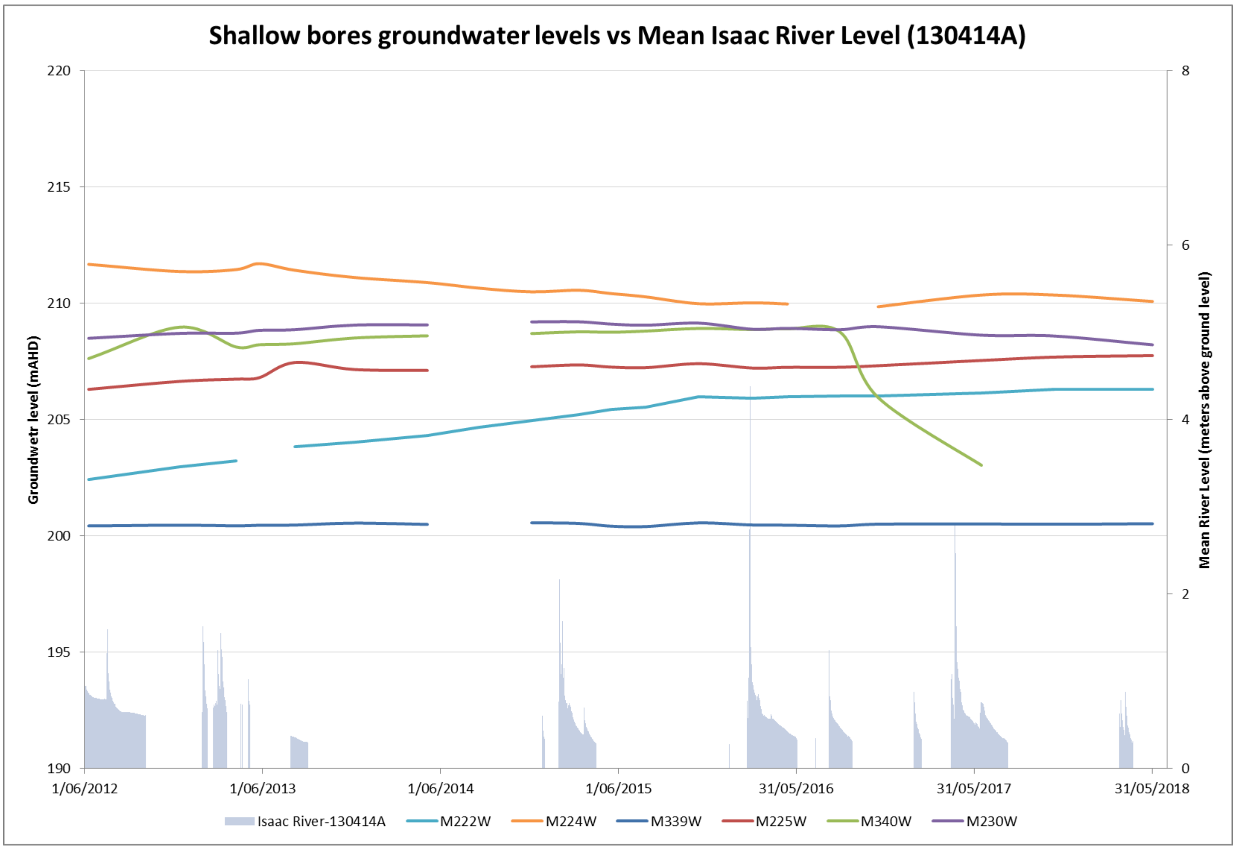

Figure 12: Shallow Groundwater levels vs mean Isaac River levels

4.1.2 *Deep UWIR Monitoring Data Summary*

The location of the deep groundwater pressure monitoring bores in the MGP Area is shown in Figure 10 which forms part of the UWIR groundwater monitoring network:

- Monitoring since September 2014 for bores M313W, M314W, M324W;
- Monitoring since February 2015 for bore M325W;
- Monitoring since November 2015 for bores AN019F and M162V; and
- Monitoring since February 2016 for bore GR067V.

The groundwater monitoring borehole construction details and the coal units targeted for pressure monitoring has been summarised in Table 13. The pressure gauge data has been successfully downloaded from tabulated bores below.

Table 13: Deep Groundwater Monitoring Bores

Bore ID	Total Constructed Depth (m)	Screen Interval (mbgl)	Screened Formation
M313W	532.4	313.0 – 316.5 507.0 – 510.0	Moranbah Coal Measures (QA Seam) Back Creek Group
M314W	560.5	210.5 – 213.5 551.5 – 553.5	Moranbah Coal Measures (QA Seam) Back Creek Group
M324W	240.0	163.0 – 166.0 187.0 – 190.0	Fort Cooper Coal Measures Moranbah Coal Measures (QA Seam)
M325W	202.3	180.5 – 182.0	Fort Cooper Coal Measures
AN019F	290.0	269.0 – 271.0	Fort Cooper Coal Measures
M162V	276.0	252.0 – 256.0	Moranbah Coal Measures
GR067V	610.9	543.2 – 610.9	Moranbah Coal Measures

The groundwater pressures ranges over the monitoring period for the formations are as follow:

- Fort Cooper Coal Measures (FCCM) – levels fluctuated between 49.62 to 206.87mAHD
- Moranbah Coal Measures (MCM) – levels fluctuated between 74.56 to 204.58mAHD
- Back Creek Group (BCG) – levels fluctuated between 211.39 to 215.92mAHD

The monitoring bores discussed below have been selected due to identification of noticeable trends:

- The pressure monitoring data from bore GR067V in the MCM has been excluded due to the large artificially induced fluctuations that are unrepresentative of the MCM pressures. The CSG production well was converted to a groundwater monitoring well in November 2015 and fitted with a low flow sampling pump in August 2016. This well forms part of a cluster of production wells which were previously on pump before being suspended. The pressure trends presented in Figure 13 for GR067V are a result the well being converted from pumping to monitoring, the build-up of gas and regional pressure recovery which resulted in multiple attempts to set the low flow pump. Bore threshold has not been applied to the monitoring bore at this stage.
- Monitoring data from M325W has not been compared to the bore trigger threshold because water levels have exhibited a consistently increasing pressure trend since monitoring commenced in 2014. As presented in Figure 13, the available pressure data for M325W indicates groundwater levels in the FCCM have increased past the previously-observed peak of 69.99m AHD (recorded in 22/05/2016) and recovered to 74.11m AHD by 23/10/2018. As the starting water level of the bore is unknown and cannot be determined, including the ongoing increase in water level in the bore, the bore trigger threshold has not been applied to the monitoring bore.
- The decline on groundwater levels in M313W (MCM) that exceeded the bore trigger threshold of 5 m (Figure 15) due to the proximity and hydraulic communication with production well GM052V, 300m to the southwest and within the MCM. The monitoring data from the MCM monitoring bore M324W is also presented in Figure 15 and indicate the hydraulic communication with the production well.

- The current production from M134GMV within the MCM, located 470m to the northwest of monitoring bore M162V, has resulted in the bore trigger threshold of 5m being exceeded (Figure 15). The information suggests the water pressures will continue to decline in the area in line with the CSG production.

In Figure 14 the graphically presented pressure data indicates pressures less than the 5m bore trigger threshold and the figure provides a more detailed presentation of the FCCM and BCG pressures, not clearly presented in Figure 13. The recorded FCCM pressures (Figure 14) in bores M324W and AN019F, located 11 km apart, reflect similar trends. The pressures in both bores have gradually changed with a small recovery (0.09m) in AN019F and a small drawdown (0.14m) in M324W against the model forecast of no drawdown in the monitoring bores.

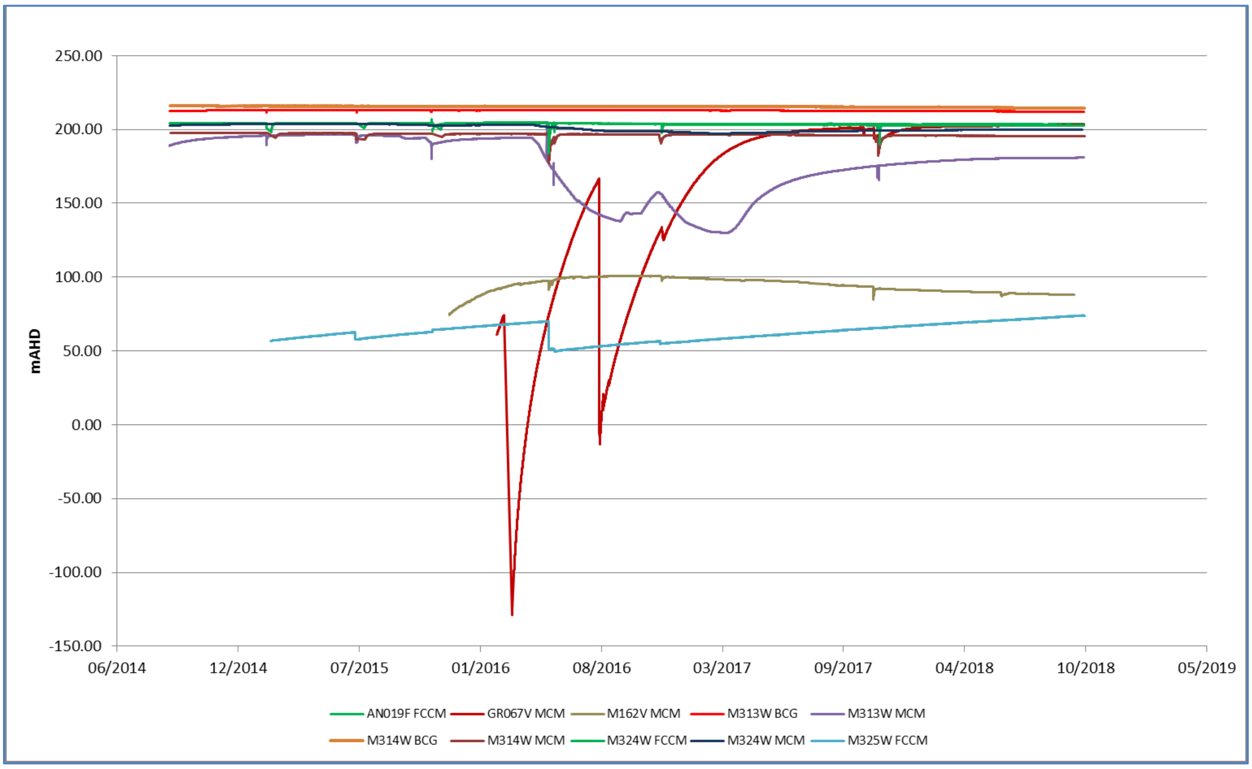

Figure 13: UWIR Deep Bores Water Pressure Monitoring Results

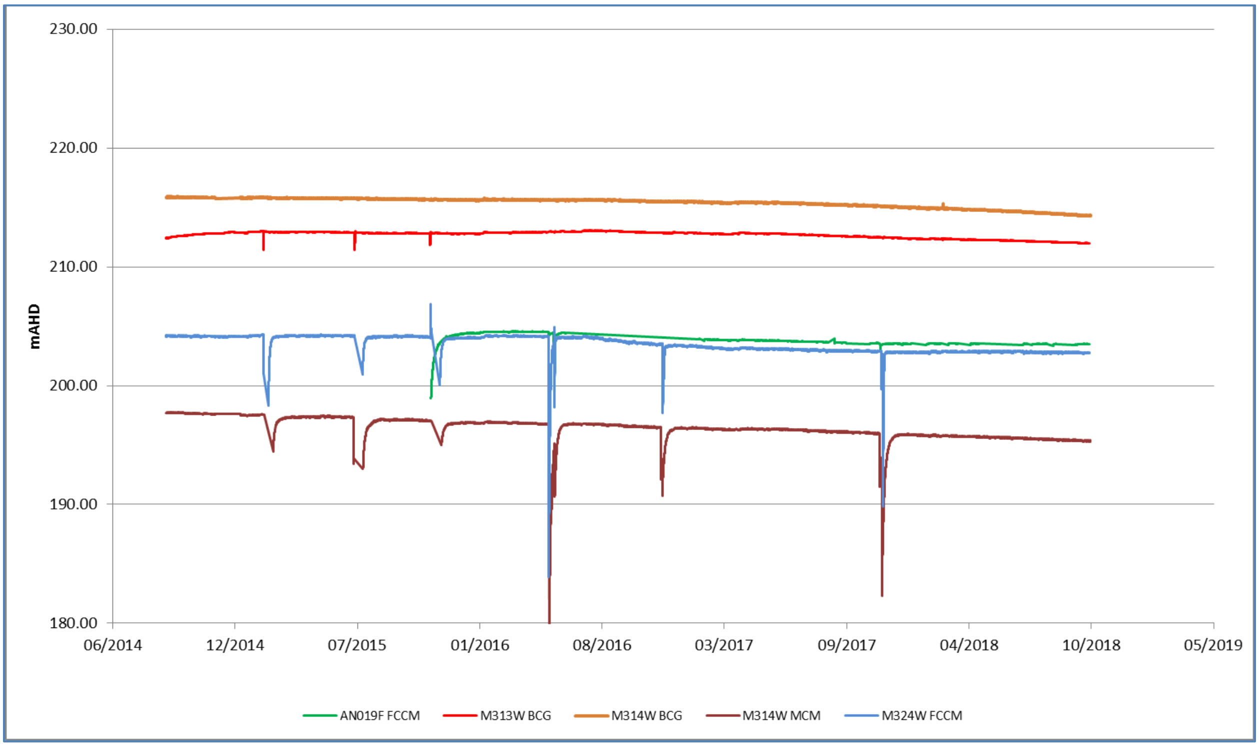

Figure 14: Deep Bores with level changes less than the Bore Trigger Threshold

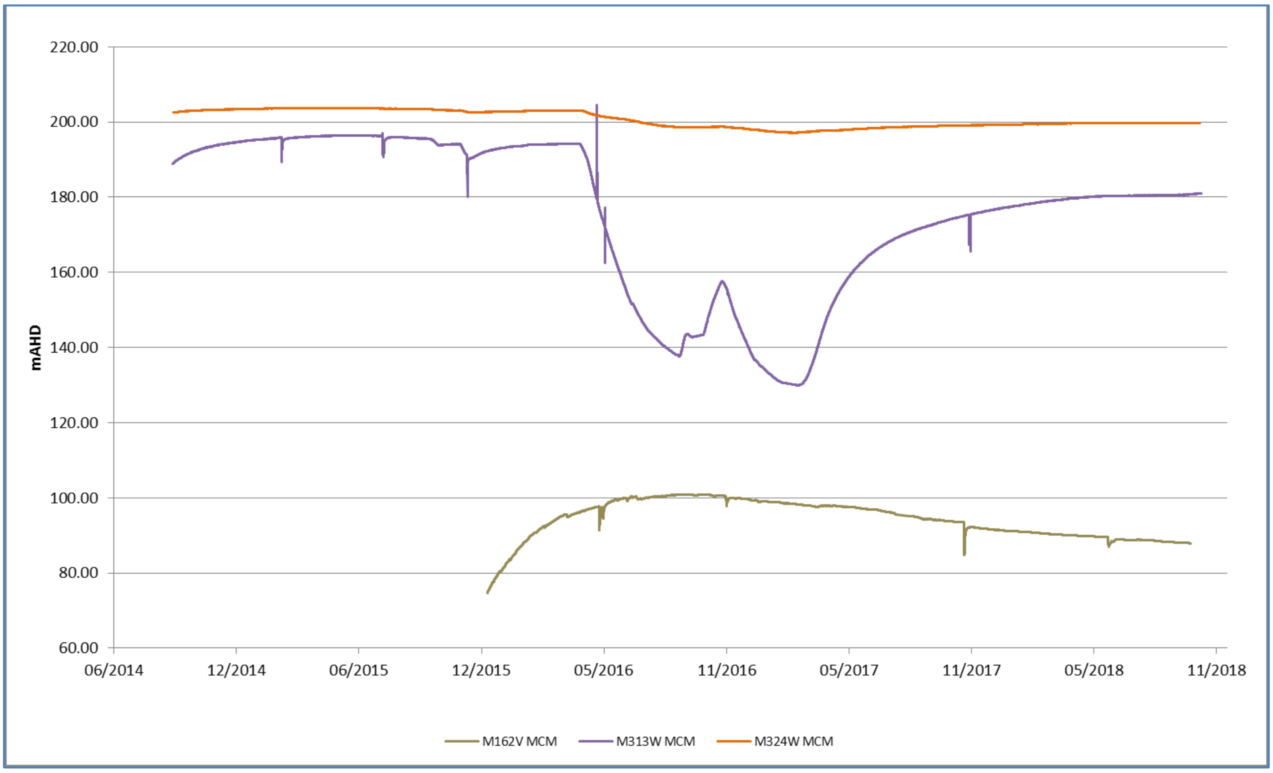

Figure 15: Deep Bores with level changes greater than the Bore Trigger Threshold

4.2 Groundwater Flow

A review of vertical gradients was undertaken for two monitoring locations in the MGP Area. Monitoring at each site included:

- Site 1: From deepest to shallowest; Back Creek Group (M314W) ,Moranbah Coal Measures (M314W), Fort Cooper Coal Measures (M325W) as well as data from monitoring approximately 3 km north west in the weathered Fort Cooper Coal Measures (M222W) and Quaternary Alluvium (M224W).
- Site 2: From deepest to shallowest; Back Creek Group (M313W), Moranbah Coal Measures (M313W), Moranbah Coal Measures (M324W) and Fort Cooper Coal Measures (M324W).

Figure 9 provides a cross section of the aquifers underlying the MGP Area. The Quaternary Alluvium (QA) aquifer forms the shallowest aquifer within this area. This is underlain by the weathered FCCM aquifer. Both aquifer systems are considered to be unconfined to semi-confined in nature. The deeper MCM aquifer is a confined, sub-artesian aquifer system. The deepest aquifer system is the confined BCG aquifer.

Figure 16 shows the vertical gradients for Site 1. Based on this data, the MCM aquifer has the lowest pressure. There is an apparent gradient toward the MCM i.e. upward from the BCG and downward from the Quaternary Alluvium, to the FCCM and then to the MCM.

The Site 1 vertical hydraulic gradients are presented in Figure 16 below:

- The CSG production in and around Site 1 is continuing from the MCM
- The water levels in the shallow aquifers do not indicate any direct hydraulic connectivity with the river or response after a significant rainfall event.
- The ongoing recovery within M325W FCCM could relate back to the bore development after drilling completion. As indicated in Figure 16, the pressures are different and separate from the overlying alluvial and no direct hydraulic link can be identified.
- The deeper MCM and BCG show a similar downward trend over the last 4 year period. The level in the MCM has declined in the order of 2.39m in relation to the 1.57m in the BCG over the same period.
- The current BCG pressures have gradually been reducing over the monitoring period.
- Based on the pressures and graphically presented pressures trends, no vertical hydraulic connectivity can be identified between the shallow and deep aquifer/units. The only possible hydraulic connectivity, due to similar drawdown trends over the monitoring period will be between the MCM and the BCG due to the CSG water production from the MCM in the area.

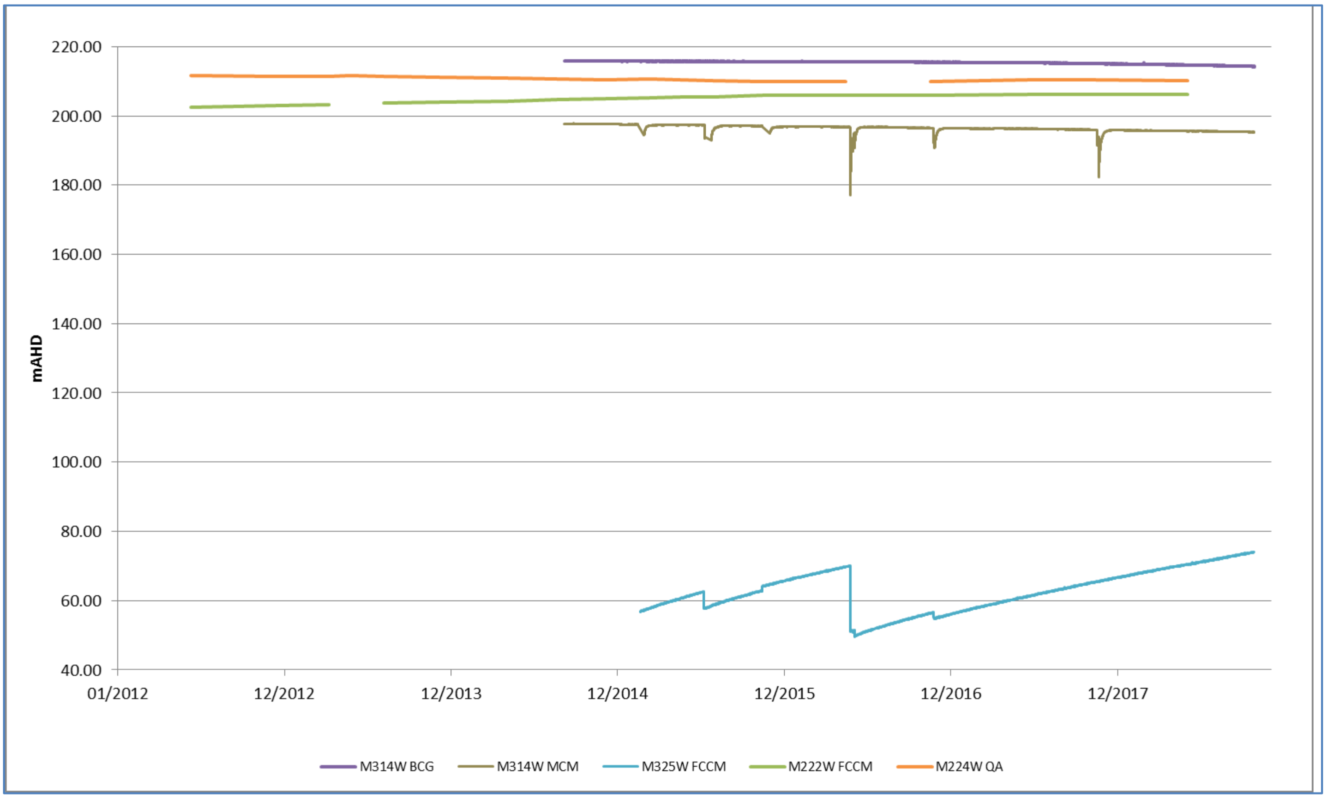

Figure 16: Site 1 - Review of vertical gradients for M222W, M224W, M314 and M325W

The Site 2 vertical hydraulic gradients are discussed on the back of the data graphically presented in Figure 17 below:

- The CSG production in the vicinity of Site 2 was from the MCM, reporting the lowest pressures and resulting in communication with the overlying FCCM and underlying BCG. The hydraulic communication as discussed previously is due to the proximity to CSG production well GM052V.
- The MCM in M324W has been screened at shallower depth (187 to190 mbgl) vs the deeper M313W (313 to 316 mbgl) and the hydraulic connection between the shallower and deeper screened MCM are clearly presented in the figure below. The pressure data indicates an approximate 2 day time lag before the response manifests in the shallower MCM unit.
- The drawdown as a result of water production in CSG wells to the MCM aquifer is evident at site M313W and M324W but since the production ceased in April 2017, the water level recovery is evident in both monitoring bores.
- A decline in pressures occurred in August 2016 for the FCCM that correlate to the water production in CSG wells and consequential drawdown in the underlying MCM. The transition of the drawdown impact manifests approximately 4 months after drawdown occurred in the MCM. The drawdown has started to stabilise but the data suggests that a small degree of vertical hydraulic connectivity exists between the MCM and the FCCM.
- The reduction in the pressure and presented water level data in the BCG in September 2016, approximately 5 months after the drawdown response in the MCM, indicate possible hydraulic connectivity. The latest pressure data indicates the water level is still drawing down and ongoing monitoring will indicate if the recovery, occurring within the monitoring wells at the site, will also occurs within the BCG over time. This will assist to determine if the drawdown is linked to the MCM production or if in isolation.

Ongoing monitoring at these sites will provide further information on the interconnectivity of the aquifers at these sites.

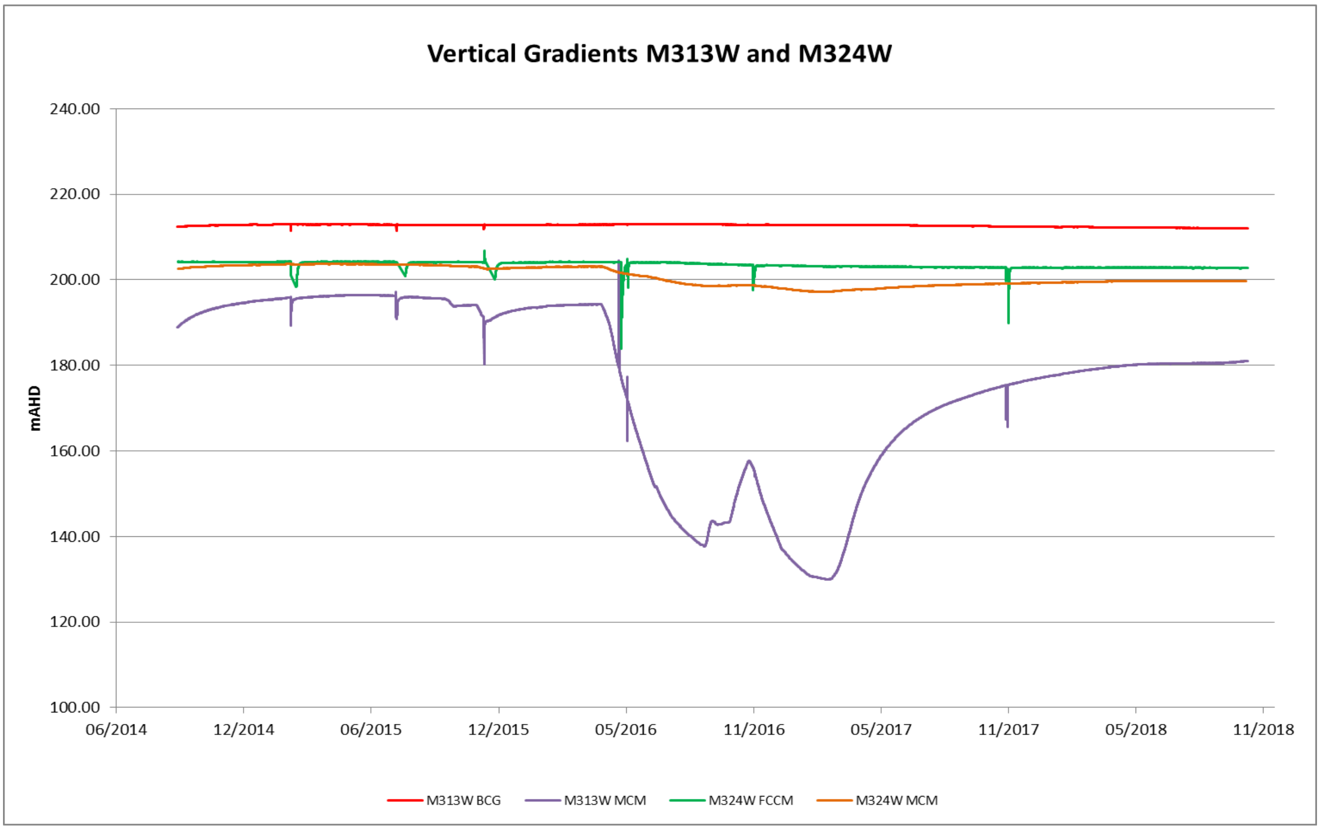

Figure 17: Site 2 - Review of Vertical Gradients for M313W and M324W

4.3 Groundwater Quality

Groundwater quality monitoring for PL 191, 196, 223 and 224 has being undertaken in eight shallow groundwater monitoring bores since June 2012 and forms part of the Bowen UWIR WMS groundwater monitoring network. It should be noted that one shallow groundwater monitoring bore AN021F, has been dry and no sampling has been able to be undertaken at this site. An adjacent bore AN020F, drilled and completed into the Rewan Formation, has been sampled since 13/05/2016 as the replacement.

Groundwater quality monitoring is undertaken in eight deep groundwater monitoring bores, four were completed in July 2014, two deep groundwater monitoring bores were completed in November 2015, one deep groundwater monitoring bore that was completed in August 2016 and one in November 2017. All these monitoring bores are part of the 2019 Bowen UWIR WMS groundwater monitoring network.

It should be noted that the water level in monitoring bore M162V dropped below the pump intake and water quality sampling was unable to be undertaken at this site. Instead, a replacement sampling bore was selected in the immediate area intersecting the MCM. The production bore M134W, located approx. 480 m north of the monitoring bore was selected and included in the sampling undertaken in November 2017. The selected bore has been completed to approximately the same depth intersecting the MCM seam.

The groundwater quality monitoring results are shown in Appendix B. The primary purpose of groundwater quality monitoring is to identify changes in water quality.

4.3.1 *Shallow aquifer water quality*

Table 14 provides a summary of water quality results obtained from bores targeting the shallow aquifers (M339W, M225W, M340W, M230W, M250W, M224W, M222W and AN020F). This provides an indication of water quality ranges for each parameter analysed based on aquifer type. Results for some parameters between different monitoring locations in the Tertiary Basalt show a high degree of variation which is likely to be attributable to the spatial heterogeneity of the hydrogeological system. Review of this data indicates that there are no notable trends. It should be noted that there is a separate groundwater monitoring program, required by the EA, to monitor potential impacts of CSG related infrastructure, which is outside the scope of this report.

In general the salinity ranges[1] for the underlying units can be described as follow:

- Groundwater quality of the quaternary alluvium varies from brackish to saline
- Groundwater quality of the tertiary basalt aquifer varies from brackish to saline
- Groundwater quality of the tertiary sediment aquifer is fresh to brackish
- Groundwater quality of the weathered coal measures is saline
- Groundwater quality of the Rewan Formation is saline

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[1] Environmental Protection Agency (EPA) of South Australia

Table 14: Water Quality – Shallow Monitoring Bores

Parameter	Units	Quaternary Alluvium		Tertiary Basalt		Tertiary Sediment		Weathered Coal Measures		Rewan Formation	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Field pH		5.73	7.48	6.28	8.49	5.42	7.76	6.1	8.16	6.2	7.39
Electrical Conductivity	µS/cm	4240	31600	5300	41300	2170	2650	9090	11000	10600	10900
Total Dissolved Solids	mg/L	2360	27000	3000	29000	1300	1620	5190	9600	6210	7210
Hydroxide Alkalinity (OH-) as CaCO3	mg/L	<1	<5	<1	<5	<1	<5	<1	<5	<1	<1
Carbonate Alkalinity as CaCO3	mg/L	<1	<5	<1	94	<1	<5	<1	<5	<1	<1
Bicarbonate Alkalinity as CaCO3	mg/L	101	360	390	827	53	116	271	457	21	47
Total Alkalinity as CaCO3	mg/L	101	360	380	827	53	116	271	457	21	47
Sulphate, SO4	mg/L	541	6200	60	1140	54	106	78	177	<1	1
Chloride, Cl	mg/L	1020	14000	1490	17000	660	794	3140	4100	3750	4030
Calcium - Dissolved	mg/L	172	1000	55	204	12	20	290	440	429	456
Magnesium - Dissolved	mg/L	107	1400	85	792	38	52	340	492	174	182
Sodium - Dissolved	mg/L	543	6200	891	13000	344	510	932	1400	1450	1650
Potassium - Dissolved	mg/L	5	17	12	150	9	13	9	14	26	29
Aluminium	mg/L	0	0	644	644	0	0	0	0	<0.01	<0.01
Arsenic-Dissolved	mg/L	0.002	0.008	<0.001	0.002	<0.001	<0.01	<0.001	0.011	<0.001	<0.001
Beryllium-Dissolved	mg/L	<0.00001	0.193	<0.0005	<0.005	<0.0005	<0.001	<0.000001	<0.001	<0.001	<0.001
Barium-Dissolved	mg/L	0.06	0.2	0.05	0.283	0.047	0.11	0.184	3.9	3.42	3.72
Cadmium-Dissolved	mg/L	<0.0001	0.0002	<0.0001	0.0012	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium-Dissolved	mg/L	<0.001	0.015	<0.001	0.01	0.001	0.076	<0.001	0.002	<0.001	<0.001
Cobalt-Dissolved	mg/L	<0.001	0.027	<0.001	0.005	<0.0001	0.005	<0.001	0.002	<0.001	0.001
Copper-Dissolved	mg/L	<0.00005	0.006	<0.001	0.059	<0.001	0.005	<0.001	0.004	<0.001	<0.001
Lead-Dissolved	mg/L	<0.001	<0.01	<0.001	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Manganese-Dissolved	mg/L	0.834	8.1	<0.005	0.611	0.007	0.095	1.1	1.86	1.17	1.92
Molybdenum	mg/L	0.001	0.003	0.003	0.008	<0.001	<0.001	0.003	0.004	<0.001	0.005
Nickel-Dissolved	mg/L	<0.00005	0.17	0.005	0.253	0.006	0.048	<0.001	0.125	<0.001	0.006
Selenium	mg/L	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Strontium	mg/L	<0.01	14	1.52	8.98	0.686	0.725	6.67	8.96	11	11.3
Vanadium-Dissolved	mg/L	<0.001	0.002	<0.001	0.042	<0.001	<0.01	<0.001	<0.01	<0.01	<0.01
Zinc-Dissolved	mg/L	0.008	0.302	<0.005	0.185	<0.005	0.131	<0.005	0.115	<0.005	<0.005
Boron	mg/L	0.13	0.34	0.42	2.74	0.61	0.76	0.32	0.34	0.14	0.19
Iron	mg/L	0.13	0.34	0.42	2.74	0.61	0.76	0.32	0.34	0.14	0.19
Mercury-Dissolved	mg/L	<0.00005	<0.0001	0.00008	0.001	<0.00005	<0.0001	<0.0001	<0.00005	<0.0001	<0.0001
Fluoride, F	mg/L	0.2	0.9	0.29	2	0.13	0.6	0.4	1	<0.1	<0.1
Phosphate as P in water	mg/L	0.007	0.79	0.026	12.6	0.01	1.3	0.11	2.09	<0.01	0.11

4.3.2 *Deep aquifer water quality*

Table 15 provides a summary of water quality results obtained from bores targeting the deep aquifers (M313W, M314W, M324W, M325W, AN019F, GR067V, M162V and M134GM). This provides an indication of water quality ranges for each parameter analysed based on aquifer type. Results for some parameters between different monitoring locations show high degree of variation which is likely to be attributable to the spatial heterogeneity and low permeability of the hydrogeological system. In addition to this, as displayed by the groundwater pressure data, groundwater recovery for some sites is slow and this is likely to result in variations in some parameters at the same monitoring location. Overall, a review of this data indicates that there are no notable trends. In general this data shows that:

- Groundwater quality of the Fort Cooper Coal Measures aquifer is fresh to saline[2]
- Groundwater quality of the Moranbah Coal Measures is fresh to saline

The water level in monitoring bore M162V dropped below the pump intake and sampling was unable to be undertaken at this site. A replacement sampling bore was selected in the immediate area intersecting the MCM. The production bore M134W; located approx. 480 m north of the monitoring bore was selected and included in the sampling undertaken in November 2017. The selected bore has been completed to approximately the same depth intersecting the MCM seam. The water quality results vary slightly from M162V as shown in the Appendix B table and sampling will continue in M134W until water levels recover within M162V.

Table 15: Background Water Quality – Deep Monitoring Bores

Parameters	Units	Fort Cooper Coal Measures		Moranbah Coal Measures	
		Min	Max	Min	Max
Field pH		8.13	11.8	7.7	9.42
Electrical Conductivity	µS/cm	1170	11100	1710	15600
Total Dissolved Solids	mg/L	707	6140	1160	9810
Hydroxide Alkalinity (OH-) as CaCO3	mg/L	<1	456	<1	<1
Carbonate Alkalinity as CaCO3	mg/L	<1	135	<1	407
Bicarbonate Alkalinity as CaCO3	mg/L	<1	635	168	2310
Total Alkalinity as CaCO3	mg/L	225	720	168	2360
Sulphate, SO4	mg/L	<1	68	<1	134
Chloride, Cl	mg/L	188	3400	198	5770
Calcium - Dissolved	mg/L	2	168	7	209
Magnesium - Dissolved	mg/L	<1	5	<1	62
Sodium - Dissolved	mg/L	199	2330	212	3490
Potassium - Dissolved	mg/L	12	73	12	1450
Arsenic-Dissolved	mg/L	<0.001	0.005	<0.001	0.013
Beryllium-Dissolved	mg/L	<0.001	<0.001	<0.001	<0.001
Barium-Dissolved	mg/L	0.005	3.25	0.236	23
Cadmium-Dissolved	mg/L	<0.001	<0.001	<0.001	0.001

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[2] Environmental Protection Agency (EPA) of South Australia

Parameters	Units	Fort Cooper Coal Measures		Moranbah Coal Measures	
		Min	Max	Min	Max
Chromium-Dissolved	mg/L	<0.001	0.004	<0.001	0.018
Cobalt-Dissolved	mg/L	<0.001	0.004	<0.001	0.01
Copper-Dissolved	mg/L	<0.001	0.582	<0.001	7.08
Lead-Dissolved	mg/L	<0.001	0.459	<0.001	2.19
Manganese-Dissolved	mg/L	<0.001	0.304	0.008	0.446
Molybdenum	mg/L	0.02	0.114	0.001	0.068
Nickel-Dissolved	mg/L	<0.001	0.009	<0.001	0.032
Selenium	mg/L	<0.01	<0.01	<0.01	<0.01
Strontium	mg/L	0.639	8.18	1.18	10.8
Vanadium-Dissolved	mg/L	<0.01	<0.01	<0.01	0.02
Zinc-Dissolved	mg/L	<0.005	0.427	<0.005	0.568
Boron	mg/L	0.42	1.17	0.46	2.4
Iron	mg/L	<0.05	0.24	0.1	3
Mercury-Dissolved	mg/L	0.42	0.42	0.87	0.87
Fluoride, F	mg/L	0.7	4.5	0.4	2.6
Phosphate as P in water	mg/L	<0.05	2.01	<0.05	65.6

4.4 Groundwater Use

The results from baseline assessments completed by Arrow have been considered as they provide information on groundwater bores and use.

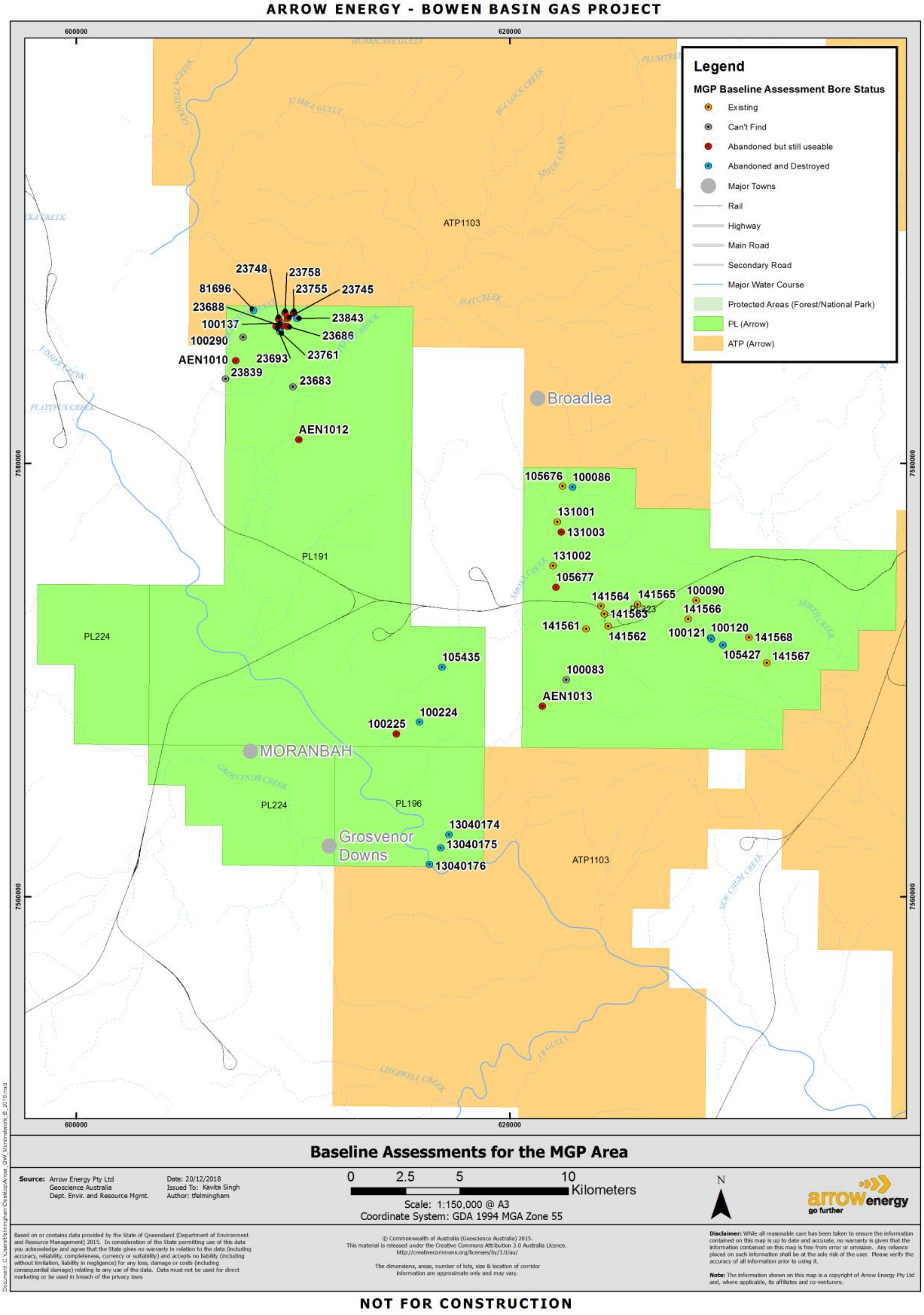
Baseline Assessment Plans (BAP) have been prepared for the BGP Area and submitted to DES. The results of the assessments undertaken as part of these are presented in the following sections. The completed baseline assessments have been submitted to the Office of Groundwater Impact Assessment (OGIA).

4.4.1 *MGP Area*

A BAP was submitted for the MGP Area and approved by the DES on 3 July 2012. The baseline assessment process included undertaking field assessments, sourcing information from mining companies and undertaking desktop assessments. A total of 42 assessments including registered (39) and unregistered bores (3) were undertaken which identified:

- 5 bores which could not be found (12%)
- 12 bores were abandoned and destroyed (29%)
- 13 bores were abandoned but still useable (29%)
- 12 bores have been verified to exist (29%)

All bores in the baseline assessments were classified in accordance with the status as defined in the groundwater database by DNRME. The exception to this was where bores which could not be found during the baseline assessment. The bores classified as ‘could not be found’ included those where the identified bore owner was not aware of the existence of any bore at that location or where a physical site inspection did not find any evidence of the bore in the specified location. The locations of these bores are shown in Figure 18. Based on this data, the majority of existing bores are located on PL223, which suggests that groundwater use is limited on PL 191, 196 and 224.



Baseline Assessments for the MGP Area

Source: Arrow Energy Pty Ltd
Geoscience Australia
Dept. Envir. and Resource Mgmt.

Date: 20/12/2018
Issued To: Kavita Singh
Author: tfelmingham

Scale: 1:150,000 @ A3
Coordinate System: GDA 1994 MGA Zone 55

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Figure 18: Completed Baseline Assessments for MGP

4.4.2 *ATP 1103*

A BAP was submitted for ATP1103 and approved on 12 November 2013. Based on the information presented in the DNRME Groundwater Database, baseline assessments have been completed on all registered bores that exist within 2 km of production testing wells on ATP1103. A total of 133 assessments, including registered (76) and unregistered bores (57), have been undertaken on ATP1103. The results concluded that:

- 30 bores could not be found (23%)
- 6 bores are abandoned and destroyed (5%)
- 29 bores are abandoned but still useable (22%)
- 68 bores have been verified to exist (51%)

The locations of these bores are shown in **Figure 19**.

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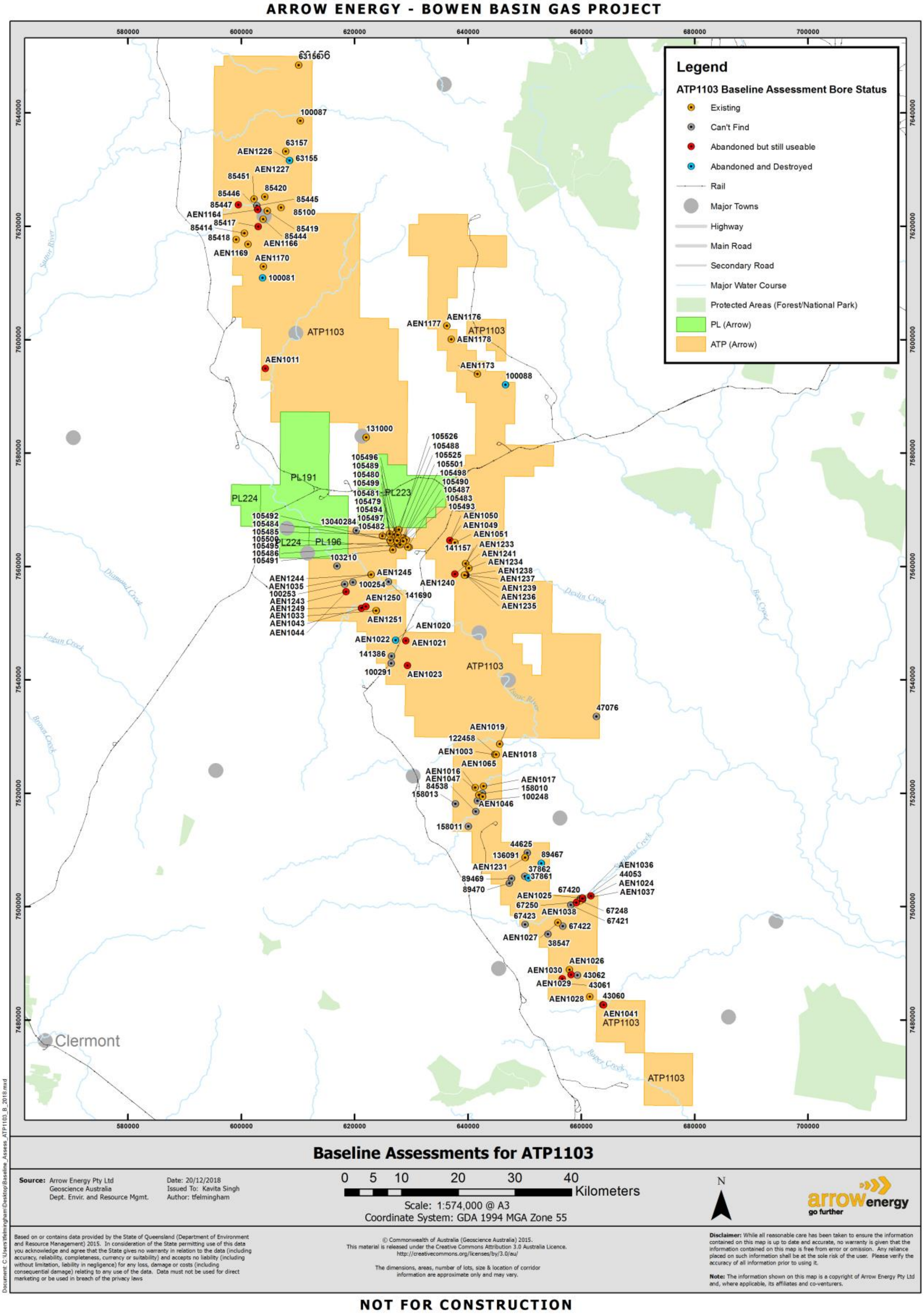

Figure 19: Completed Baseline Assessments for ATP 1103

4.4.3 *ATP 1031*

A BAP was submitted for ATP1031 and approved on 16 April 2013. Based on the information presented in the DNRME Groundwater Database, baseline assessments have been completed on all registered bores that exist within 2 km of production testing wells on ATP 1031. To date, 49 assessments, including registered (39) and unregistered bores (10), have been undertaken on ATP1031. The results concluded that:

- 24 bores could not be found (49%)
- 5 bores are abandoned and destroyed (10%)
- 11 bores are abandoned but still useable (22%)
- 9 bores have been verified to exist (18%)

The locations of these bores are shown in **Figure 20**.

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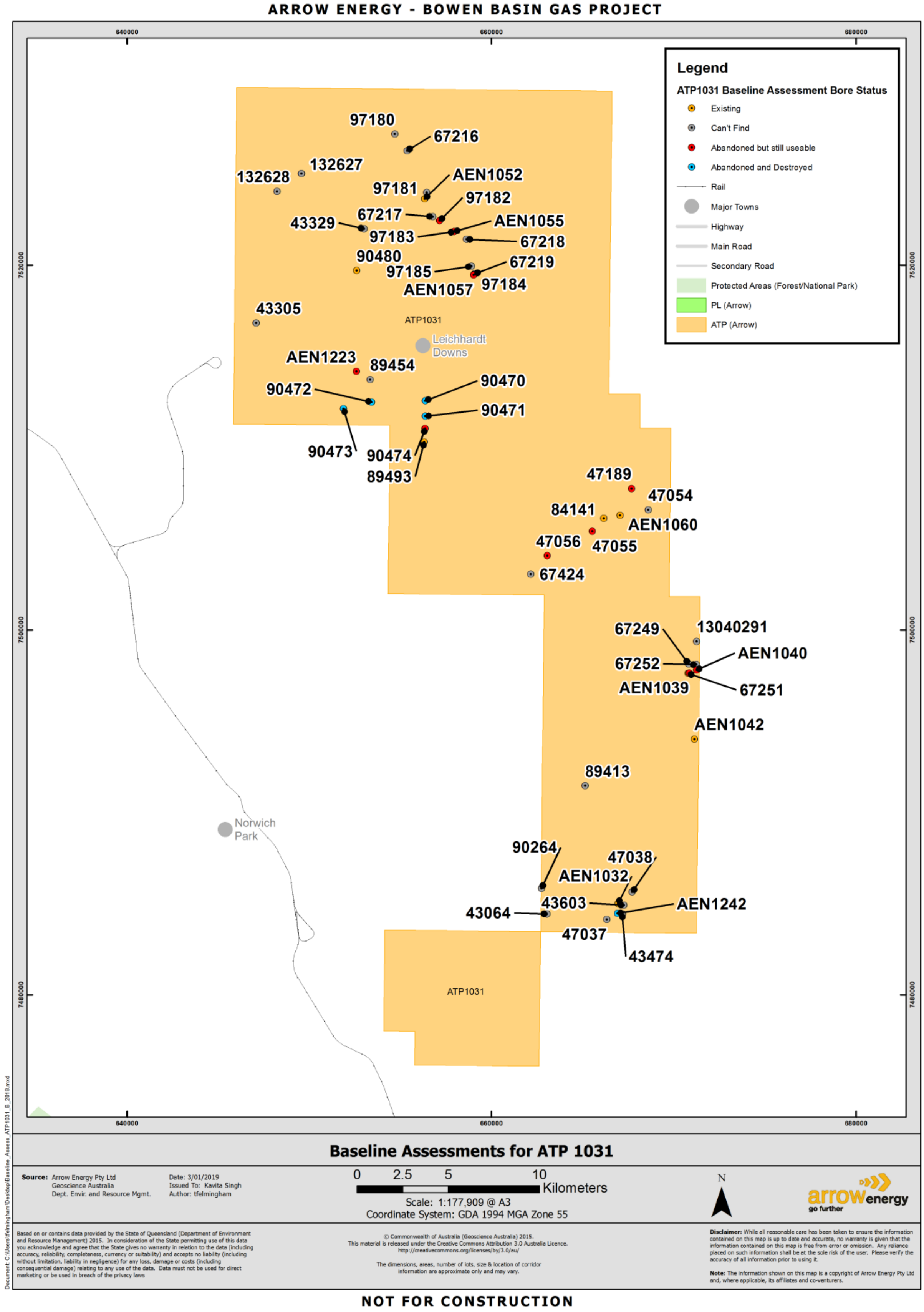


Figure 20: Completed Baseline Assessments for ATP 1031

4.4.4 *ATP 742*

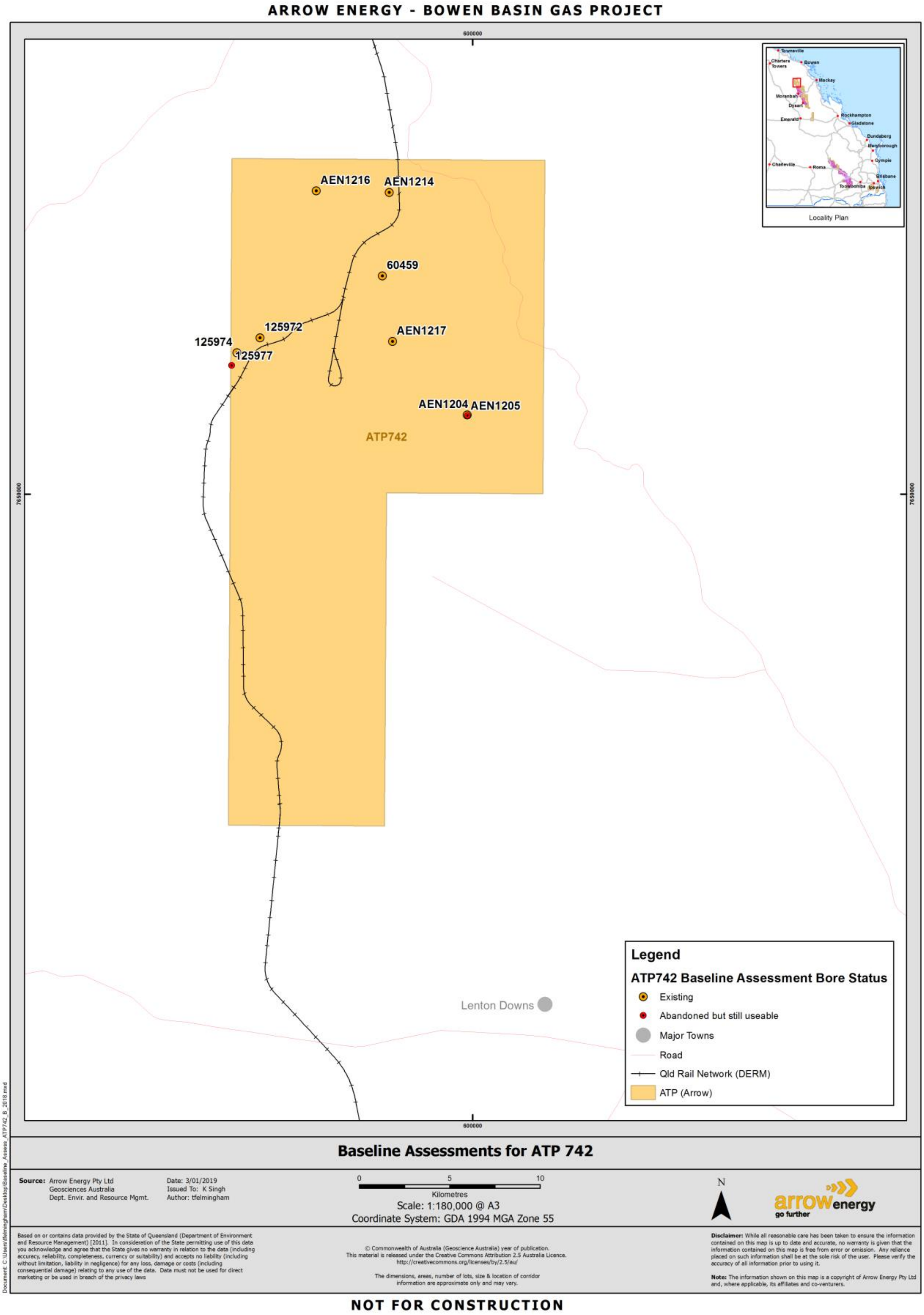
A BAP was submitted for ATP742 and approved on 22 October 2015. Based on the information presented in the DNRME Groundwater Database, baseline assessments have been completed on all registered bores that exist within 2 km of production testing wells on ATP 742. To date, a total of 9 assessments have been undertaken on ATP742. The results concluded that:

- 2 bores are abandoned but still useable (23%)
- 7 bores have been verified to exist (77%)

The locations of these bores are shown **Error! Reference source not found.**in Figure 21.

4.4.5 *Future Baseline Assessments*

Ongoing assessments will be carried out as outlined in the baseline assessment plans for each tenure.



Source: Arrow Energy Pty Ltd
Geosciences Australia
Dept. Envir. and Resource Mgmt.

Date: 3/01/2019
Issued To: K Singh
Author: tfelmingham

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Figure 21: Completed Baseline Assessments for ATP 742

5 UPDATED CONCEPTUAL HYDROGEOLOGICAL MODEL

A conceptual hydrogeological model was developed as part of the EIS and SREIS and was updated as part of the 2016 UWIR for the Project Area as has been depicted in Section 3 of this report. The validity of the existing conceptual hydrogeological model was reviewed in light of the new data presented in Section 5 of this UWIR. This review is presented below.

5.1 Water Levels and Flow

The groundwater monitoring network detailed in the WMS for the MGP Area has been implemented. Data obtained from groundwater monitoring bores making up the WMS provide site specific observations on groundwater levels/pressures and interconnectivity. The table below provides a comparison of this data. Overall, the existing conceptual model as presented in Section 3 remains valid. Whilst site specific data is provided in the table below, on a regional scale groundwater levels, flow and quality will vary.

Table 16: Data comparison

Existing Conceptual Model	Change since previous UWIR and supporting data
Shallow aquifers are recharged mainly through direct infiltration of rainfall, overland flow and surface water flow. The extent of recharge to water table aquifers from rainfall, overland flow and surface water are site and location specific.	No change
Shallow aquifers are hydraulically connected to surface water systems. The assumption has been made that water table aquifers in some locations are in connection with rivers/streams (generally losing stream)	No change
Rewan Formation is considered to be a regional-scale confining unit (aquitard). The coal seams are further confined by low permeability overburden and interburden. The pressure data presents evidence of limited interconnectivity between deep aquifers Depressurisation impacts notable within the coal measures in monitoring bores located within 350m of existing production wells Propagation of impacts within the coal measures not readily identifiable in monitoring bores located 4.5 km from existing production wells, thus suggesting low permeability target formations	No change
Coal seams are low to moderately permeable Water pressure recovery data suggests that the permeability of the coal seams is considered to be low to very low. Water quality of the coal seam aquifers is highly variable indicating spatial heterogeneity of the hydrogeological system	No change
Groundwater quality of the Quaternary Alluvium aquifer is highly variable ranging from brackish to saline.	No Change
Groundwater quality of the Tertiary Basalt aquifer is variable ranging from brackish to saline.	No change

Existing Conceptual Model	Change since previous UWIR and supporting data
Groundwater quality of the Tertiary sediment aquifer is considered fresh to brackish.	No change.
Groundwater quality of the Permian aquifers is considered to range from fresh to brackish.	Groundwater quality of the Permian aquifers is considered to range from fresh to saline.

5.2 Groundwater Users

Baseline assessments have been undertaken by Arrow as discussed in Section 4. This data provides information on groundwater users within the Project Area and suggests that groundwater use is limited on PLs 191, 196 and 224.

5.3 Conclusion

Groundwater monitoring data obtained to date was focussed around the MGP Area as this is Arrow's only production field in the Project Area. Whilst the above monitoring data provides some updates, it is concluded that the groundwater monitoring data obtained to date is in support of the conceptual hydrogeological model as presented in Section 3 of this report. The 2018 groundwater model assess the regional scale groundwater impacts of Arrows MGP Area and BGP area. This model has been updated and re-calibrated to take into consideration the available new data. There are no other material changes to the hydrogeological understanding of the Project Area since the development of the previous UWIR in 2016.

6 UWIR NUMERICAL GROUNDWATER MODEL UPDATE

Arrow Energy's 2019 Bowen basin UWIR model has included improvements from Arrow Energy's 2012 Bowen basin model used in Arrow Energy's Bowen SREIS and 2016 UWIR. It uses the MODFLOW-USG code. This allowed for an increase in the resolution of the model mesh around the MGP area and to better delineate fault structures. The model boundary was identical to the extent of active model cells in the previous model (hereafter referred to as the 2012 model) prepared to support the SREIS and 2016 UWIR (Norwest, 2012). The model domain is approximately 157 km wide (west to east direction) and 395 km long (north to south direction) as shown in Figure 23. The model domain was discretised and arranged into 22 layers comprising up to 18,082 cell nodes in each layer with the dimensions of the cells varying according to the features that required representation. A technical report on the modelling (AGE 2018) is provided in Apprendix C.

The following cell dimensions were adopted:

- MGP area: ~200 x 200 m hexagonal cells aligned to in seam wells;
- BGP area: ~1500 x 1500 Voronoi/rectangle cells centred on downhole CSG production wells;
- Faults: ~1000 x 1000 centred on either side of fault trace;
- Surficial aquifer systems (e.g. basalt): ~1000 x 1000m centred either side of aquifer extents; and
- Major drainage systems: ~500 x 500m centred along river lines proximal to the MGP.

The model layer elevations used the same regional geological model that the 2012 model was based on with a minor change in Layer 18. The previous model Layer 18 was split into five separate layers to more accurately represent targeted coal resources in the region. The model layers are shown in Table 2-1 in the 2018 model report (AGE, 2018) which is attached as Appendix C.

6.1 Groundwater Model Development

Groundwater modelling has been undertaken previously for the Project Area to predict depressurisation impacts on groundwater resources as a result of CSG production, which include:

- PLs 191, 196, 223, 224 and ATP 1103 UWIRs (2012) using a Modflow-Surfact numerical groundwater model (NTEC, 2012)
- Bowen Gas Project EIS (2012): and 2016 UWIR modelled using a Modflow-Surfact numerical groundwater model (Ausenco-Norwest, 2012); and
- ATP 1031 (2014): MLU Analytical groundwater model

As described above Arrow Energy has updated the 2012 model and subsequent annual review to take advantage of:

- developments in predictive modelling software
- incorporation of additional field data
- improved understanding of the aquifer hydraulic characteristics

6.1.1 *Domain and Grid Design*

The initial 2012 model developed by Ausenco Norwest for Arrow Energy used a rectilinear model grid with a uniform grid cell dimension of 1,500 m. The development of voronoi meshing tools using Algomesh (HydroAlgorithmics, 2014) allowed for variable grid cell dimensions to better represent important model features including:

- 200 m dimension hexagonal cells aligned to in seam well traces in the MGP area;
- 500 m dimension cells along rivers near the MGP;
- 1000 m dimension cells for surficial aquifer systems (e.g. basalts) and around faults; and
- 1500 m dimension cells centres around BGP wells.

Layering was extended to 22 layers from 18 in the 2012 model to allow for explicit representation of coal units that have been investigated by Arrow. The increased layer count resulted from splitting the original layer 18 (lumped Collinsville Formation-Back Creek Group) into 5 layers (2 coal seams, 2 interburden layers, and a basal Permian layer).

These improvements were achieved whilst reducing the number of model cells from 530, 640 to 188,516 cells, enabling faster runtimes with better resolution in specific model areas. The active model domain covers 42,000 km^2 of the northern Bowen Basin, similar to the 2012 model and presented in Figure 23.

6.1.2 *Boundary conditions and parameterisation*

Boundary conditions were adopted from the previous calibrated 2016 UWIR model and represented areas of outcrop to the east and west, river cells and a general head boundary (GHB) at the southern boundary of the model. Starting hydraulic parameters, with the exception of coal seam hydraulic conductivity, were also adopted from the previous calibrated 2012 model. Approximated depth decline equations were applied for the Moranbah and Rangal Coal Measures, with separate relationships for each that were derived from production tests in the BGP area.

The predicative model was run forward in time at annual time slices starting in 2018 and ending in 2181 to predict the potential impact from CSG. The minor differences in results between the models indicate this timeframe still captures the impact of the proposed operations.

6.1.3 *Model Calibration*

Model calibration included steady state and transient calibrations to provide an initial parameter set prior to implementation of uncertainty analysis.

6.1.3.1 Calibration

Steady state calibration included a pre-mining steady-state simulation using available groundwater level data, including a total of 529 monitoring points compared to 482 points in the 2016 UWIR model. Transient calibration included 47 monitoring locations. These points were reviewed for potential affects by surrounding mining activities and were weighted based upon the likely impact of mining on this data as shown in the report in Appendix C, to reduce biased impact in the model prediction from mining activities that are not simulated in the model.

6.1.3.2 Pilot Point Calibration

Pilot points were used in the calibration and the assessment of predictive uncertainty. Pilot points were placed as indicated and parameter values were allowed to vary up and down by two orders of magnitude around the initial parameter. Acceptable ranges of parameters were set as summarised and these relationships of hydraulic conductivity were checked to ensure that unrealistic relationships such as very low storage with very high hydraulic conductivity did not occur.

6.1.3.3 Calibration Results

Observed and simulated water levels are shown in Figure 22**Error! Reference source not found.**. Calibration achieved a RMS error of 5.8%, a SRMS of -1.54% indicating a good match between observed and simulated calibration points.

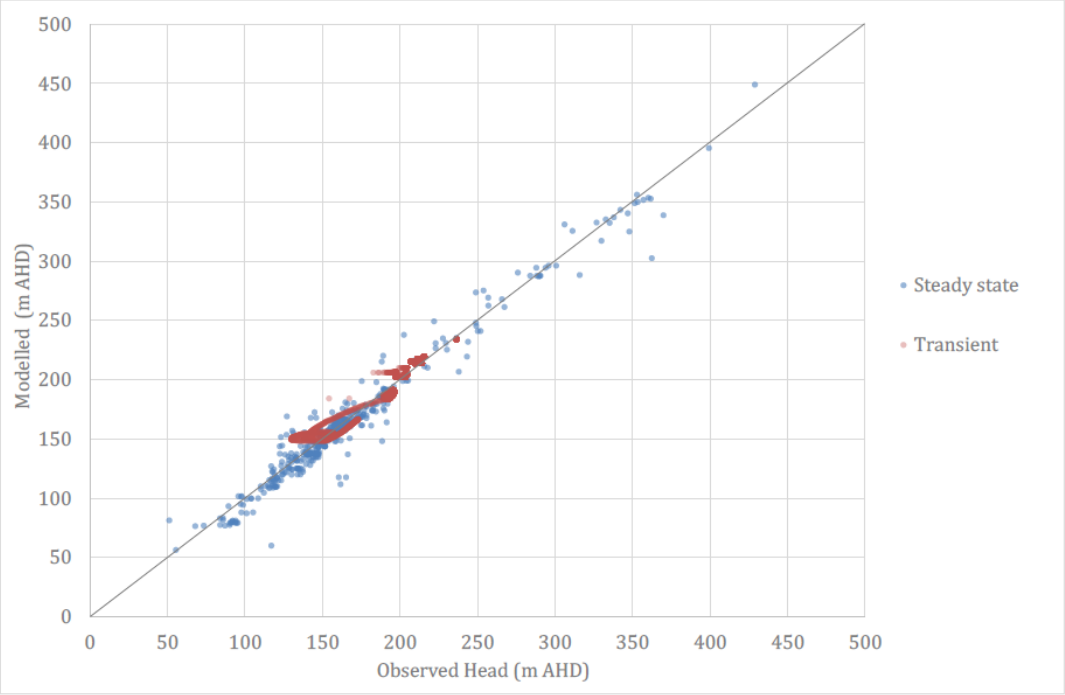

Figure 22: Model residuals (measured vs. simulated)

The model water balance budget of 0% error indicated a stable and numerically accurate solution.

6.1.4 *Prediction Approach*

The 2019 UWIR field development scenario included the following Arrow development areas:

- Historical and forecast MGP production;
- Red Hill;
- Mavis Downs; and
- Remainder of the FDP.

The development areas and associated water production in the model described in section 2.2.

The impact due to Arrow CSG activities is derived by subtracting results from a 'no CSG' production scenario from the above scenario.

To represent a conservative maximum drawdown in the MCM and RCM drawdowns form each individual coal seam within these each of these units was combined to form a spatial composite of the area of drawdown. Where a bore intersects a specific seam or seams the drawdown extent would be less than that shown by this method.

6.1.4.1 Uncertainty analysis

The null-space Monte Carlo (NSMC) analysis method was used to quantify the uncertainty in predicted impacts, through multiple model simulations with differing parameter realisations, accepting only the realisations that could be calibrated.

The uncertainty analysis indicates the variability in potential predicted outcomes and provides confidence level of a prediction with a low potential to be exceeded.

Uncertainty analysis was undertaken by firstly applying parameter ranges around the base case parameters using multipliers on the base case parameters to achieve these ranges and set the prior uncertainty.

Using the multipliers 350 model realisations were created, each having differing values of the non-unique pilot point parameters. Realisations were constrained using calibration datasets. The constrained realisations were tested and the models that failed to converge or could not achieve adequate calibration were rejected, leaving only the output from 208 successful models. This yielded the posterior uncertainty range (see Appendix B in AGE report).

The 95th percentile of these outputs was calculated to provide a prediction of the extent of the LAA only exceeded in 5% of cases.

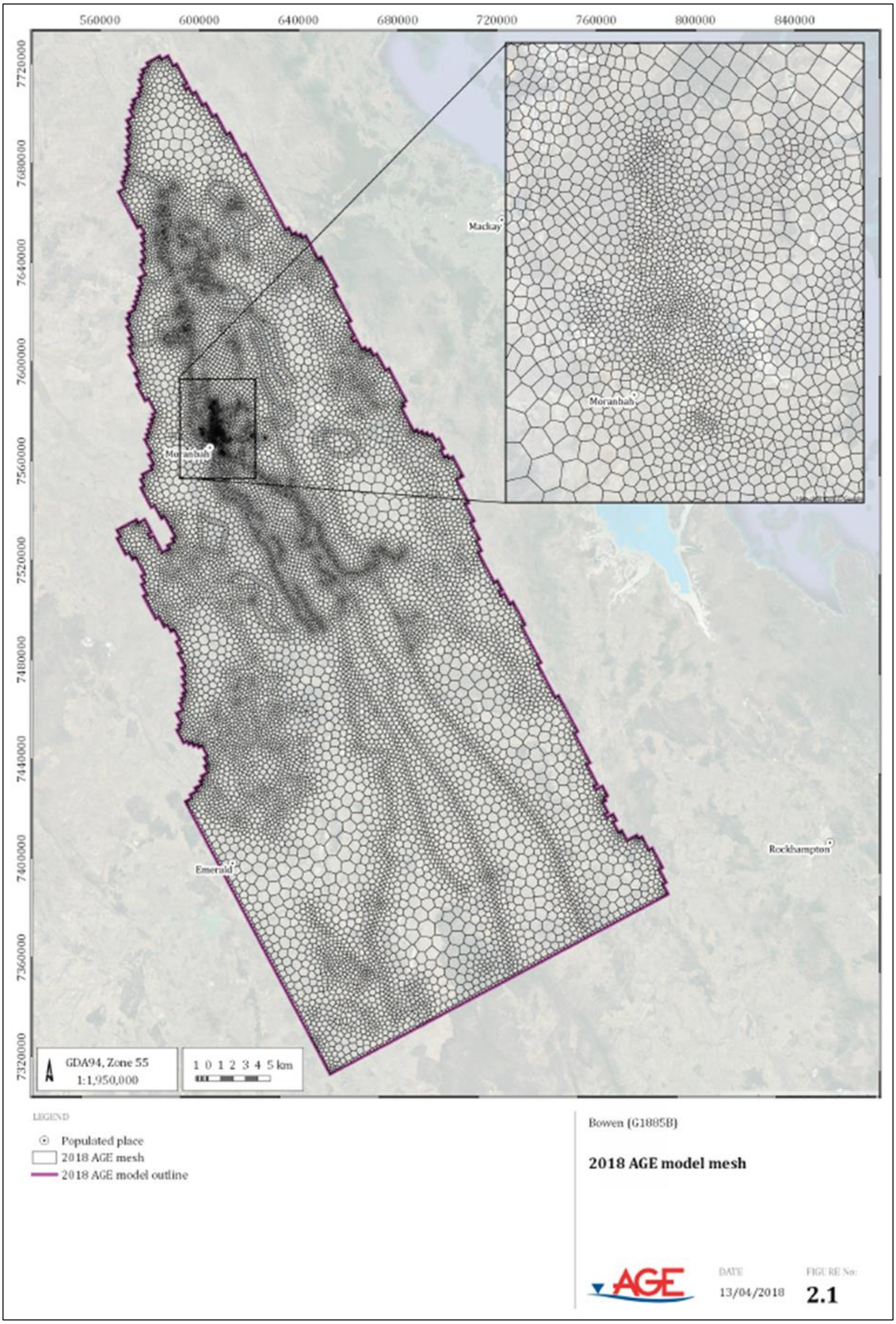

Figure 23: Bowen Model Area Domain

7 PREDICTION OF IMPACTS

Model predictions (AGE, 2018) indicate that drawdown greater than trigger thresholds will be restricted to the MCM and RCM as described in the model report in Appendix C.

The method to derive cumulative drawdowns for the UWIR scenario are described below:

- For each scenario the cumulative drawdowns are calculated by subtracting the heads from the scenario with no CSG production' (NC scenario) from the heads in a scenario with CSG production.
- All drawdowns represent maximum drawdowns queried across the entire simulation period and recorded for each cell, drawdowns therefore represent a composite result from the entire simulation.

The extent of maximum drawdown for the Moranbah (MCM) and Rangal Coal Measures (RCM) has been presented as a composite of the cumulative drawdown from each coal seam in the coal measure to present the area of maximum drawdown across all coal seam layers within that coal measure. This provides a conservative overestimate of the extent of impact and this mirrors the method used by OGIA to derive LAAs in the coal measures in the Surat CMA

It should be noted that the predictions made in the groundwater model will be validated against future monitoring data as part of the annual review process. This will provide confirmation of predicted impacts against actual impacts occurring, if any.

7.1 Immediately Affected Area (IAA)

The IAA of an aquifer is the area within which water levels are predicted to decline as a result of CSG water extraction by more than the trigger threshold within three years of the consultation day for the report (January 2022). The trigger thresholds are specified in the *Water Act 2000*. They are 5 m for consolidated aquifers (such as sandstone) and 2 m for unconsolidated aquifers (such as sands). Table 17 shows the layers with an IAA exceeding the trigger threshold

Table 17: IAA Exceeding the trigger threshold

Unit	IAA trigger threshold exceeded
Moranbah Coal Measures	Yes
Rangal Coal Measures	Yes

Drawdown less than the bore trigger threshold was identified in layers 1 and 2.

Figure 24 shows the IAA for the consolidated aquifers and the impacts associated with the MGP Area are restricted to the MCM. With the exception of GR067V in the north and AN019F and AN020F out to the east, all the UWIR monitoring wells are within the IAA area footprint of the MCM. The landholder bore located within the IAA is discussed in more detail in Section 8.2.4 but is a shallow bore, not completed into the MCM and RCM aquifers.

Because production testing is relatively short term the IAAs and LAAs for these are the same, however, LAAs are overprinted by the extent of the LAA of the longer term field development plans. As discussed in section 2.4 the IAAs for the production testing are based on a combination of historical production test data and simulation of recent production test data up to the end of 2017. This indicates that the extent of IAAs is 1 Km from production test wells. It should be noted that production testing was undertaken in Red Hill 98-100 wells during 2018. These wells produced approximately 177kL of water. Based on the assessment methodology outlined in section 2.4, the water produced is less than the Peak Downs IAA site and therefore the potential IAA for these production testing wells will be less than 1km from the Red Hill 98-100 wells.

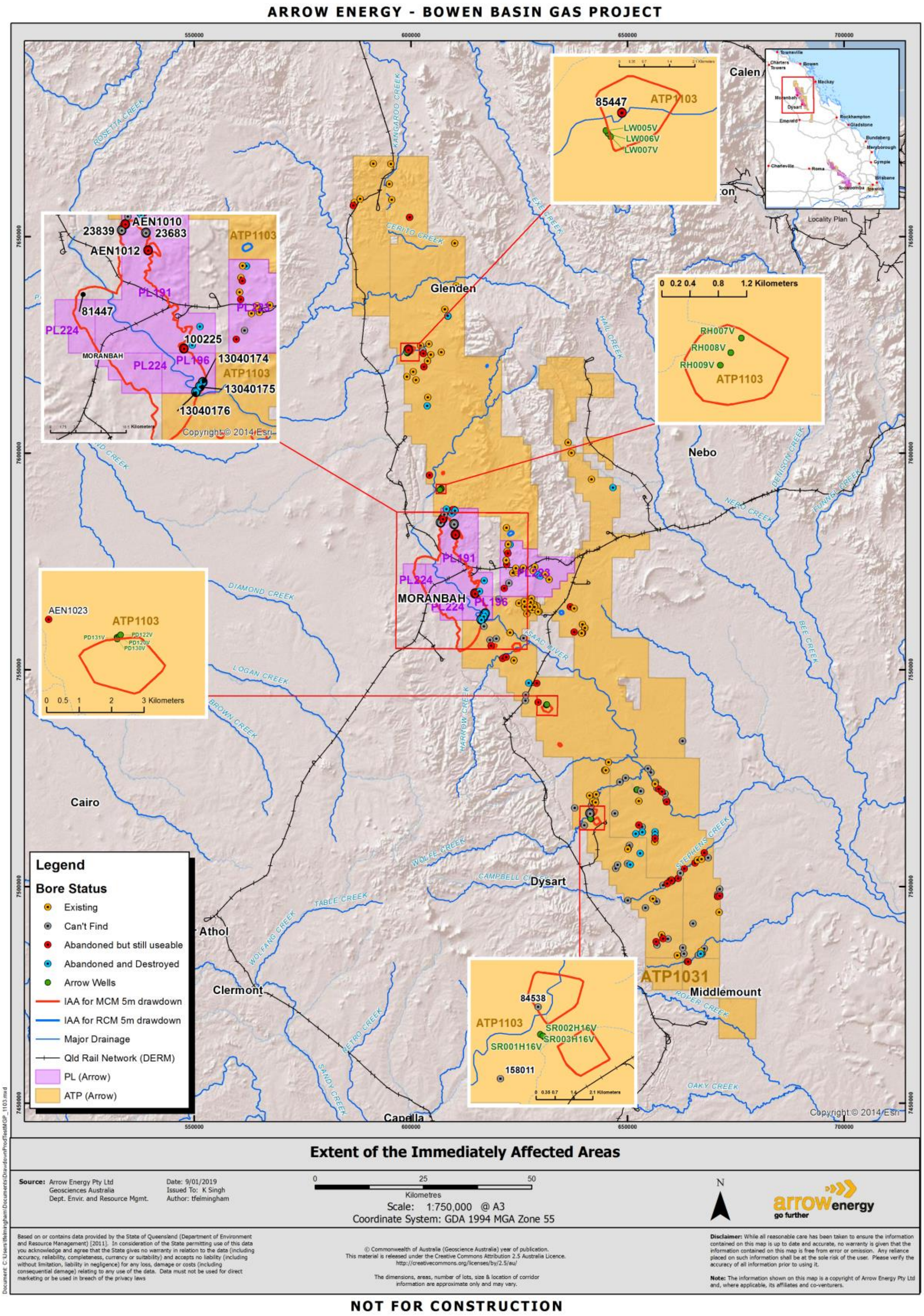

Figure 24 : Extent of the Immediately Affected Areas

7.2 Long-term Affected Area (LAA)

The LAA of an aquifer is the area within which water levels are predicted to decline by more than the trigger thresholds at any time in the future. The trigger thresholds are specified in the Water Act 2000. They are 5 m for consolidated aquifers (such as sandstone) and 2 m for unconsolidated aquifers (such as sands). The timeframe within which the LAA has been determined is up until 2181.

Figure 25 presents the extent of the LAA for the MCM and the RCM. The LAA for the MCM shows a very similar footprint to the IAA for the MCM overlying the MGP Area. The LAA for the MCM also extends 103km north and up to 67km south based on the BGP.

The footprints of the LAA for the RCM do not fall within the MGP area but are located to the direct north and further south within the BGP. The RCM footprints are generally located more to the east of the MCM footprint due to RCM located above the MCM and the formation dips is to the east as indicated in the figure, and covers a significantly smaller area than the MCM.

Future production testing volumes cannot be provided given that they are undertaken for exploration and appraisal purposes. This approach is consistent with the 2014 and 2016 UWIR Modelled predictions of impacts are based on historical production testing volumes as at end of 2017 in the BGP area. Based on available data, the impacts predicted for the IAA is the same as the LAA for production testing wells as depicted in Figure 24 above.

The methodology for developing forecast water production data for the MGP is based on a Decline Curve Analysis (DCA) discussed in Section 2.2. and the accuracy of the prediction is subject to uncertainties in the measurement and reporting of the historical water rates

Key observations about the LAA are as follows:

- There is no LAA (predicted drawdown greater than 2 m trigger threshold) for unconsolidated aquifers in the Project Area.
- There are larger areas of LAA (predicted drawdown greater than 5 m trigger threshold) for the MCM in comparison to the RCM. This is associated with proposed production from the MCM in the BGP as well as the MGP.
- There are localised areas of LAA’s (predicted drawdown greater than 5 m trigger threshold) within the immediate vicinity of some production testing wells for the Moranbah and Rangal coal measures
- There is no predicted LAA in any other consolidated aquifers.

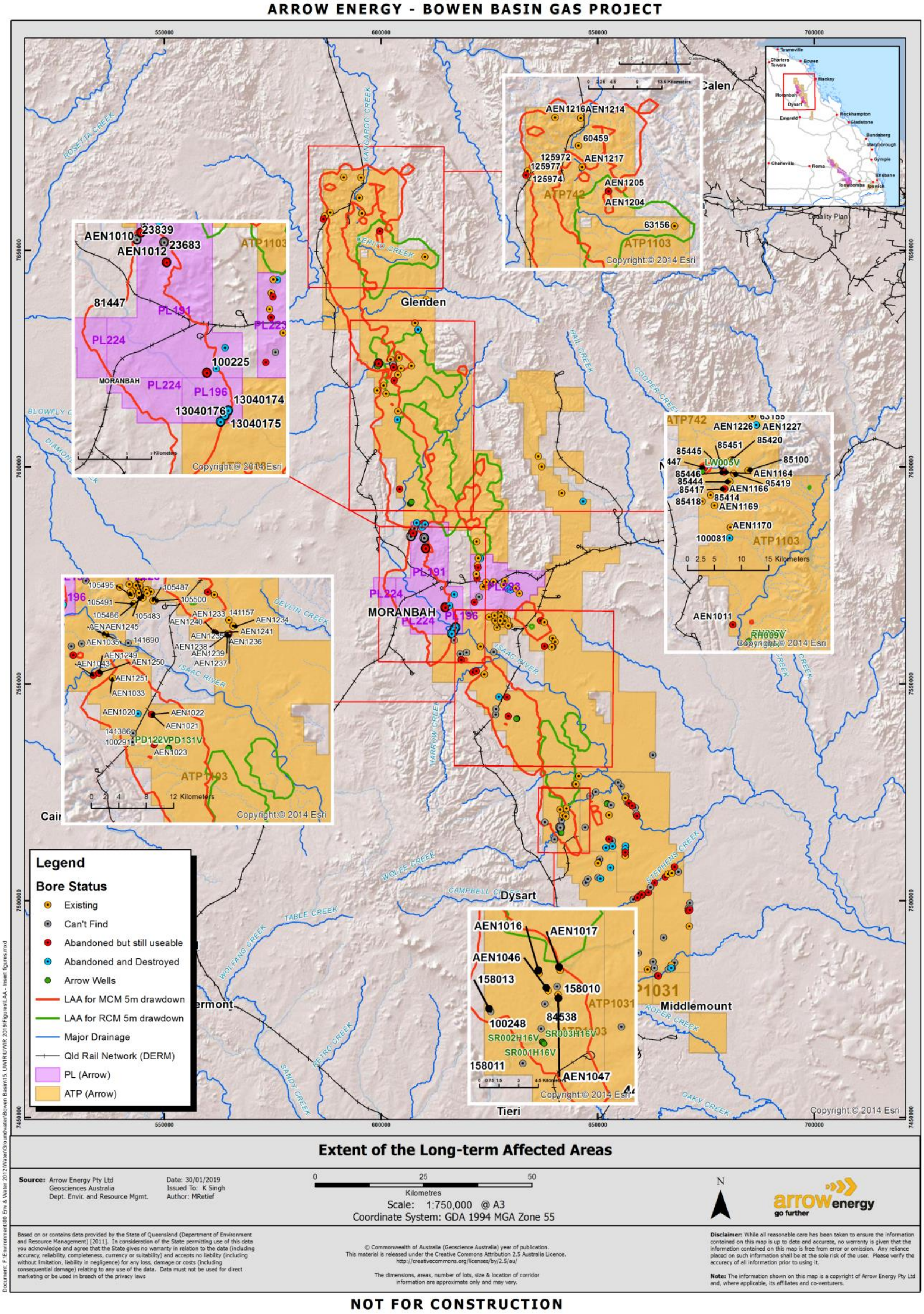

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Figure 25 : Extent of the Long-term Affected Areas

8 WATER MONITORING STRATEGY

8.1 Groundwater Monitoring Program

A water monitoring strategy is required for the Project Area shown in Figure 24 and Figure 25. This incorporates the development of a groundwater monitoring program.

The groundwater monitoring program has been developed to undertake:

- Site and regional groundwater level monitoring data in the deeper aquifers;
- Site and regional groundwater level and quality monitoring data in the shallow aquifers;
- Assessment of site aquifer parameters for shallow and deep aquifers through model calibration;
- Characterisation of interconnectivity of aquifers underlying the site; and
- Characterisation of surface water – groundwater interaction (particularly with Isaac River on-site).

In order to meet the aforementioned objectives, a groundwater monitoring program that includes a representative suite of bores in the shallow, intermediate and deep groundwater systems is proposed. The major groundwater systems to be monitored include:

- Shallow groundwater systems (water-table) comprised of:
    - Quaternary alluvium, and
    - Tertiary basalt and sediments.
- Intermediate groundwater systems (confined / unconfined) of Triassic outcrop formations including the Clematis Sandstone; and
- Deep groundwater systems (confined aquifers) of:
    - Blackwater Group at the CSG target depths, and
    - Blackwater Group sub-crops including the Rangal Coal Measures, Fort Cooper Coal Measures and Moranbah Coal Measures.

Given that CSG operations in the Project Area have been on-going for a number of years and the extent and potential for impacts greater than the bore trigger threshold appears limited, data reflecting background conditions exists beyond the local area of the Project Area. Therefore, the proposed groundwater monitoring program comprises two phases, being proximal and distal monitoring during and post CSG extraction.

Site specific geological and hydrogeological data collected during drilling will be used to update the conceptual model. This will provide further data to monitor for predicted future impacts to groundwater levels and quality.

The scope for establishing an appropriate groundwater monitoring program for the Project Area includes:

- Identifying existing bores (such as groundwater monitoring bores installed to satisfy conditions of the relevant Environmental Authorities or landholder bores) which may provide data suitable for inclusion to the monitoring program;
- Identifying where additional dedicated groundwater monitoring bores are required. Target aquifers and locations are influenced by the areas of water level decline in excess of the bore trigger threshold and monitoring of aquifers unaffected by taking of water, i.e. background sites;
- Identifying existing Arrow well sites that are located within the vicinity of target monitoring locations for conversion to future groundwater monitoring bores; and
- Review and report results of monitoring annually.

A desktop bore inventory will be undertaken to identify other existing bores in the region. It is likely that data for some of the bores identified in the inventory will be appropriate for inclusion in the monitoring program. Data will be considered suitable if bores are:

- Screened in aquifers where impacts have been predicted;
- Compliant with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003) or the Code of Practice for constructing and abandoning coal seam gas wells and associated bores in Queensland (DNRM, 2013)
- In good condition;
- Suitable for conversion to a groundwater monitoring bore; and
- The owners grant access to their bore for monitoring.

Depending on the level of detail of the bore inventory, additional work (such as bore condition assessments) may have to be undertaken before an existing bore can be considered to be suitable.

The proposed groundwater monitoring network is discussed in more detail in the following sections of this report.

8.1.1 *Groundwater Monitoring Network*

A regional aquifer groundwater monitoring network has been developed. The purpose of this monitoring network is to monitor the future effects of decline in water level and establish baseline groundwater level and quality data.

8.1.1.1 MGP Area

The spatial distribution of the 16 groundwater monitoring bores that comprise the groundwater monitoring network for the MGP Area is shown in Figure 10. The groundwater monitoring is being undertaken in these bores in accordance with the WMS in the approved 2016 Bowen UWIR and approval conditions.

Possible sensitive ecosystems exist in association with the Isaac River which runs through the predicted peak decline area for the MCM. Shallow formations (alluvium and basalt) in this area have a higher environmental value and are more likely to be used as a groundwater source. Whilst impacts greater than the bore trigger threshold are not predicted to occur in the shallow formations, seven groundwater bores monitoring shallow aquifers (Quaternary alluvium, Tertiary basalt) have been installed as at June 2012. Groundwater monitoring has been undertaken in these bores and an adequate baseline dataset has been established. It should be noted that some of these bores have been installed to provide information on vertical movement and transmission of impacts to shallow aquifers.

Within the Project Area, drawdown that is predicted to be greater than the bore trigger threshold is centred around PLs 191, 196 and 224. Based on this, the groundwater monitoring network includes four deep groundwater bores within the predicted maximum impact area (greater than 5 m drawdown) for the IAA and monitors the deep CSG target (Moranbah Coal Measures), Fort Cooper Coal Measures and the underlying Back Creek Group. The monitoring wells subjected to water quality sampling in the WMS prove sufficient in meeting the monitoring objectives as defined above.

Following the completion of the Baseline Assessment, it was concluded that there are no existing landholder bores on PLs 224, 191, and 196. Existing landholder bores however, are located on PL 223. Five monitoring bores were installed to monitor impacts between the IAA and the existing landholder bores on PL 223, as well as locations distal to the IAA for background monitoring.. Appendix G provides the status of these bores

8.1.1.2 BGP

The design of the groundwater monitoring network, including the network locations and specifications is discussed in more details below to support the BGP project phases. The following is a brief summary of the monitoring plan for the Red Hill Central, Mavis Downs and remainder of the BGP FDP project areas.

A groundwater monitoring network has been developed for the BGP. A structured analysis was undertaken to identify where predicted groundwater drawdowns may correspond to potential risks, and to rationalise the monitoring locations. The selection of monitoring locations takes into consideration the requirement to provide baseline data before development impacts occur, and to enable early warning impact detection through analysis of groundwater hydrograph trends, as monitoring data is acquired over time.

The design and layout of the groundwater monitoring network is underpinned by the 2018 numerical groundwater modelling that simulates the MGP and BGP groundwater abstraction and predicts the degree and extent of aquifer depressurisation in a spatial and temporal context. A geospatial analysis has been used to enable the magnitude, extent and timing of depressurisation to be related to the location of connected environmental features and existing water users, thereby providing an informed basis for establishing monitoring locations.

In summary, in designing the monitoring network consideration has been afforded to the following:

- acquisition of baseline data;
- spatial extent and timing of predicted aquifer depressurisation;
- geological formations that require monitoring and potential migration pathways;
- potential changes to the groundwater balance;
- environmental features that require monitoring; and
- groundwater level or pressure impacts that are anticipated to occur in the context of connected receptors.

The layout of the groundwater monitoring network is specified separately for each of the BGP project phases, Red Hill Central development, Mavis Downs development and the remainder of the BGP FDP and takes into consideration their differences in gas development, both in a spatial and temporal context. The locations of the monitoring sites are presented in Figure 26 and Figure 27 and summarised in Table 18.

The development of the Red Hill Central groundwater monitoring network identified existing production testing wells, earmarked to be plugged and abandoned, that can be converted into monitoring wells as indicated in Table 18. The 3 production testing wells selected will monitor the following coal units/formations:

- Well MW1-S,I,D – horizons targeted will be MCM, RC and Tertiary Sediments
- Well MW2-D – target the MCM formation
- Well MW3-D – target the MCM formation

The monitoring bores used in developing the initial baseline will be augmented with additional monitoring bores to close out any monitoring/data gaps identified. The specifications, including the primary and secondary purpose of the bores, formations targeted, provisional installation years, are shown in Table 18

In total, 27 bores are proposed for groundwater monitoring at 16 selected locations of potential future impacts associated with the proposed BGP. All monitoring locations intend to inform changes to the groundwater regime and the groundwater balance in the BGP and each location has been targeted to fulfil specific (primary and secondary) purposes and knowledge gaps. Selected monitoring wells were also identified for baseline data capture and/or early warning monitoring to ensure a sufficient level of coverage across the area and within key aquifers is achieved.

The installation schedule is phased according to the following:

- Monitoring well locations with a primary purpose of baseline monitoring will be installed prior to the commencement of production in the corresponding development phase to enable the collection and interrogation of baseline data.
- Monitoring well locations where baseline monitoring is not required will be installed immediately prior to the commencement of production in the corresponding development area.

- Contingent locations will be installed only in circumstances where the criteria for contingency (specified in the notes to Table 18) are met.

Both field and laboratory based quality monitoring will assist in aquifer characterisation and baselining, serving as a benchmark against which potential impacts can be assessed.

It needs to be recognised that the ultimate location of the monitoring wells will be subject to site and access constraints that may lead to re-positioning.

Table 18: Specifications of the BGP monitoring network

Monitoring Location	Development Area	Primary Purpose	Secondary Purpose	Target Formation	Indicative Installation Year	Comments
MW1-S MW1-I MW1-D	Red Hill Central	Baseline Data Capture Coal Mine cumulative impact monitoring Early warning monitoring	Groundwater quality	Quaternary / Tertiary RCM MCM	2019	Production testing well to be converted Nested Monitoring well site
MW2-D		Baseline Data Capture Formation hydraulic interconnectivity Early warning monitoring		MCM	2019	Production testing well - pressure monitoring
MW3-D		Baseline Data Capture Formation hydraulic interconnectivity Early warning monitoring		MCM	2019	Production testing well - pressure monitoring
MW4	Mavis Downs	Baseline Data Capture Coal Mine cumulative impact monitoring Early warning monitoring	Groundwater quality	Tertiary/Triassic	2020	
MW5	Remainder of the FDP	Baseline Data Capture Coal Mine cumulative impact monitoring Early warning monitoring	Groundwater quality	Quaternary/Tertiary	Contingent	Inferred fault Rewan Formation is absent Contingent location
MW6-S MW6-D		Baseline Data Capture Early warning monitoring	Groundwater quality	Tertiary RCM	2028	Nested monitoring well site
MW7		Formation hydraulic interconnectivity Coal mine cumulative impact monitoring	Groundwater quality	Quaternary/Tertiary	2030	Rewan Formation is absent
MW8-S MW8-I MW8-D		Baseline Data Capture Formation hydraulic interconnectivity Interconnection via preferred pathway	Groundwater quality	Quaternary / Tertiary RCM MCM	2028	Nested monitoring well site Rewan Formation is absent Inferred fault
MW9		Early warning monitoring	Groundwater quality	Tertiary	2030	Rewan Formation is absent
MW10-S MW10-D		Baseline data capture Formation hydraulic interconnectivity Interconnection via preferred pathway Early warning monitoring	Groundwater quality Coal mine cumulative impact monitoring MNES monitoring	Quaternary / Tertiary or Rewan Formation RCM	2028	Nested monitoring well site Close to boundary of Rewan Formation Inferred fault
MW11		Baseline data capture Coal mine cumulative impact monitoring Formation hydraulic interconnectivity Early warning monitoring		Quaternary / Tertiary	2028	Rewan Formation is absent
MW12-S MW12-D		Interconnection via preferred pathway	Groundwater quality	Quaternary / Tertiary (if present) Blackwater Group (RCM/MCM)	Contingent	Nested monitoring well site Inferred fault Contingent location (MW12-D)
MW13-S MW13-I MW13-D		Baseline data capture Formation hydraulic interconnectivity Early warning monitoring	Coal mine cumulative impact monitoring	Quaternary / Tertiary RCM MCM	2028	Nested monitoring well site Rewan Formation is absent
MW14-S MW14-I		Baseline data capture Interconnection via preferred pathway Early warning monitoring	Groundwater level monitoring in proximity to potential riparian vegetation Groundwater quality	Unconfined alluvials Tertiary / Triassic	2028	Nested monitoring well site Inferred faults In proximity to Isaac River
MW15		Baseline data capture Formation hydraulic interconnectivity Early warning monitoring	Coal mine cumulative impact monitoring Groundwater quality	Tertiary	2028	Rewan Formation is absent
MW16-S MW16-I	ATP 1103 (in proximity to Lake Elphinstone)	MNES monitoring Groundwater-surface water connectivity Formation hydraulic interconnectivity Early warning monitoring	Groundwater quality	Unconfined alluvials Rewan Formation	Contingent	Nested monitoring well site Contingent location

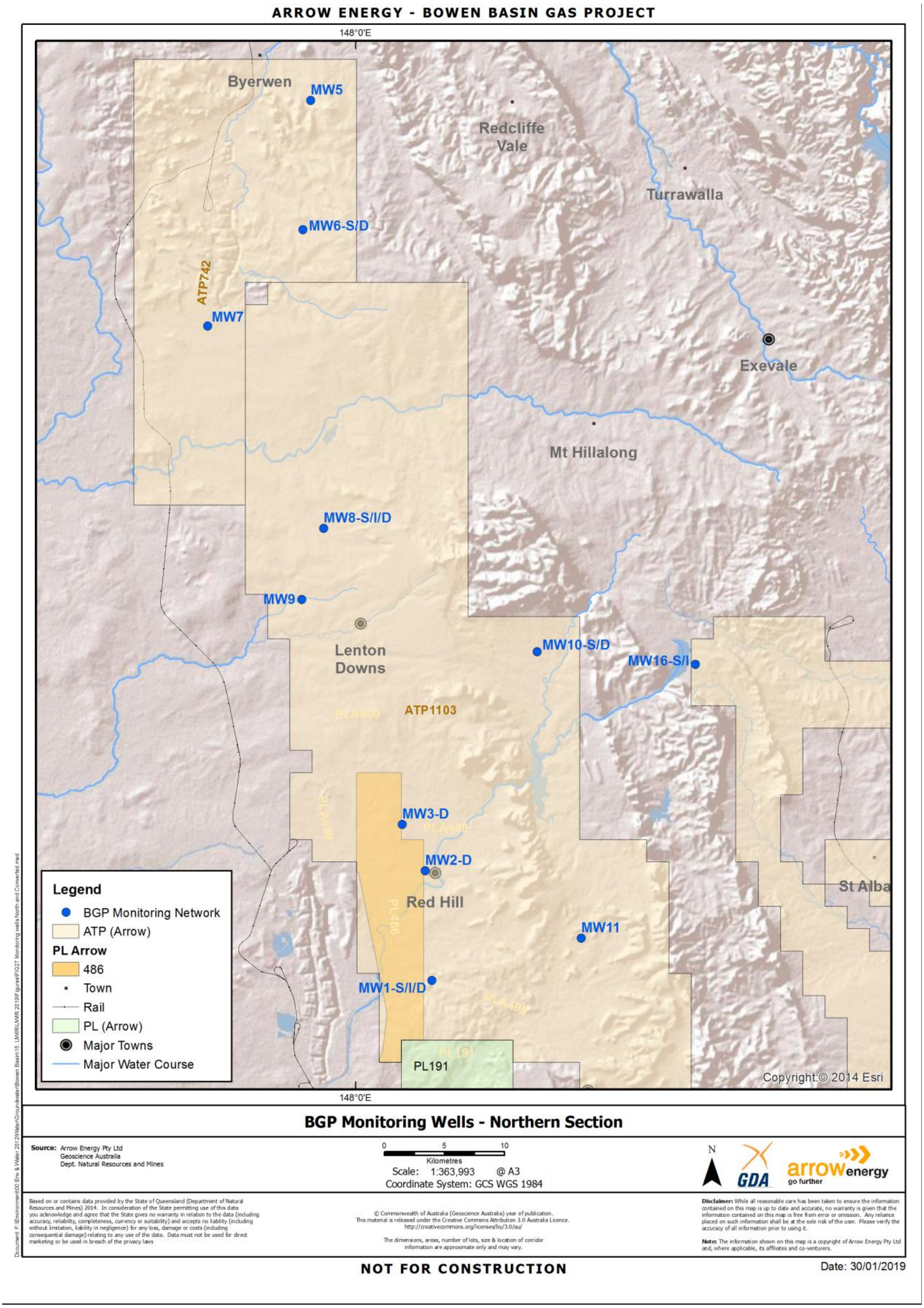


Figure 26: Groundwater Monitoring Network – Northern Section

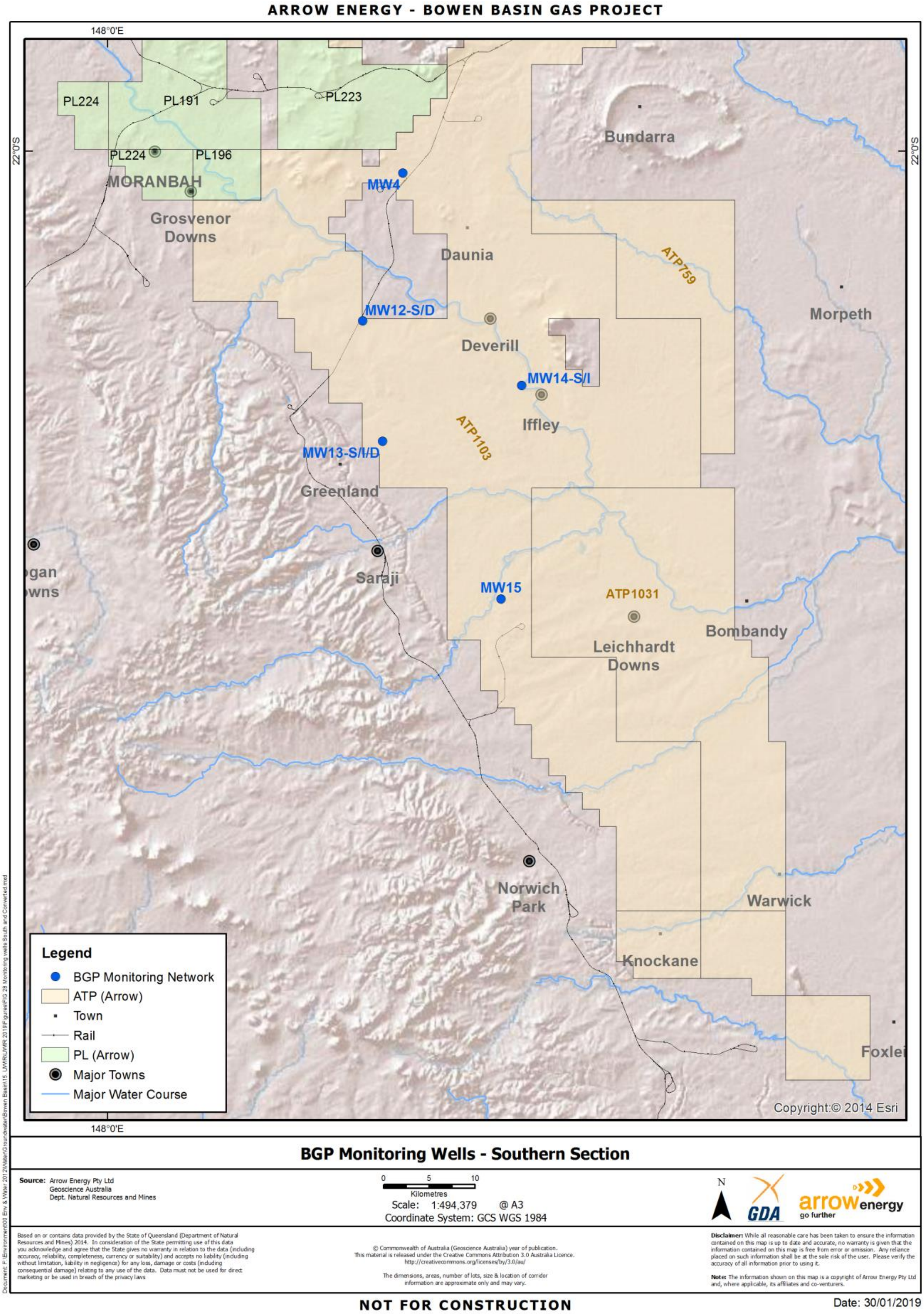


Figure 27: Groundwater Monitoring Network – Southern Section

8.2 Groundwater Monitoring Frequency

The groundwater monitoring frequency for the exiting WMS MGP bores are shown in the table below.

Table 19: Existing WMS groundwater monitoring frequency

Bore	Shallow/Deep	Monthly Water Level	6 Monthly Water Quality	6 Monthly Water Level	Annual Water Quality
M339W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M225W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M340W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M230W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M250W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M224W	Shallow	June 2012 to January 2016		January 2016 Onwards	
M222W	Deep	June 2012 to January 2016		January 2016 Onwards	
M313W	Deep	July 2014 to January 2016		January 2016 Onwards	
M314W	Deep	July 2014 to January 2016		January 2016 Onwards	
M324W	Deep	July 2014 to January 2016		January 2016 Onwards	
M325W	Deep	July 2014 to January 2016		January 2016 Onwards	No Water Quality Monitoring
GR067V	Deep	November 2015 to November 2016		December 2016 Onwards	
M162V	Deep	November 2015 to November 2016		December 2016 Onwards	
AN019F	Deep	November 2015 to November 2016		December 2016 Onwards	
AN020F	Deep	November 2015 to November 2016		December 2016 Onwards	
AN021F	Deep	November 2015 to November 2016		January 2016 Onwards	No Water Quality Monitoring

For any future WMS bores (MGP and BGP), groundwater quality monitoring is proposed to be undertaken on a six-monthly basis for a period of 12 months and thereafter groundwater quality monitoring is proposed to be undertaken annually for the remainder of the CSG operations.

The groundwater monitoring frequency is based on:

- Limited groundwater level variation from climatic or seasonal fluctuations due to the depth of these confined formations (low recharge) and low permeability – for determining baseline levels
- Length of time over which groundwater level impacts develop as a result of the CSG development
- Stability of groundwater quality in these low permeability formations, and the delayed impact of CSG development on groundwater quality (if there is any impact on groundwater quality) relative to impact on groundwater levels (as change in groundwater quality is dependent on inducing flow)
- Data will be reviewed on an annual basis and presented in the annual review report to DES as prescribed in Section 10. This review will include a comparison of groundwater data to model predictions.

Following the establishment of baseline groundwater quality, the frequency of sampling and analyses may be modified for some or all of the chemical parameters.

8.2.1 *Groundwater Monitoring Procedure*

Groundwater monitoring will be conducted in accordance with Arrow Energy's (Arrow's) Water Quality Sampling Manual This procedure has been prepared with reference to; the DEHP's (2009) Monitoring and Sampling Manual 2009, Version 2, AS/NZS 5667.1:1998 Water quality - Sampling - Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples, and AS/NZS 5667.11:1998 Water quality - Sampling - Guidance on sampling of groundwaters.

During monitoring events, visual inspections will be undertaken by field staff to provide an assessment on bore integrity. Any observed bore defects will be noted and reported with follow up maintenance actions proposed. This aims to ensure that the bore is maintained and in a secured and operating condition.

8.2.2 *Groundwater Monitoring Parameters*

It is proposed that an initial comprehensive laboratory analysis should be carried out for the first four groundwater monitoring events. Following this, an assessment should be undertaken by a suitably qualified hydrogeologist to assess the suitability of the groundwater quality parameters monitored. If considered appropriate, a reduced suite of chemical parameters and sample frequencies may be proposed.

The proposed field parameters and the laboratory analytical schedule for groundwater samples are listed in Table 20 and Table 21 below respectively.

Table 20: Field parameters monitoring suite

Parameter	
Temperature (^{o}C)	Redox Potential (Eh)
Electrical Conductivity (EC)	Dissolved Oxygen (DO)
pH	

Table 21: Chemical parameters monitoring suite

Parameter	
EC and Total Dissolved Solids (TDS)	Calcium (Ca^{2+})
Total Alkalinity	Sodium (Na^{+})
Bicarbonate/Carbonate HCO_3^-/CO_3^{2-}	Potassium (K^{+})
Fluoride (F^-)	Magnesium (Mg^{2+})
Strontium (Sr)	Nitrite (NO^{2-}), Nitrate (NO^{3-}), Ammonia (NH^{4+})
Chloride (Cl^-)	Total Phosphorous (PO_4^{3-})
Sulphate (SO_4^{2-})	Total and Dissolved organic carbon (TOC/DOC)
Dissolved Methane (CH_2)	Metals (dissolved): arsenic (As), barium (Ba), boron (B), chromium (Cr), cobolt (Co), Copper (Cu), Iron (Fe), Lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), zinc (Zn)

8.2.3 *Assessment of Aquifer Parameters*

Groundwater pressure data collected as part of the WMS will provide the basis for future groundwater numerical model updates. As part of this, re-calibration of the numerical groundwater model using transient groundwater level data will enable the refinement of parameterisation of hydraulic conductivity values.

8.2.4 *Baseline Assessment Program*

The Water Act requires petroleum tenure holders to carry out baseline assessments as indicated in Section 1.2.4.

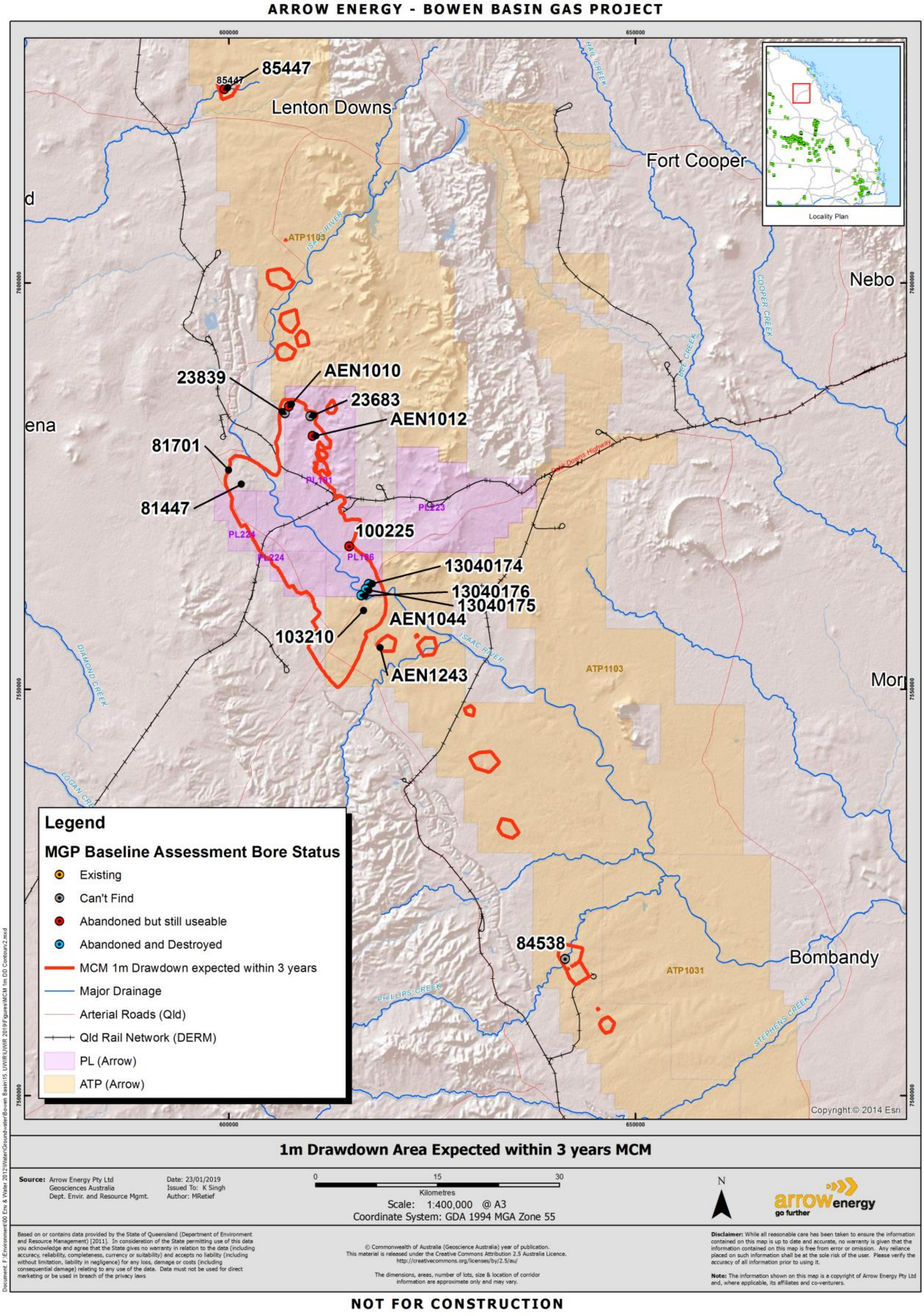
A program for baseline assessment for the LAAs is also required as part of the WMS. This program incorporates water bores predicted to be impacted on land outside the tenures. Since water level or water pressure impacts in many parts of the LAAs will not occur for a very long time, it is not proposed to undertake the baseline assessments for bores in the entire LAA. Baseline assessments are best carried out just before the impacts are expected to occur. If they are carried out too early the information collected will be out of date and be of degraded use for assessing changes.

Based on this, the program for carrying out baseline assessments for the LAAs is to progressively expand the area assessed so that assessments are completed soon before impact is predicted to occur. A predicted impact of 1 m within three years has been adopted as the trigger for carrying out a baseline assessment. When a new UWIR is prepared in three years' time, a new 1 m impact area will be established. This is consistent with the approach adopted for the Surat Cumulative Management Area UWIR.

In Figure 28 shows the area within which water pressure decline of more than 1 m is expected within three years. The baseline assessment program will include all water bores located in the IAA aquifer the area of an aquifer where at least 1 m of drawdown is predicted within the next three years.

The figure identifies two potential bores (RN 81701 and 81447) located off tenure but within the 1m drawdown area, however after further investigation of these two bores, it was found that they are not installed into the area of an aquifer where at least 1m of drawdown is predicted within the next three years. Bore 81701 is a mineral exploration bore and is not a water bore. Bore 81447 is located within the Basalt aquifer. Less than 1m of drawdown is predicted in this aquifer within the next three years at the location of this bore.

Based on this, there are no water bores located off tenure but within the 1 m drawdown area that are in the IAA aquifer within the area of an aquifer where at least 1 m of drawdown is predicted within the next three years. Therefore no additional baseline assessments are required off tenure for the 1 m drawdown area.



1m Drawdown Area Expected within 3 years MCM

Source: Arrow Energy Pty Ltd
Geosciences Australia
Dept. Envir. and Resource Mgmt.

Date: 23/01/2019
Issued To: K Singh
Author: MRetief

Scale: 1:400,000 @ A3
Coordinate System: GDA 1994 MGA Zone 55

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Figure 28: 1m Drawdown Area Expected with 3 years for MCM

8.3 Water Production Monitoring

The quantity of water taken during production of CSG will be monitored according to the process described in Section 2.

9 SPRINGS AND GROUNDWATER DEPENDENT ECOSYSTEMS

Section 379 of the Water Act 2000 defines a potentially affected spring as a spring overlying an aquifer affected by underground water rights if

- The water level in the aquifer is predicted, in an underground water impact report or final report, to decline by more than the spring trigger threshold at the location of the spring at any time; and
- The cause of the predicted decline is, or is likely to be, the exercise of the underground water rights.

The spring trigger threshold for an aquifer is a decline in the water level of the aquifer that is 0.2 m. Hence, an assessment of potentially affected springs is based on where the long term predicted impact on water pressures at the location of the springs resulting from the extraction of water exceeds 0.2 m.

Springs are considered to be spring vents, spring complexes or watercourse springs. Spring vents are a single point in the landscape where groundwater is discharged at the surface. A spring complex is a group of spring vents located in close proximity to each other. A watercourse spring is a section of a watercourse where groundwater enters the stream from an aquifer through the stream bed. DES maintains an inventory of identified springs in the Queensland Springs Dataset. Many of these sites have been studied in detail through the completion of field surveys including those completed in 2011 by KCB and the Queensland Herbarium (KCB, 2012 and Queensland Herbarium, 2012).

Based on this data, the springs (Palustrine springs) identified proximal the Project Area are found to the west and south-west and are located greater than a 100 km south of ATP 1103. Predicted impacts to the identified Palustrine springs, as a result of production and production testing within the Project Area do not exceed the spring trigger threshold. As such, impacts to these springs as a result of the project will not be considered further in this UWIR.

The following watercourse springs were identified in the BGP SREIS and located outside the BGP project area:

- Upper reaches of the Connors River, Funnel Creek, Denison Creek and Lotus Creek approximate 40km east of the BGP;
- Mid reaches of the Connors River and Funnel Creek, approximately 45km east of the BGP; and
- Lower reaches of the Isaac River approximately 37km from the BGP

The locations of these watercourse springs, and where the water level is predicted to decline in 0.2m in the shallow and deep aquifer (based on 2018 model), are shown in **Error! Reference source not found.**. As indicated on the map, the maximum 0.2 m drawdowns for the shallow aquifers are isolated occurrences with limited spatial extent. In addition to this, in some instances the 0.2 m drawdown areas overly existing open cut mines and therefore these areas are not considered relevant as they have been mined out and will not contain any previously unidentified springs.

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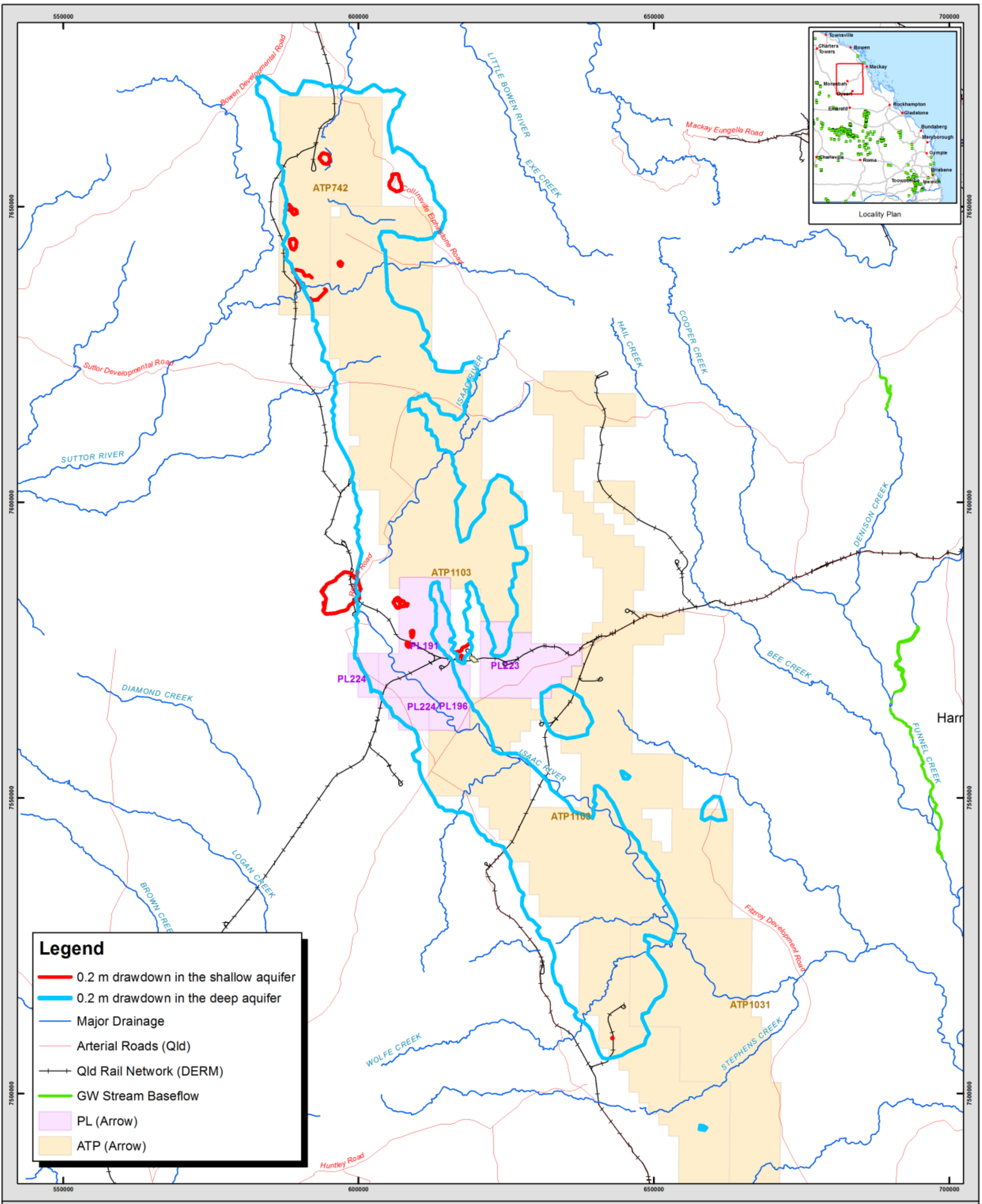

Location of Springs

Source: Arrow Energy Pty Ltd
Geosciences Australia
Dept. Envir. and Resource Mgmt.

Date: 14/01/2019
Issued To: K Singh
Author: tfelmingham

0 25 50
Kilometres
Scale: 1:590,802 @ A3
Coordinate System: GDA 1994 MGA Zone 55

N

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Figure 29: Springs and Drawdown in Shallow and Deep Aquifer

The identification of landscapes that may contain groundwater dependent ecosystems (GDEs) is documented in detail in the BGP EIS/SREIS and included known and potential GDEs as mapped in the Atlas of Groundwater Dependent Ecosystems (GDE Atlas).

The types of GDEs that have been considered include:

- Surface expression GDEs: springs, baseflow contribution to watercourses and groundwater dependent wetlands (including wetlands classified as a matter of national environmental significance (MNES) under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)); and
- Non-spring GDEs: vegetation dependent on the subsurface presence of groundwater (i.e. deep-rooted vegetation), referred to in this document as terrestrial GDE

A site inspection was carried out end 2015 to visually inspect the areas identified in the GDE Atlas and to further refine these locations, a site visit was conducted in November 2015 to inspect locations identified as having the potential to support GDEs. Following the site visit, a detailed analysis of the potential for GDEs to be present across the project area was completed and findings summarised below:

- Depth to groundwater data and mapped vegetation communities indicate riparian vegetation along major watercourses may be supported by groundwater on a facultative basis (i.e. use groundwater but capable of functioning without it). Within the Project area this includes the following watercourses:
    - Upper Isaac River.
    - Suttor Creek.
    - Cherwell Creek.
    - Phillips Creek.
- Terrestrial vegetation away from immediate riparian environments is not considered supported by regional groundwater systems. This conclusion is based on:
    - Available depth to groundwater information and known rooting depth characteristics of the vegetation in these areas.
    - Site observation which includes rapidly diminished vegetation stature with distance from watercourse channels and/or as depth of the alluvial soil profile over basement rock diminishes.
    - Groundwater baseflow contribution to stream reaches does not occur. This is supported by the ephemeral nature of all streams in the project area, rainfall correlated flow duration and depth to groundwater exceeding channel incision depth. Release of bank storage, which will occur following recession of surface flows, is not considered to represent groundwater baseflow contribution

It is acknowledged that the riparian environments (i.e. terrestrial GDEs) described above as being potentially dependent on groundwater do not necessarily represent all groundwater dependent riparian environments across the Project area. Rather, they represent what has been identified to date. Where impact to the watertable aquifer in the vicinity of a watercourse is predicted by numerical modelling, the riparian environment should be adequately assessed to identify whether similar characteristics exist that indicate the potential for groundwater dependence

The current field development plan (FDP) and the 2019 groundwater model assessment did not identify any potential spring GDEs or non-spring GDEs at risk of impact from the proposed FDP. The predicted 0.2m watertable drawdown contour in shallow aquifers does not intersect any locations identified as potential sites.

Lake Elphinstone is categorised as a Matter of National Environment Significance (MNES) wetland and located immediately outside Arrow tenure and described as having a high potential for interaction with the surface expression of groundwater. The predicted 0.2m watertable drawdown contour in the shallow aquifers does not intersect the area.

If required, the monitoring network described herein can be adapted and applied to spring and non-spring GDEs should such features be identified, or if monitoring indicates a potential for the field verified riparian vegetation to be affected by groundwater drawdown in connected underlying aquifers, at any stage in the future, as additional information becomes available, or changes to the FDP are proposed. As indicated no drawdown in excess of 0.2m in proximity to spring vents, spring complexes or watercourse springs, springs GDEs or non-spring GDEs, have been identified to exist in the area. A Spring Impact Management Strategy will not be prepared as part of this UWIR.

10 ANNUAL DATA REVIEW

This report will be reviewed annually. The review will consider:

- new hydrogeological data that significantly alters the conceptual model;
- whether new production testing or production has been undertaken or is planned; and
- whether the predictions made in Section 8 have materially changed.

The program for the implementation of the strategy will be reported to DES on an annual basis as part of the annual review. The annual review will provide progress on the implementation of the WMS. In addition to the annual review, the UWIR will be updated every three years. As required under section 378(1)(d) of the Water Act 2000, an annual update will also be provided to the OGIA about the implementation of the WMS.

Glossary

Term	Meaning
Abstraction	The removal of water from a resource e.g. the pumping of groundwater from an aquifer.
Adsorption	The adhesion of molecules of gas, liquid, or dissolved constituents to a surface (compare Desorption)
Aeolian	Sedimentary deposits formed by wind.
Alluvium	Unconsolidated deposits such as sands, gravels and clays deposited by flowing water such as rivers and streams.
Anistropy	Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies homogeneity in all directions.
Anthropogenic	Caused by human activity.
Aquatic Ecosystems	The abiotic and biotic components, habitats and ecological processes contained within rivers and their riparian zones and reservoirs, lakes, wetlands and their fringing vegetation.
Aquifer	A saturated geological layer or formation that is permeable enough to yield economic quantities of water.
Aquiclude	A geological formation having zero permeability to water, such as un-fractured crystalline rock.
Aquitard	A geological formation having low (but not zero) permeability to water, such as a silty or clayey layer.
Argillaceous	A geological formation containing significant proportions of clay minerals.
Artesian Aquifer	A confined aquifer with the potentiometric level above ground level.
Artesian Bore	A borehole where the potentiometric level is above ground level.
Attenuation	The reduction in concentration of a contaminant. This may be due to degradation, dispersion or dilution.
Avulsion	Abandonment of an old river channel and the creation of a new one.
Baseflow	Sustained flow of a stream in the absence of direct run-off, due to groundwater discharge.
Bore	A hole drilled in the ground to obtain samples of soil or rock, intersect groundwater for extractive use, monitoring or investigation, or for a range of other purposes. In Australia is also a commonly used term for a constructed groundwater well.
Brackish	Water containing moderate salt concentrations significantly less than sea water, with Total Dissolved Solids typically between 1,000 and 10,000 mg/L. (Compare Fresh, Saline and Brine).
Brine	Saline water with a total dissolved solids concentration greater than 40,000 mg/L or coal seam gas water after it has been concentrated through water treatment processes and/or evaporation.
Calcareous	Containing significant proportions of calcium carbonate.
Catchment	An area which discharges to a common point.

Term	Meaning
Coal Seam Gas Water	Groundwater that is necessarily or unavoidably brought to the surface in the process of coal seam gas exploration or production. Coal seam gas water typically contains significant dissolved salts, has a high sodium adsorption ratio (SAR) and may contain other components that have the potential to cause environmental harm if released to land or waters through inappropriate management. Coal seam gas water is a waste, as defined under the section 13 of the Environment Protection Act. (DEHP, 2011).
Colluvium	Sedimentary deposit formed primarily by gravity forces, typically at the base of a slope or a cliff.
Cone of Depression	The area of drawdown produced in the watertable or groundwater potentiometric surface due to pumping.
Confined Aquifer	An aquifer in which groundwater is confined under pressure.
Confining Layer	Geological material through which significant quantities of water cannot move, located below unconfined aquifers, above and below confined aquifers.
Contaminant	A contaminant can be a gas, liquid or solid, an odour, an organism (whether alive or dead), including a virus, energy (including noise, heat, radioactivity and electromagnetic radiation), or a combination of contaminants.
Contamination	The release (whether by act or omission) of a contaminant into the environment.
Cuesta	A ridge formed by gently tilted sedimentary rock strata.
Desorption	The processes releasing molecules of gas, liquid, or dissolved constituents from a surface (compare Adsorption).
Discharge	Removal of water from or flow out of an aquifer, including flow to surface water, another aquifer, or artificial means such as pumping. See also ‘abstraction’.
Discharge Area	An area where groundwater flows out of an aquifer.
Disconformity	A break in the sequence of sedimentary deposition followed by resumed sedimentation, where the buried non-depositional surface lies between parallel strata on a regional scale.
Dissolved Solids	Soluble compounds such as salts which are in solution.
Down Warp	A downward bend in sedimentary layering caused by tectonic movement.
Drawdown	The drop in the watertable or potentiometric level when water is being pumped from a well.
Ecosystem	A system made up of the community of living things (animals, plants, and microorganisms) which are interrelated to each other and the physical and chemical environment in which they live.
Facies	A horizon of sedimentary rock formed under a particular set of environmental conditions, resulting in a distinct assemblage of sedimentary structures, mineralogy, grainsize, fossils and other features.
Fault	A structural discontinuity in a rock mass or geological formation.
Fluvial	Pertaining to a river or stream.
Fluvio-Lacustrine	Pertaining to a combined environment involving a river or stream and lake conditions.
Flux	The rate of flow (mass transport) of a fluid or other material or compound transported by that fluid.
Formation	A geological structure such as a rock mass or layer.
Fresh Water	Water containing low salt concentrations, typically less than 1,000 mg/L. (Compare Brackish, Saline and Brine).

Term	Meaning
Gilgai	A group of undulations and closed depressions at the soil surface, caused by the presence of swelling clays and seasonal movement due to changes in moisture content. Gilgai may range in size from a few meters up to 100 m across, and have a typical vertical amplitude of 30-50 cm.
Groundwater	Any sub-surface water, generally present in an aquifer or aquitard.
Groundwater Flow	The movement of water in an aquifer.
Heavy Metals	Metallic elements of atomic weight greater than that of Iron (e.g. Copper Arsenic, Mercury, Chromium, Cadmium, Lead, Nickel and Zinc).
Heterogeneous	Having different properties or composition at different locations.
Hydraulic Conductivity	A standard measure of the permeability of a geological formation or its ability to transmit groundwater flow.
Hydraulic Gradient	The slope of the watertable in an unconfined aquifer, or the potentiometric surface in a confined aquifer.
Hydraulic Head	A measure of the pressure head of water in aquifer, commonly measured as the elevation to which water will rise in a constructed well.
Hydrogeology	The study of the inter-relationships of geologic materials and processes with water, especially groundwater.
Hydrostatic Pressure	The pressure exerted by a fluid at equilibrium due to the force of gravity.
Indurated	Pertaining to a rock or soil hardened by mineral re-crystallisation due to heat, pressure or chemical precipitation.
Infiltration	Rainfall penetration into the soil profile or sub-surface. Infiltrated water that accesses the water table is one component of groundwater recharge.
Jam-ups	The flat tops of mesas formed by erosional processes.
Labile	Unstable, likely to change or decompose.
Lateritisation	A process of weathering, dissolution and leaching resulting in a hard crust dominated by iron and aluminium oxides.
Lithology	The physical composition of a rock.
Marine Regression	A period of sea level fall over geological time.
Marine Transgression	A period of sea level rise over geological time.
Meander Scar	A remnant landform caused by the abandonment of a stream bend which has first produced a cutoff-meander, oxbow lake or billabong, and been gradually infilled by sediment such that it no longer contains open water.
Mesa	An elevated area of land with a flat top and sides that are usually steep cliffs.
Montmorillonite	A clay mineral with swelling properties.
Mound spring	A naturally occurring outlet of upwelling groundwater, with a characteristic mound or crater shape formed by deposition of minerals.
Nutrients	A chemical that an organism needs to live and grow, or a substance used in an organism's metabolism obtained from its environment.
Onlap	A sedimentation regime occurring during a marine transgression.
Offlap	A sedimentation regime occurring during a marine regression.
Palaeochannel	Unconsolidated sediments or semi-consolidated sedimentary rocks deposited in ancient, currently inactive river and stream channel systems.
Peat	A sedimentary deposit dominated by partially-decomposed plant material, and considered to be an early stage in the formation of coal.
Perched Aquifer	An unconfined aquifer of limited extent located above the true watertable.

Term	Meaning
Perennial	A stream or river (channel) that has continuous flow in parts of its bed all year round during years of normal rainfall.
Permeability	The ability to transmit fluids through a porous medium.
Piezometer	A type of well specifically constructed in an aquifer for monitoring purposes, and screened at a specific depth to provide measurements of pressure head at that point.
Piezometric Level	The pressure head of water measured in a piezometer, from a specific depth or point in an aquifer.
Porosity	The ratio of void spaces in a geological formation compared to the bulk formation volume.
Potable Water	Water of suitable quality for human consumption.
Potentiometric Level	A measure of the pressure head of water in an aquifer at a given location, usually used in reference to a confined aquifer.
Potentiometric Surface	An imaginary layer which defines the potentiometric levels for a confined aquifer. In an unconfined aquifer it is more commonly termed as the watertable.
Pyroclastic	Material which is deposited from air-borne particles ejected by a volcanic eruption.
Recharge	Addition of water to or flow into an aquifer (generally) from rain. Also used to describe water entering an aquifer from surface water, groundwater, or artificial means.
Recharge Area	An area in which water enters an aquifer.
Reactivated Fault	A pre-existing fault in a geological setting which becomes the preferred surface to accommodate movement during a new period of tectonic activity.
Regolith	The unconsolidated or weathered geological material at the Earth's surface.
Runoff	Rain water that flows across the land surface without entering the sub-surface.
Saline Water	Water containing high levels of dissolved salts, typically between 10,000 and 40,000 mg/L. (Compare Fresh, Brackish and Brine).
Saturated Zone	The zone in which the voids in the rock are completely filled with water. The water table represents the top of the saturated zone in an unconfined aquifer.
Sediment	Unconsolidated geological material which has been formed by a process of deposition as discrete particles.
Sedimentary Sequence	A succession of layers of sedimentary rock caused by sequential deposition.
Semi-Confined Aquifer	A confined aquifer having a leaky confining layer.
Specific Yield	The ratio of the volume of water a rock will release by gravity drainage to the bulk volume of the rock.
Spring	The land to which water rises naturally from below the ground and the land over which the water then flows.
Standing Water Level	The depth below natural ground surface to the water level in a well or bore when it is at equilibrium with the surrounding formation (i.e. 'at rest' or 'fully recovered' from pumping). Also referred to as Static Water Level.
Storage Coefficient	A measure of the ability of aquifer material to store water, due to volumetric storage (Specific Yield) plus elastic storage.
Storativity	A measure of the ability of an aquifer to store water. Storativity is a function of storage coefficient and aquifer thickness.
Stratigraphy	The sequential classification of geological materials based on their age of formation.

Term	Meaning
Sustainable Yield	Amount of water that can be abstracted from an aquifer over a long period of time without dewatering the aquifer or impacting the resource.
Total Dissolved Solids	Concentration of dissolved salts (TDS).
Through Flow	The horizontal movement of water beneath the ground surface, including flow in the unsaturated zone (eg. soil) or saturated zone (eg. aquifer).
Transmissivity	The rate at which an aquifer can transmit water. It is a function of properties of the aquifer material and the thickness of the porous media.
Travertine	A mineral commonly found in caves, composed of finely crystalline calcium carbonate which has been precipitated from solution in groundwater.
Unconfined Aquifer	An aquifer with no confining layer between the water table and the ground surface where the water table is free to rise and fall.
Unsaturated Zone	The part of the geological stratum above the saturated zone, also called the vadose zone. The unsaturated zone may be dry, or may contain water under partially saturated conditions.
Uplift	The relative upward movement of rocks due to tectonic forces.
Vertical Anisotropy	Differing properties of a geological material in the vertical direction compared to horizontal direction.
Water table	The top of the saturated zone in an unconfined aquifer.
Well	A hole drilled into a groundwater resource (aquifer), oil or gas resource reservoir) and constructed with a casing and screen or similar. In Australia also commonly referred to as a 'bore'.
Well Field	A group of boreholes in a particular area having a common use, such as for groundwater, oil or gas extraction.
Well Yield	The flow rate obtainable from an extraction well or bore.

References

- AGE, Bowen Groundwater Management and Monitoring Plan Uncertainty Analysis (2018)
- Arrow Energy, Underground Water Impact Report for PLs 191, 196, 223, 224 (2012a)
- Arrow Energy, Underground Water Impact Report for ATP 1103 (2012b)
- Arrow Energy, Bowen Gas Project Environmental Impact Statement (2012c)
- Arrow Energy, Underground Water Impact Report for ATP 1031 (2014a)
- Arrow Energy, Bowen Gas Project Supplementary Report to the EIS (2014b)
- Ausenco and Norwest, Groundwater Model Northern Bowen Basin Regional Model Impact Predictions (2012)
- Ausenco and Norwest, Parameter and Predictive Error/Uncertainty Assessment Northern Bowen Basin Regional Groundwater Model (2013)
- BMA, Caval Ridge EIS (2009)
- BMA, Daunia EIS (2009)
- CWiMi, Scoping Study: Groundwater Impacts of Coal Seam Gas Development – Assessment and Monitoring (2008)
- CRC LEME, A Geoscience atlas for natural resource management in the Upper Burdekin and Fitzroy Catchments, Queensland Australia (2006)
- CSIRO, Bowen Basin Supermodel 2000 (2002)
- CSIRO, Bowen Basin Structural Geology (2008)
- DNRM, Groundwater Database search results (2011)
- Arrow Energy (internal document), Regional Bowen Geology (2011)
- ArrowCOM, Arrow Energy: Moranbah Groundwater Assessment (2011)
- CHRRUP, Central Highlands Natural Resource Management Plan (2003)
- Mutton, A. J. (Compiler), 2003: Queensland Coals 14th Edition. Queensland Department of Natural Resources and Mines
- Peabody Energy Australia, Eaglefield Expansion Project EIS (2010)
- Pearce, B; Hansen, J; Hydrogeological Investigations of the Comet River Sub-Catchment, Central Queensland, Australia (2006a)
- Pearce, B; Hansen, J; Jackson, J; Hydrogeological Investigation of the Dawson River Sub-Catchment, Central Queensland, Australia (2006)
- Pearce, B; Hansen, J; Hydrogeological Investigations of the Fitzroy River Sub-Catchment, Central Queensland, Australia (2006b)
- Pearce, B; Hansen, J; Hydrogeological Investigations of the Isaac and Mackenzie River Sub-Catchment, Central Queensland, Australia (2006c)
- Pearce, B; Hansen, J; Hydrogeological Investigations of the Nogoa River Sub-Catchment, Central Queensland, Australia (2006d)
- SKM, Fitzroy Basin Water Resource Plan Amendment – Callide Catchment Groundwater Project Groundwater Dependent Ecosystem Assessment (2008)
- DEHP, Fitzroy Basin Draft Water Resource Plan Environmental Assessment – Stage 1 Background Report (2009)

- DEHP, Fitzroy Basin Draft Water Resource Plan Environmental Assessment – Stage 2 Assessment Report (2010)
- Rio Tinto, Clermont Coal Mine EIS (2004)
- SKM, Isaac Connors Groundwater Project Part A: Conceptual Model for Groundwater (2009a)
- SKM, Isaac Connors Groundwater Project Part B: Assessment of Groundwater Dependent Ecosystems (2009b)
- JBT Consulting Pty Ltd, Grosvenor Coal Project Environmental Impact Study Groundwater Impact Assessment (2010)
- URS, Caval Ridge Groundwater Impact Assessment (2009)
- Cranstoun Geological Pty Ltd, North Bowen Basin Rangal Coal Measures Geological Compilation & Preliminary Ranking of Potential Coal Seam Gas Targets (2004)
- Clifton, C.; Evans, R. Environmental water requirements to maintain groundwater dependent ecosystems. Environmental flows initiative technical report (2001)
- Hatton, T.; Evans, R. Dependence of Ecosystems on Groundwater and its significance to Australia (1998)
- Fetter, C.W. Applied Hydrogeology, Volume 1 (1994)
- Freeze, R.A. and Cherry, J.A. Groundwater (1979)
- Haitjema, H.M. and Mitchell – Bruker, S. Are water tables a subdued replica of the topography, Ground Water (2005)
- Water Management System (WMS), Groundwater Use and Allocation search results (2015)
- Zhou, Y. And Li, W. A review of regional groundwater flow modelling, Geoscience Frontiers (2011)

APPENDIX A: SHALLLOW MONITORING BORE WATER LEVEL RESULTS

Bore Name	SWL (mAHD)																				
	9/06/2012	13/12/2012	8/04/2013	25/05/2013	6/08/2013	6/12/2013	5/05/2014	19/08/2014	5/12/2014	11/03/2015	17/05/2015	27/07/2015	13/11/2015	2/03/2016	13/05/2016	29/08/2016	15/11/2016	15/06/2017	12/11/2017	1/06/2018
M339W	200.426	200.456	200.43	200.451	200.462	200.546	200.49		200.56	200.533	200.416	200.398	200.556	200.466	200.456	200.426	200.500	200.507	200.498	200.520
M225W	206.298	206.641	206.737	206.8	207.455	207.152	207.11		207.27	207.349	207.257	207.23	207.402	207.215	207.245	207.248	207.316	207.54	207.685	207.75
M340W	207.621	208.973	208.118	208.216	208.261	208.507	208.6		208.7	208.771	208.753	208.805	208.918	208.869	208.9	208.761	205.946	203.032		
M230W	208.495	208.705	208.715	208.837	208.865	209.062	209.07		209.2	209.204	209.106	209.058	209.145	208.884	208.922	208.863	208.992	208.629	208.591	208.214
M250W	233.288	233.248	233.238	233.232	233.248	233.308	233.26		233.33	233.289	233.25	233.221	233.25	233.243	233.258	233.328	233.237	233.283	233.273	233.29
M224W	211.675	211.365	211.45	211.705	211.42	211.11	210.89	210.65	210.49	210.561	210.419	210.277	209.982	210.02	209.969		209.852	210.354	210.355	210.08
M222W	202.414	202.974	203.209		203.819	204.014	204.3	204.65	204.95	205.21	205.44	205.54	205.994	205.929	205.969	206.014	206.014	206.149	206.301	206.3
AN020F														238.37	238.366	238.48	238.44		237.18	238.61

APPENDIX B – WATER QUALITY RESULTS

SHALLOW MONITORING BORES

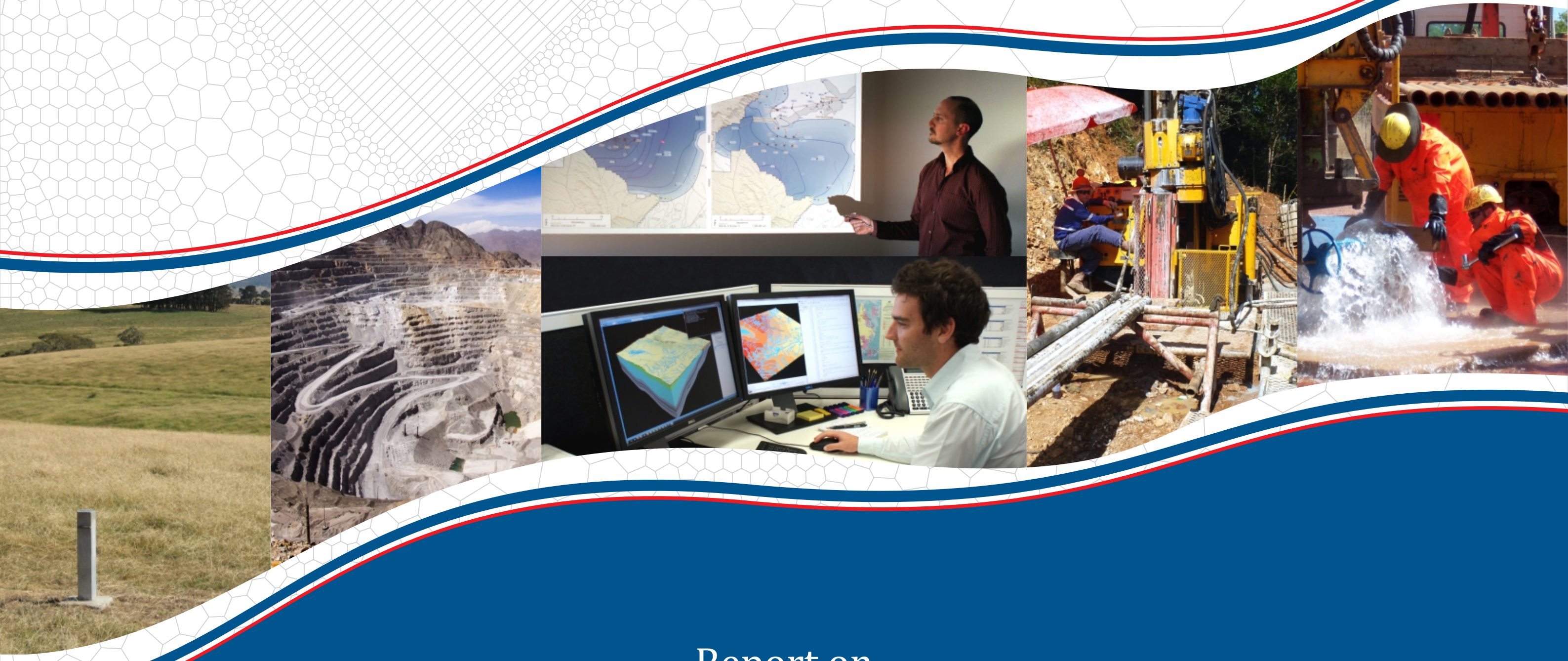
Monitoring Bore ID	Sample Date	Field pH	Electrical Conductivity µS/cm	Total Dissolved Solids (grav) mg/L	Bicarbonate Alkalinity as CaCO3 mg/L	Total Alkalinity as CaCO3 mg/L	Sulphate, SO4 mg/L	Chloride, Cl mg/L	Calcium - Dissolved mg/L	Magnesium - Dissolved mg/L	Sodium - Dissolved mg/L	Potassium - Dissolved mg/L	Arsenic-Dissolved mg/L	Beryllium-Dissolved mg/L	Barium-Dissolved mg/L	Cadmium-Dissolved mg/L	Chromium-Dissolved mg/L	Cobalt-Dissolved mg/L	Copper-Dissolved mg/L	Lead-Dissolved mg/L	Manganese-Dissolved mg/L	Molybdenum mg/L	Nickel-Dissolved mg/L	Selenium mg/L	Strontium mg/L	Vanadium-Dissolved mg/L	Zinc-Dissolved mg/L	Boron mg/L	Iron mg/L	Mercury-Dissolved mg/L	Fluoride, F mg/L	Phosphate as P in water mg/L
M339W	11/12/2012	6.46	38000	26000	680	680	980	15000	150	670	10000	110	<0.001	<0.0005	0.056	0.0004	0.006	<0.001	0.007	<0.001	0.016		0.018			0.003	0.05			0.00008	0.45	0.1
M339W	4/04/2013	6.28	36000	22000	690	690	830	14000	160	700	9700	120	<0.001	<0.0005	0.057	0.0003	0.007	<0.001	0.005	<0.001	0.013		0.027			0.003	0.039			<0.00005	0.44	0.11
M339W	21/05/2013	8.09	37000	29000	680	680	1100	17000	150	710	10000	120	<0.001	<0.0005	0.067	0.0005	0.004	<0.001	0.059	<0.001	0.012		0.014			0.003	0.068			0.00009	0.33	0.026
M339W	7/08/2013	6.42	37000	25000	660	660	990	15000	190	670	13000	150	<0.002	<0.0005	0.061	0.0004	0.003	<0.001	0.004	<0.001	0.007		0.014			0.003	0.078			<0.00005	0.29	0.19
M339W	5/12/2013	6.6	39000	28000	660	660	1100	16000	160	740	11000	110	<0.001	<0.0005	0.055	0.0005	0.006	<0.001	0.007	<0.001	0.007		0.015			0.003	0.06			<0.00005	0.37	0.085
M339W	11/05/2014	6.6	37900	24600	698	698	1020	13800	150	722	7740	100							<0.05		<0.01						<0.05			<0.0001		0.26
M339W	9/12/2014	6.46	39300	25400	706	706	893	13700	158	780	8220	138							<0.005		<0.005						0.04			<0.0001	0.4	0.08
M339W	10/03/2015	6.53	39000	27100	644	644	932	13900	183	682	8360	98	<0.005	<0.005	0.058		<0.005	<0.005	<0.005	<0.005	0.009		0.026			<0.05	0.053				0.8	
M339W	16/05/2015	6.67	37500	24200	647	647	1140	12200	167	668	7770	82	<0.001	<0.001	0.124	0.0007	0.002	<0.001	0.009	<0.001	0.009		0.012			<0.01	0.128			0.0008	0.4	
M339W	27/07/2015	6.53	38200	25400	658	658	1020	13500	180	676	7600	90	<0.001	<0.001	0.051	0.0004	<0.001	<0.001	0.001	<0.001	0.003		0.012			<0.01	0.016			0.001	0.5	
M339W	16/11/2015	6.43	32300	21200	714	714	987	12700	147	669	7170	81	<0.005	<0.005	0.053	<0.0005	<0.005	<0.005	0.01	<0.005	<0.005		0.014			<0.05	0.149			0.0006	0.4	0.1
M339W	2/03/2016	7.56	39800	21200	712	712	1000	13400	160	747	8710	104	<0.001	<0.001	0.050		0.007	<0.001	0.002	<0.001	0.002		0.014			<0.01	0.046				0.4	0.24
M339W	13/05/2016		39000	24400	681	681	1020	13000	178	712	7850	89	0.001	<0.001	0.055		0.01	<0.001	0.008	<0.001	0.005	0.003	0.014	0.01	8.48	<0.01	0.051	2.58	<0.05	<0.0001	0.4	0.62
M339W	29/08/2016	8.37	41300	28200	714	757	993	12600	170	688	7790	93	<0.005	<0.005	0.058		0.01	<0.005	0.005	<0.005	<0.005	<0.005	0.014	<0.05	8.98	<0.05	0.027	2.66	<0.05		0.5	0.07
M339W	15/11/2016	7.13	37100	22900	652	652	1050	12600	171	743	8440	92	<0.001	<0.001	0.055	0.0001	0.002	<0.001	<0.001	<0.001	0.006	0.003	0.014	<0.01	8.36	<0.01	0.021	2.42	<0.05	<0.0001	0.5	0.15
M339W	13/06/2017		38600	25100	726	726	964	13500	186	780	9040	105							0.006		<0.005						<0.025	2.74	<0.05	<0.0001	0.5	
M339W	12/11/2017	6.99	39800	27100	708	708	923	13700	204	792	9570	102	<0.005	<0.005	0.062		0.008	<0.005		<0.005	<0.005	<0.005	0.015	<0.05		<0.05	<0.025	2.96	0.06		0.4	0.07
M339W	1/06/2018	6.58	39300			644	974	12900	181	772	8990	97							<0.005		<0.005						<0.025	2.66	<0.05	0.001	0.4	0.09
M225W	3/04/2013	7.54	28000	17000	810	810	710	11000	150	510	7200	84	<0.001	<0.0005	0.063	0.0006	0.003	<0.001	0.01	<0.001	0.011		0.025			0.015	0.042			<0.00005	0.48	0.2
M225W	21/05/2013	6.53	28000	21000	790	790	660	10000	150	520	7500	82	0.001	<0.0005	0.140	0.0006	0.002	0.001	0.01	<0.001	0.21		0.034			0.009	0.053			<0.00005	0.37	0.11
M225W	8/08/2013	6.59	29000	20000	780	780	700	11000	160	480	7500	75	<0.001	<0.0005	0.120	0.001	0.002	0.001	0.03	<0.001	0.18		0.068			0.013	0.036			<0.00005	0.32	0.19
M225W	5/12/2013	6.84	30000	21000	780	780	780	11000	180	490	9500	95	<0.001	<0.0005	0.120	0.0007	0.002	0.002	0.009	<0.001	0.35		0.056			0.009	0.031			<0.00005	0.37	0.11
M225W	6/05/2014	6.98	29900	19400	745	745	369	9940	142	495	5440	72							<0.05		<0.01						0.059			<0.0001		0.1
M225W	5/12/2014	6.73	30500	20100	808	808	617	9880	151	523	6450	76							0.028		0.004						0.058			0.0001	0.5	0.27
M225W	11/03/2015	6.82	30100	20000	716	716	827	10200	163	508	6600	75	<0.005	<0.005	0.075		<0.005	<0.005	<0.005	<0.005	0.009		0.026			<0.05	0.096				0.8	
M225W	17/05/2015	6.89	30200	19800	780	780	884	9850	161	518	6430	64	0.001	<0.001	0.112	0.0012	0.001	<0.001	0.022	<0.001	0.161		0.048			0.01	0.029			<0.0001	0.4	
M225W	28/07/2015	6.96	28700	19300	790	790	735	9660	157	478	5670	65	0.001	<0.001	0.089	0.0006	<0.001	<0.001	0.011	<0.001	0.033		0.016			0.01	0.018			<0.0001	0.6	
M225W	16/11/2015	6.38	23700	17400	826	826	738	9870	134	485	5460	59	<0.005	<0.005	0.055	0.0006	<0.005	<0.005	0.012	<0.005	<0.005		0.022			<0.05	0.099			0.0001	0.6	0.18
M225W	2/03/2016	7.71	30500	19400	817	817	721	10300	153	541	6530	76	<0.001	<0.001	0.053		0.002	<0.001	0.02	<0.001	0.001		0.012			0.01	0.035				0.5	0.25
M225W	13/05/2016	7.57	29600	18400	779	779	752	9390	158	532	6570	66	<0.001	<0.001	0.062	0.0005	0.002	<0.001	0.006	<0.001	0.01	0.004	0.028	<0.01	4.25	0.01	0.036	2.48	<0.05	<0.0001	0.5	0.13
M225W	29/08/2016	7.45	29600	17900	799	799	727	9750	158	532	6220	68	<0.001	<0.001	0.065		0.002	<0.001	0.012	<0.001	0.006	0.004	0.022	<0.01	4.58	0.01	0.038	2.1	<0.05		0.6	0.22
M225W	15/11/2016	7.31	30200	19800	778	778	711	9620	169	567	6560	72	<0.001	<0.001	0.068	0.0006	0.002	<0.001	0.006	<0.001	0.008	0.006	0.058	<0.01	4.93	0.01	0.062	2.32	<0.05	0.0002	0.7	0.12
M225W	13/06/2017		29900	18300	827	827	786	10800	150	492	6780	66							0.013		0.005						0.018	1.92	<0.05	<0.0001	0.4	0.43
M225W	12/11/2017	7.15	30700	20100	814	814	691	10400	144	507	5930	64	<0.001	<0.001	0.060		0.003	<0.001		<0.001	0.008	0.004	0.253	<0.01		0.01	0.015	1.95	<0.05		0.5	0.17
M225W	31/05/2018	7.16	30100			701	701	9900	169	578	6960	70							0.012		0.027						<0.025	2.07	<0.05	<0.0001	0.6	0.1
M340W	11/12/2012	6.6	8600	5200	620	620	240	2900	57	110	2100	25	<0.001	<0.0005	0.056	0.0002	<0.001	0.0002	0.005	<0.001	0.1		0.012			0.003	0.035			<0.00005	0.45	0.1
M340W	4/04/2013	6.3	8300	5200	620	620	230	2600	62	120	1900	32	<0.001	<0.0005	0.056	<0.0001	<0.001	0.002	0.004	<0.001	0.085		0.014			0.002	0.028			<0.00005	1.6	0.077
M340W	22/05/2013	6.81	8400	5000	610	610	240	2700	59	120	1900	25	<0.001	<0.0005	0.057	<0.0001	<0.001	0.002	0.005	<0.001	0.086		0.007			0.002	0.036			<0.00005	1.4	0.055
M340W	7/08/2013	6.63	8600	5000	620	620	230	2700	55	110	2000	26	<0.001	<0.0005	0.061	<0.0001	<0.001	0.002	0.002	<0.001	0.095		0.006			0.001	0.037			<0.00005	1.3	0.1
M340W	5/12/2013	6.63	9100	5700	610	610	260	2800	56	110	2200	27	<0.001	<0.0005	0.058	<0.0001	<0.001	0.002	<0.001	<0.001	0.1		0.013			0.001	0.021			<0.00005	1.5	0.063
M340W	10/05/2014	6.74	10000	6500	661	661	246	3150	71	141	1920	25							0.007		0.075						0.041			<0.0001		0.12
M340W	8/12/2014	6.69	11100	6390	708	708	257	3400	85	172	2050	33							0.008		0.081						0.076			<0.0001	1.8	0.08
M340W	12/03/2015	6.81	11400	6500	689	689	269	3760	102	174	2240	32	<0.001	<0.001	0.068		<0.001	0.002	0.003	<0.001	0.058		0.022			<0.01	0.013				1.7	
M340W	17/05/2015	6.82	11700	6900	679	679	383	3740	96	179	2060	27	<0.001	<0.001	0.194	<0.0001	<0.001	0.001	0.024	<0.001	0.051		0.009			<0.01	0.185			<0.0001	1.6	
M340W	28/07/2015	6.68	11400	6280	668	668	319	3670	100	177	2120	29	<0.001	<0.001	0.113	<0.0001	<0.001	<0.001	0.011	<0.001	0.049		0.038			<0.01	0.06			<0.0001	1.9	
M340W	16/11/2015	6.38	10700	7320	727	727	322	3850	89	193	2180	28	<0.001	<0.001	0.057	<0.0001	0.001	0.001	0.018	<0.001	0.047		0.01			<0.01	0.098			<0.0001	1.6	0.04
M340W	2/03/2016	8.43	12600	6400	681	725	320	4060	101	203	2480	33	<0.001	<0.001	0.060		<0.001	0.002	0.002	<0.001	0.044		0.01				0.018				2.0	0.08
M340W	13/05/2016	7.67	12400	7140	693	693	342	3790	100	200	2310	30	<0.001	<0.001	0.070	<0.0001	<0.001	0.001	0.012	<0.001	0.034	0.004	0.005	<0.01	2.95	<0.01	0.132	2.26	<0.05	<0.0001	1.8	0.05
M340W	29/08/2016	8.49	13000	7250	636	730	345	3780	107	198	2340	30	<0.001	<0.001	0.073		0.001	0.003	0.002	<0.001	0.06	0.004	0.008	<0.01	3.32	<0.01	0.005	1.83	<0.05		2.0	0.05
M340W	15/11/2016	7.44	13100	7430	668	668	371	4310	109	216	2420	31	<0.001	<0.001	0.075	<0.0001	0.002	0.002	<0.001	<0.001	0.056		0.006	<0.01		<0.01	0.014	2.14		<0.0001	1.6	0.08
M340W	13/06/2017		11300	6590	651	651	353	3690	90	180	2180	27							<0.001		0.611						<0.005	1.75	<0.05	<0.0001	1.9	12.6
M230W	11/12/2012	7.15	5600	3300	420	420	64	1600	55	93	1200	18	0.002	<0.0005	0.150	<0.0001	<0.001	<0.001	0.001	<0.001	0.097		0.005			<0.001	0.014			<0.00005	0.79	0.67
M230W	3/04/2013	6.66	5400	3200	420	420	66	1600	60	96	1000	19	0.002	<0.0005	0.170	<0.0001	<0.001	0.002	0.002	<0.001	0.26		0.01			<0.001	0.027			<0.00005	0.76	0.16
M230W	21/05/2013	7.01	5300	3300	410	410	60	1700	60	96	1100	18	0.002	<0.0005	0.180	<0.0001	<0.001	0.002	0.004	<0.001	0.18		0.014			<0.001	0.021			<0.00005	0.54	0.094
M230W	7/08/2013	7.05	5600	3000	400	400	77	1700	58	93	1100	16	0.002	<0.0005	0.180	<0.0001	<0.001	<0.001	0.003	<0.001	0.091		0.01			<0.001	0.033			<0.00005	0.46	0.27
M230W	7/12/2013	6.96	5900	3700	390	390	83	1700	56	85	1200	15	0.002	<0.0005	0.180	<0.0001	<0.001	0.002	0.003	<0.001	0.16		0.008			<0.001	0.017			<0.00005	0.63	0.11
M230W	11/05/2014	6.99	6010	3910	426	426	82	1660	67	100	1040	14							0.003		0.212						0.037			<0.0001		0.17
M230W	5/12/2014	7.05	6100	3120	418	418	73	1490	70	103	970	17							0.001		0.317						0.06			<0.0001	0.7	0.3
M230W	12/03/2015	7	6080	3360	410	410	69	1730	74	100	1030	16	0.002	<0.001	0.195		<0.001	0.003	0.001	<0.001	0.251		0.131			<0.01	0.013				0.8	
M230W	17/05/2015	7	6180	3580	407	407	97	1550	75	106	985	14	0.002	<0.001	0.283	<0.0001	<0.001	0.003	0.002	<0.001	0.243		0.01			<0.01	0.024			<0.0001	0.6	
M230W	28/07/2015	7.05	6000	3210	404	404	87	1500	74	107	1050	16	0.002	<0.001	0.237	<0.0001	<0.001	0.001	0.004	<0.001	0.146		0.012			<0.01	0.049			<0.0001	0.7	
M230W	15/11/2015	6.62	6260	3440	419	419	82	1840	69	101	891	12	0.002	<0.001	0.175	<0.0001	0.002	<0.001	0.002	<0.001	0.046		0.06			<0.01	0.068			<0.0001	0.8	0.17
M230W	2/03/2016	7.82	6350	3350	431	431	84	1760	68	104	995	17	0.001	<0.001	0.164		<0.001	0.001	0.002	<0.001	0.035		0.006			0.042	<0.01				0.7	0.19
M230W	13/05/2016	7.78	6120	3500	419	419	80	1760	72	110	1050	16	0.001	<0.001	0.184	<0.0001	<0.001	<0.001	0.001	<0.001	0.04	0.006	0.021	<0.01	1.52	<0.01	0.024	0.6	<0.05	<0.0001	0.7	0.1
M230W	29/08/2016	7.48	6130	3450	417	417	79	1680	76	111	1050	18	0.001	<0.001	0.186		<0.001	<0.001	0.007	<0.001	0.027	0.008	0.039	<0.01	1.68	<0.01	0.026	0.42	<0.05		0.7	0.1
M230W	15/11/2016	7.51	6220	3500	414	414	83	1750	68	117	1100	15	0.002	<0.001	0.186	<0.0001	<0.001	<0.001	0.002	<0.001	0.097	0.008	0.026	<0.01	1.71	<0.01	0.036	0.47	<0.05	<0.0001	0.6	0.08
M230W	13/06/2017		6270	3470	442	442	78	1870	65	110	1100	15							0.001		0.451						0.014	0.45	0.36	<0.0001	0.8	0.18
M230W	12/11/2017	7.5	6400	3710	420	420	79	1820	70	114	1070	15	0.002	<0.001	0.206		<0.001	0.005		<0.001	0.203	0.005	0.014	<0.01		<0.01	0.065	0.47	<0.05		0.7	0.23
M230W	1/06/2018	6.95	6860			380	99	1920	78	121	1170	17							0.001		0.188						0.012	0.44	0.43	<0.0001	0.7	0.17
M250W	13/12/2012	5.42	2400	1400	61	61	54	700	14	39	380	11	<0.001	<0.0005	0.1	<0.0001	0.002	<0.001	0.002	<0.001	0.027		0.008			<0.001	0.023			<0.00005	0.18	0.012
M250W	6/04/2013	5.77	2400	1600	69	69	69	660	17	45	490	13	<0.001	<0.0005	0.11	<0.0001	0.001	<0.001	0.002	<0.001	0.054		0.014			<0.001	0.02			<0.00005	0.14	0.01
M250W	25/05/2013	5.86	2500	1600	67	67	83	730	18	46	510	13	<0.001	<0.0005	0.1	<0.0001	0.003	<0.001	0.004	<0.001	0.015		0.007			<0.001	0.018			<0.00005	0.14	0.012
M250W	6/08/2013	5.82	2300	1300	72	72	81	730	19	43	450	11	<0.001	<0.0005	0.1	<0.0001	0.002	<0.001	0.002	<0.001	0.007		0.006			<0.001	0.016			<0.00005	0.13	0.079
M250W	5/12/2013	5.92	2500	1600	60	60	84	710	14	39	480	12	<0.001	<0.0005	0.083	<0.0001	0.002	<0.001	0.001	<0.001	0.019		0.01			<0.001	0.014			<0.00005	0.14	<0.005
M250W	9/05/2014	5.64	2440	1590	76	76	76	682	13	43	393	12							0.004		0.018						0.019			<0.0001		1.3
M250W	7/12/2014	5.65	2530	1380	58	58	76	717	13	45	432	11							<0.001		0.017						<0.005			<0.0001	0.2	0.08
M250W	10/03/2015	5.5	2540	1580	58	58	92	768	19	42	420	10	<0.001	<0.001	0.07		0.003	<0.001	<0.001	<0.001	0.013		0.01			<0.01	0.018				0.6	
M250W	18/05/2015	5.75	2560	1420	55	55	92	763	17	44	398	10	<0.001	<0.001	0.07	<0.0001	0.002	0.001	<0.001	<0.001	0.015		0.011			<0.01	0.019				0.2	
M250W	29/07/2015	5.48	2430	1430	59	59	89	729	15	44	387	11	<0.001	<0.001	0.078	<0.0001	0.003	0.001	<0.001	<0.001	0.028		0.01			<0.01	0.106			<0.0001	0.2	
M250W	16/11/2015	5.72	2170	1300	72	72	76	664	12	38	344	9	<0.001	<0.001	0.061	<0.0001	0.001	0.004	0.005	<0.001	0.076		0.048			<0.01	0.131			<0.0001	0.2	0.4
M250W	2/03/2016	6.54	2650	1490	53	53	92	787	15	45	408	12	<0.001	<0.001	0.047		0.002	<0.001	0.001	<0.001	0.014		0.01			<0.01	0.048				0.2	0.16
M250W	13/05/2016	6.74	2620	1530	116	116	95	774	18	52	461	11	<0.01	<0.001	<0.001		0.076	<0.0001	0.002	<0.001	0.011	<0.001	0.009	<0.01	0.725	<0.01	0.016	0.76	0.05	<0.0001	0.2	0.91
M250W	29/08/2016	7.76	2600	1440	64	64	81	678	14	44	396	10	<0.001	<0.001	0.055		0.002	0.001	0.001	<0.001	0.012	<0.001	0.01	<0.01	0.686	<0.01	0.008	0.61	<0.05		0.2	0.51
M250W	15/11/2016	6.36	2460	1400	60	60	86	715	12	46	411	10	<0.001	<0.001	0.05	<0.0001	0.002	0.001	<0.001	<0.001	0.012	<0.001	0.008	<0.01	0.698	<0.01	0.032	0.73	<0.05	<0.0001	0.2	0.47
M250W	18/06/2017		2450	1360	63	63	80	708	12	42	402	10							0.001		0.014						0.021	0.67	<0.05	<0.0001	0.2	0.44
M250W	13/11/2017	7.23	2650	1620	55	55	106	794	20	50	465	11	<0.001	<0.001	0.072		0.002	0.005	0.002	<0.001	0.095	0.002	0.043	<0.01		<0.01	0.111	0.7	<0.05		0.3	0.62
M250W	2/06/2018	5.8	2530			55	77	708	15	48	440	10							<0.001		0.014						0.006	0.73	0.43	<0.0001	0.2	0.63
M222W	16/06/2012	6.43	9520	6690	457	457	85	3140	326	355	1120	14	0.003	<0.000001	3.9	<0.0001	0.002	0.002	0.002	<0.001	1.17		0.125			<0.01	0.041			<0.0001	0.6	
M222W	14/12/2012	6.52	9300	6500	420	420	78	3500	290	340	1000	14	<0.001	<0.0005	1.2	<0.0001	<0.001	0.002	0.003	<0.001	1.3		0.005			<0.001	0.043			<0.00005	0.48	<0.005
M222W	5/04/2013	6.22	9100	6500	300	300	140	4100	320	440	1100	14	<0.001	<0.0005	0.26	<0.0001	<0.001	<0.001	0.002	<0.001	1.1		0.019			<0.001	0.037			<0.00005	0.68	<0.005
M222W	26/05/2013	6.67	9400	7500	290	290	100	3200	350	450	1100	14	0.001	<0.0005	0.24	<0.0001	<0.001	<0.001	0.002	<0.001	1.3		0.004			<0.001	0.007			<0.00005	0.47	<0.005
M222W	9/08/2013	6.17	9200	6200	310	310	110	3400	340	400	1100	11	0.003	<0.0005	0.23	<0.0001	<0.001	<0.001	0.001	<0.001	1.2		<0.001			<0.001	0.011			<0.00005	0.44	<0.005
M222W	6/12/2013	6.26	9700	9600	300	300	130	3300	440	380	1400	12	0.006	<0.0005	0.24	<0.0001	<0.001	<0.001	0.002	<0.001	1.7		0.001			<0.001	0.018			<0.00005	0.59	<0.005
M222W	10/05/2014	6.16	9480	6160	316	316	129	3420	363	428	1010	10							0.004		1.35						0.019			<0.0001		2.09
M222W	19/08/2014	6.81	9090	8950	275	275	128	3450	365	448	1020	12							0.001		1.54						0.036			<0.0001	0.4	0.18
M222W	4/12/2014	6.25	10200	7520	303	303	116	3330	361	451	1080	12							<0.001		1.45						0.115			<0.0001	0.8	0.74
M222W	11/03/2015	6.55	10000	6810	295	295	122	3450	395	395	999	10	0.003	<0.001	0.248		<0.001	<0.001	<0.001	<0.001	1.27		<0.001			<0.01	0.02				1	
M222W	17/05/2015	6.32	9890	7160	304	304	165	3480	374	426	943	9	0.011	<0.001	0.202	<0.0001	<0.001	<0.001	<0.001	<0.001	1.57		0.002			<0.01	0.021			<0.0001	0.7	
M222W	27/07/2015	6.23	9670	6150	290	290	129	3420	385	434	956	10	0.004	<0.001	0.226	<0.0001	<0.001	<0.001	<0.001	<0.001	1.28		0.007			<0.01	<0.005			<0.0001	0.8	
M222W	17/11/2015	6.1	10200	6820	296	296	124	3560	352	376	932	10	0.004	<0.001	0.22	<0.0001	<0.001	<0.001	0.001	<0.001	1.37		<0.001			<0.01	0.074			<0.0001	0.9	0.53
M222W	2/03/2016	7.19	10700	5190	318	318	118	3560	342	434	1040	12	0.003	<0.001	0.219		0.002	<0.001	<0.001	<0.001	1.27		0.017			<0.01	0.043				0.8	0.11
M222W	13/05/2016	7.22	9890	5740	282	282	177	3340	376	456	1040	10	0.009	<0.001	0.201	<0.0001	<0.001	<0.001	<0.001	<0.001	1.59	0.004	<0.001	<0.01	6.67	<0.01	<0.005	0.33	17.6	<0.0001	0.7	0.43
M222W	29/08/2016	8.16	10400	7370	280	280	155	3170	414	474	1080	10	0.01	<0.001	0.184		<0.001	<0.001	<0.001	<0.001	1.86	0.004	0.003	<0.01	8.96	<0.01	<0.005	0.32	21.1		0.8	0.55
M222W	15/11/2016	6.62	10300	6300	292	292	140	3660	407	492	1170	11	0.005	<0.001	0.252	<0.0001	<0.001	<0.001	<0.001	<0.001	1.59	0.003	0.002	<0.01	8.73	<0.01	0.015	0.34	13.6	<0.0001	0.8	0.19
M222W	13/06/2017		10600	6320	310	310	145	3920	379	448	1140	11							<0.001		1.55						<0.005	0.33	11.4	<0.0001	0.7	0.32
M222W	7/11/2017	6.82	10600	6800	271	271	126	3670	399	466	1080	10	0.005	<0.001	0.288		<0.001	<0.001	<0.001	<0.001	1.63	0.002	0.001	<0.01		<0.01	<0.005	0.3	14.5		0.8	0.43
M222W	29/05/2018	6.29	11000			286	131	4020	417	478	1170	12							0.002		1.63						<0.005	0.32	15.5	<0.0001	0.7	0.46
M224W	16/06/2012	6.22	29500	22300	355	355	1600	9560	831	1260	4170	11	<0.050	<0.00001	0.078	<0.0050	<0.010	0.011	<0.00005	<0.010	7.75		<0.00005			<0.10	0.06			<0.0001	0.9	
M224W	15/12/2012	6.24	28000	22000	340	340	1500	14000	780	1100	4500	13	0.003	<0.0005	0.11	<0.0001	<0.001	0.012	<0.001	<0.001	7.8		0.023			0.001	0.009			<0.00005	0.74	0.03
M224W	7/04/2013	5.73	25000	20000	360	360	1300	11000	740	1000	4300	16	0.002	<0.0005	0.2	0.0002	<0.001	0.015	<0.001	<0.001	8.1		0.04			<0.001	0.024			<0.00005	0.45	<0.005
M224W	25/05/2013	6.11	18000	14000	220	220	880	6200	610	680	2600	17	0.004	<0.0005	0.14	<0.0001	<0.001	0.007	<0.001	<0.001	4.8		0.083			0.002	0.008			<0.00005	0.23	<0.005
M224W	6/08/2013	6.07	23000	17000	240	240	1200	9100	840	980	4500	12	0.005	<0.0005	0.13	<0.0001	<0.001	0.01	<0.001	<0.001	6.8		0.018			<0.001	0.027			<0.00005	0.37	0.052
M224W	6/12/2013	6.15	28000	27000	280	280	6200	11000	1000	1400	6200	13	0.007	<0.0005	0.13	<0.0001	<0.001	0.012	<0.001	<0.001	8		0.015			<0.001	0.021			<0.00005	0.51	0.007
M224W	10/05/2014	6.24	27200	17700	253	253	1250	10200	779	1080	3690	11							<0.05		7.57						0.056			<0.0001		0.3
M224W	19/08/2014	6.34	27600	21000	192	192	1060	10800	822	1300	4590	13							<0.001		7.98						0.302			<0.0001	0.4	0.79
M224W	4/12/2014	6.14	31600	22900	186	186	842	9710	764	1320	4080	13							<0.001		6.83						0.067			<0.0001	0.4	0.17
M224W	12/03/2015	6.46	22900	16500	174	174	710	8850	661	842	3240	10	0.004	<0.001	0.157		<0.001	0.016	0.006	<0.001	4.4		0.119			<0.01	0.044				0.6	
M224W	17/05/2015	6.36	21000	16800	184	184	978	7200	640	768	2760	8	0.006	<0.001	0.164	<0.0001	<0.001	0.021	0.001	<0.001	4.59		0.025			<0.01	0.05			<0.0001	0.3	
M224W	27/07/2015	6.13	24700	17100	188	188	948	8670	712	984	3390	9	0.008	<0.001	0.157	0.0001	<0.001	0.019	0.003	<0.001	4.51		0.17			<0.01	0.059			<0.0001	0.5	
M224W	17/11/2015	6.13	27700	17500	158	158	890	9930	613	870	3320	7	0.008	<0.001	0.163	<0.0001	<0.001	0.027	<0.001	<0.001	3.78		0.014			<0.01	0.101			<0.0001	0.4	0.11
M224W	2/03/2016	7.38	10800	5950	128	128	656	3350	316	360	1600	6	0.005	<0.001	0.065		<0.001	0.009	0.002	<0.001	1.36		0.021			<0.01	0.037				0.4	0.06
M224W	13/05/2016	7.48	17900	11100	202	202	799	5860	512	664	2680	9	0.008	<0.001	0.159	<0.0001	<0.001	0.011	0.005	<0.001	3.42	0.001	0.007	<0.01	11.4	<0.01	0.176	0.34	4.8	<0.0001	0.4	<0.05
M224W	29/08/2016	7.21	4240	2360	101	101	541	1020	172	107	543	5	0.003	<0.001	0.06		<0.001	0.005	<0.001	<0.001	0.834	0.001	0.004	<0.01	3.19	<0.01	0.037	0.13	0.2		0.2	0.09
M224W	15/11/2016	6.77	17700	11700	192	192	802	6210	570	696	2650	8	0.008	<0.001	0.182	<0.0001	<0.001	0.017	<0.001	<0.001	3.75	0.002	0.02	<0.01	14	<0.01	0.21	0.24	5.39	<0.0001	0.4	0.07
M224W	13/06/2017		17600	11000	238	238	1070	6490	676	630	2400	9							<0.001		4.04						0.052	0.22	7.91	<0.0001	0.3	0.08
M224W	07/11/2017	6.97	20400	14100	232	232	1000	7120	774	778	2650	10	<0.001	0.193	<0.001		0.015	<0.001		<0.001	4.94	0.003	0.042	<0.01	<0.01	<0.01	0.044	0.22	10.1		0.4	0.3
M224W	29/05/2018	6.28	27200			304	1240	10100	870	1090	4100	10							0.002		6.72						0.062	0.34	7.2	<0.0001	0.5	0.22
AN020F	13/05/2016	6.2	10800	6210	22	22	<1	3750	429	178	1550	29	<0.001	<0.001	3.72	<0.0001	<0.001	0.001	<0.001	<0.001	1.92	<0.001	<0.001	<0.01	11.3	<0.01	<0.005	0.14	14.3	<0.0001	<0.1	<0.01
AN020F	15/11/2016	6.32	10600	7210	21	21	1	4030	439	174	1450	26	<0.001	<0.001	3.62		<0.001	<0.001	<0.001	<0.001	1.85	0.001	0.001	<0.01	11	<0.01	<0.005	0.19	8.25		<0.1	<0.05
AN020F	15/11/2017	7.39	10900	7010	47	47	<1	3790	456	182	1650	29	<0.001	<0.001	3.42		<0.001	<0.001	<0.001	<0.001	1.17	0.005	0.006	<0.01		<0.01	<0.005	0.14	5.01		<0.1	0.11
AN021F		DRY																															

DEEP MONITORING BORES

Monitoring Bore ID	Sample Date	Field pH	Electrical Conductivity	Total Dissolved Solids (grav)	Hydroxide Alkalinity (OH-) as CaCO3	Carbonate Alkalinity as CaCO3	Bicarbonate Alkalinity as CaCO3	Total Alkalinity as CaCO3	Sulphate, SO4	Chloride, Cl	Calcium - Dissolved	Magnesium - Dissolved	Sodium - Dissolved	Potassium - Dissolved	Arsenic-Dissolved	Beryllium-Dissolved	Barium-Dissolved	Cadmium-Dissolved	Chromium-Dissolved	Cobalt-Dissolved	Copper-Dissolved	Lead-Dissolved	Manganese-Dissolved	Molybdenum	Nickel-Dissolved	Selenium	Strontium	Vanadium-Dissolved	Zinc-Dissolved	Boron	Iron	Mercury-Dissolved	Fluoride, F	Phosphate as P in water
			µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
M313W	25/07/2014	9.42	1710	1160	<1	51	283	334	12	252	7	<1	319	98	0.004	<0.001	0.843		0.018	0.01	2.12	2.19	0.429		0.032			0.02	0.568				0.6	2.28
M313W	13/02/2015	8.12	6940	4110	<1	<1	781	781	4	1810	26	5	1420	126	<0.001	<0.001	4.88		<0.001	<0.001	0.055	<0.001	0.139		0.004			<0.01	<0.005				2.4	2.32
M313W	11/11/2015	8.3	6890	3870	<1	<1	666	667	2	1910	22	4	1250	56	<0.001	<0.001	2.8		<0.001	<0.001	0.002	<0.001	0.099		0.002			<0.01	<0.005				2.4	0.87
M313W	30/05/2016	8.48	4570	2420	<1	41	443	484	2	1130	10	1	1000	60	<0.001	<0.001	1.23	<0.001	<0.001	<0.001	<0.001	<0.001	0.04	0.017	<0.001	<0.01	1.39	<0.01	0.008	0.5	0.28			0.16
M313W	15/11/2016	7.8	5620	2950	<1	<1	634	634	<1	1420	20	3	1170	62	0.002	<0.001	2.63	<0.001	<0.001	<0.001	0.002	<0.001	0.077	0.035	0.003	<0.01	3.02	<0.01	0.018	0.95	1.08		2.3	0.89
M313W																																		
M313W	19/011/2017	8.59	6020	3320	<1	48	587	636	<1	1720	24	4	1370	60	0.003	<0.001	2.54		<0.001	<0.001	<0.001	<0.001	0.071	0.035	0.002	<0.01		<0.01	<0.005	0.92	0.57		2	0.83
M314W	24/07/2014	8.57	5090	4790	<1	9	1210	1220	134	198	46	1	212	1450	0.013	<0.001	0.575		0.015	0.005	7.08	0.562	0.446		0.018			<0.01	0.472				0.4	65.6
M314W	13/02/2015	8.04	7150	5470	<1	<1	1180	1180	69	1370	29	6	1040	795	0.004	<0.001	1.37		<0.001	0.002	0.995	<0.001	0.141		0.01			<0.01	<0.005				0.9	20.6
M314W	13/11/2015	8.01	8210	5280	<1	<1	836	836	2	2190	17	5	1420	335	0.003	<0.001	1.31		<0.001	<0.001	0.031	<0.001	0.14		0.013			<0.01	0.011				1.1	17.4
M314W	30/05/2016	8.6	8500	4880	<1	49	767	817	<1	2370	22	6	1640	326	0.003	<0.001	5.21	<0.001		<0.001	0.022	<0.001	0.028	0.053	0.001	<0.01	5.5	<0.01	0.01	0.87	0.1	0.87		9.67
M314W	15/11/2016	8.88	8180	4810	<1	108	827	934	<1	2290	19	6	1500	404	0.004	<0.001	3.88	<0.001	<0.001	<0.001	0.03	<0.001	0.036	0.062	0.002	<0.01	3.67	<0.01	0.009	0.9	0.21		1.3	12.1
M314W																																		
M314W	18/11/2017	8.9	8300	4860	<1	169	908	1080	<1	2190	17	5	1880	543	0.004	<0.001	2.91		<0.001	<0.001	0.024	<0.001	0.053	0.068	0.002	<0.01		<0.01	<0.005	0.76	0.18		1.2	14.2
M324W	26/07/2014	9.17	1170	707	<1	48	177	225	24	188	26	5	199	31	0.005	<0.001	0.31		0.004	0.004	0.582	0.459	0.304		0.008			<0.01	0.427				1	2.01
M324W	13/02/2015	8.83	2660	1540	<1	105	615	720	1	505	7	2	627	29	<0.001	<0.001	0.482		<0.001	<0.001	<0.001	<0.001	0.018		0.002			<0.01	0.093				3.7	0.88
M324W	30/05/2016	8.57	2750	1390	<1	64	624	688	6	522	6	1	599	12	<0.001	<0.001	0.921	<0.001	<0.001	<0.001	<0.001	<0.001	0.025	0.02	<0.001	<0.01	0.889	<0.01	0.006	0.76	0.22			0.46
M324W	15/11/2016	8.58	2650	1540	<1	59	635	694	<1	503	5	1	612	12	0.001	<0.001	0.738	<0.001	<0.001	<0.001	<0.001	<0.001	0.009	0.024	<0.001	<0.01	0.807	<0.01	0.01	0.78	0.13		4.5	0.44
M324W																																		
M324W	19/11/2017	8.86	2740	1300	<1	104	568	672	<1	536	4	1	666	13	0.001	<0.001	0.572		<0.001	<0.001	<0.001	<0.001	0.006	0.027	<0.001	<0.01		<0.01	<0.005	0.72	<0.05		3.9	0.57
M325W	25/07/2014	able to Sample												Unable to Sample																				
M325W	13/02/2015	8.55	3410	2260	<1	14	252	297	68	906	2	<1	709	73	0.002	<0.001	0.005		<0.001	0.003	0.016	<0.001	0.009		0.009			<0.01	0.024				0.7	0.56
M325W	13/11/2015	8.13	5000	2730	<1	<1	450	450	4	1400	8	1	919	40	0.001	<0.001	0.252		<0.001	0.002	<0.001	<0.001	0.086		<0.001			<0.01	<0.005				1.1	0.45
M325W	30/05/2016	8.74	6150	3310	<1	75	370	446	1	1600	6	<1	1250	39	0.002	<0.001	0.384	<0.001	<0.001	<0.001	0.008	<0.001	0.057	0.114	0.002	<0.01	0.639	<0.01	0.009	1.17	0.24			0.4
M325W	15/11/2016																																	
AN019F	10/11/2015	11.8	10200	5430	456	82	<1	539	33	2920	154	<1	1620	19	0.002	<0.001	2.79		<0.001	<0.001	0.006	<0.001	<0.001		0.007			<0.01	0.01				0.8	0.04
AN019F	30/05/2016	11.6	10800	5970	410	100	<1	510	38	3180	168	<1	1840	29	0.004	<0.001	3.25	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.056	0.008	<0.01	8.18	<0.01	<0.005	0.42	<0.05	0.42		0.05
AN019F	15/11/2016	11.8	11100	6140	428	125	<1	553	37	3400	162	<1	1970	28	0.004	<0.001	2.65	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.036	0.006	<0.01	5.92	<0.01	0.014	0.46	<0.05		0.7	<0.05
AN019F																																		
AN019F	15/11/2017	11.1	10700	5890	123	135	<1	258	35	3340	104	<1	2330	27	0.004	<0.001	2.40		<0.001	<0.001	<0.001	<0.001	<0.001	0.027	0.003	<0.01		<0.01	0.006	0.45	<0.05		0.7	0.13
GR067V	30/08/2016	9.05	7020	4000	<1	407	1550	1960	19	1180	7	1	1580	14	0.003	<0.001	1.48	0.001	0.001	<0.001	0.002	<0.001	0.11	0.032	0.006	<0.01	1.18	<0.01	0.011	0.81	1.56			0.6
GR067V	15/11/2016	8.12	7850	4640	<1	<1	2310	2310	3	1260	15	3	1850	13	0.003	<0.001	4.94	0.001	0.001	<0.001	<0.001	<0.001	0.024	0.024	0.001	<0.01	3.72	<0.01	0.018	1.17	0.68		1.8	0.3
GR067V																																		
GR067V	19/11/2017	8.72	8210	4910	<1	238	2120	2360	4	1440	19	3	2190	12	0.003	<0.001	3.83		<0.001	<0.001	<0.001	<0.001	0.008	0.019	<0.001	<0.01		<0.01	0.008	1.03	0.16		1.7	0.3
M162V	14/11/2015	8.44	11500	6970	<1	38	1060	1090	3	3640	10	6	2370	12	<0.001	<0.001	0.236		<0.001	<0.001	<0.001	<0.001	0.092		<0.001			<0.01	<0.005				1.9	1.13
M162V	30/05/2016	7.91	12700	7250	<1	<1	1050	1050	2	4040	56	19	2590	12	<0.001	<0.001	11	<0.001	<0.001	<0.001	0.01	<0.001	0.063	0.002	0.001	<0.01	10.8	<0.01	0.16	2.4	3			<0.05
M162V	15/11/2016	7.7	12300	6660	<1	<1	1060	1060	<1	3870	69	18	2670	12	<0.001	<0.001	9.93	<0.001	<0.001	<0.001	<0.001	<0.001	0.034	0.001	<0.001	<0.01	9.77	<0.01	0.032	2.02	2.19		2.6	0.03
M134W	14/11/2017	8.1	15600	9810	<1	<1	168	168	<1	5770	209	62	3490	12	<0.001	<0.001	23		<0.001	<0.001	<0.001	<0.001	0.064	0.001	<0.001	<0.01		<0.01	0.009	0.46	0.40		0.5	0.04

APPENDIX C – Australian Groundwater and Environmental Consultants Pty Ltd (AGE) - Arrow Project – Bowen Groundwater Monitoring Management Plan Uncertainty Analysis

Australasian Groundwater and
Environmental Consultants Pty Ltd



Report on

Arrow Project

Bowen Groundwater Management and Monitoring Plan Uncertainty Analysis

Prepared for
Arrow Energy Pty Ltd

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Australasian Groundwater and Environmental Consultants Pty Ltd

AGE Head Office
Level 2 / 15 Mallon Street,
Bowen Hills, QLD 4006, Australia
T. +61 7 3257 2055
F. +61 7 3257 2088
brisbane@ageconsultants.com.au

AGE Newcastle Office
4 Hudson Street
Hamilton, NSW 2303, Australia
T. +61 2 4962 2091
F. +61 2 4962 2096
newcastle@ageconsultants.com.au

AGE Townsville Office
Unit 3, Building A, 10 Cummins Street
Hyde Park, QLD 4812, Australia
T. +61 7 4413 2020
F. +61 7 3257 2088
townsville@ageconsultants.com.au

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Bowen Groundwater Management Monitoring Plan Uncertainty Analysis

1 Introduction

Arrow Energy Pty Ltd (Arrow) appointed Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) to undertake numerical groundwater modelling work related to the Arrow Moranbah and Bowen Gas Expansion Project (MGP and BGP) for use with the Bowen Underground Water Impact Report (UWIR) and the Bowen Groundwater Management and Monitoring Plan (GMMP).

The Moranbah Gas Project has been producing gas for the domestic market since 2004, operated by Arrow and part owned by AGL. In 2012, Arrow submitted an Environmental Impact Statement to develop the Bowen Gas Project, followed by a Supplementary Report to the EIS in 2014. Arrow submitted the UWIR (Arrow Energy, 2016), outlining potential immediate and long-term groundwater impacts to groundwater levels due to CSG production.

This report provides a summary of the predictive modelling work undertaken by AGE in order to assess the regional scale groundwater impacts of Arrow's current MGP and BGP development plan.

2 Model development

2.1 Background

2.1.1 Grid

The Northern Bowen Basin numerical groundwater model was developed by Ausenco Norwest for Arrow Energy in 2012 to predict and delineate groundwater impacts where drawdowns exceed the Queensland Department of Environmental and Heritage Protection (DEHP) threshold criteria. The model was built in MODFLOW-SURFACT™ using the Groundwater Vistas 6 software package. A uniform mesh of 1500 x 1500m cells was simulated over 18 model layers. The origin of the model is 660,000 mE, 7,315,000 mN (GDA Zone 55), rotated about 32 degrees anticlockwise from the origin (bottom left corner).

2.1.2 Time

The model run commenced a steady state simulation representing the pre-1980 time period followed by monthly time steps starting from Jan 2000 to December 2017 to simulate the historical CSG water production. The model was then run forward in time at annual time slices starting in 2018 and ending in 2181 to predict the potential the impact of CSG activity.

2.1.3 Boundary conditions

The calibrated basecase model was surrounded by 'No flow' model cells, defined by the hydrogeological conceptualization and geologic model extent. No flow cells exist below the Back Creek Group and along the edges of the model, which are defined by the Back Creek Group outcrop.

The MODFLOW River package (RIV) was used to represent the Perennial reaches of the Bowen and Isaac Connors River system. River elevations, stage heights, incisions depths and vertical conductivity rates were assigned according to the Isaac Connors Groundwater Project (SKM, 2009).

A general head boundary (GHB) package was used to define the southern boundary of the model with a low conductance factor to limit potential inflow to the model. Groundwater levels at the boundary were assigned to a level that allowed the model to replicate regional groundwater gradients.

2.1.4 Hydraulic stresses

Recharge was applied to the model based on annual averages of groundwater seepage, defined within the model domain using the same geological zones used defining hydraulic conductivity and storage.

The Bureau of Meteorology (BOM) potential/actual evapotranspiration dataset was applied to the model using the MODFLOW Evapotranspiration (EVT) package. Rates were defined as the difference between the potential and the actual evapotranspiration rates, ranging from 0.0025-0.0033 m/day, at an extinction depth of 15 m below the ground surface.

Groundwater production from the CSG activity was simulated using the WEL package, simulating well abstraction using downhole, single point extraction locations. This methodology was similar to the methods used by the Office of Groundwater Impact Assessment (OGIA) to develop a regional model of cumulative impacts in the Surat Basin at the time of model development.

Two-phase flow relative permeability effects encountered in the vicinity of CSG production results in a reduction of effective permeability due to the presence of gas.. MODFLOW-SURFACT™ does not replicate these effects, and therefore drawdowns in the immediate vicinity of the production wells have the potential to be misrepresented. In addition to this, there is a considerable amount of upscaling for regional scale models representing the interburden units surrounding the in-seam wells. This too contributes to the uncertainty of the groundwater pressures proximal to CSG productions. Generally, these effects are local, with minimal implications to regional groundwater drawdown predictions.

2.1.5 Predictions

The 2012 Norwest model report presented predictions from the calibrated version of the model, and subsequent modelling presented the outcomes from a null-space Monte Carlo uncertainty analysis.

In 2016, Arrow adjusted field development plans and reproduced predictive impacts for the 2016 UWIR. One major difference to the Norwest model (Norwest, 2012) was the reduced BGP field development plan. In 2017 this model was re-run by AGE with some refined water production rates in the area of the MGP and revised predictive impacts were produced by AGE in 2017.

2.2 AGE re-meshing and structure update

The numerical modelling work undertaken for this project largely represents a repeat of the groundwater impact assessment work completed by Norwest and Arrow. With the release of MODFLOW-USG, AGE took the opportunity to increase the resolution of the Bowen model mesh around the MGP area and better delineate groundwater structures.

The input files for the MODFLOW-USG model were created using custom Fortran code and a MODFLOW-USG edition of the Groundwater Data Utilities by Watermark Numerical Computing (2016). The mesh was generated using Algomesh (HydroAlgorithmics, 2014).

The model boundary was identical to the extent of active model cells in the previous Norwest model. The model domain is approximately 157 km wide (west to east direction) and 395 km long (north to south direction) as shown in .

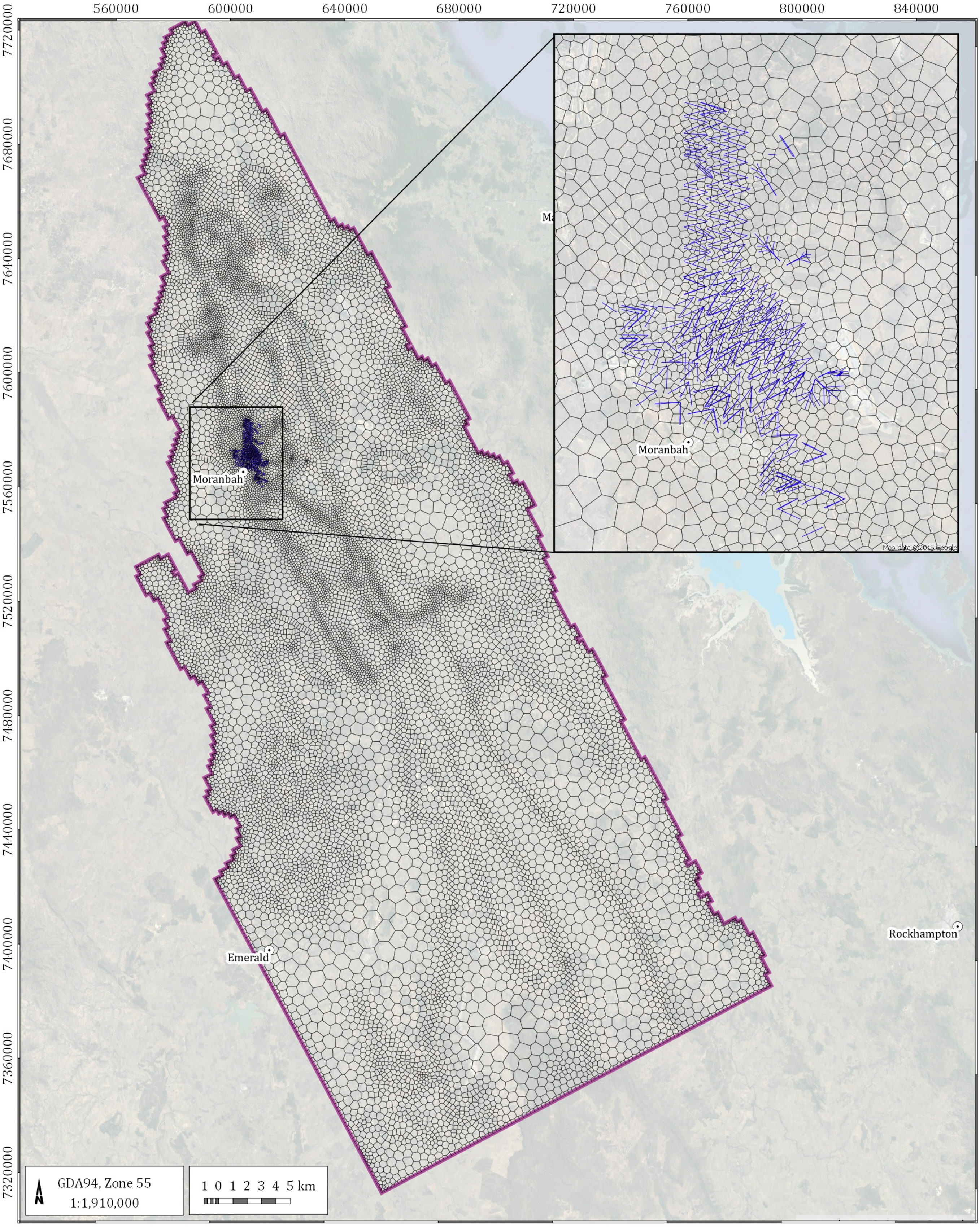
The model domain was discretised and arranged into 22 layers comprising up to 18,082 cell nodes in each layer with the dimensions of the cells varying according to the features that required representation. The following cell dimensions were adopted:

- MGP area: ~200 x 200 m hexagonal cells aligned to in seam wells;
- BGP area: ~1500 x 1500 Voronoi/rectangle cells centred on downhole CSG production wells;
- Faults: ~1000 x 1000 centred on either side of fault trace;
- Surficial aquifer systems (e.g. basalt): ~1000 x 1000m centred either side of aquifer extents; and
- Major drainage systems: ~500 x 500m centred along river lines proximal to the MGP.

Overall, the model comprised 188,516 cells across the 22 layers. Compared to the previous model, which consisted of 530,640 cells over 18 layers, this represents a significant decrease in the number of cells in the model. Coupled with the improved cell communication between Voronoi cells close to dewatered zones, the updated model runs faster than its predecessors.

Groundwater layer types were prescribed as convertible layers, with unsaturated flow represented using the ‘upstream weighting’ function, which is similar to pseudo-soil function in MODFLOW-SURFACT™.

Model layer elevations were based on the same regional geological model that the Norwest (Norwest, 2012) groundwater model was based on. The only subtle change occurred in Layer 18, where the previous model layer was split into five separate layers to more accurately represent targeted coal resources in the region. **Table** 2-1 presents a summary of the revised layering compared to the Norwest model layers.



LEGEND

⊙ Populated place

☐ 2018 AGE mesh

— 2018 AGE model outline

— MGP CSG production laterals

Bowen (G1885B)

2018 AGE model mesh

AGE

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15/06/2018

FIGURE No:
2.1

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Table 2-1 2012-2018 Bowen Model layering

Norwest 2012-2017 Model Layer	AGE 2018 Model Layer	Primary Formation/Group	Unit
1	1	Quaternary Alluvium, weathered materials	Surficial Coverage
2	2	Tertiary sediments (Duringa), Basalts (Anakie) & Moolayember	Tertiary, Triassic
3	3	Clematis Sandstone	Triassic
4	4	Rewan/Rangal Coal Measures	Triassic
5	5	Rangal Coal Measures (RCM)	Leichardt seam
6	6		Interburden
7	7		Vermont seam
8	8	Fort Cooper Coal Measures (FCCM)	FCCM
9	9		FCCM
10	10		FCCM
11	11	Moranbah Coal Measures (MCM)	Q Seam
12	12		Interburden
13	13		P seam
14	14		Interburden
15	15		GM seam
16	16		Interburden
17	17		GML seam
18	18		Interburden
	19		DYU seam
	20		Interburden
	21		DYR seam
	22	Collinsville, Back Creek Group	Permian basement

In terms of boundary conditions, Recharge (RCH), Evapotranspiration (EVT), General Head Boundary (GHB), River (RIV), and Basic (BAS) packages were translated into the new model mesh and were left essentially unchanged from the Norwest (2012) model.

The majority of the aquifer parameters used in the Norwest (2012) model to represent the 'calibrated' version of the groundwater system were translated into the new mesh as closely as possible, with the exception of the representation of coal seam hydraulic conductivity.. These values serve as a starting position for the revised model calibration. To better replicate the observed depth decline relationships discussed and presented in Section 2.2.1.1 of the Norwest report, an approximated average depth decline equation was applied to the groundwater model on a cell-by-cell basis for the coal seams in the Moranbah and Rangal Coal Measures. Figure 2-2 presents the MCM depth decline equations for the sub-regions in the model domain, based on production tests in the BGP area (dashed lines) compared to a simplistic example of how these rates were applied in the Norwest model. The black solid line shows the coal seam permeability directly applied the 2018 AGE model. Figure 2-3 presents RCM depth decline equations for measured and modelled data. The results imply the RCM is hydraulically tighter at depth than the MCM. Figure 2-4 presents the location of the MCM subregions.

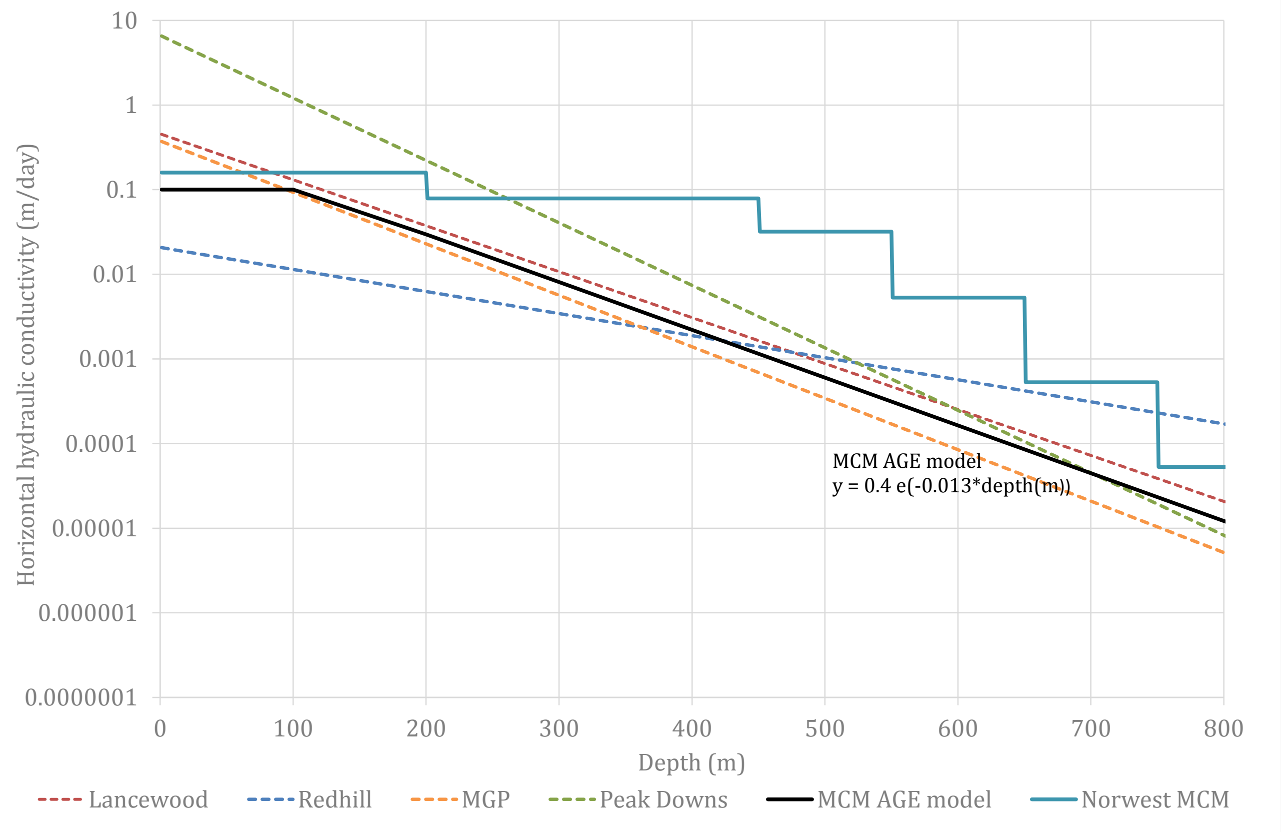


Figure 2-2 MCM Coal hydraulic conductivity distribution graph

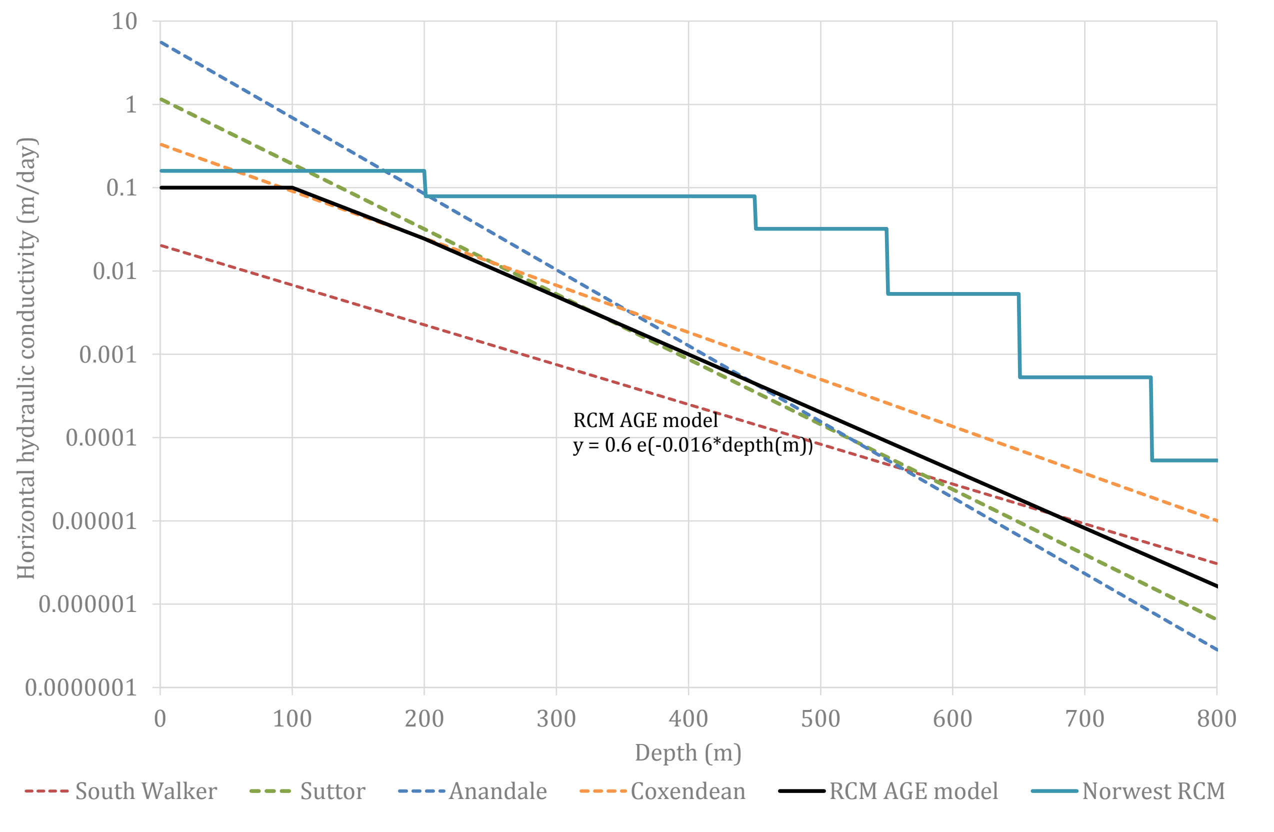
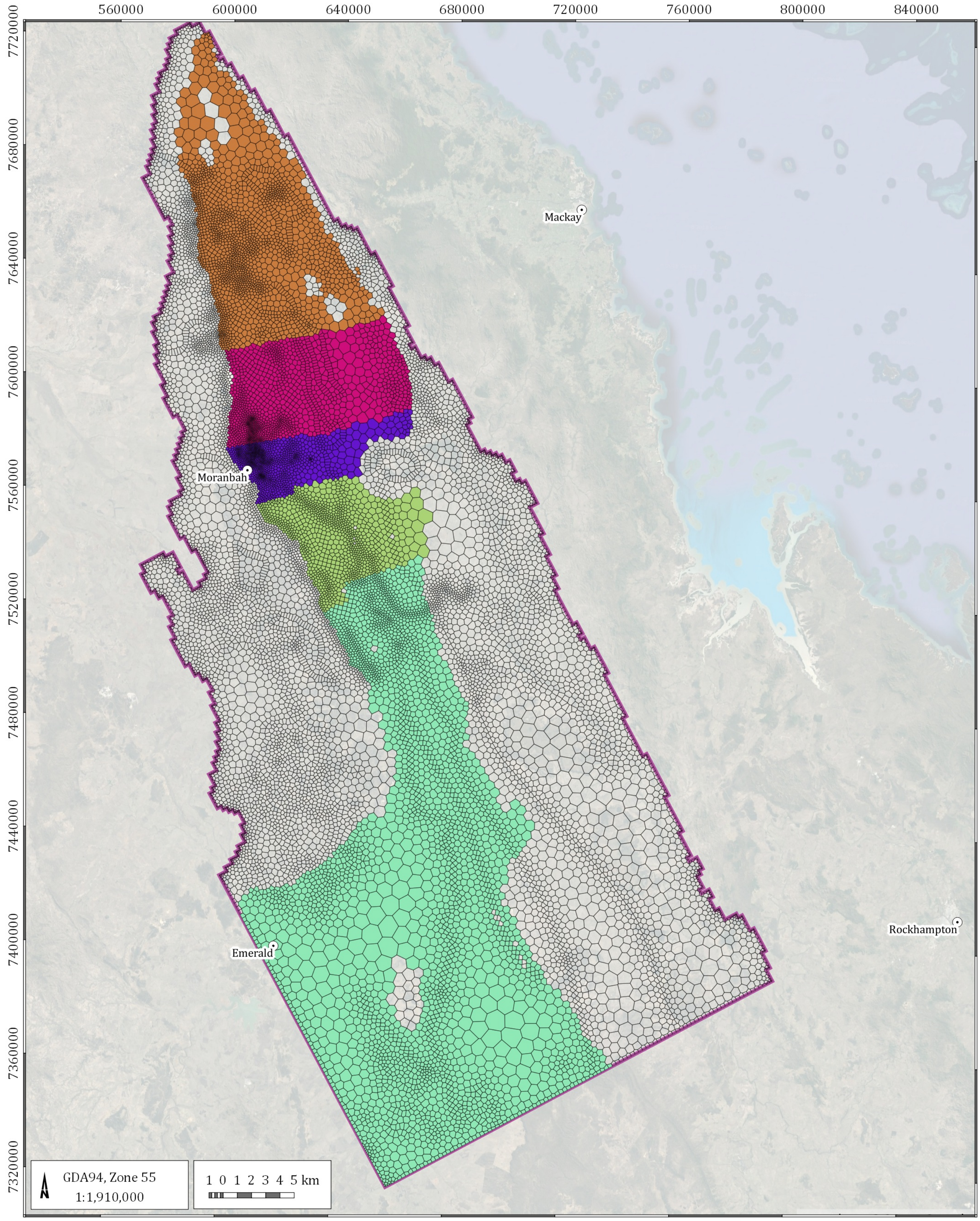


Figure 2-3 RCM Coal hydraulic conductivity distribution graph



LEGEND

- ⊙ Populated place
- ☐ 2018 AGE mesh
- — 2018 AGE model outline

MCM Coal Measures Subregion

- 🟧 1_Lancewood
- 🟥 2_Red Hill
- 🟪 3_MGP
- 🟩 4_Peak Downs
- 🟩 5_Noriwck Park, Saraji, German Creek

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Moranbah Coal Measures Subregions

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2.3 Field development plan data

Arrow Energy provided the historical and future Field Development Plans (FDP) for the MGP and a FDP for Mavis Downs, PLa486, and the BGP. Model iterations run using these field development plans were run in independently to assess to impact of the various FDPs across the tenure.

Table 2-2 summarises the scenarios simulated for this study. Figure 2-5 graphically illustrates the total daily production from each of these scenarios with time.

Table 2-2 Scenario CSG production summary

Scenario	Description
NC	No Arrow CSG production
0	Historical MGP (2003 – Dec 2017)
1	Historical MGP (2003 – Dec 2017) + Future MGP (to 2030)
2	Historical MGP (2003 – Dec 2017) + Future MGP (to 2030) + PLa486 (Phase 1 & 2) + Mavis Downs + BGP delayed half train case (2030 – 2060)
UWIR	CSG production as per 2016 UWIR

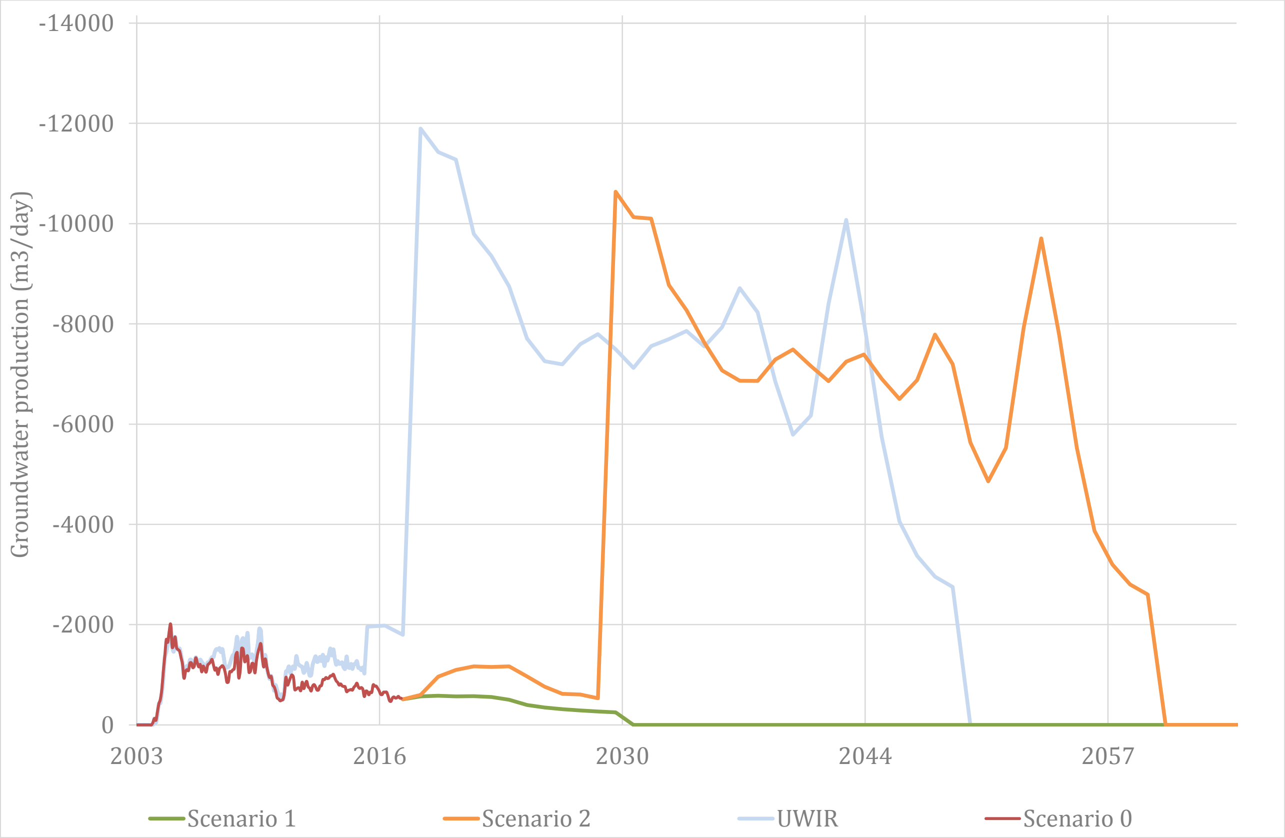


Figure 2-5 Scenario production summary

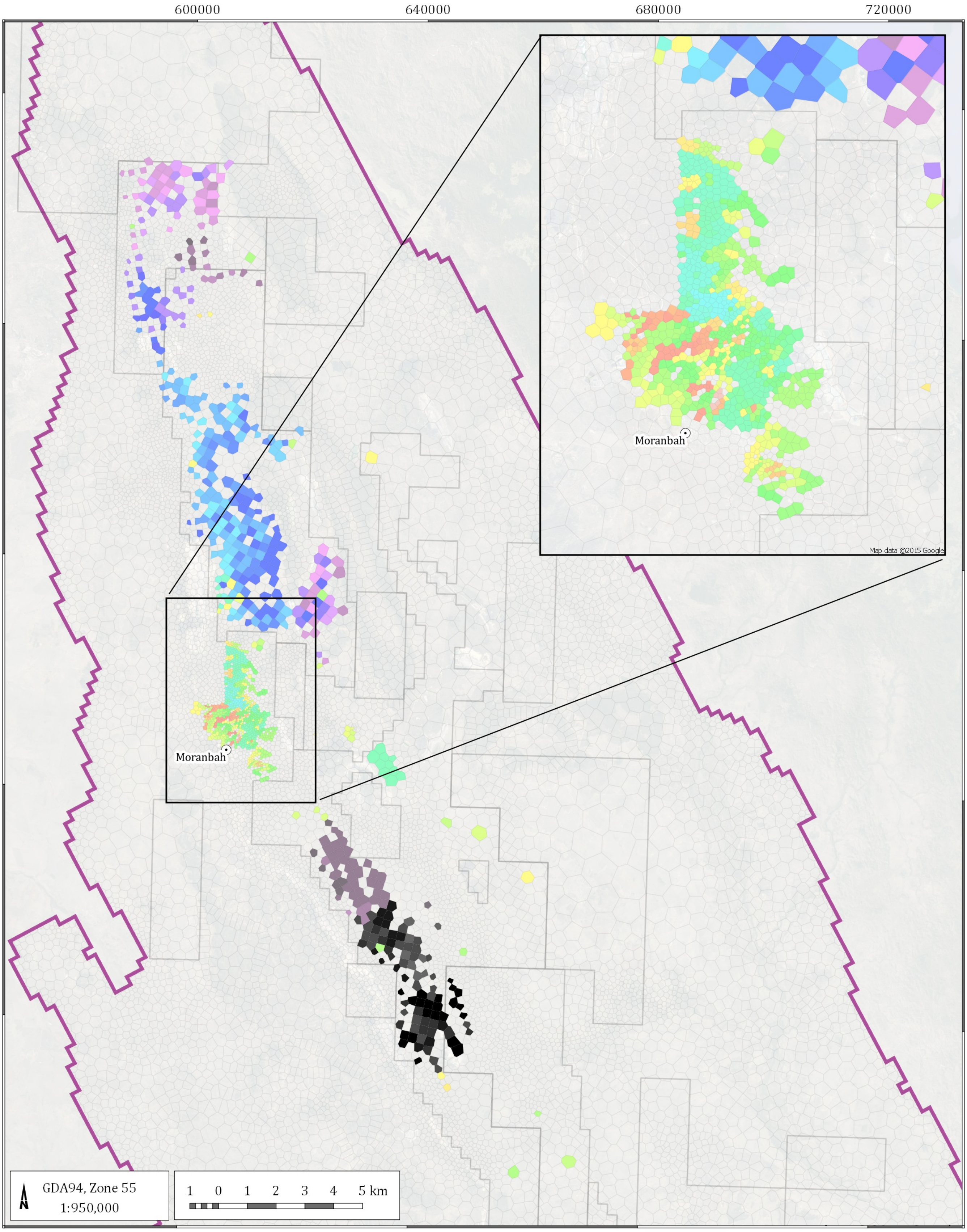
Figure 2-6 graphically presents cumulative production for Scenario 2 from each of the production fields.

Figure 2-6 **Cumulative production – BGP, MGP, Mavis Downs, PLa486**

2.4 Well package (WEL) construction

Production data from Arrow Energy was provided on a monthly basis, per production bore. To best represent pumping in the model, a Fortran script was written to most efficiently replicate future production. Where a particular in-seam well intercepts a series model cells, the WEL package was applied and the total flux rate was divided by the number of intercepted model cells.

Figure 2-7 and Figure 2-8 show the model wells on the updated mesh, showing the start and end year respectively for each production area in Scenario 2.



LEGEND

⊙ Populated place
□ 2018 AGE mesh
— 2018 AGE model outline

WEL start (year)

■ 2003
■ 2004
■ 2005
■ 2006
■ 2007
■ 2008
■ 2010
■ 2011
■ 2012
■ 2013
■ 2014
■ 2015
■ 2016
■ 2017
■ 2018
■ 2019
■ 2020
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■ 2052
■ 2054
■ 2055
■ 2056

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Well production start year (Scenario 2)

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FIGURE No:
2.7

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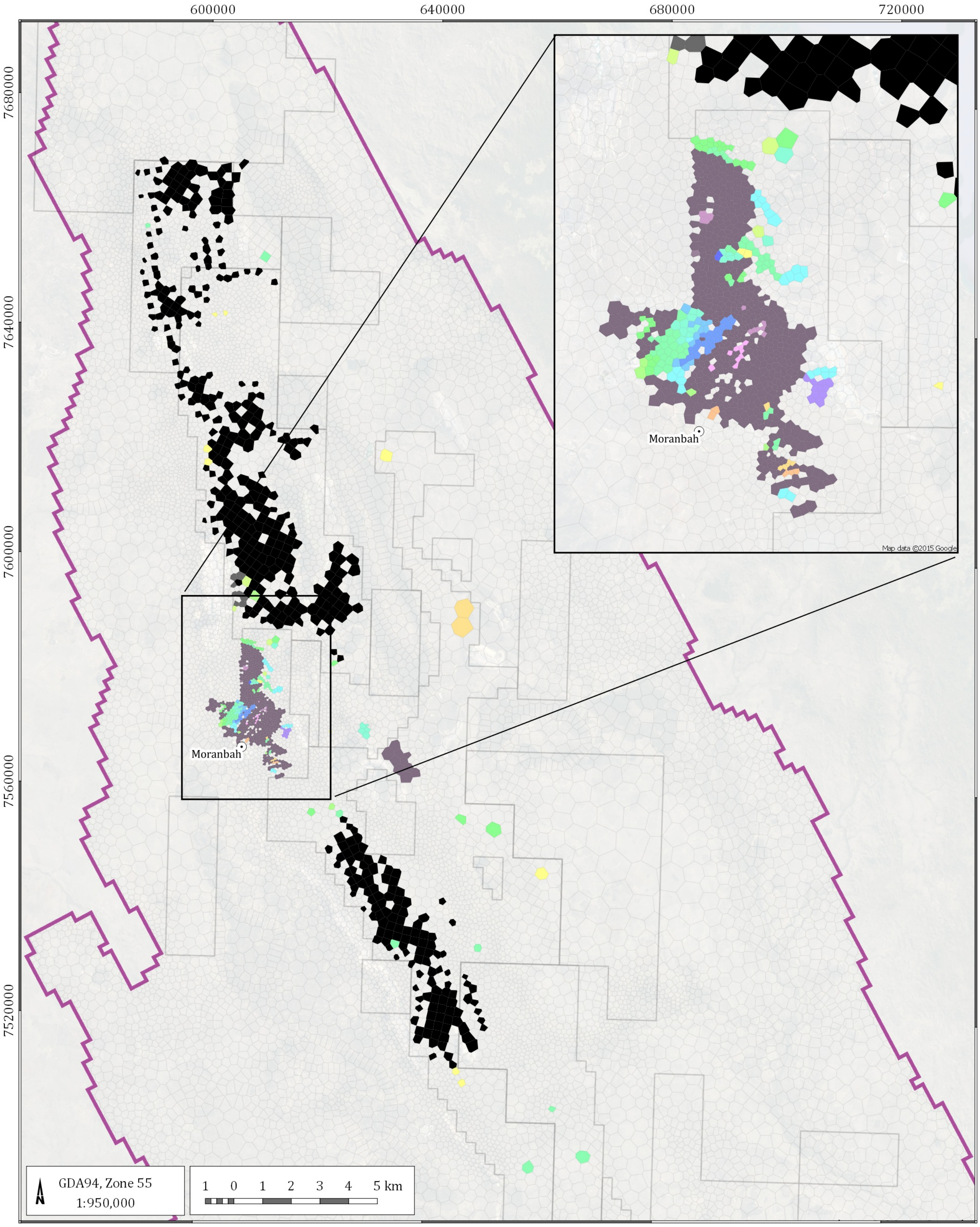

LEGEND

⊙ Populated place
⬜ 2018 AGE mesh
— 2018 AGE model outline

WEL start (year)

🟧 2008
🟨 2009
🟨 2011

🟩 2012
🟩 2013
🟩 2014
🟩 2015
🟩 2016
🟦 2017
🟦 2019
🟦 2020
🟦 2024

🟪 2026
🟪 2027
🟪 2028
🟪 2030
🟪 2031
⬛ 2040
⬛ 2050
⬛ 2060

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Well production end year (Scenario 2)

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FIGURE No:
2.8

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
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3 Calibration

The updated 2018 groundwater model was calibrated with a pre-development steady state run and a transient run (2000–2017) using available groundwater level records up to Nov, 2017 and documented production rates. The model aquifer parameters were adjusted using an inverse automated method whereby hydraulic conductivity and storage were adjusted using pilot point multiplying fields to match groundwater observation levels with time. This was achieved using automated calibration software - PEST_HP (S.S. Papadopulos & Associates, Watermark Numerical Computing, 2018).

3.1 Calibration targets

The steady state and transient model simulated water levels in all available monitoring bores within the hydrostratigraphic units. A total of 529 monitoring points were used to calibrate the model, comprising:

- 47 Arrow Energy transient monitoring locations (transient 2014 – 2017); and
- 482 government and landholder monitoring locations (steady state).

Figure 3-1 presents the observation bores that were used in the calibration.

Throughout the observation dataset the frequency of observations vary between bores, hence the number of available records for each bore varies. To overcome this, the observation data was weighted to normalise the error on a bore by bore basis. Weighting to each bore was applied by using the following equation:

$$weight\ per\ observation\ record = \frac{1}{\sqrt{n}}$$

where:

n = number of observation records at a monitoring location.

A number of bores are likely to be impacted by longwall, board and pillar and open cut mining in the region. Where possible, the weighting of these observations was reduced as to not significantly impact the integrity of the calibration and uncertainty analysis. Table 3-1 presents the weighting assigned to bores as well as the observed drawdowns and distance from surrounding mine and production wells.

Table 3-1 Observation bores and weighting assigned to each bore

	Bore	Total weight per group	Observed drawdowns (m)	Distance from production well cell @ 2018	Distance from active mining	Comment
1	AN019F	21	1 m	0.5km	5.1km	----
2	AN020F	17.6	0	0.5km	5.1km	----
3	GR067V	2.3	8 m	1.5km	11.9km	This bore shows unrealistic heads - lower weighting
4	M162GMV	2.5	9 m	0km	----	This bore shows unrealistic heads s- lower weighting
5	M225W	33.3	0	0km	----	----
6	M229W	15.3	0	0km	----	-----
7	M230W	34.6	0	0km	----	----
8	M231W	31.3	0	0km	----	----
9	M232W	15.4	0	0km	----	----
10	M234W	31.7	0	0km	----	----
11	M235W	15.4	0	0km	----	----
12	M236W	15.4	0	0km	----	----
13	M237W	15.4	0	0km	----	----
14	M313_BK_1p	33.5	0	0.2km	----	2km from planned Moranbah north workings
15	M313_GM_1p	167	60 m max, 19m (2017)	0.2km	----	2km from planned Moranbah north workings
16	M314_BK_1p	32.8	0	0.1km	2.9km	2km from planned Moranbah north workings
17	M314_QA_1p	100.3	0	0.1km	2.9km	2km from planned Moranbah north workings
18	M324_FL_1p	33.5	3 m	0.2km	----	----
19	M324_QA_1p	15	0	0.2km	----	----
20	M325_FL_1p	3.1	0	0.1km	2.9km	This bore shows local drawdown not due to Arrow - lower weighting
21	M345W	3.8	0	0.1km	----	----
22	Steady state bores	1.000	----	----	----	Weight of one was assigned to each bore.

3.2 Pilot point multipliers

A series of pilot point multipliers were used to help calibrate the model and to explore uncertainty for the predictive analysis. Figure 3-2 presents the pilot points applied to all layers in the model. Pilot points were interpolated across the model domain in each layer of the model using ordinary automatic kriging through PLPROC (Watermark Numerical Computing, 2015). The multipliers for all pilot points were allowed to vary ±2 orders of magnitude from the starting parameters. Horizontal and vertical conductivity were adjusted, and the absolute values were capped to ensure maximum and minimum values did not exceed literature ranges for their respective units. Specific storage values are constrained by literature ranges derived from regional studies of similar strata, using the relationship between bulk modulus, poisons ratio, and effective porosity to calculate a physically possible value. Table 3-2 presents the general parameter constraints applied to the multiplied model cells between layers 3 and 22. The relationship between horizontal and vertical hydraulic conductivity were dynamically checked to ensure expected ratios are honoured.

Table 3-2 General parameter constraints

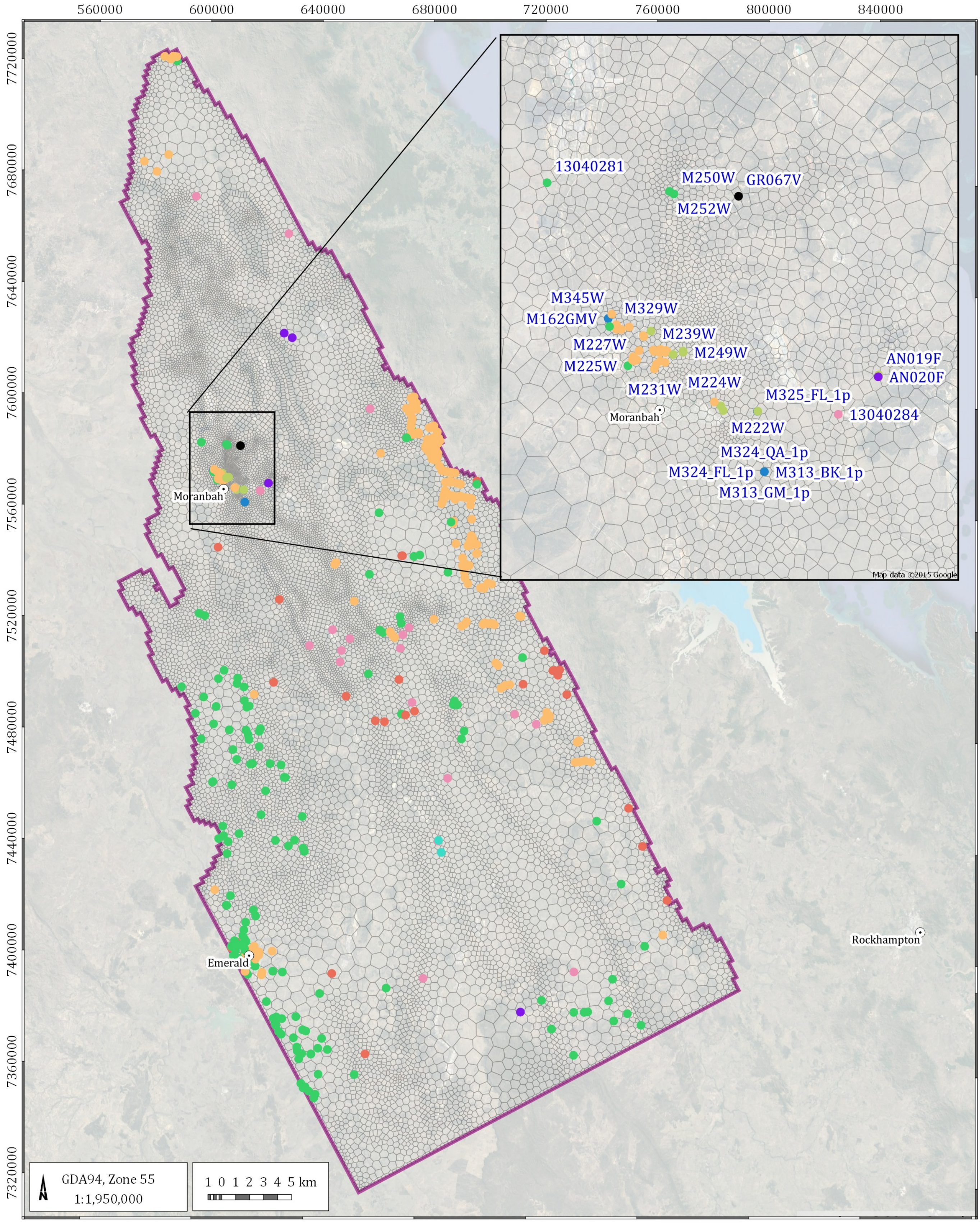
Unit	Min Kx (m/day)	Max Kx (m/day)	Min Kz (m/day)	Max Kz (m/day)	Min Sy (%)	Max sy (%)	Min_Ss (m^{-1})	Max_Ss (m^{-1})	Max Kx:Kz
Interburden	8.6E-06	1.0E-02	1.0E-08	5.0E-03	0.1	6	7.0E-07	1.0E-04	0.5
Coal	8.6E-06	1.0E-01	8.6E-06	1.0E-01	0.1	5	2.0E-06	1.0E-04	1
Sandstone	1.0E-05	1	1.0E-05	1	0.1	20	9.0E-07	1.0E-04	1

Specific yield and specific storage were dynamically checked to ensure calibrated ranges did not exceed physically impossible values, based upon the relationship between Young's modulus, porosity and specific storage. Most calibrated pilot points were within the middle of the range limits while only two pilot points approached the upper and lower ranges. The final values were checked to ensure that the Hydraulic conductivities are consistent with associated storage values. Table 3-3 summarises the hydraulic conductivity, specific storage and specific yield for each geology unit in the model domain. The calibrated results show that generally the storage values were situated in the middle of their expected ranges for the bulk modulus/porosity values assumed for these strata. Appendix C provides a comparison of Norwest 2016 model and current model developed in this work.

Table 3-3 Summary of groundwater hydraulic parameters

Zone	Hydrostratigraphic unit	Depth interval (m)	Hydraulic conductivity			Specific storage (m^{-1})	Specific yield (%)
			Horizontal (Kh) (m/day)	Vertical (Kv) (m/day)	Depth dependency		
3	Clematis sandstone	-----	0.17	0.014	No	3.5E-05	11
4	Overburden	0 - 100	6.15E-04	8.59E-08	No	8.5E-06	6
		100 - 250	8.05E-04	5.69E-08			
		250 - 500	8.94E-04	5.49E-08			
		500 - 1500	6.15E-04	8.59E-08			
5	Leichardt seam	0 - 100	8.96E-02	5.21E-02	Yes	7.2E-05	4.5
		100 - 250	5.01E-02	1.57E-02			
		250 - 500	5.98E-03	1.21E-03			
		500 - 1500	3.66E-05	1.23E-05			
6	Interburden	0 - 100	1.69E-04	3.73E-08	No	8.4E-5	3.7
		100 - 250	2.25E-04	2.95E-08			
		250 - 500	3.16E-04	3.96E-08			
		500 - 1500	2.11E-04	2.31E-08			
7	Vermont seam	0 - 100	8.06E-02	3.52E-02	Yes	5.3E-05	4.1
		100 - 250	4.73E-02	1.20E-02			

Zone	Hydrostratigraphic unit	Depth interval (m)	Hydraulic conductivity			Specific storage (m^{-1})	Specific yield (%)
			Horizontal (Kh) (m/day)	Vertical (Kv) (m/day)	Depth dependency		
		250 - 500	8.56E-03	1.53E-03			
		500 - 1500	2.02E-05	5.26E-06			
8	Interburden (FCCM)	0 - 100	1.36E-02	3.72E-04	No	5.1E-04	2.8
		100 - 250	9.78E-03	2.07E-04			
		250 - 500	8.66E-03	2.93E-04			
		500 - 1500	9.52E-03	1.64E-04			
9	Q seam	0 - 100	8.79E-02	4.31E-02	Yes	7.7E-05	3.5
		100 - 250	4.42E-02	1.49E-02			
		250 - 500	7.57E-03	2.70E-03			
		500 - 1500	1.36E-04	6.24E-05			
10	Interburden	0 - 100	2.65E-04	1.02E-07	No	1.1E-05	3.5
		100 - 250	1.83E-04	7.45E-08			
		250 - 500	1.77E-04	1.49E-07			
		500 - 1500	2.61E-04	8.43E-08			
11	P seam	0 - 100	8.23E-02	5.48E-02	Yes	7.8E-05	2.1
		100 - 250	5.93E-02	2.40E-02			
		250 - 500	1.20E-02	4.37E-03			
		500 - 1500	1.37E-04	5.66E-05			
12	Interburden	0 - 100	1.81E-04	2.06E-07	No	2.1E-05	3.5
		100 - 250	1.57E-04	3.48E-07			
		250 - 500	1.79E-04	7.27E-07			
		500 - 1500	2.10E-04	6.27E-07			
13	GM seam	0 - 100	6.25E-02	4.03E-02	Yes	7.2E-05	3.5
		100 - 250	3.10E-02	1.51E-02			
		250 - 500	5.39E-03	1.64E-03			
		500 - 1500	6.79E-05	2.42E-05			
14	Interburden	0 - 100	1.30E-04	1.41E-07	No	7.0E-6	3.1
		100 - 250	2.03E-04	2.32E-07			
		250 - 500	4.72E-04	1.46E-06			
		500 - 1500	1.96E-04	5.91E-07			
15	GML seam	0 - 100	1.00E-01	3.23E-02	Yes	5.6E-05	3.7
		100 - 250	4.80E-02	1.14E-02			
		250 - 500	4.39E-03	8.85E-04			
		500 - 1500	4.77E-05	1.01E-05			
16	Interburden	0 - 100	1.40E-04	9.87E-08	No	6.9E-06	5
		100 - 250	1.42E-04	9.97E-08			
		250 - 500	1.01E-04	7.13E-08			
		500 - 1500	1.50E-04	1.05E-07			
17	DYU seam	0 - 100	5.91E-02	2.04E-02	Yes	6.6E-05	3.8
		100 - 250	3.87E-02	1.00E-02			
		250 - 500	4.05E-03	6.68E-04			
		500 - 1500	3.70E-05	7.86E-06			
18	Interburden	0 - 100	4.86E-04	1.33E-06	No	9.9E-06	3.9
		100 - 250	4.69E-04	7.28E-07			
		250 - 500	3.26E-04	2.31E-07			
		500 - 1500	3.14E-04	1.90E-07			
19	DYR seam	0 - 100	7.42E-02	2.31E-02	Yes	5.4E-05	3.9
		100 - 250	4.56E-02	1.47E-02			
		250 - 500	4.53E-03	1.49E-03			
		500 - 1500	5.49E-05	1.13E-05			
20	Underburden	0 - 100	2.50E-04	2.10E-05	No	5.2E-5	4.5
		100 - 250	3.36E-04	3.45E-05			
		250 - 500	2.99E-04	3.78E-05			
		500 - 1500	4.21E-04	3.16E-05			



LEGEND

⊙ Populated place

▭ 2018 AGE mesh

— 2018 AGE model outline

★ Pilot point multiplier

Observation bore model layer

● lay1 - Alluvium

● lay2 - Tertiary

● lay4 - Interburden

● lay5 - Leichardt seam

● lay9 - Fort Cooper Coal Measures

● lay10 - Fort Cooper Coal Measures

● lay15 - GM seam

● lay17 - GML seam

● lay 18 - Interburden

● lay 22 - Permian basement

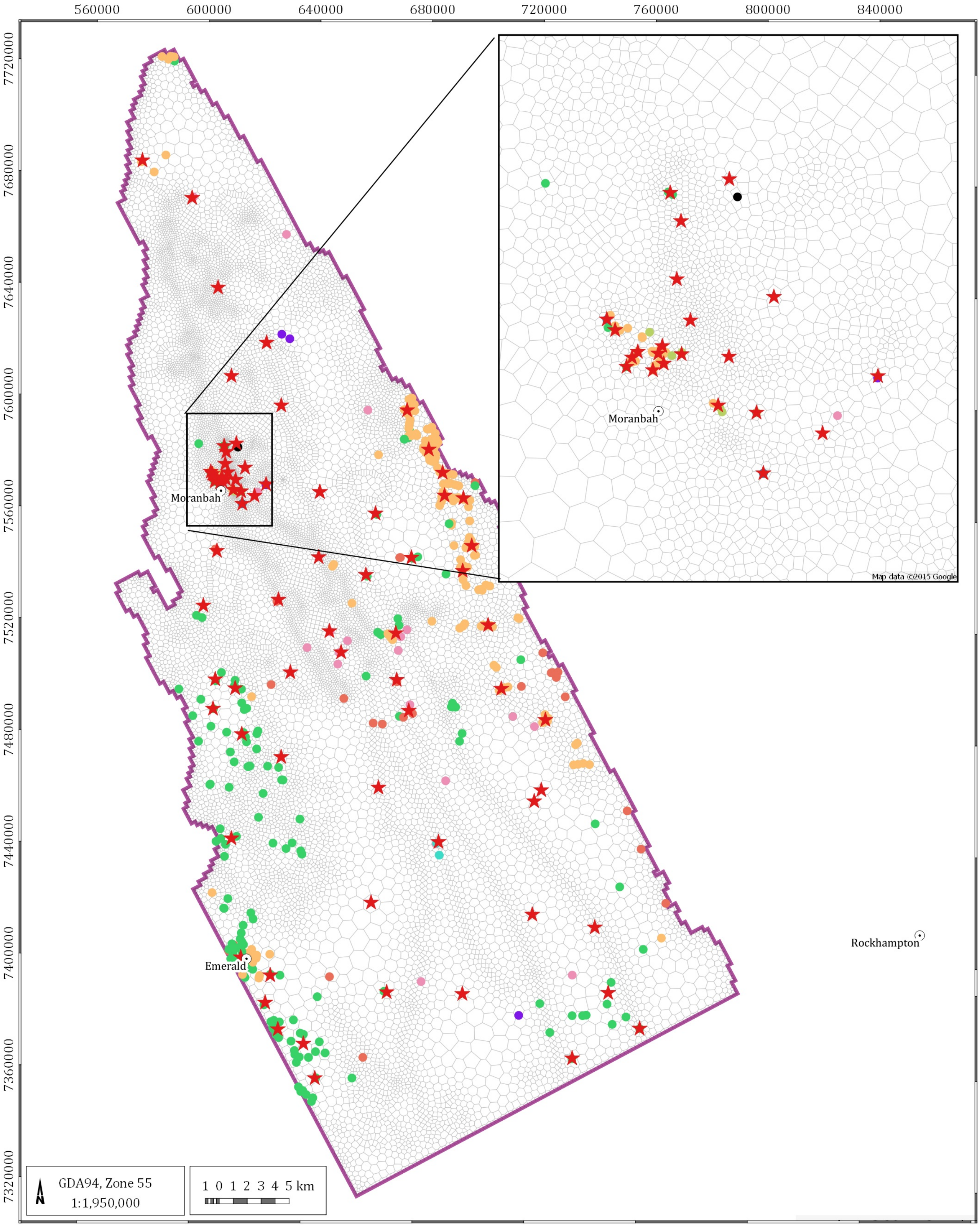
Bowen (G1885B)

Observation targets

DATE 23/04/2018

FIGURE No: 3.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/Fig_3-1_Observations.qgs



LEGEND

- ⊙ Populated place
- ☐ 2018 AGE mesh
- ▬ 2018 AGE model outline
- ★ Pilot point multiplier

Observation bore model layer

- ● Lay1 - Alluvium
- ● Lay2 - Tertiary
- ● lay4- Interburden
- ● lay5 - Leichardt seam
- ● lay9 - Fort Cooper Coal Measures
- ● lay10 - Fort Cooper Coal Measures
- ● lay15 - GM seam
- ● lay17 - GML seam
- ● lay18 - Interburden
- ● lay22 - Permian basement

Bowen (G1885B)

Pilot point multipliers

DATE
14/06/2018

FIGURE No:
3.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/Fig_3-2_Pilot_points.qgs

3.3 Water budget

Table 3-4 shows the water budget for the steady state (pre-mining) model. The mass balance error, that is, the difference between calculated model inflows and outflows at the completion of the steady state calibration was 0%. The maximum percent discrepancy at any time step in the simulation was also 0%. This value indicates that the model is stable and achieves an accurate numerical solution. Comparing budgets also indicate that the revised steady-state budget was comparable to that from the original Ausenco Norwest model.

Table 3-4 Model budgets – steady state

Parameter	In (m3/day)	Out (m3/day)	In - Out (m3/day)
Rainfall recharge	313,100	-	313,100
River	0	32,208	-32,208
Evapotranspiration	-	274,930	-274,930
General head boundary	1,171	7,133	-5,962
Total	**314,271**	**314,271**	**0**

3.4 Calibration results

Figure 3-3 presents the observed and corresponding simulated groundwater levels graphically as a scattergram for the historic transient calibration. The water levels used for calibration are shown as the blue points in Figure 3-3. The red points are the transient monitoring datasets proximal to the MGP. Three bores M162GMV, GR067 and M325 were not included in the calibration statistics since these bores appear to show local drawdown due to sampling, and/or erroneous measurements.

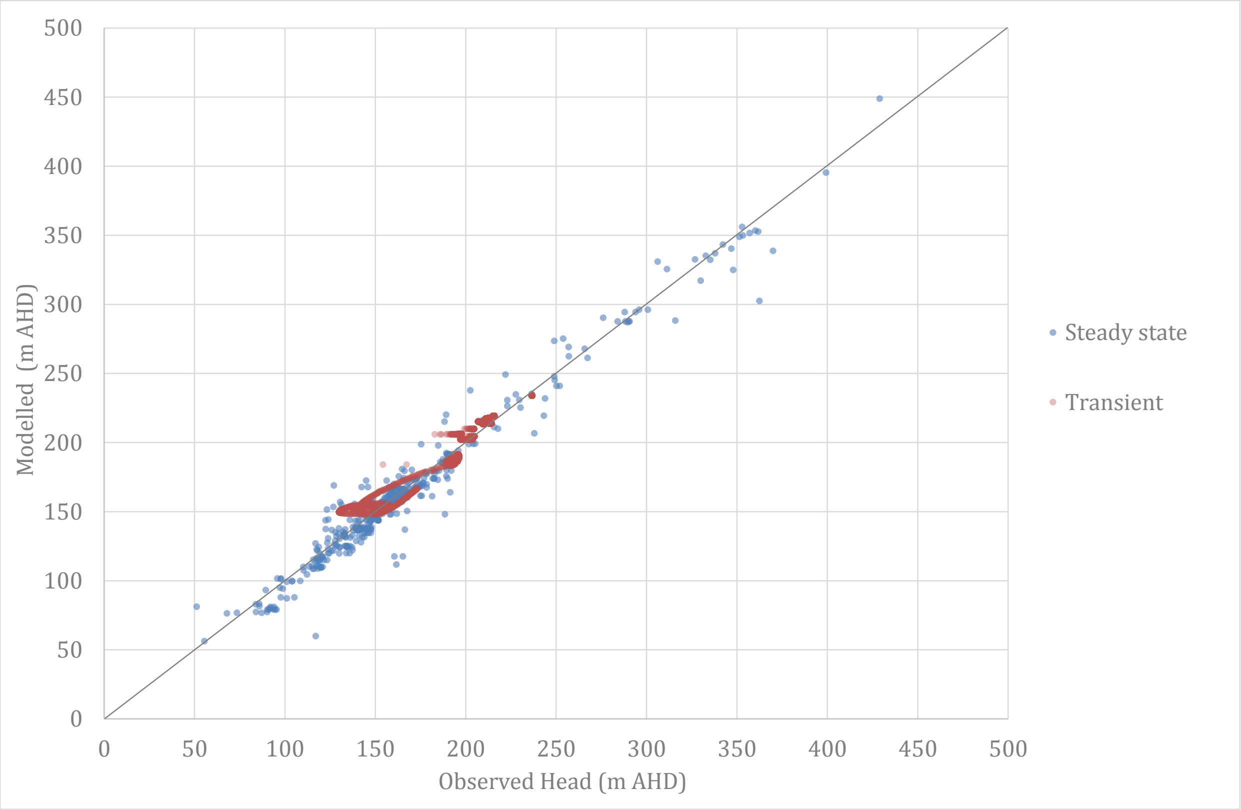


Figure 3-3 Model residuals (measured vs. simulated)

The root mean square (RMS) error calculated for the calibrated model was 5.8 m. The total measured head change across the model domain was 377.7 m, with a standardised unweighted RMS (SRMS) of 1.54%, indicating a good match for the type of system being modelled. Table 3-5 presents the unweighted statistics for the transient calibration model.

Table 3-5 Statistical analysis

Calibration performance measure	Unweighted value
Sum of Residuals (SR) (m)	-47011
Mean Sum of Residuals (MSR) (m)	-3.42
Scaled Mean Sum of Residuals (SMSR) (%)	-0.91
Sum of Squares (SSQ) (m2)	-464201
Mean Sum of Squares (MSSQ) (m2)	-33.8
Root Mean Square (RMS) (m)	-5.81
Root Mean Fraction Square (RMFS) (%)	0.1
Scaled RMFS (SRMFS) (%)	-0.06
Scaled RMS (SRMS) (%)	-1.54

Figure 3-4 shows the modelled and observed water levels at bores M313 and M324. It shows that the model simulated the overall decline, particularly at bore M324. Appendix A presents the historic calibration hydrographs, showing the fit between modelled and observed groundwater levels from 2014 to 2017.

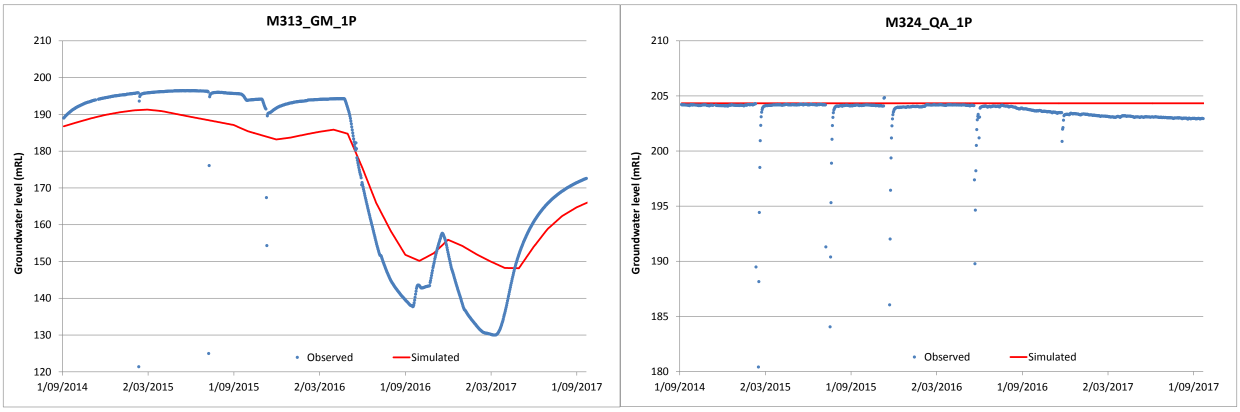


Figure 3-4 Groundwater hydrographs at bores M313GM and M324QA

Figure 3-5 presents the relationship between WEL pumping inputs and outputs. The WEL package applies an ‘Auto flow reduce’ option, which ensures flux reduces when the head encroaches on the bottom on the well layer. The fact that the inputs and outputs perfectly match in Figure 3-5 means the model has been able to extract all of the requested input WEL flux.

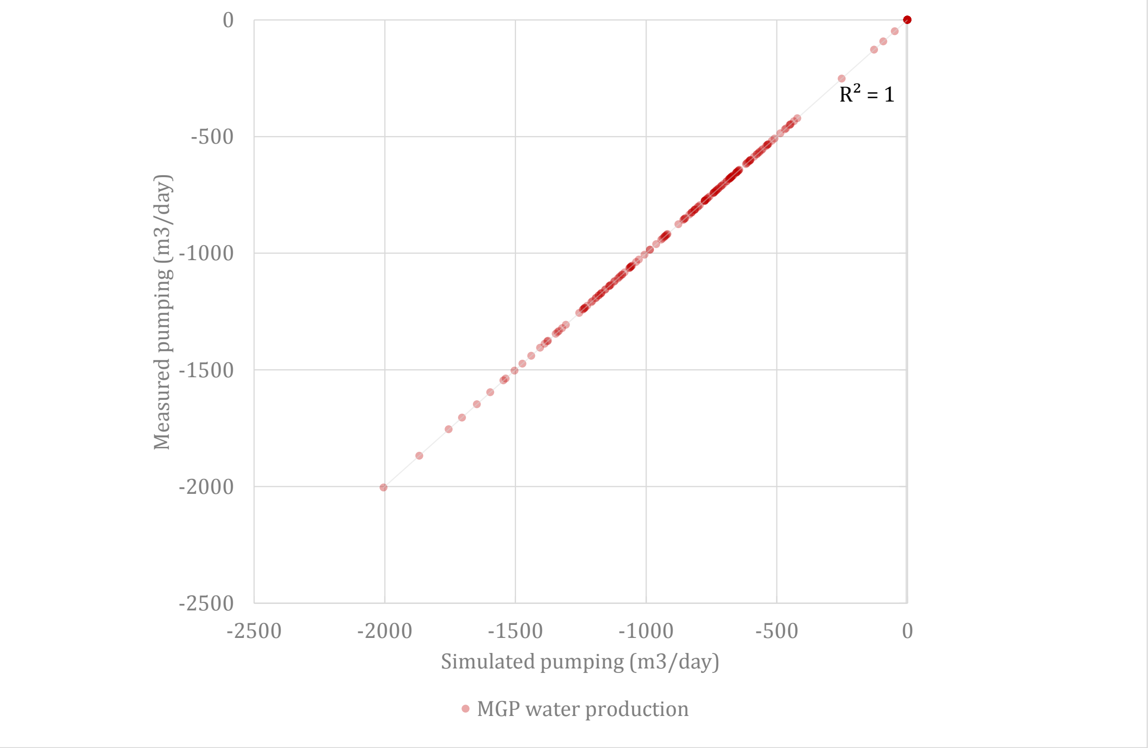


Figure 3-5 **Measured vs. simulated WEL pumping rates**

A comparison of the calibrated hydraulic conductivity arrays, and the variability explored in the calibration is presented in Section 5.4

4 Predictions

In this section, the cumulative and incremental drawdowns are presented for four scenarios mentioned in Table 2-2, viz:

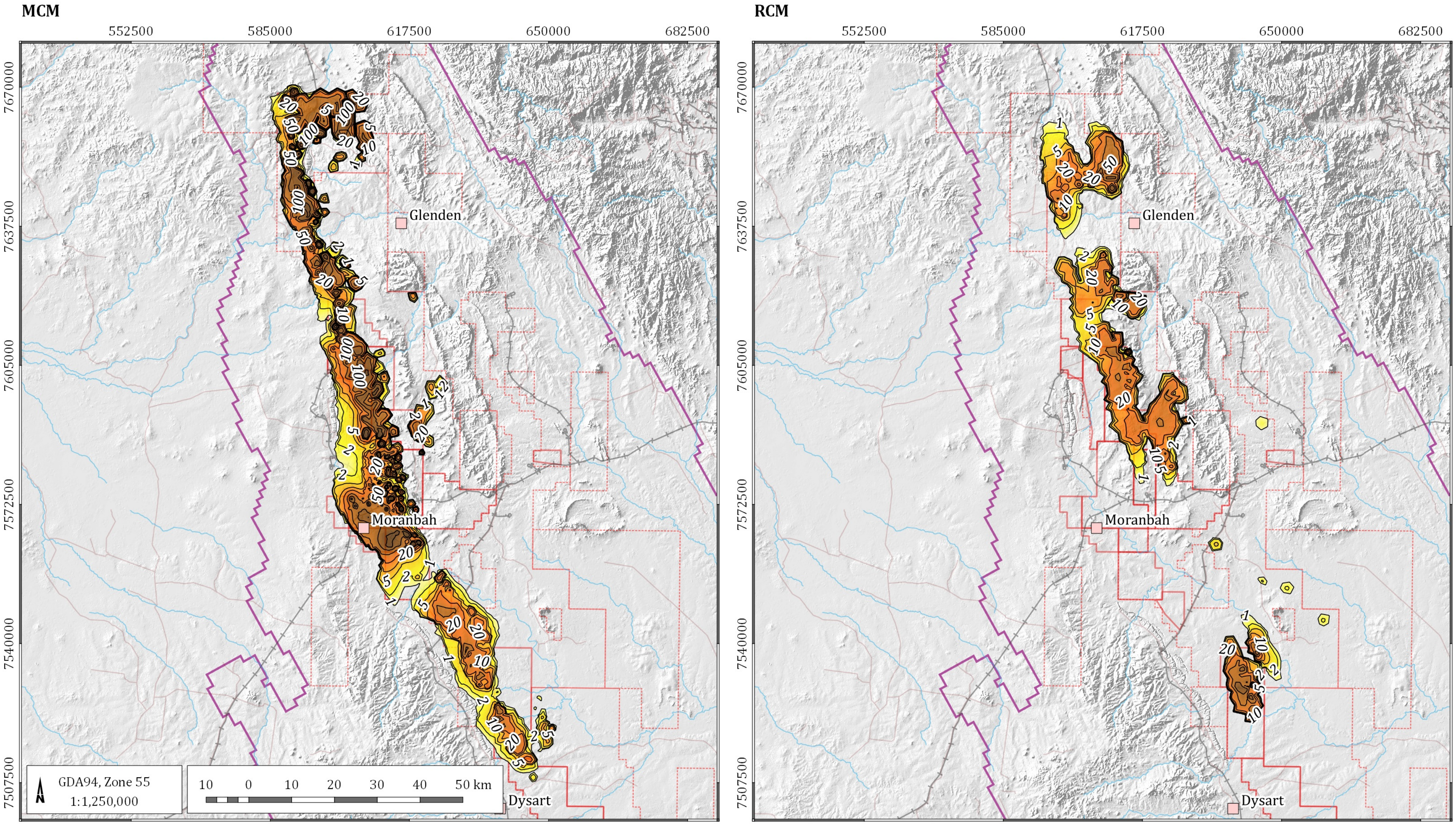
- Scenario UWIR – CSG production as per 2016 UWIR;
- Scenario 0 - Historical MGP productions (2003- Dec 2017);
- Scenario 1 - Historical MGP productions + Future MGP; and
- Scenario 2 - Historical MGP + Future MGP + PLa486 + Mavis Downs +BGP.

For each scenario, cumulative drawdowns are calculated by subtracting the heads from the 'no CSG production' (NC scenario) from the heads at the respective scenarios. The incremental drawdowns are calculated by subtracting the cumulative drawdowns from the Scenario 0 (historical production) drawdowns, i.e. represent additional drawdown post 2018. All drawdowns represent maximum drawdowns, whereby the drawdowns are queried across the entire simulation period and the maximum drawdown is recorded for each model cell, hence the drawdowns represent a composite result from the entire simulation. Scenario UWIR is included as a comparative measure to help delineate how changes to the model setup and recalibration of the model has changed the drawdown extents when compared to the 2016 UWIR results.

To represent maximum coal measure drawdown for the Moranbah (MCM) and Rangal Coal Measures (RCM), drawdowns from each coal seam within the associated coal measure were combined and presented as a spatial composite of the maximum drawdown.. It should be mentioned that the drawdown extent would be less if the drawdowns are calculated seam by seam. Hence, the impact on bores screened in a specific seam is less than the one derived from a composite of drawdown in RCM and MCM formations. With respect to landholder bores, further information on the bore intervals is required to comprehensively assess if the bore can be impacted by CSG production.

Figure 4-2 to Figure 4-5 present the groundwater drawdown resulting from CSG production in the model domain with respect to the three scenarios. The Long term Affect Area (LAA), defined by groundwater drawdown greater than 5 m, is shown, along with drawdown contours up to 0.1 m for reference.

Figure 4-6 presents the year when maximum drawdown from cumulative pumping is predicted to occur.



LEGEND

- 🟥 Populated place
- ⬚ Petroleum exploration lease
- Model boudary
- Major drainage
- Road
- Rail

Drawdown (m)

Drawdown contour (m)

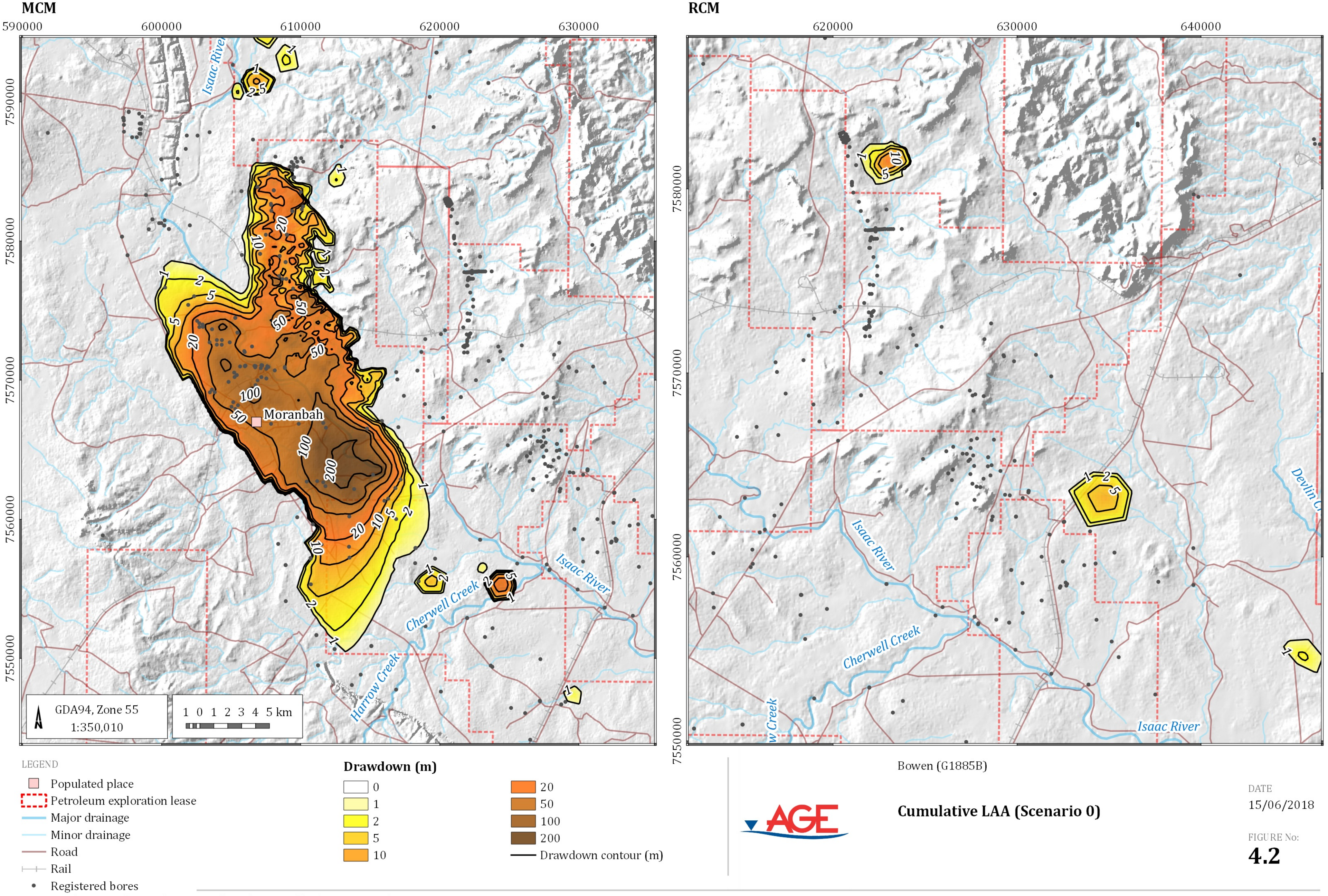
Bowen (G1885B)

Cumulative LAA (UWIR 2016)

DATE
15/06/2018

FIGURE No:
4.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.01_G1885B_Incremental LAA (UWIR).qgs



Bowen (G1885B)

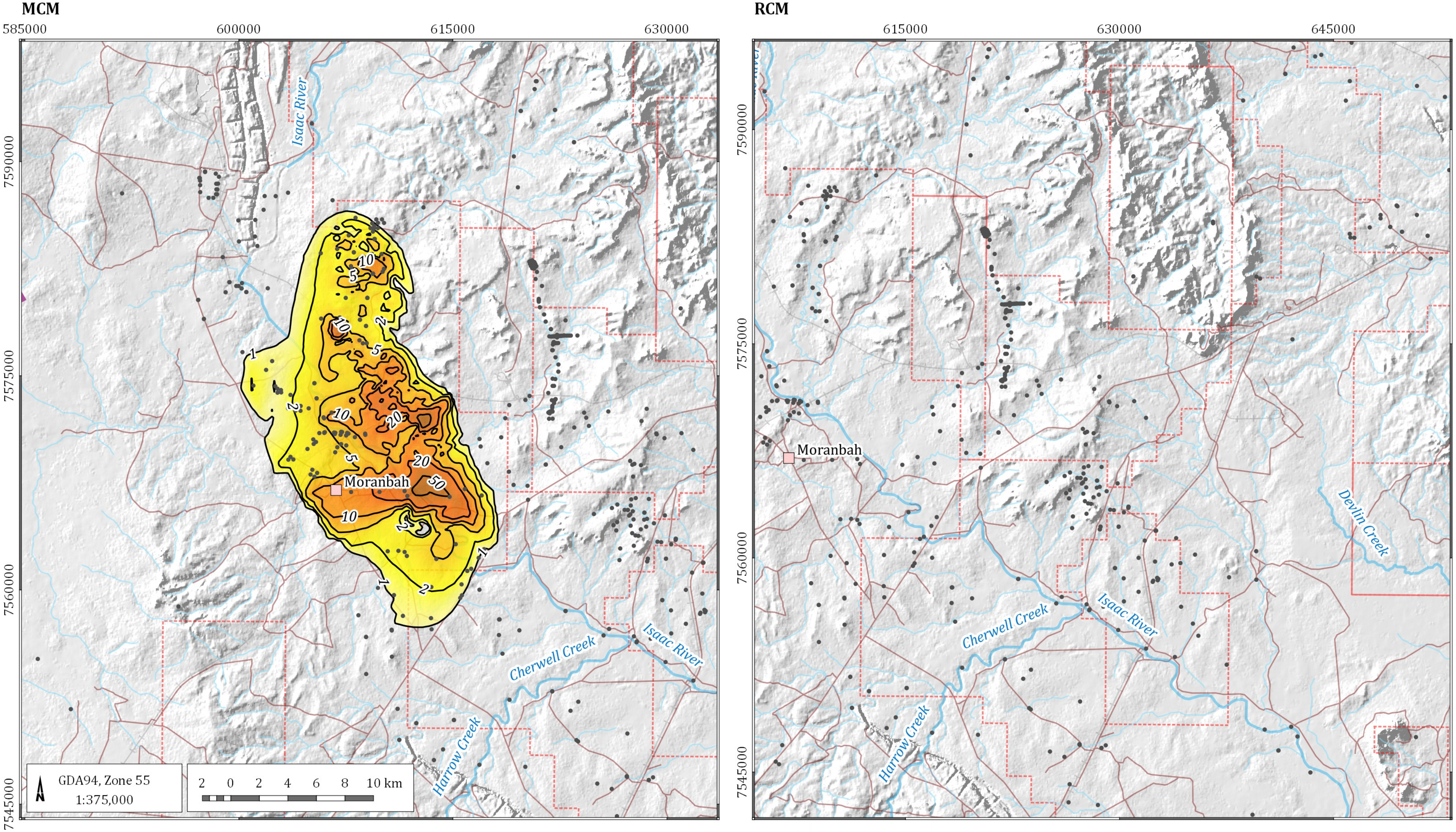
AGE

Cumulative LAA (Scenario 0)

DATE
15/06/2018

FIGURE No:
4.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.02_G1885B_Cumulative LAA (Scenario 0).qgs



LEGEND

- 🟥 Populated place
- ⬚ Petroleum exploration lease
- — Major drainage
- — Minor drainage
- — Road
- ┼ Rail
- ● Registered bores

Drawdown (m)

☐ 0	▨ 10
▨ 1	▨ 20
▨ 2	▨ 50
▨ 5	— Drawdown contour (m)

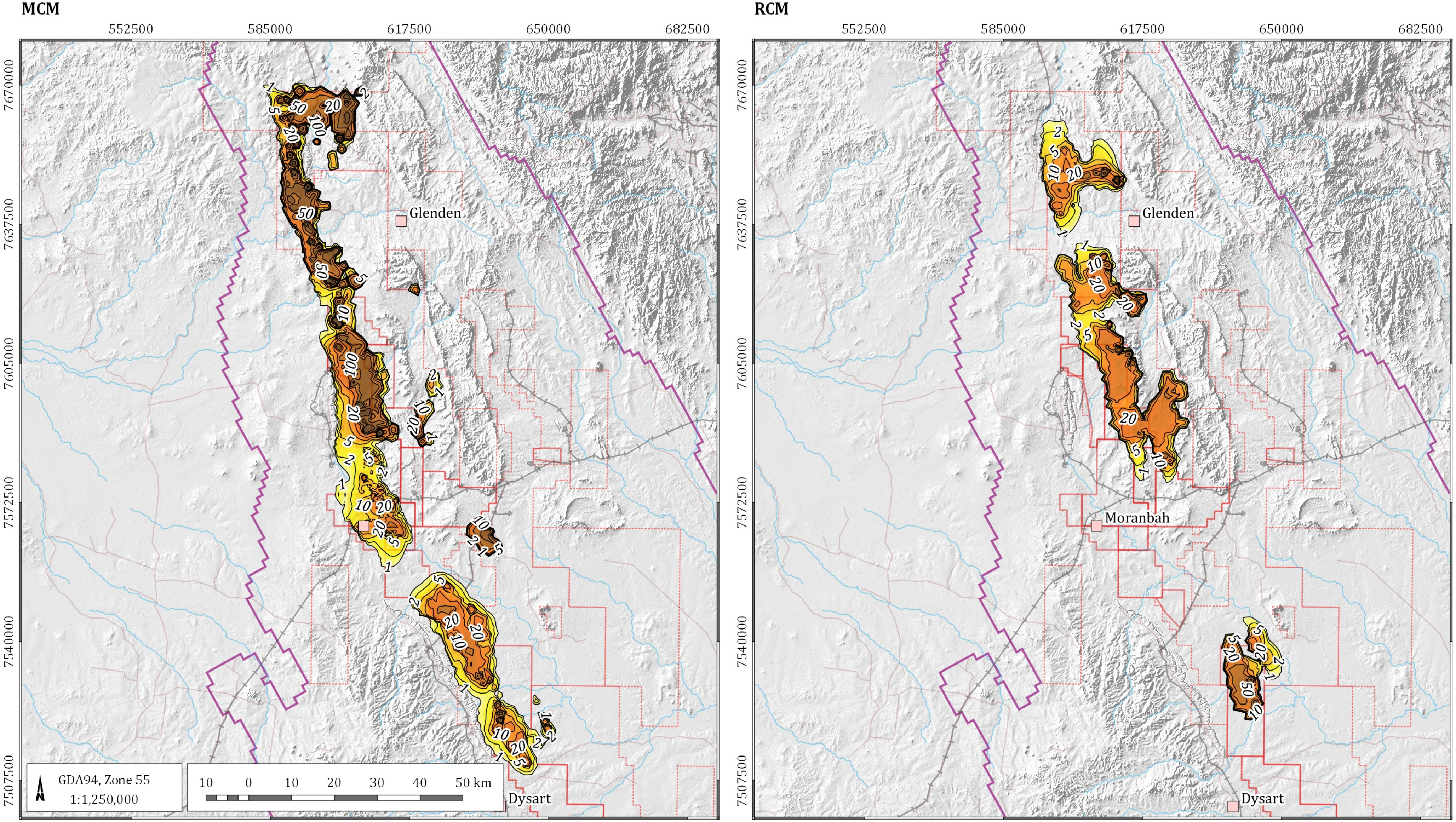
Bowen (G1885B)

Incremental LAA (Scenario 1)

DATE
15/06/2018

FIGURE No:
4.3

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.03_G1885B_ Incremental LAA (Scenario 1).qgs



LEGEND

- ▨ Populated place
- ⬚ Petroleum exploration lease
- — Model boudary
- — Major drainage
- — Road
- ┼ Rail

Drawdown (m)

▨	0	▨	20
▨	1	▨	50
▨	2	▨	100
▨	5	▨	200
▨	10	—	Drawdown contour (m)

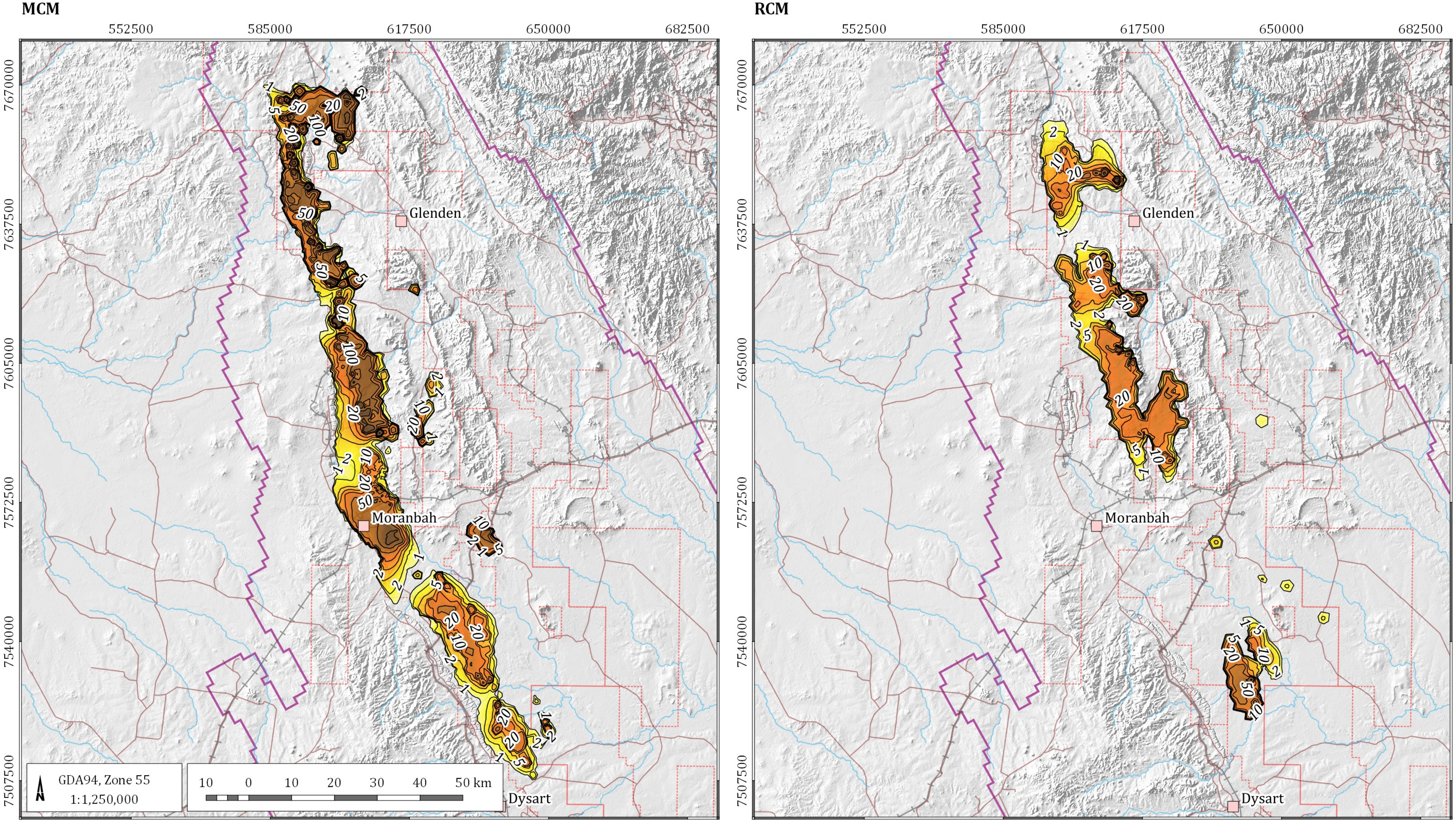
Bowen (G1885B)

Incremental LAA (Scenario 2)

DATE
11/06/2018

FIGURE No:
4.4

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.04_G1885B_Incremental LAA (Scenario 2).qgs



LEGEND

- ■ Populated place
- ⬚ Petroleum exploration lease
- — Model boundary
- — Major drainage
- — Road
- ┼ Rail

Drawdown (m)

- □ 0
- ■ 1
- ■ 2
- ■ 5
- ■ 10
- ■ 20
- ■ 50
- ■ 100
- ■ 200
- ■ 500
- — Drawdown contour (m)

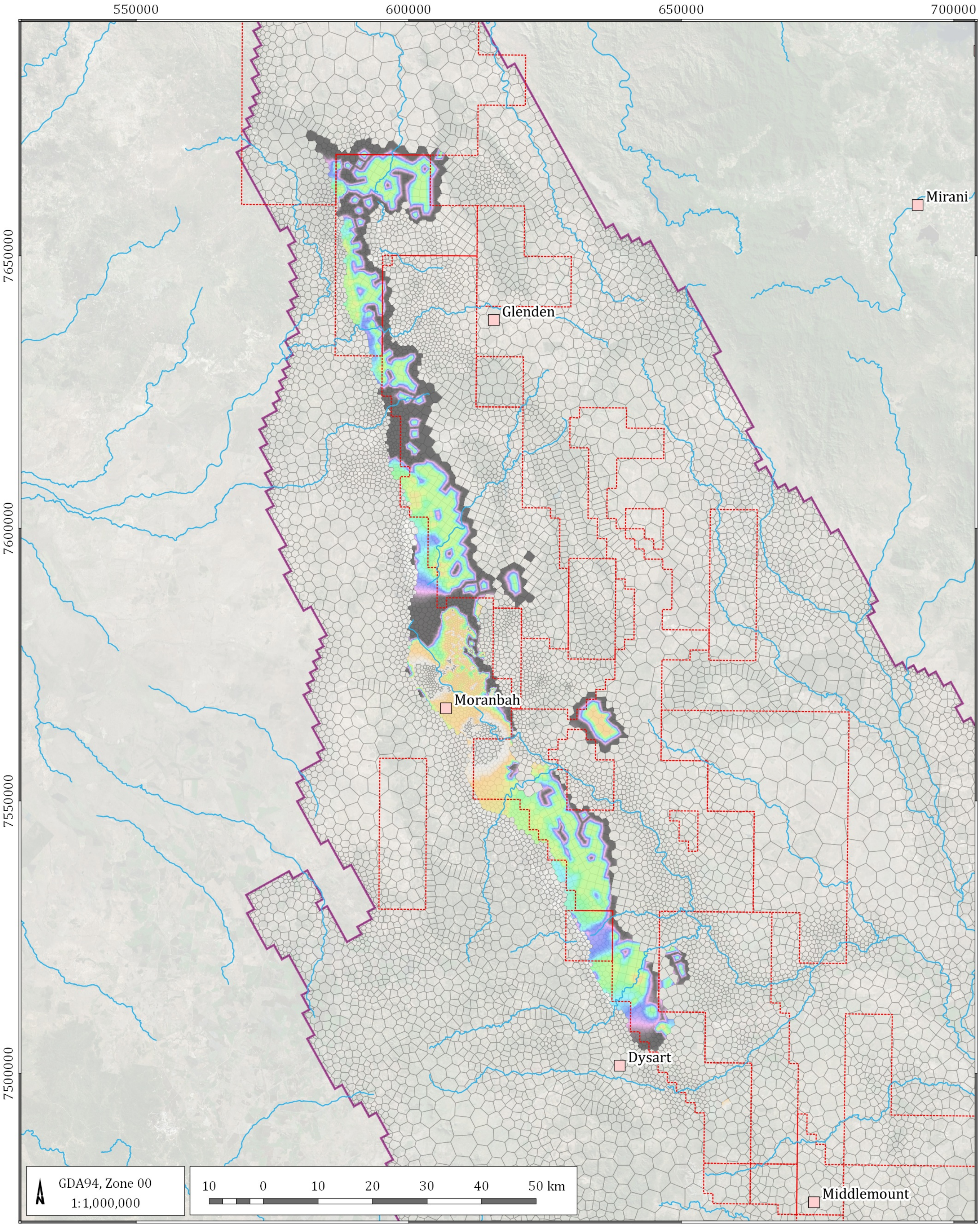
Bowen (G1885B)

Cumulative LAA (Scenario 2)

DATE
11/06/2018

FIGURE No:
4.5

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.05_G1885B_Cumulative LAA (Scenario 2).qgs



LEGEND

- 🟥 Populated place
- ▭ Petroleum exploration lease
- ▭ Model mesh
- — Model boundary
- — Major drainage
- — drawdown_L15_timing_ct

Year

- ⬜ 2018
- 🟧 2028
- 🟨 2053
- 🟩 2078
- 🟦 2098
- 🟦 2118
- 🟪 2143
- ⬛ 2163
- ⬛ 2183

Bowen (G1885B)

Time to maximum drawdown - GM seam (Layer 15 - Scenario 2)

AGE

DATE
15/06/2018

FIGURE No:
4.6

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.06_G1885B_Time to maximum drawdown.qgs

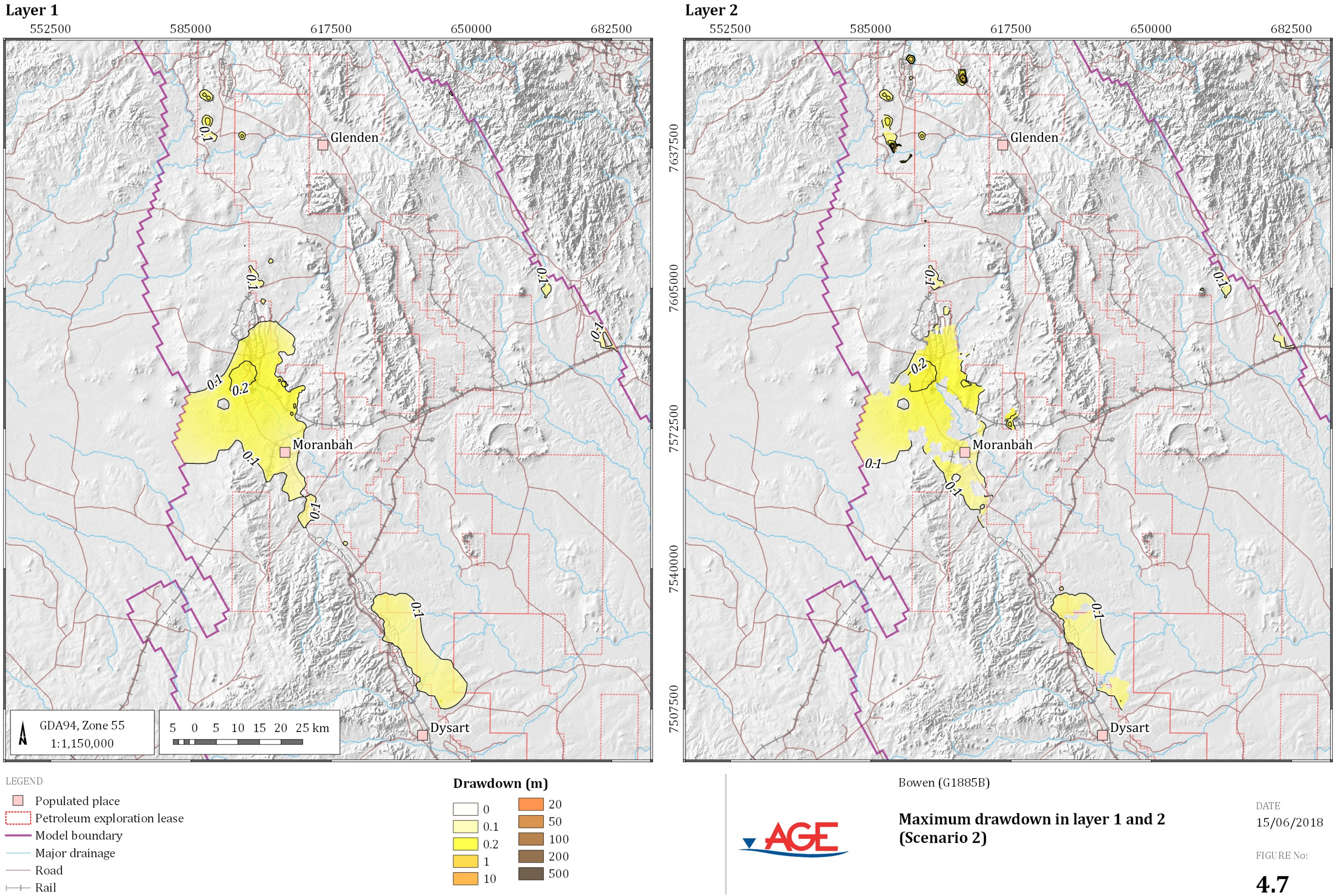
Figure 4-2 show differences to the drawdown extents that were previously presented in the 2016 UWIR (Arrow Energy, 2016). Using the same pumping schedule as the 2016 UWIR, the drawdowns have changed extent in certain areas due to the re-calibration of the model. Other visual differences compared to the 2016 UWIR predictions relate to the layer structure of the MODFLOW-USG model. Previously, SURFACT results were presented from layers that extend across the entire model domain. Model layers in MODFLOW SURFACT model need to exist across the whole model domain. Hence, the predicted drawdowns were wrongly presented for coal measures where the unit subcrops and does not exist. The revised model does not show these artefacts, as the model cells do not exist where the unit sub-crops. Additional to this discrepancy, the revised results are corrected from both available saturated drawdown within a model layer close to the subcrop. In spite of this, drawdowns greater than 5m in the MCM are generally within ±2km of the 2016 UWIR.

Figure 4-2 presents the maximum drawdown encountered since CSG production began to 2018. Drawdown is restricted to the MGP production area, extending as far as 7.2 km to the south within the MCM. Pilot-hole pumping produces minor drawdown across the model domain.

Figure 4-3 presents the additional drawdown caused by MGP CSG production from 2019 to the end of the model simulation. Results show additional drawdown is generally lower than drawdown induced at the end of 2018, and impacts do not significantly spread laterally post 2019. No significant drawdown propagates into the RCM from MGP production.

Figure 4-4 and Figure 4-5 present the additional and total drawdown caused by both the MGP and BGP. The results show that drawdown greater than 5m extends a maximum of 7.2 km from production within the MCM, which is comparable to drawdowns simulated using the approved UWIR pumping rates (Scenario UWIR). Generally, drawdowns have contracted from the 2016 UWIR predictions. This is primarily the result of a more refined and targeted CSG production field.

Figure 4-5 presents the groundwater drawdown in layers 1 and 2, which represent the alluvium and regolith. It shows that the drawdowns in layer 1 are very limited and lower than 0.1m. With respect to layer 2, there is an isolated patch of saturated drawdown in the surficial systems, east of the MGP of up to 10m. Given the extent of patch work nature of the drawdown, the impacts are considered a local model artefact mainly due to layering and lack of lateral connections to discontinuous sections of layer 2.



Bowen (G1885B)

AGE

Maximum drawdown in layer 1 and 2 (Scenario 2)

DATE
15/06/2018

FIGURE No:
4.7

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/04.07_max_dds_lay_1_2.qgs

5 Uncertainty analysis

5.1 Methodology

A Null-space Monte Carlo uncertainty analysis was undertaken to quantify the magnitude of uncertainty in the future impacts predicted by the model. This uncertainty analysis was essentially a three-part process. Firstly, the valid range for the parameters was determined and then -350 model realisations were created, each having differing values of the non-unique pilot point parameters. realisations were constrained using calibration datasets. The constrained realisations were tested and the models that failed to converge or could not achieve adequate calibration were rejected, leaving only the output from 208 successful models. This output was analysed to provide a statistical distribution of the predictions the regional model was designed to make.

5.2 Parameter generation

As mentioned in Section 5.1, it is necessary to firstly quantify the parameter variability. This requires specifying a distribution and range for each parameter, which is referred to as the "prior uncertainty range". Table 5-1 and Table 5-2 shows the 'prior' range explored for the Project. Each parameter is assumed to be log-normally distributed around the optimum value derived from calibration (basecase), and spreads gradually over the upper and lower bounds. The prior uncertainty range was constrained using information from the calibration matrix. This is achieved using Predunc7, a utility from the PEST software suite (Doherty, 2010). The derived uncertainty range is known as "posterior uncertainty range". Appendix B presents the prior and posterior parameter distributions and ranges for pilot points within the Arrow area and recharge.

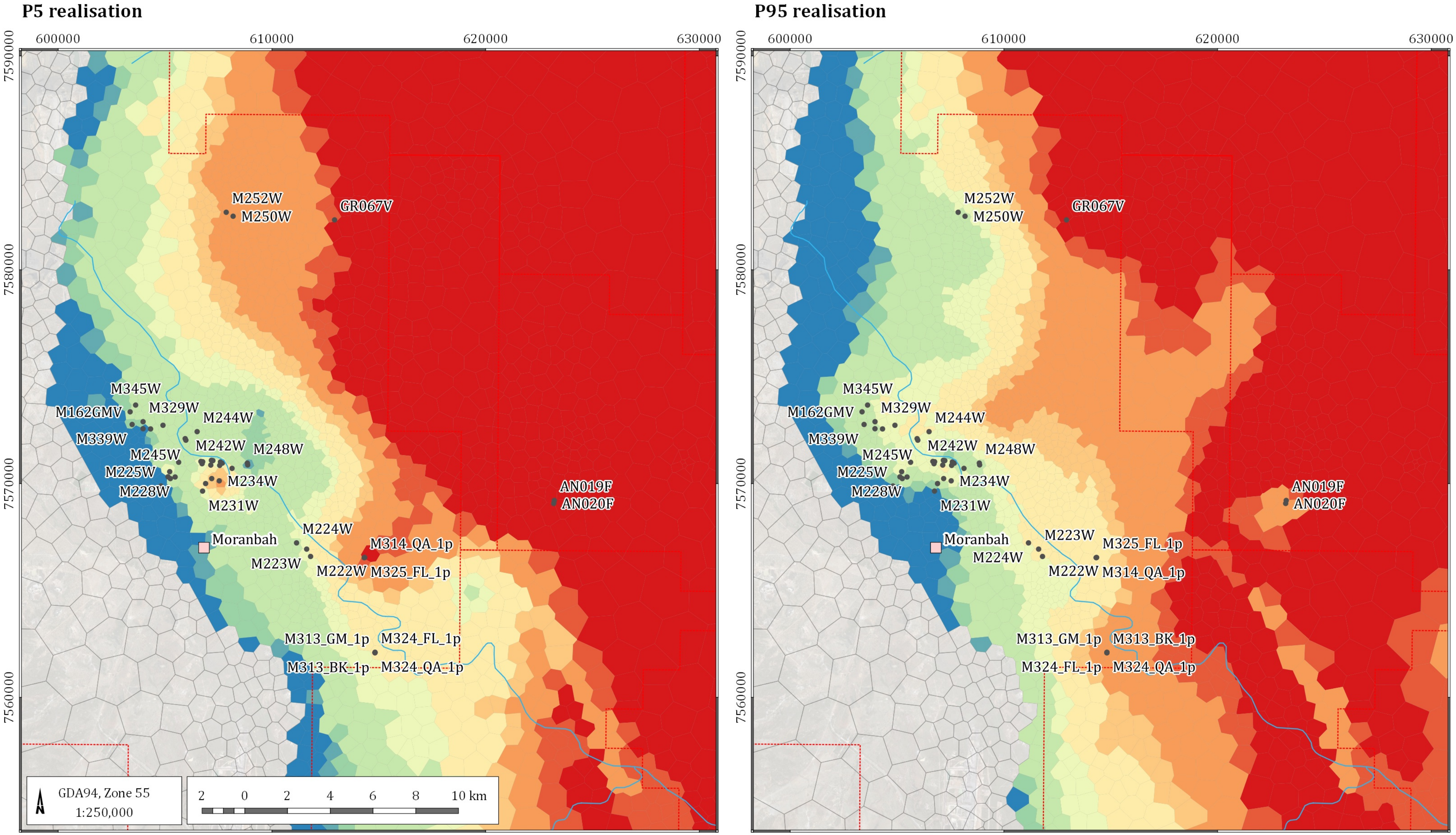
Table 5-1 Uncertainty range for pilot point multiplier

Parameter			
	Lower	Basecase	Upper
Pilot point multiplier	0.001	1-100	100

Table 5-2 Uncertainty range for recharge multiplier

Num	Lithology	Recharge rate(mm/year)		
		Lower	Basecase	Upper
1	River alluvium	0.1	23.4	100
2	Flood plain alluvium	0.1	3.6	100
3	Other sediments and alluvium	0.1	4.4	100
4	Tertiary Basalt	0.01	0.27	10
5	Triassic Emerald and Moolayember	0.01	2.19	3
6	Triassic Rewan	0.01	0.1	1

Figure 5-1 presents a comparative oblique view of the two realisations producing drawdown of 98 m and 1 m at bore 313 GM.



LEGEND

- 🟥 Populated place
- ⬚ Petroleum exploration lease
- — Model boundary
- — Major drainage
- — Road
- —+— Rail

HK (m/day)

- 🟥 0.0000001 - 0.00005
- 🟥 0.00005 - 0.0001
- 🟧 0.0001 - 0.0005
- 🟧 0.0005 - 0.001
- 🟨 0.001 - 0.005
- 🟨 0.005 - 0.01
- 🟩 0.01 - 0.05
- 🟩 0.05 - 0.07
- 🟦 0.07 - 0.09
- 🟦 0.09 - 0.1

Bowen (G1885B)

AGE

Horizontal hydraulic conductivity distribution for realisations producing P5/P95 drawdown at bore M313-GM

DATE
15/06/2018

FIGURE No:
5.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/05.01_G1885B_ Horizontal hydraulic conductivity distribution comparison-for two realisations producing drawdown of 2m (Right) and 165m (Left) in year 2018 at bore M313-GM.qgs

5.3 Calibration uncertainty

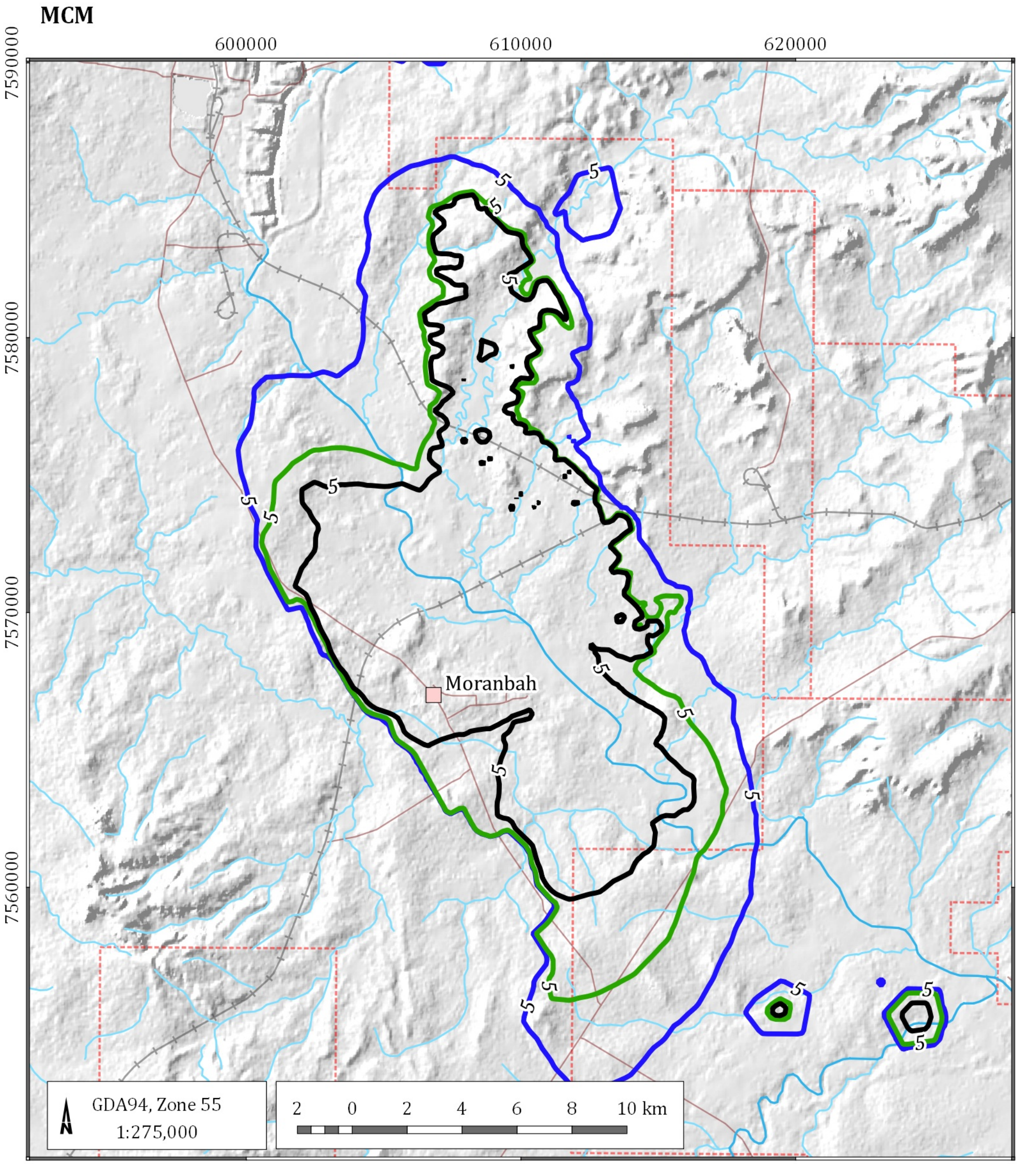
The posterior distribution of parameters was constrained using a Jacobian matrix generated around the optimal set of model parameters. The performance of the suite of models were analysed to ensure no realisations were used to assess predictive impacts did not replicate reality. Using the weightings presented in Section 3.1, an objective function threshold of +100% from the optimal case was applied. Appendix D presents the calibration hydrographs for the 208 model realisations that were below the objection function threshold. The results show sufficient spread of groundwater levels and drawdown responses to pumping. This is particularly evident at bore M313, which was highly informative to the formulation of the posterior distribution due to the higher weighting applied during the calibration process.

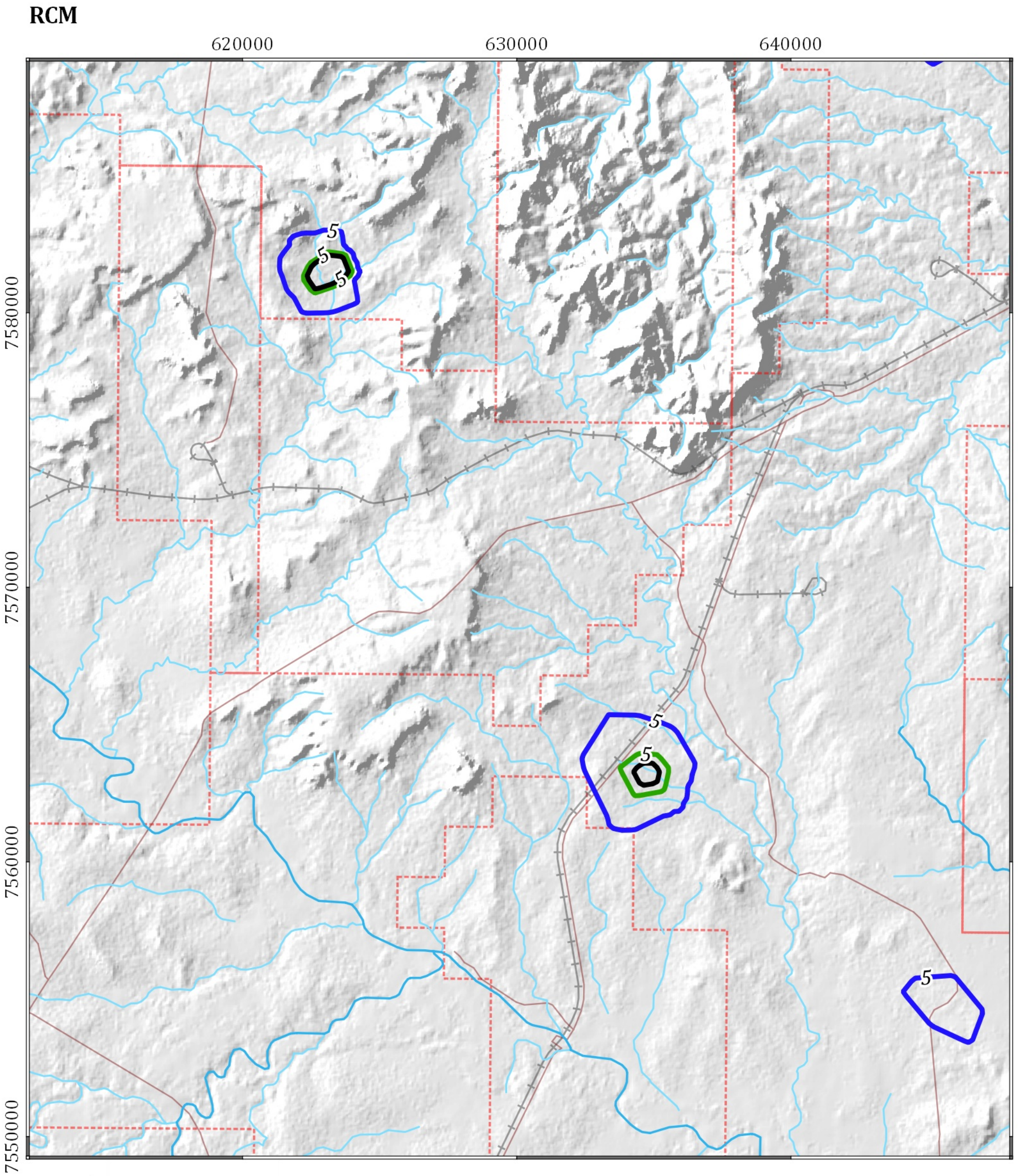
5.4 Results

5.4.1 Spatial drawdown

Figure 5-2 to Figure 5-5 present the uncertainty in regional groundwater impacts, showing the probability of the 5m drawdown contour for the 3 scenarios. The drawdown contours represent a composite drawdown array from all realisations assessed in the uncertainty analysis, expressed as the 5th, 50th and 95th percentile.

The results show expected non-linear behaviour of the system at the extremities of the datasets. 95th percentile contours are extensive, due to realisations with particularly higher permeability and lower storage.





LEGEND

- Populated place
- Petroleum exploration lease
- Major drainage
- Minor drainage
- Road
- Rail
- P05 drawdown contour (5 m)
- P50 drawdown contour (5 m)
- P95 drawdown contour (5 m)

Bowen (G1885B)

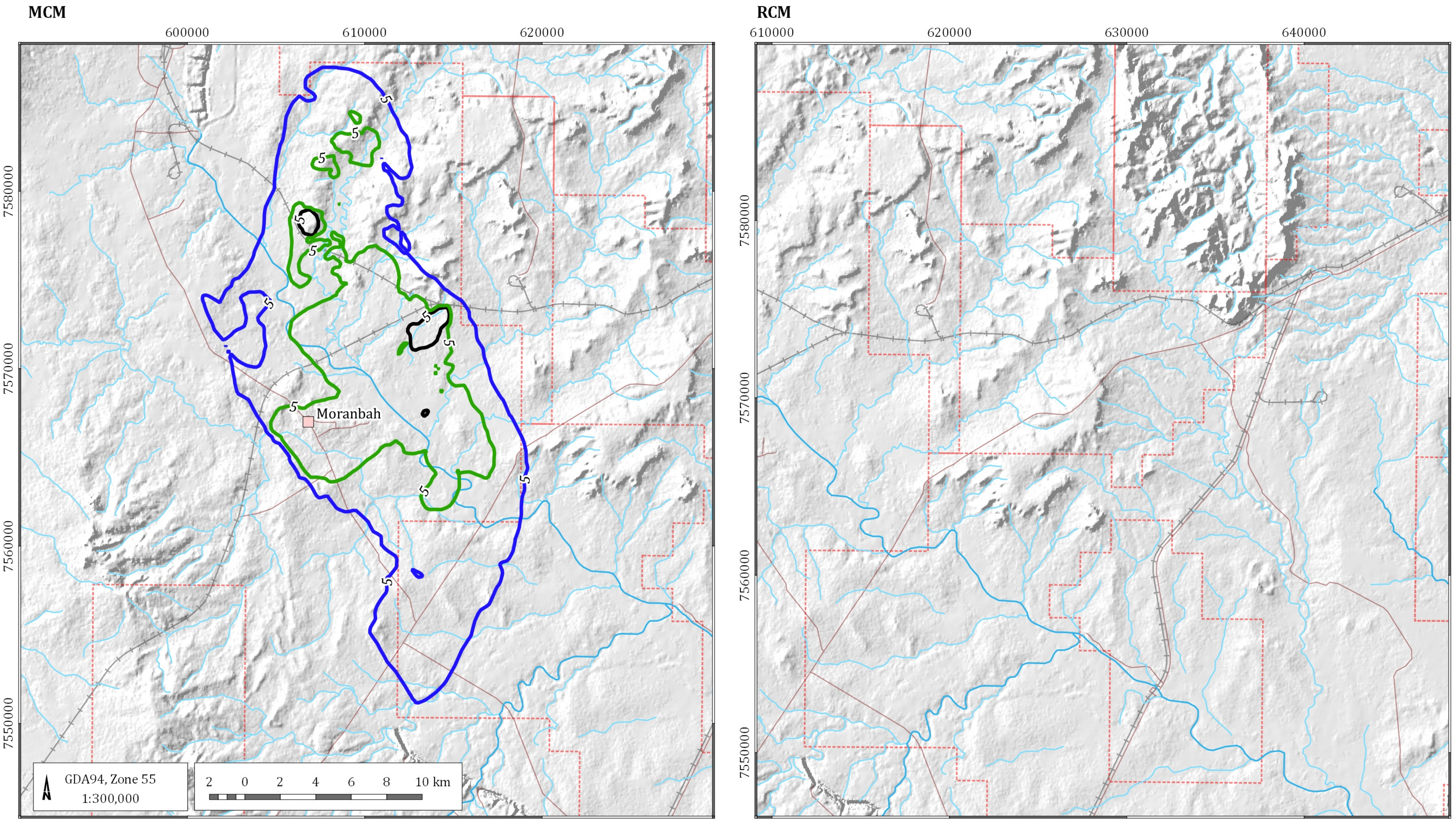
AGE

5th, 50th, 95th drawdown percentile – Cumulative LAA (Scenario 0)

DATE
15/06/2018

FIGURE No:
5.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/05.02_G1885B_ 5th, 50th, 95th drawdown percentile – cumulative IAA (Scenario 0).qgs



LEGEND

- 🟥 Populated place
- ▭ Petroleum exploration lease
- Major drainage
- Minor drainage
- Road
- Rail
- P05 drawdown contour (5 m)
- P50 drawdown contour (5 m)
- P95 drawdown contour (5 m)

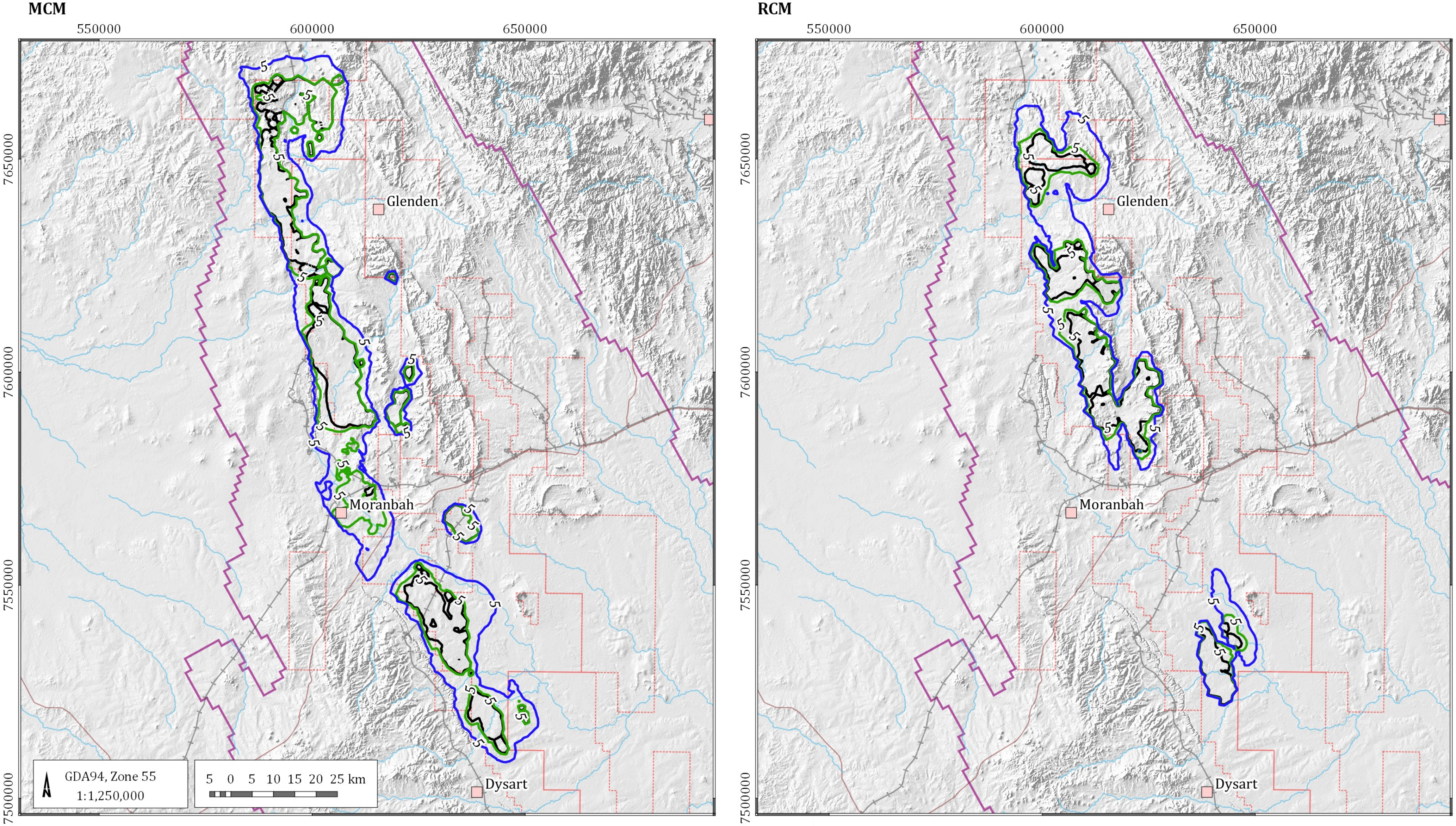
Bowen (G1885B)

5th, 50th, 95th drawdown percentile – incremental LAA (Scenario 1)

DATE
14/06/2018

FIGURE No:
5.3

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/05.03_G1885B_ 5th, 50th, 95th drawdown percentile – incremental LAA (Scenario 1).qgs



LEGEND

- ▢ Populated place
- ⬚ Petroleum exploration lease
- — Model boundary
- — Major drainage
- — Road
- ⊢+⊣ Rail
- — P05 drawdown contour (5 m)
- — P50 drawdown contour (5 m)
- — P95 drawdown contour (5 m)

Bowen (G1885B)

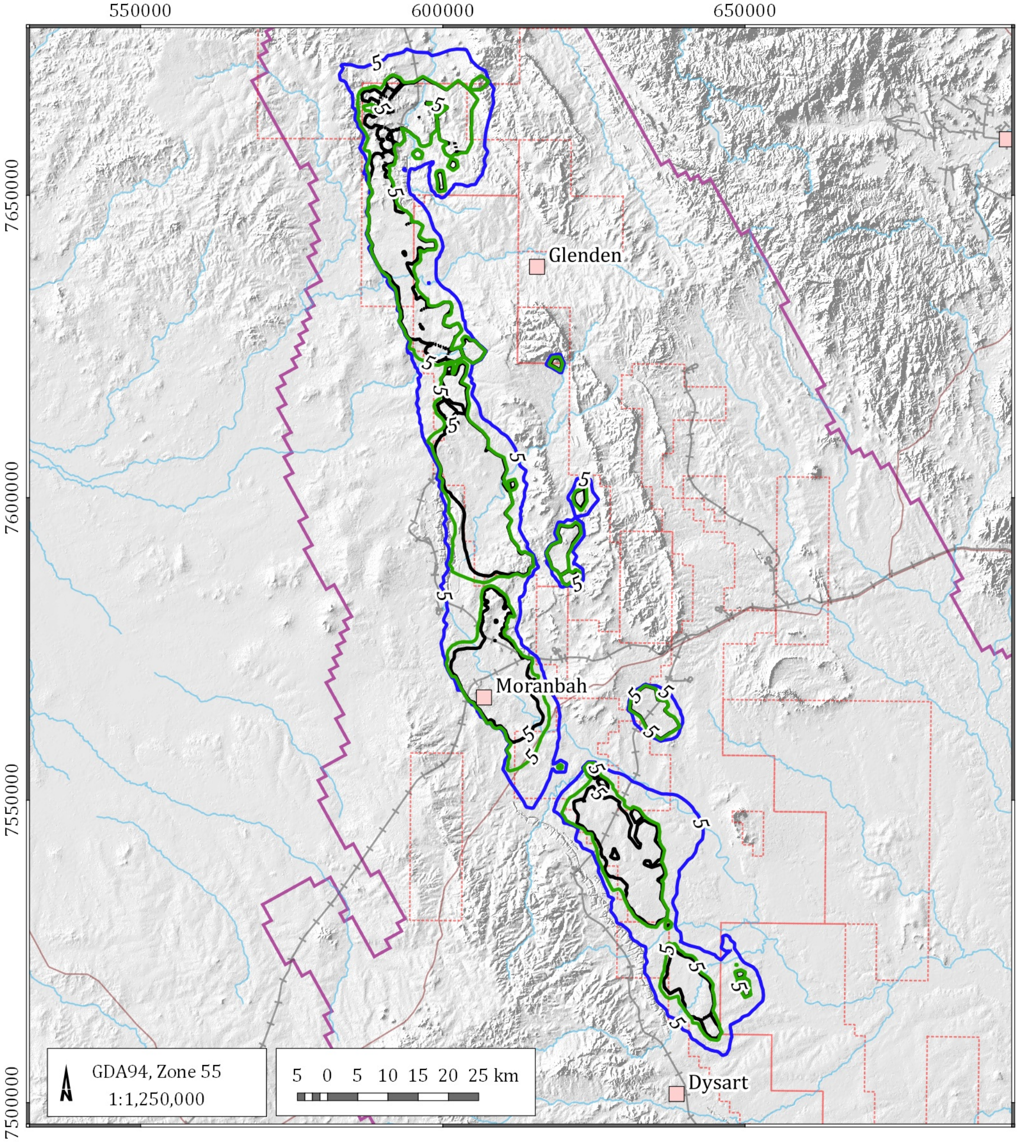
5th, 50th, 95th drawdown percentile – incremental LAA (Scenario 2)

DATE
15/06/2018

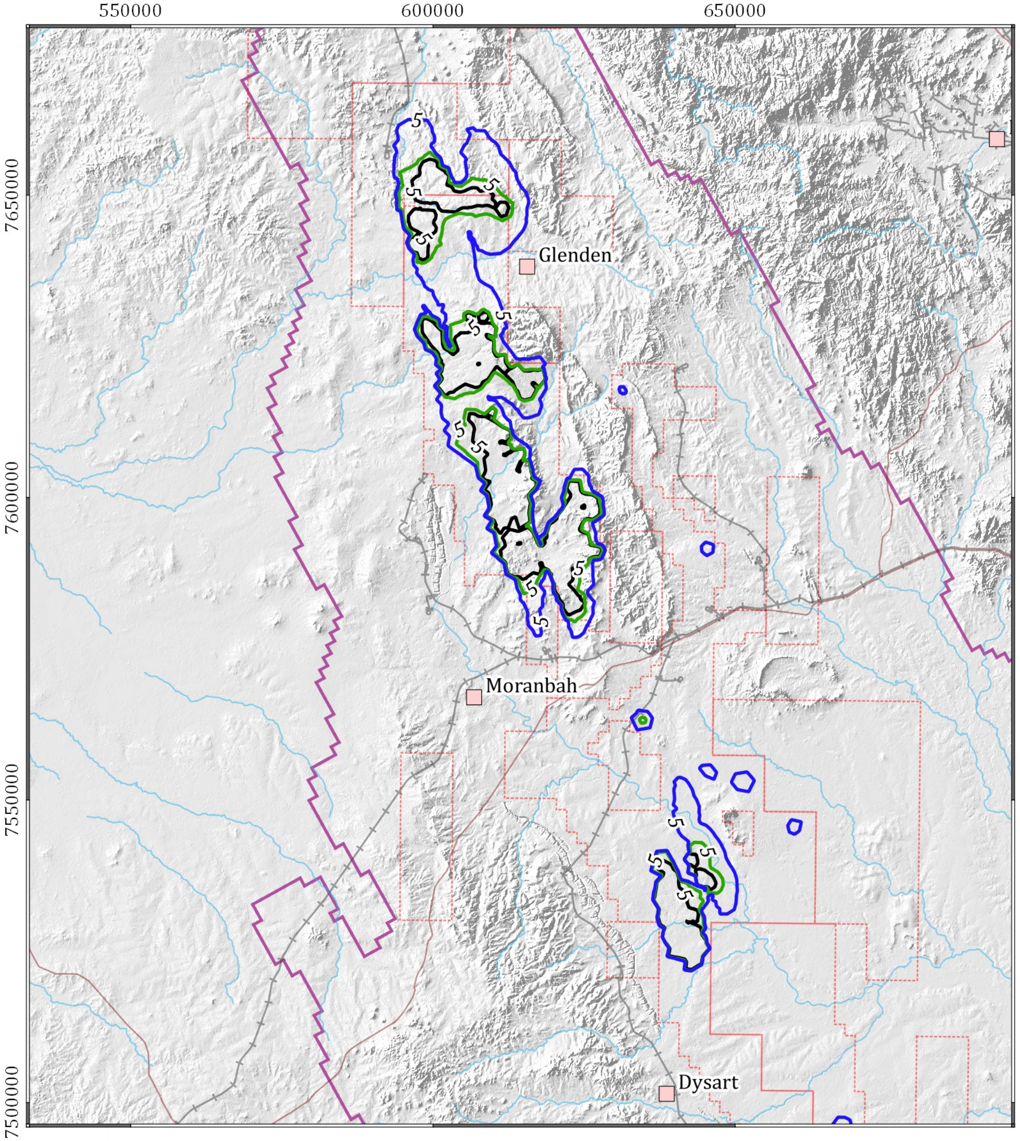
FIGURE No:
5.4

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/05.04_G1885B_5th, 50th, 95th drawdown percentile – incremental LAA (Scenario 2).qgs

MCM



RCM



LEGEND

- ■ Populated place
- ▭ Petroleum exploration lease
- ― Model boundary
- ― Major drainage
- ― Road
- ┼ Rail
- ― P05 drawdown contour (5 m)
- ― P50 drawdown contour (5 m)
- ― P95 drawdown contour (5 m)

AGE

Bowen (G1885B)

5th, 50th, 95th drawdown percentile – cumulative LAA (Scenario 2)

DATE
15/06/2018

FIGURE No:
5.5

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.;
G:/Projects/G1885B.GHD.Arrow.BOWEN.UWIR/3_GIS/Workspaces/001_Deliverable1/05.05_G1885B_5th, 50th, 95th drawdown percentile – cumulative LAA (Scenario 2).qgs

6 References

Arrow Energy (2016), *Underground Water Impact Report For Petroleum Leases 191, 196, 223, 224 and Authority to Prospect 1103, 742, 831 and 1031*, August 2016.

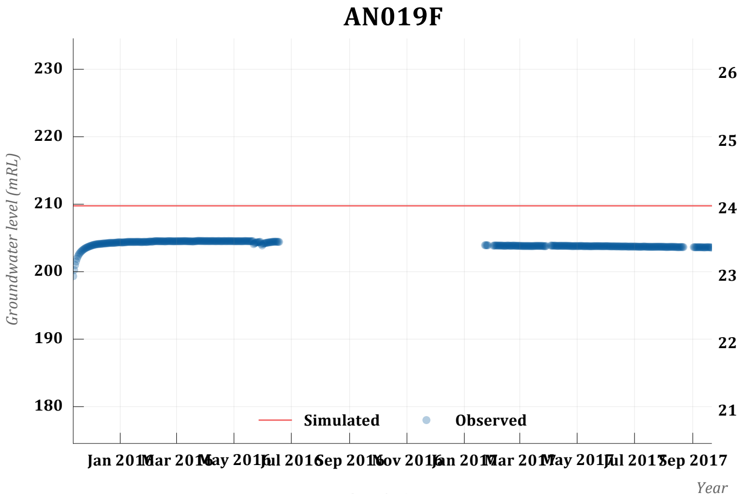
Doherty, J 2010, "*PEST – Model independent parameter estimation user manual: 5th edition*", Watermark Numerical Computing, Corinda, Australia, 2010.

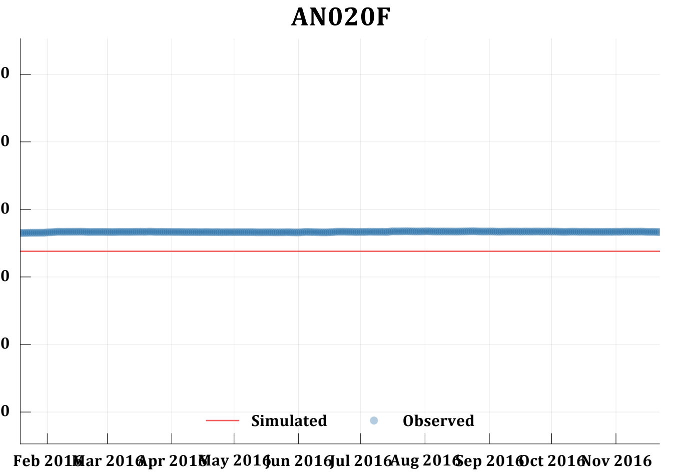
Hydroalgorithmics 2014, "*Algomesh User Guide, Version 1.4*", March 2014.

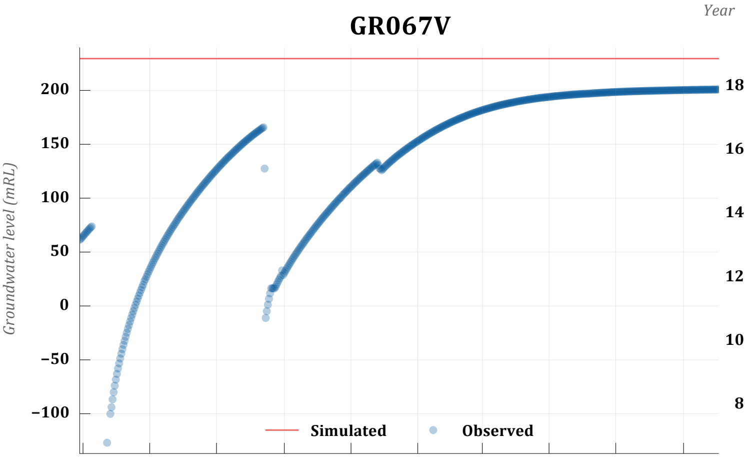
Norwest (2012), *Groundwater Model, North West Bowen Basin Regional Model Impact Predictions, Queensland, Australia*, October 10, 2012

S.S. Papadopulos & Associates, Watermark Numerical Computing, 2018, https://pest.cloud/

Appendix A Calibration hydrographs


AN019F
Groundwater level (mRL)
230
220
210
200
190
180
Simulated
Observed
Jan 2016
Mar 2016
May 2016
Jul 2016
Sep 2016
Nov 2016
Jan 2017
Mar 2017
May 2017
Jul 2017
Sep 2017
Year


AN020F
260
250
240
230
220
210
Simulated
Observed
Feb 2016
Mar 2016
Apr 2016
May 2016
Jun 2016
Jul 2016
Aug 2016
Sep 2016
Oct 2016
Nov 2016


GR067V
Groundwater level (mRL)
200
150
100
50
0
−50
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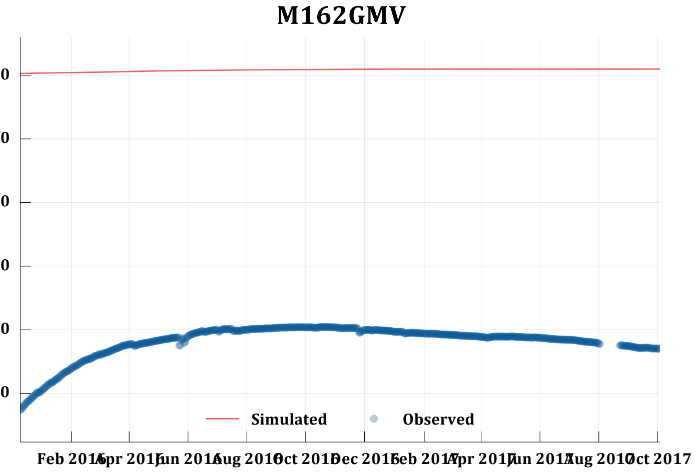
Simulated
Observed
Mar 2016
May 2016
Jul 2016
Sep 2016
Nov 2016
Jan 2017
Mar 2017
May 2017
Jul 2017
Sep 2017
Year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160
140
120
100
80
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Observed
Feb 2016
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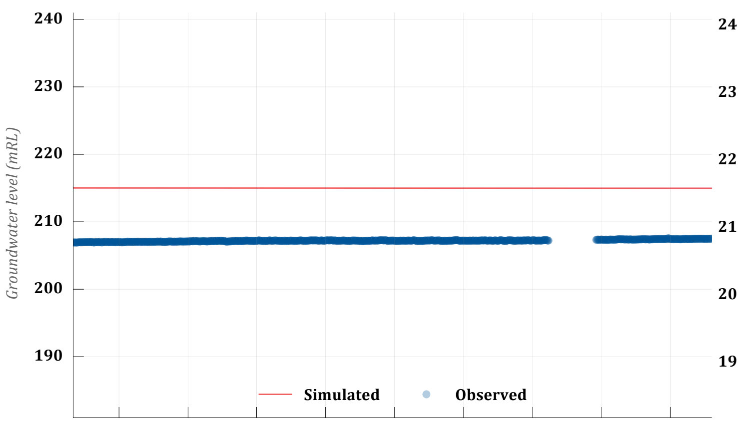
Jun 2016
Aug 2016
Oct 2016
Dec 2016
Feb 2017
Apr 2017
Jun 2017
Aug 2017
Oct 2017


M225W
Groundwater level (mRL)
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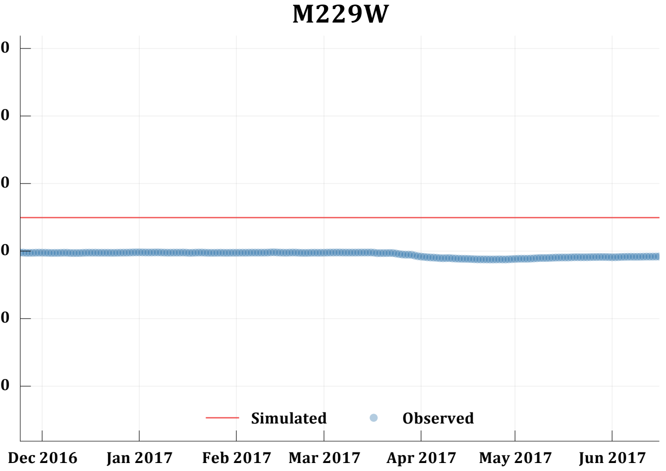
200
190
Simulated
Observed
Aug 2014
Dec 2014
Apr 2015
Aug 2015
Dec 2015
Apr 2016
Aug 2016
Dec 2016
Apr 2017
Year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Observed
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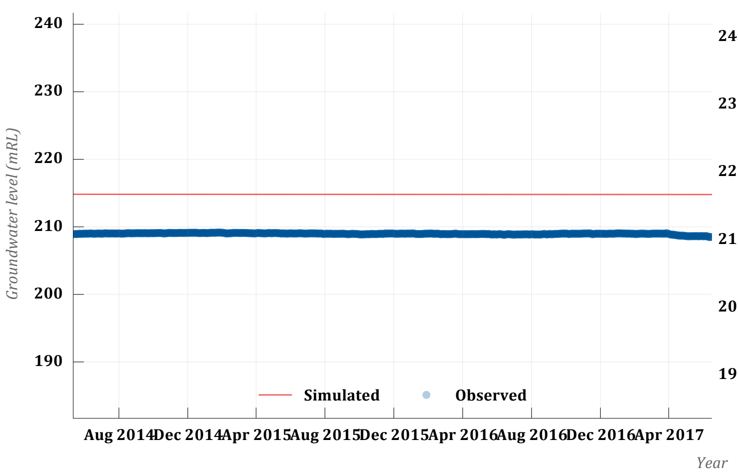
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Jun 2017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Groundwater level (mRL)
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210
200
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Simulated
Observed
Aug 2014
Dec 2014
Apr 2015
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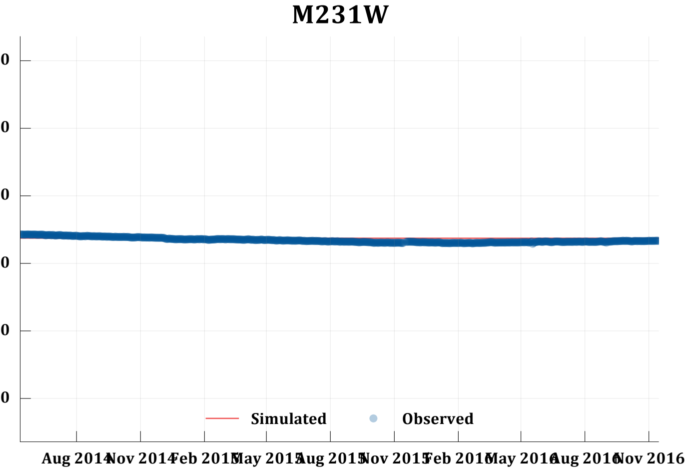
Dec 2015
Apr 2016
Aug 2016
Dec 2016
Apr 2017
Year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230
220
210
200
190
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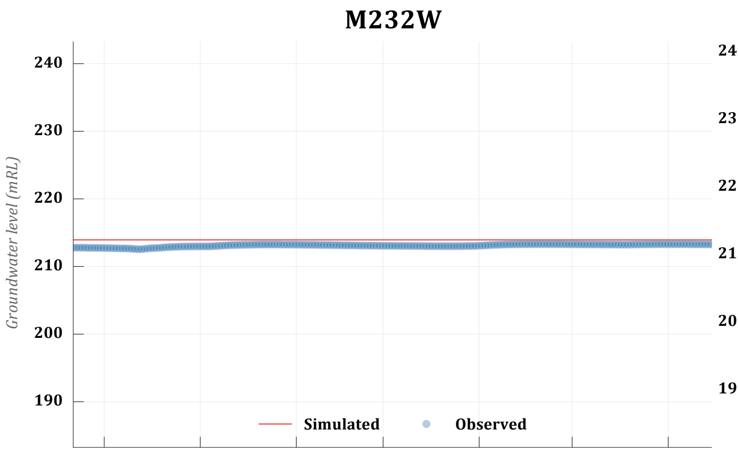
Nov 2014
Feb 2015
May 2015
Aug 2015
Nov 2015
Feb 2016
May 2016
Aug 2016
Nov 2016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Groundwater level (mRL)
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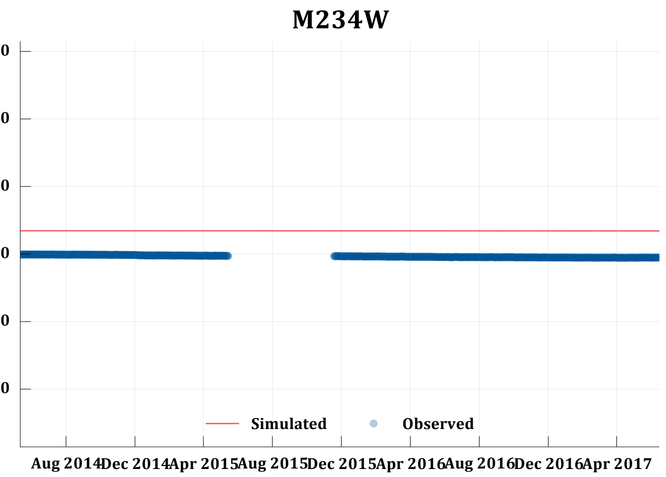
220
210
200
190
Simulated
Observed
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Jun 2017
Year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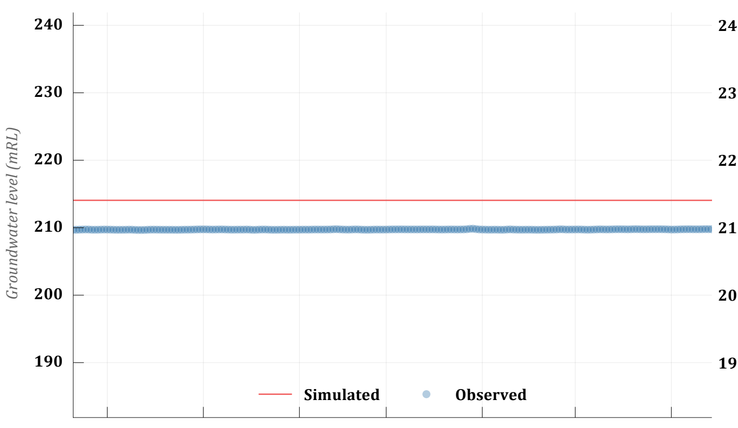
200
190
Simulated
Observed
Aug 2014
Dec 2014
Apr 2015
Aug 2015
Dec 2015
Apr 2016
Aug 2016
Dec 2016
Apr 2017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Groundwater level (mRL)
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200
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Simulated
Observed
Dec 2016
Jan 2017
Feb 2017
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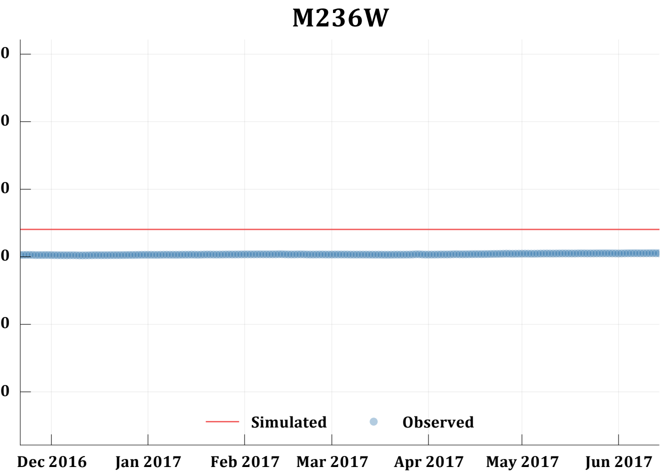
Apr 2017
May 2017
Jun 2017
Year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Jan 2017
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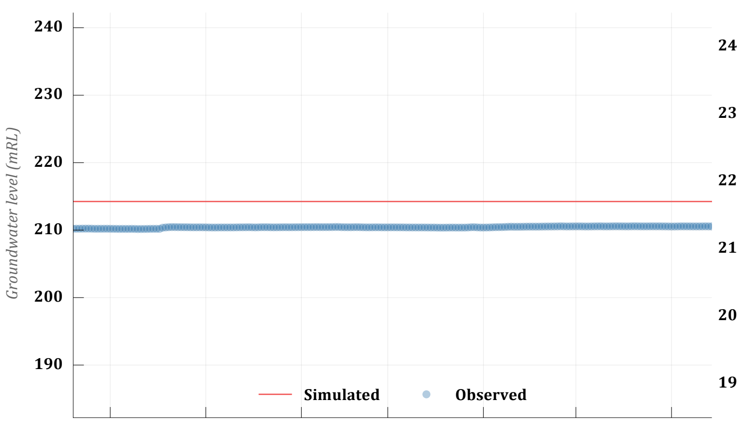
Jun 2017


M237W
Groundwater level (mRL)
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200
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Simulated
Observed
Dec 2016
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Feb 2017
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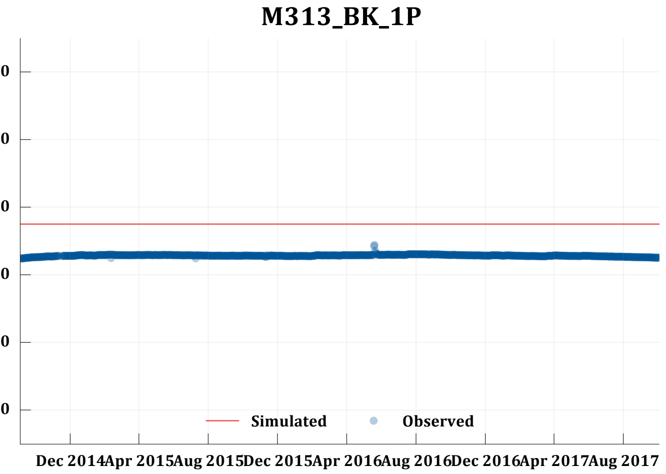
May 2017
Jun 2017
Year


M313_BK_1P
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Simulated
Observed
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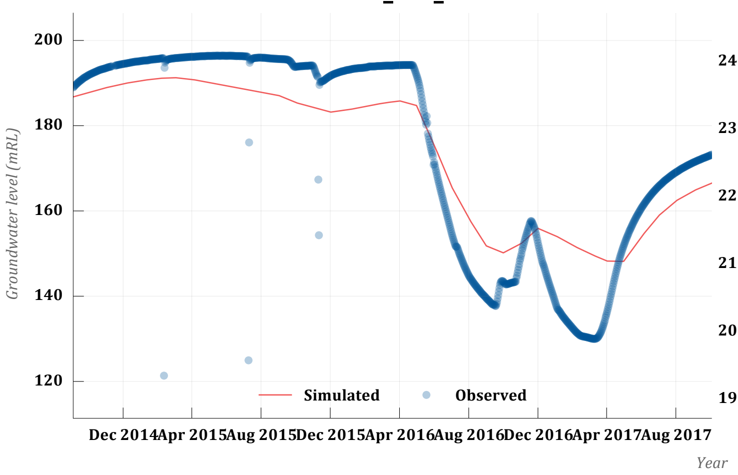
M313_GM_1P
Groundwater level (mRL)
200
180
160
140
120
Simulated
Observed
Dec 2014
Apr 2015
Aug 2015
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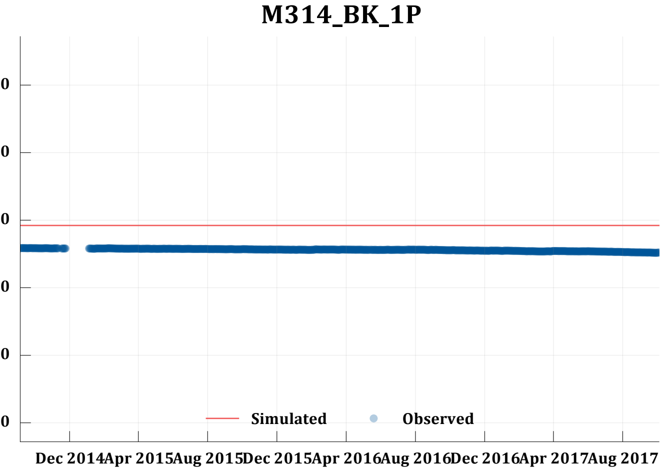
Apr 2016
Aug 2016
Dec 2016
Apr 2017
Aug 2017
Year


M314_BK_1P
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Simulated
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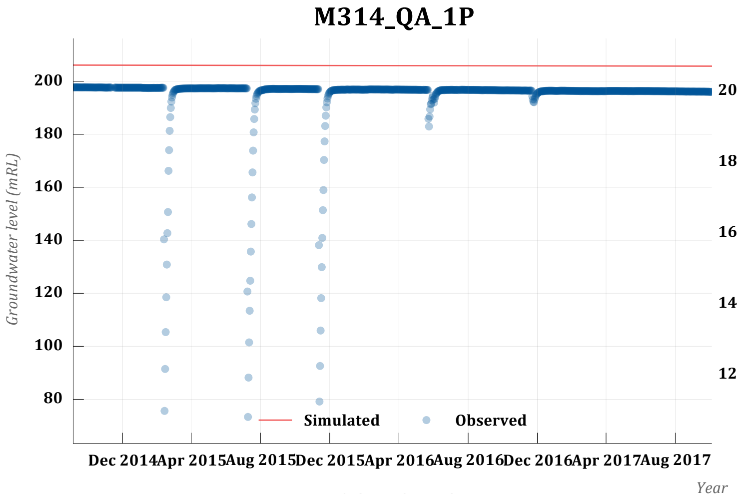
Apr 2017
Aug 2017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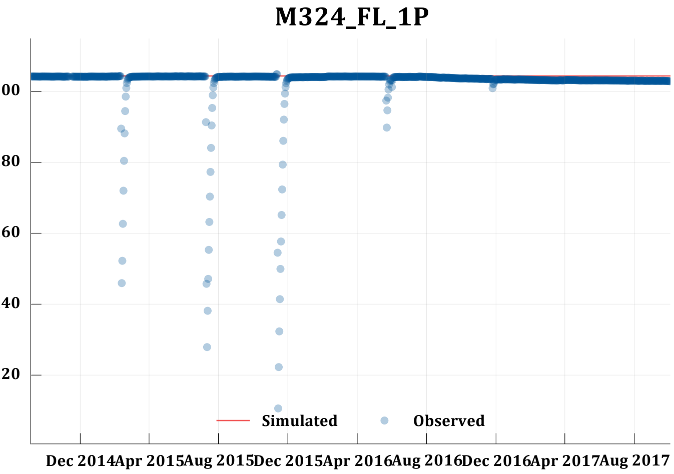
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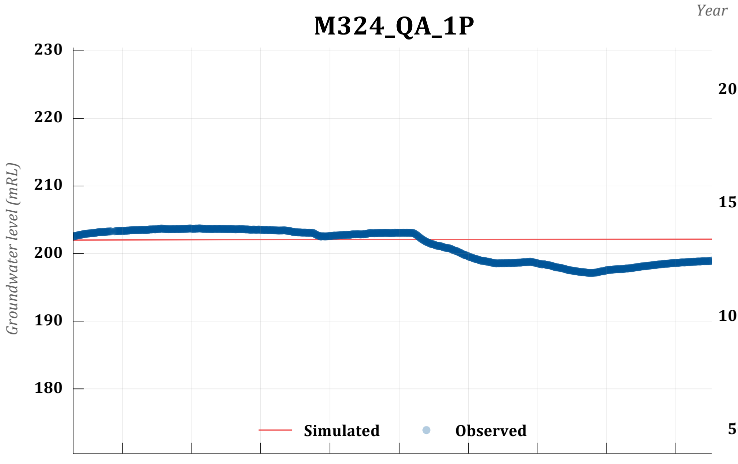
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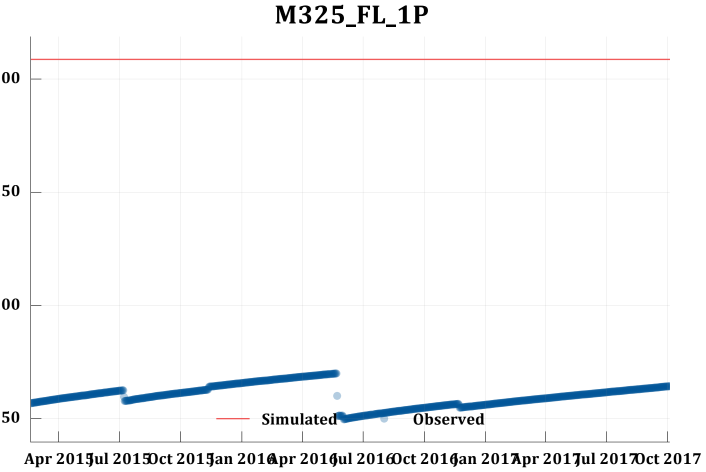
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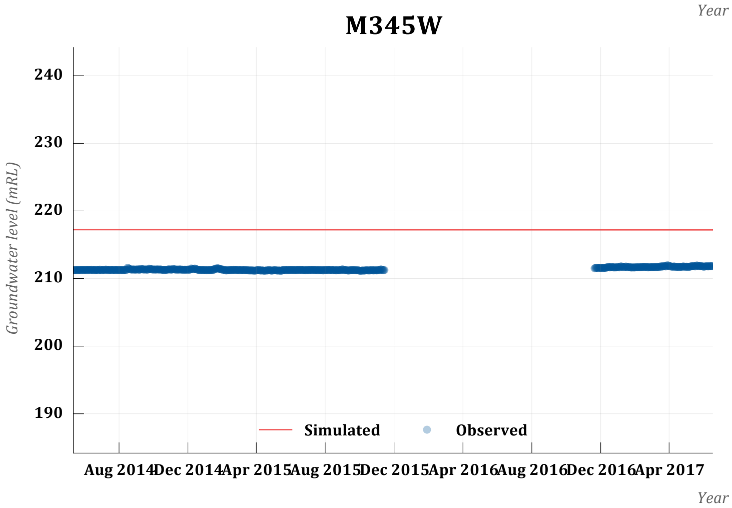
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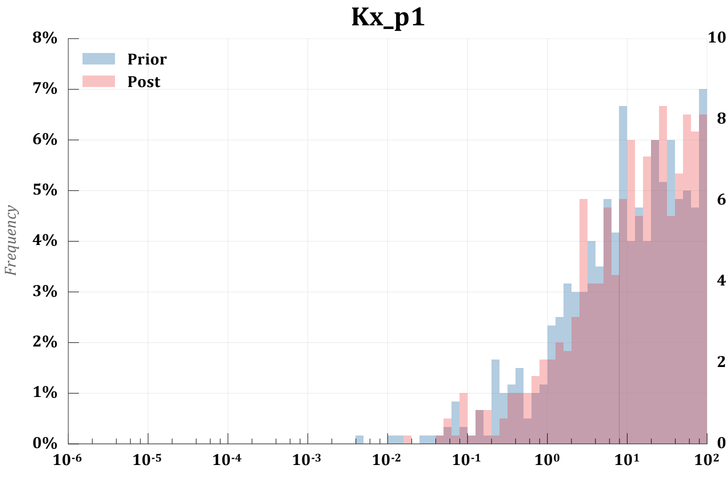
Appendix B Uncertainty parameter distributions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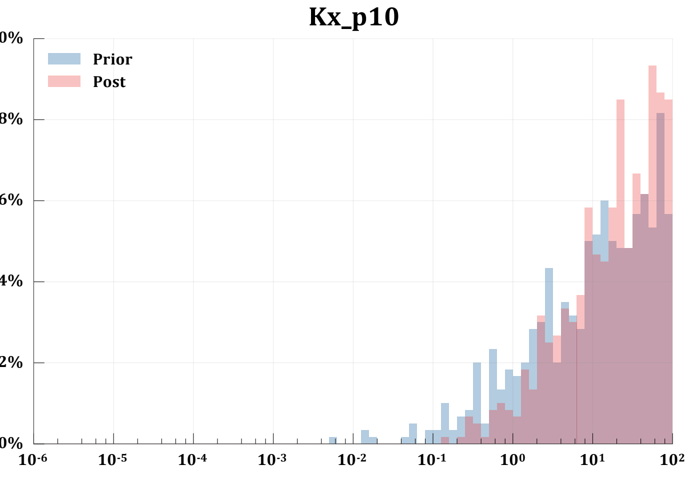
10^{1}
10^{2}
Range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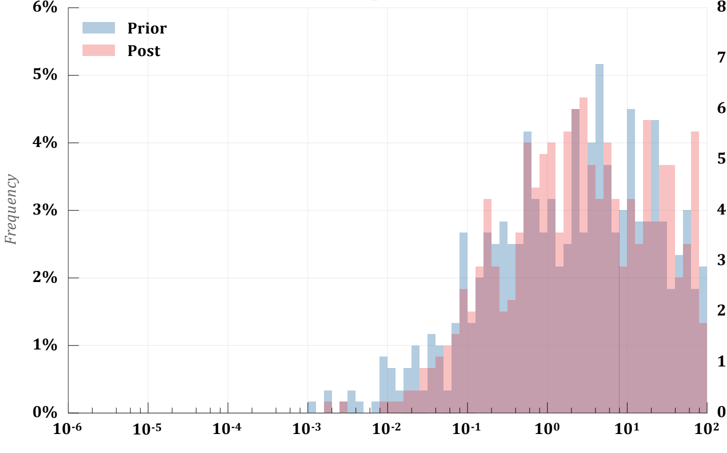
10^{2}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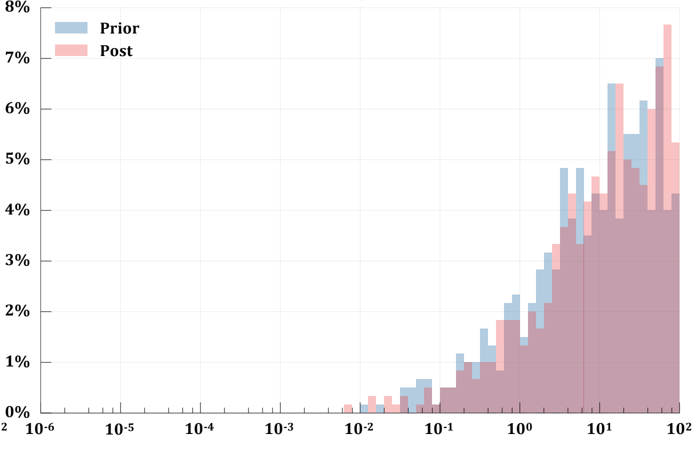
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10^{0}
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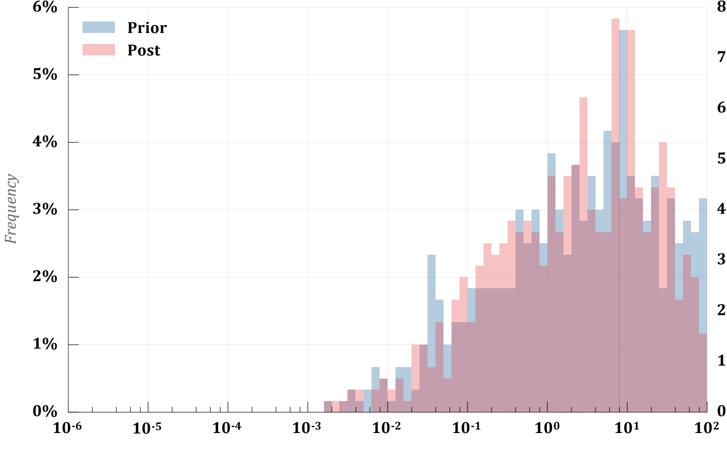
10^{2}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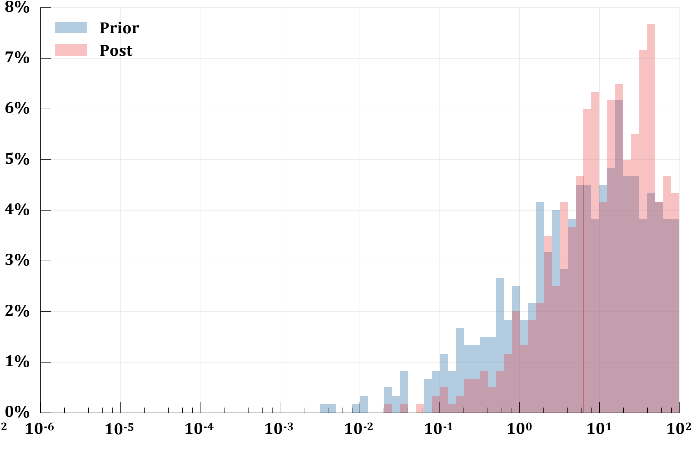
10^{1}
10^{2}
Range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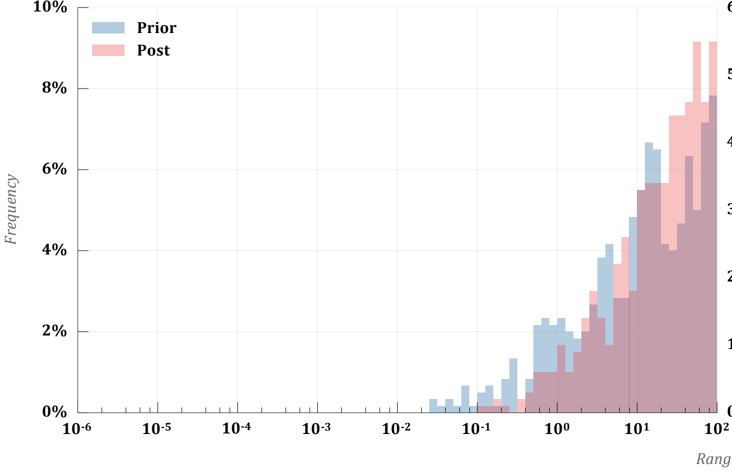
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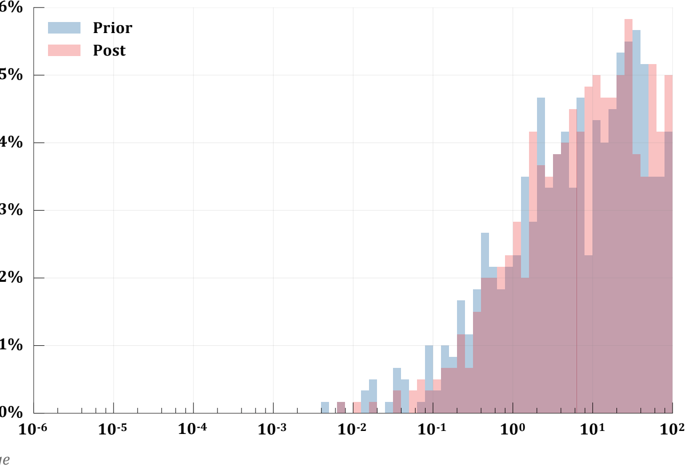
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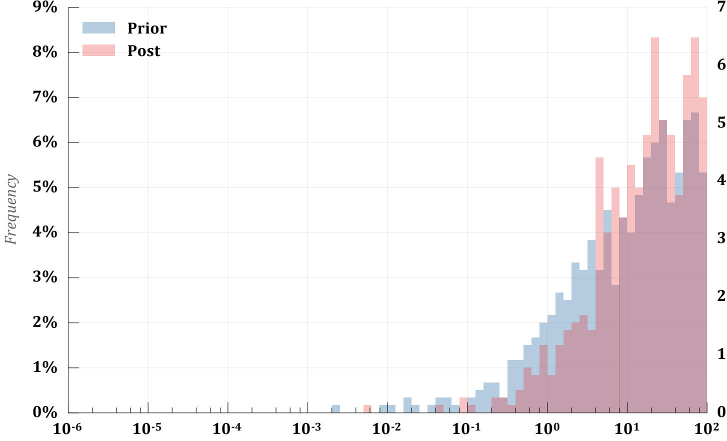
Kx_p15



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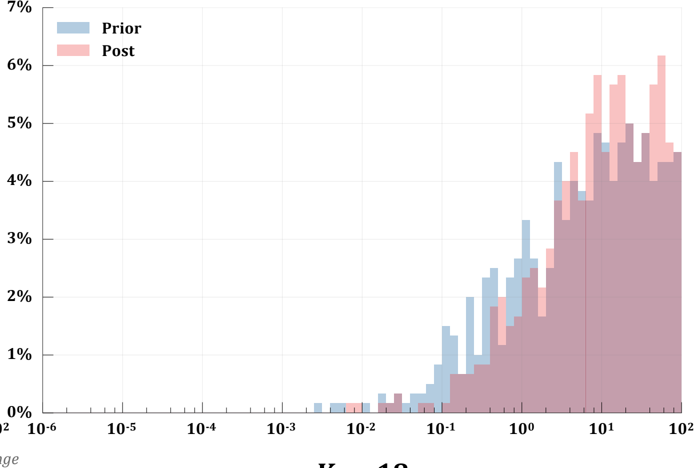

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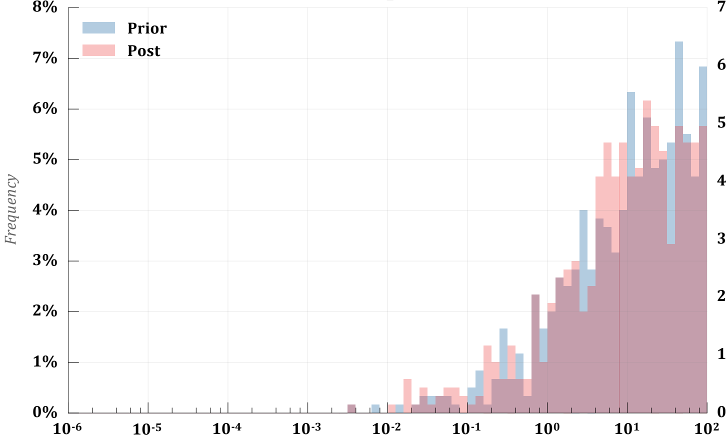

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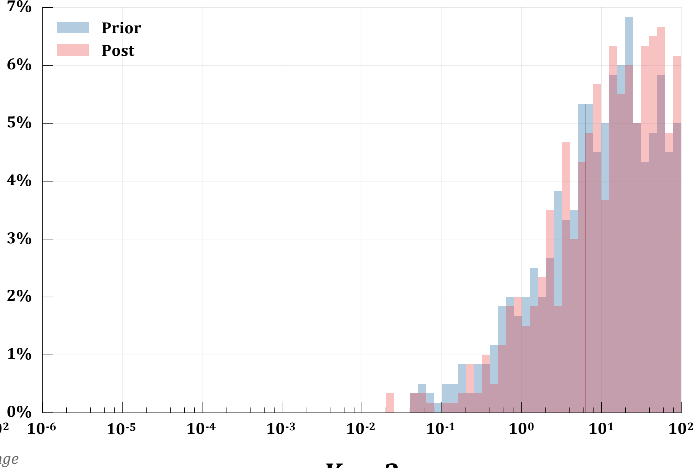

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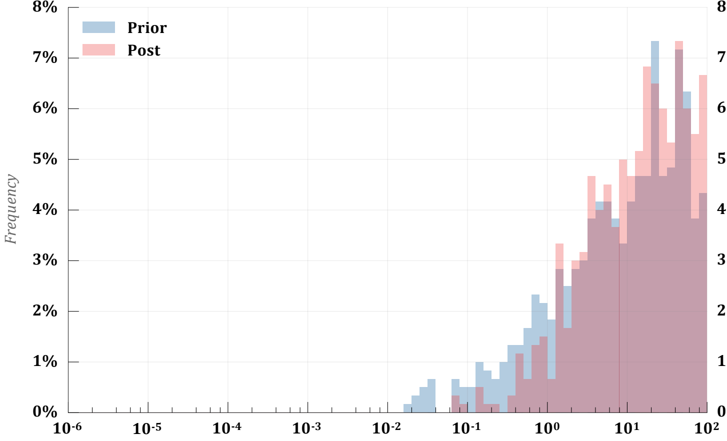

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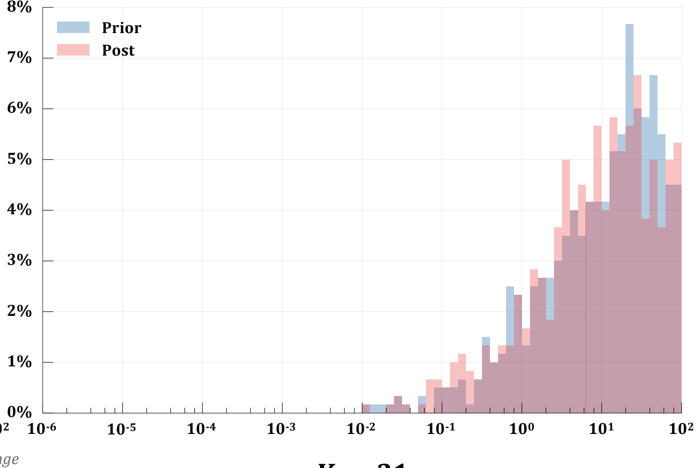

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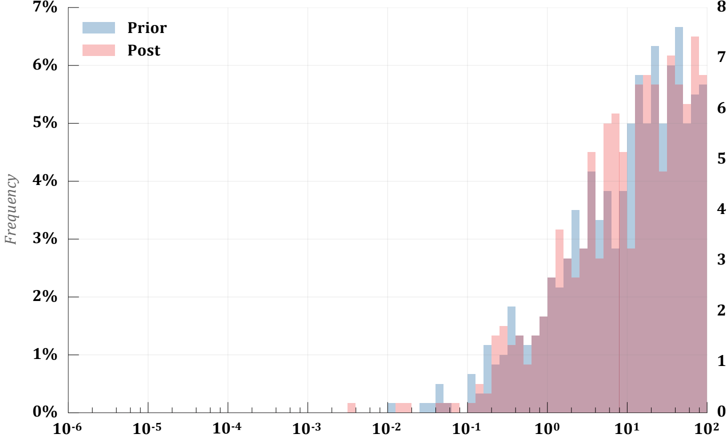

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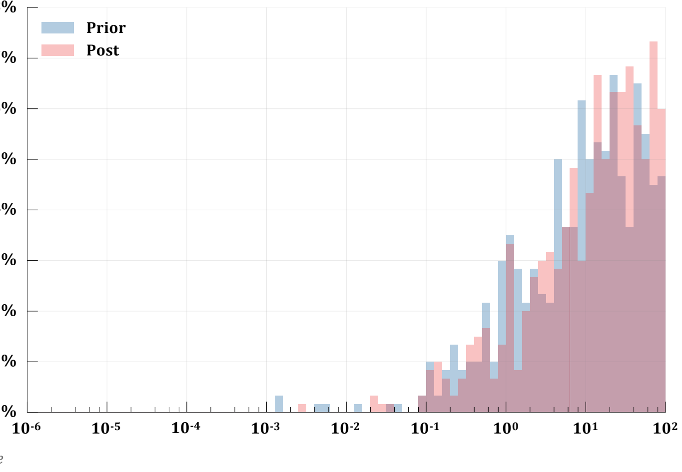

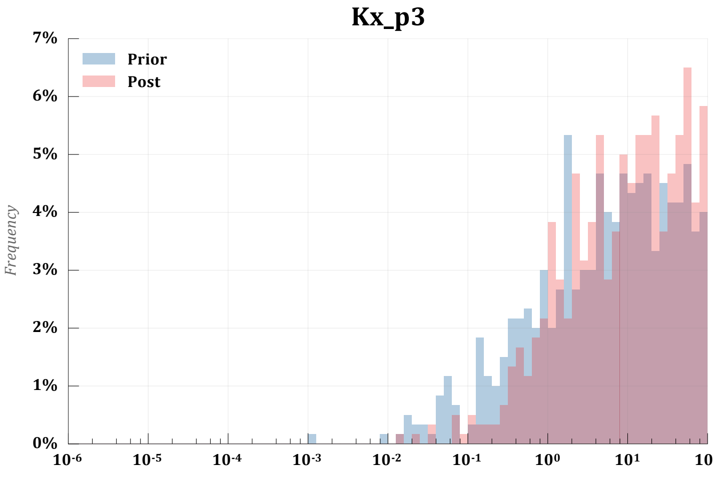
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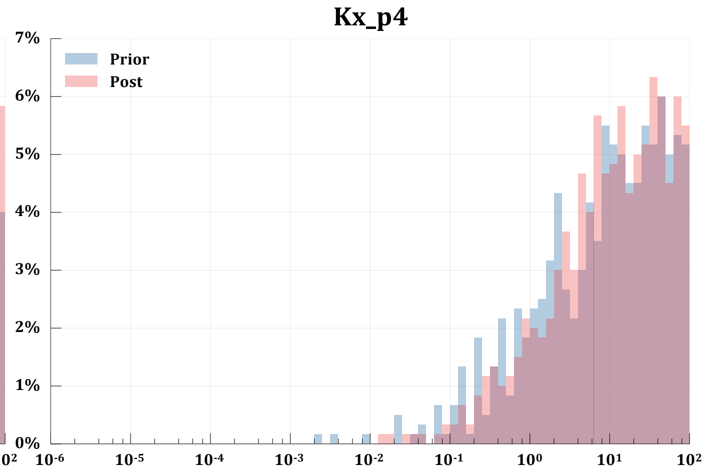
10⁰
10¹
10²
Range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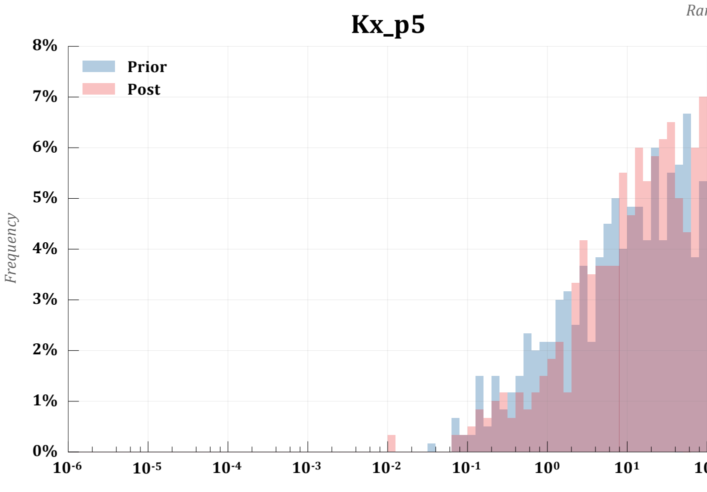
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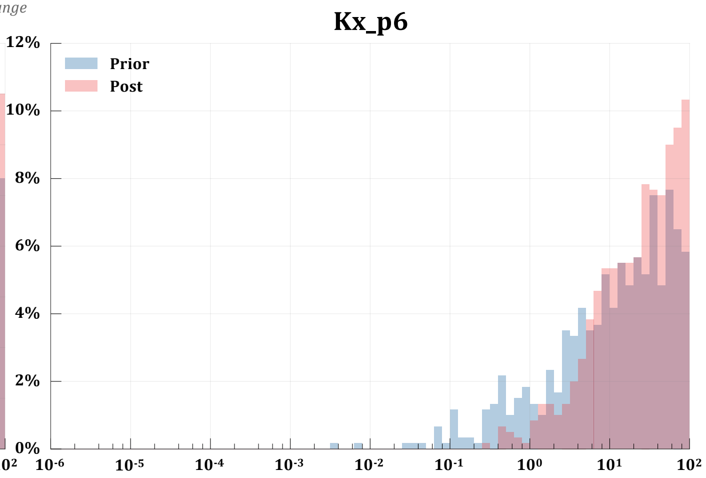
Range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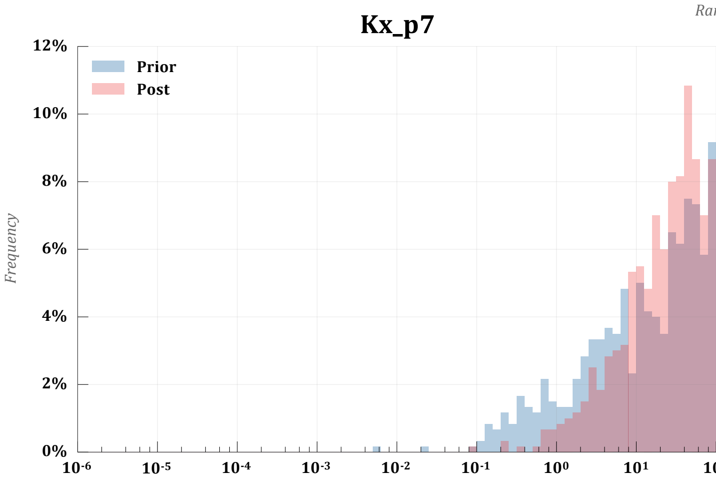
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10¹
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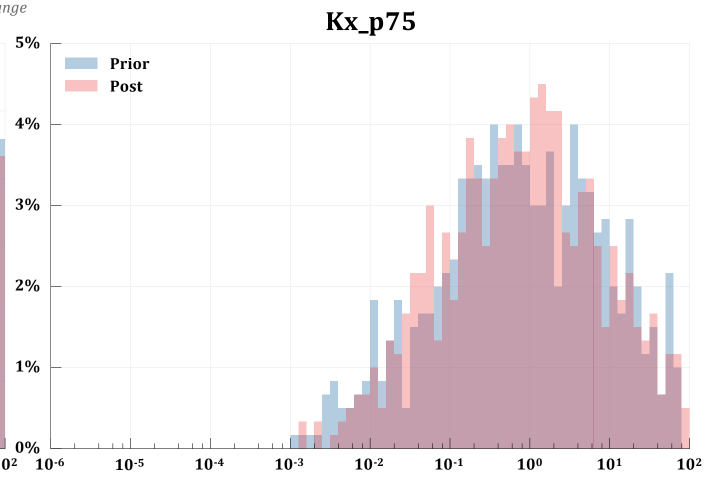
Range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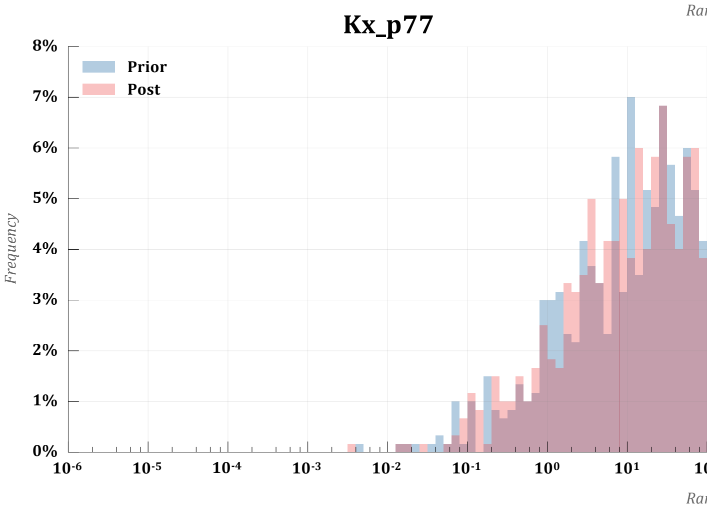
10¹
10²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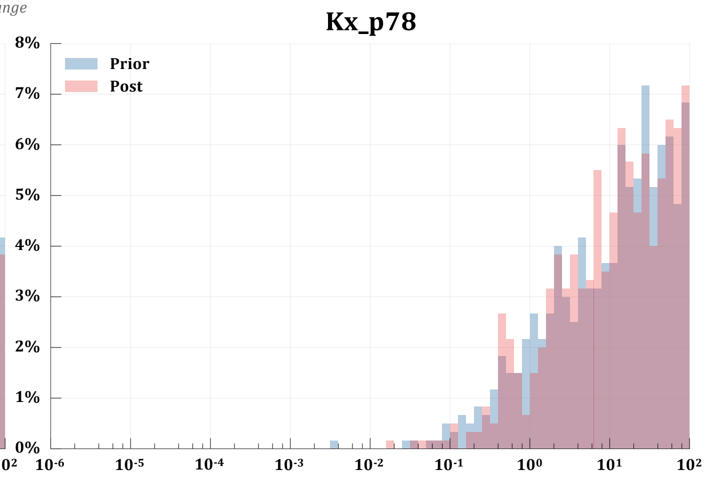
Range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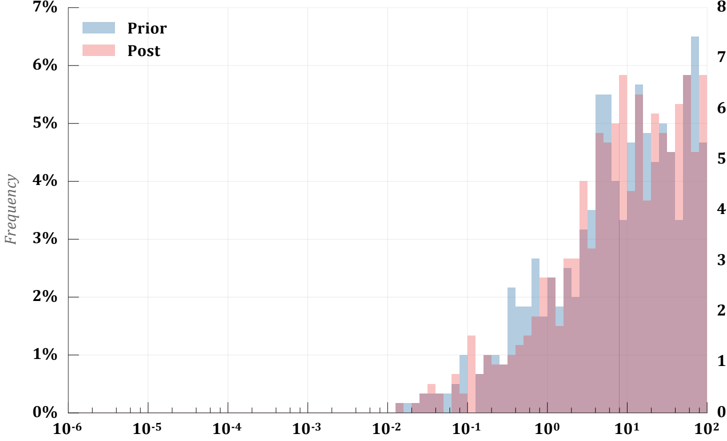
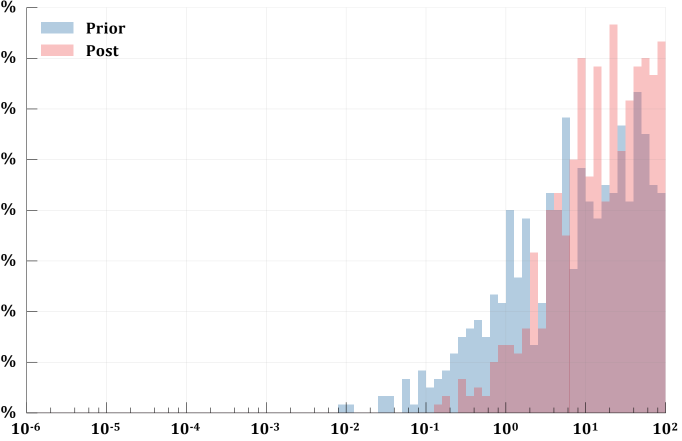
10⁰
10¹
10²



Kx_p79



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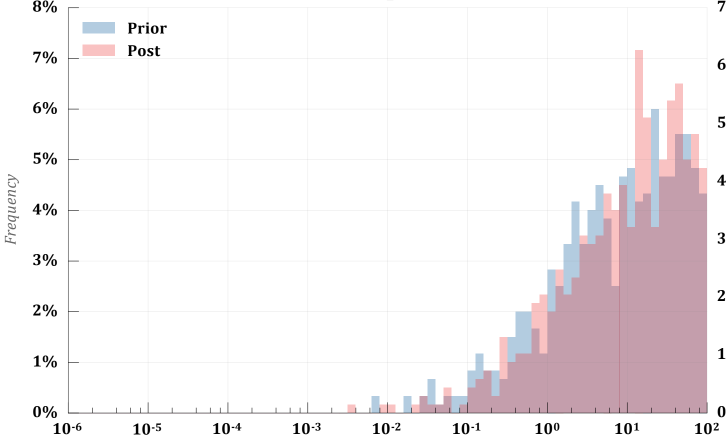

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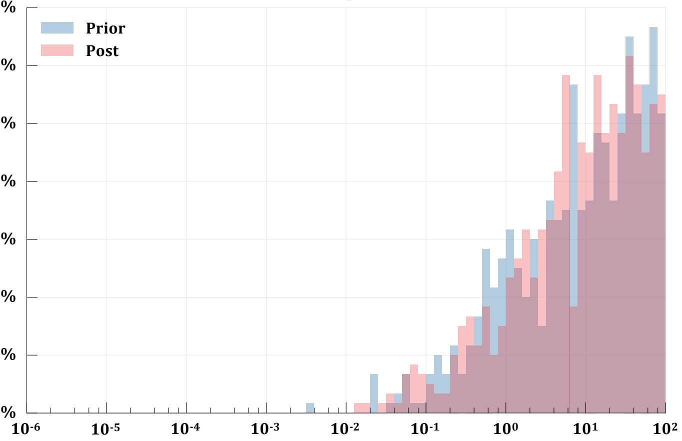

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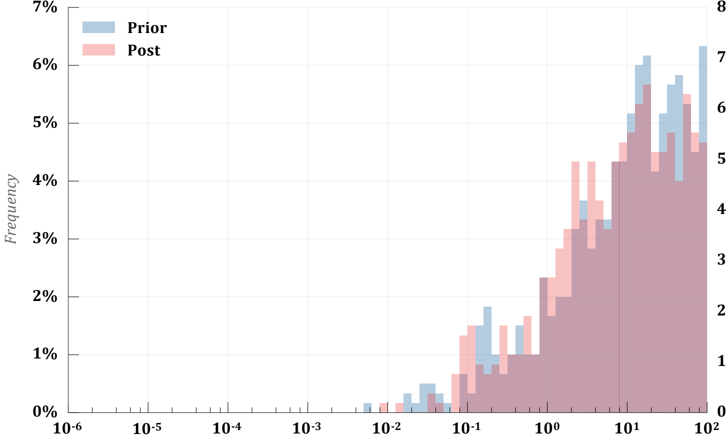

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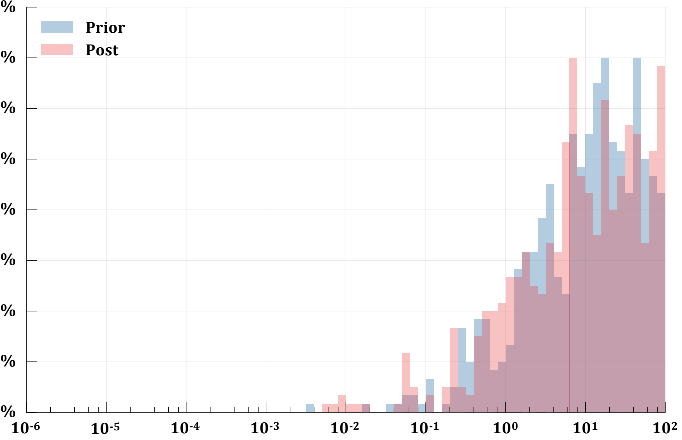

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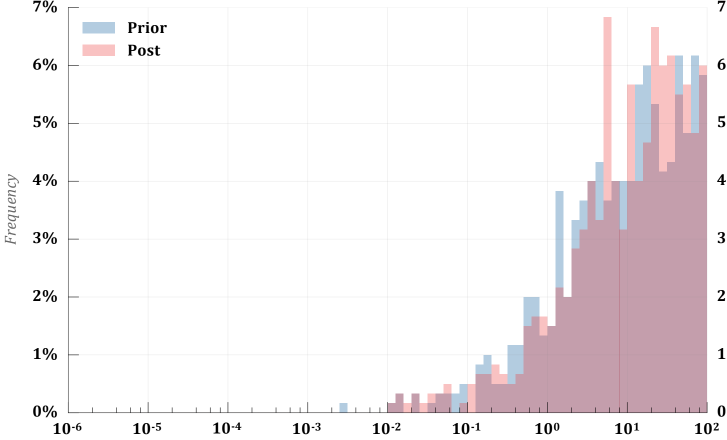

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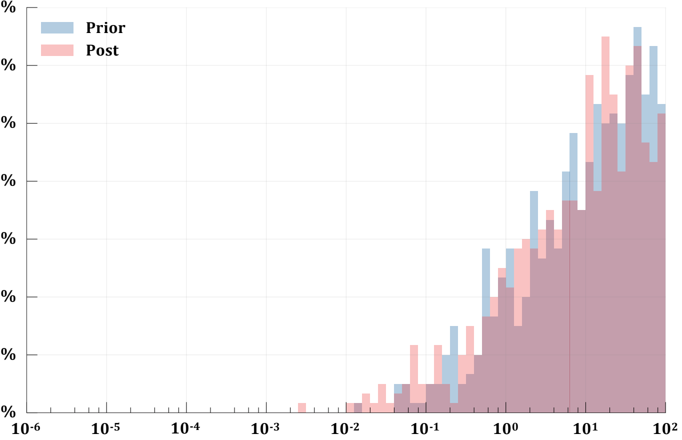

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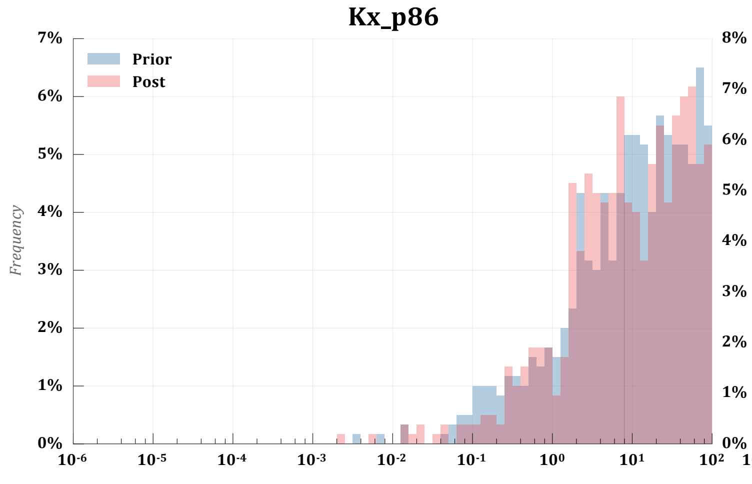
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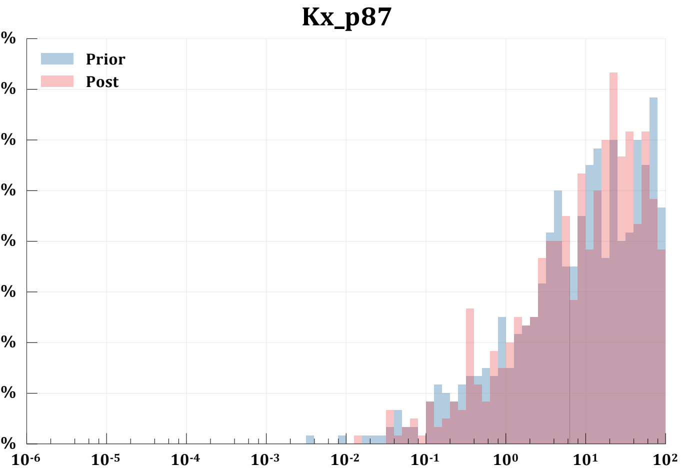
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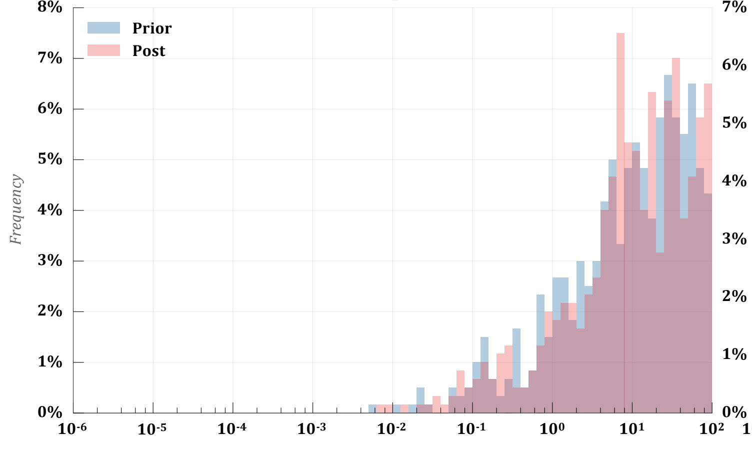
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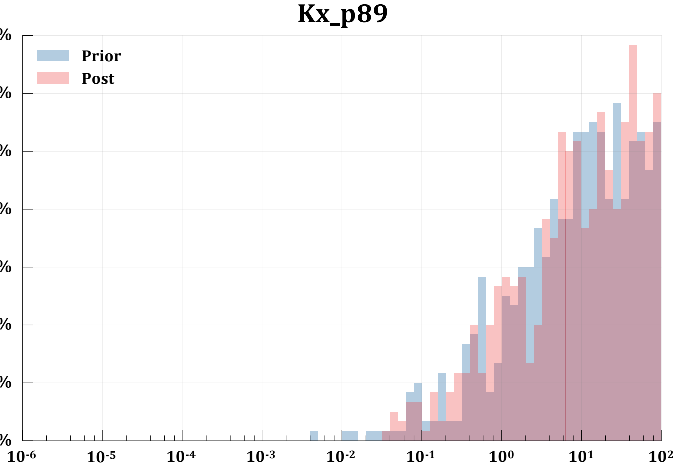
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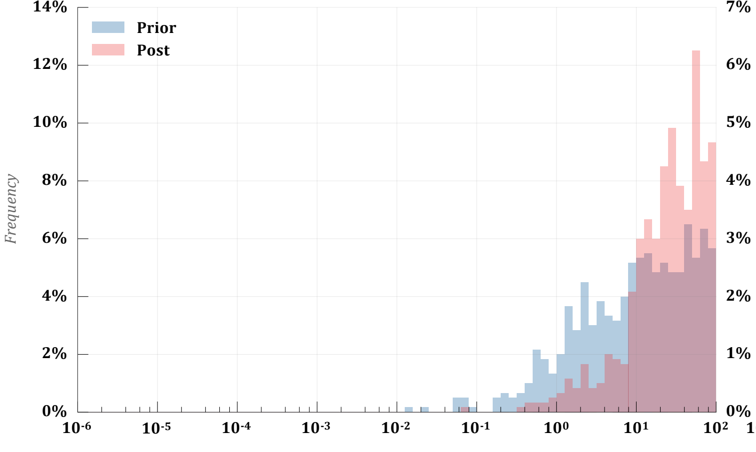
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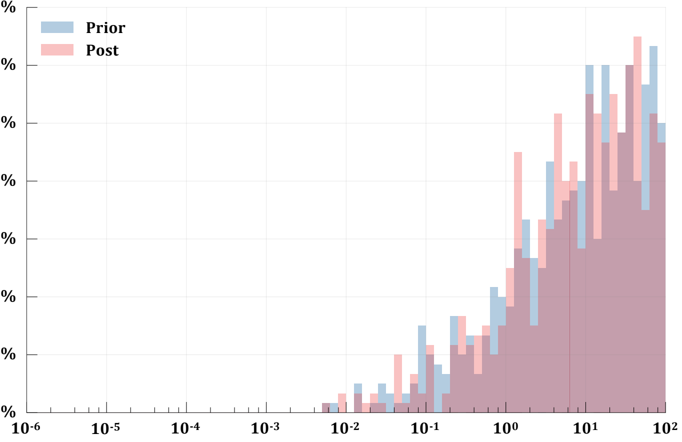
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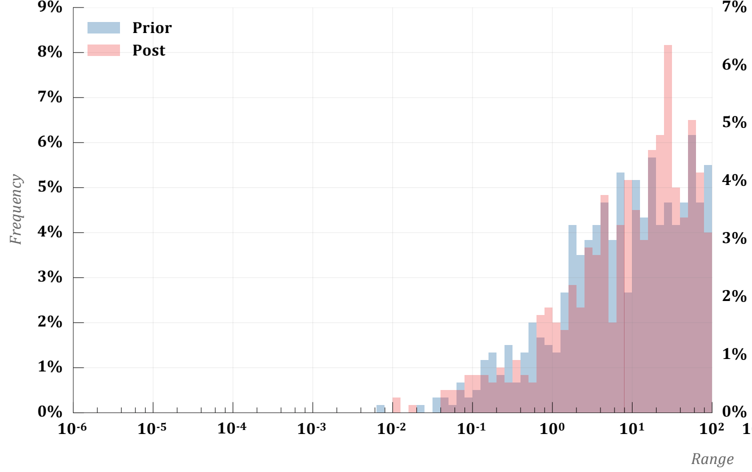
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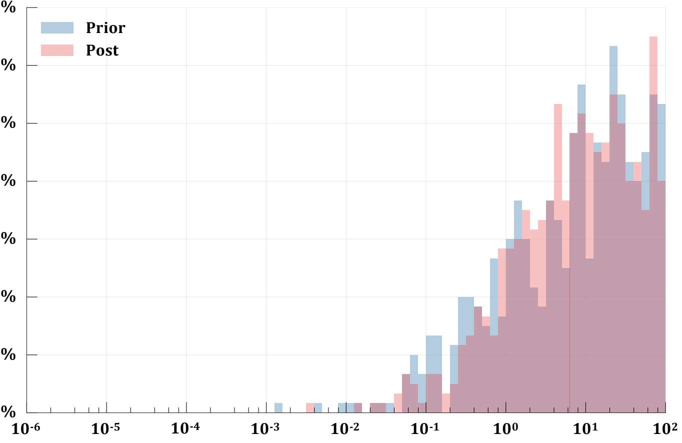
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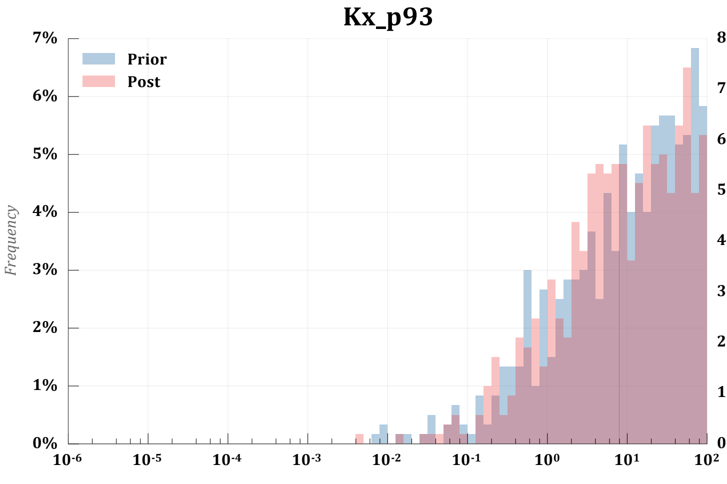
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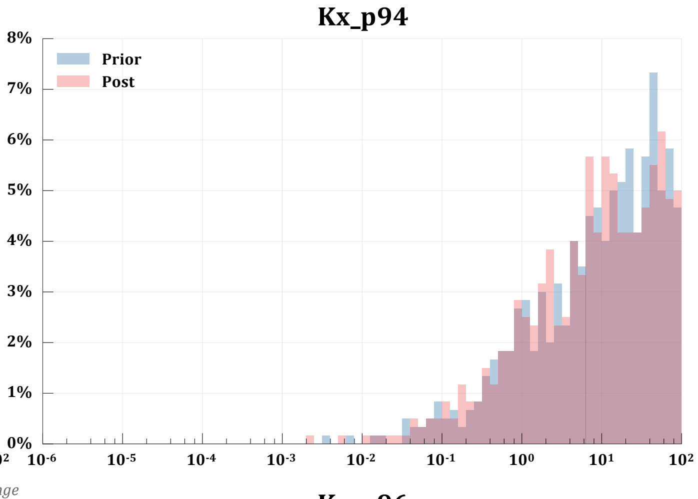
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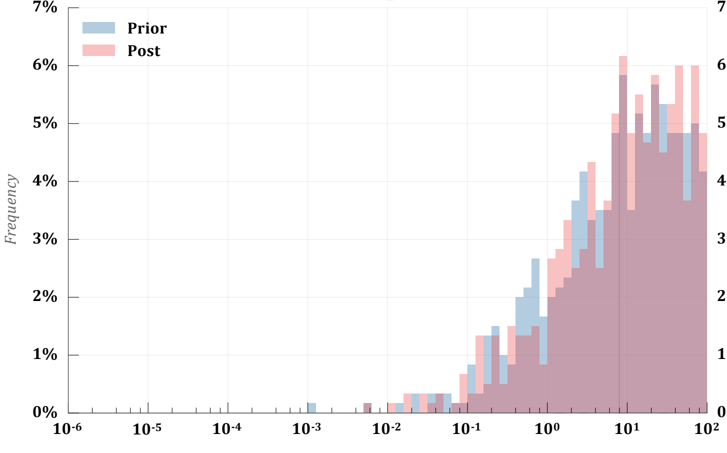
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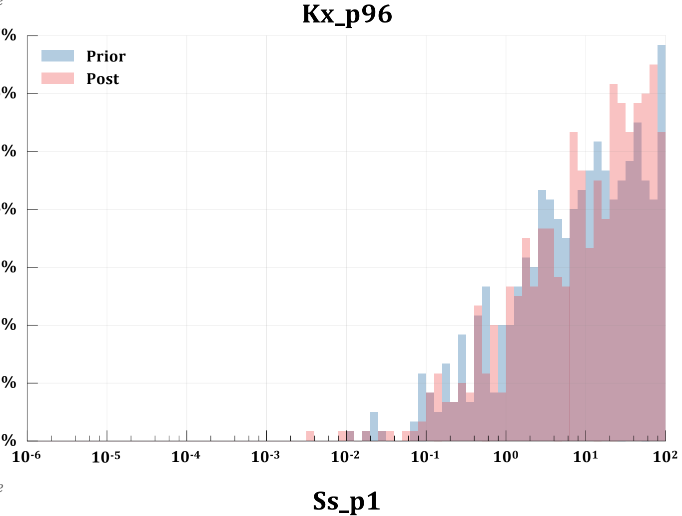
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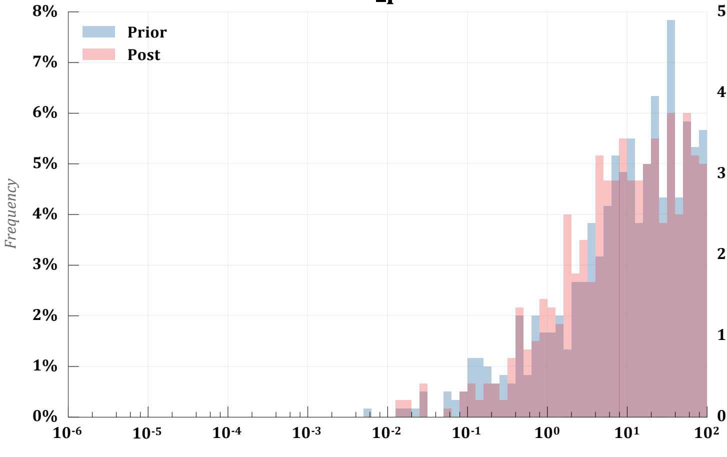
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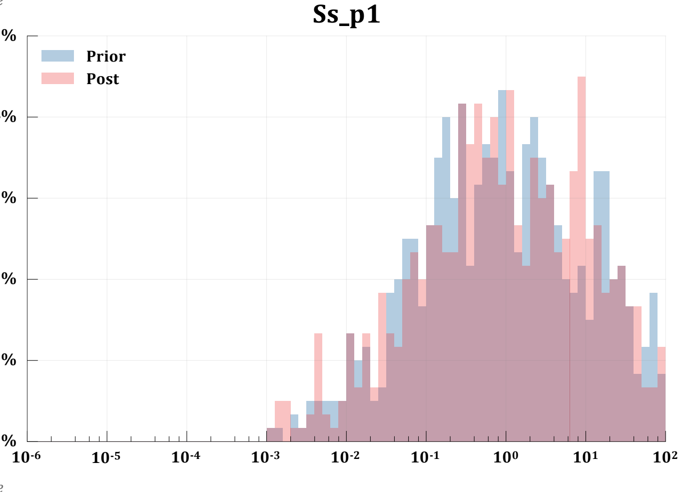
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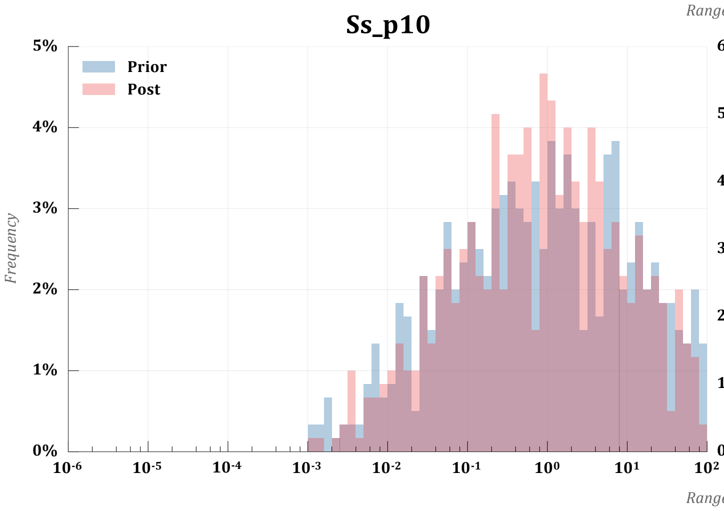
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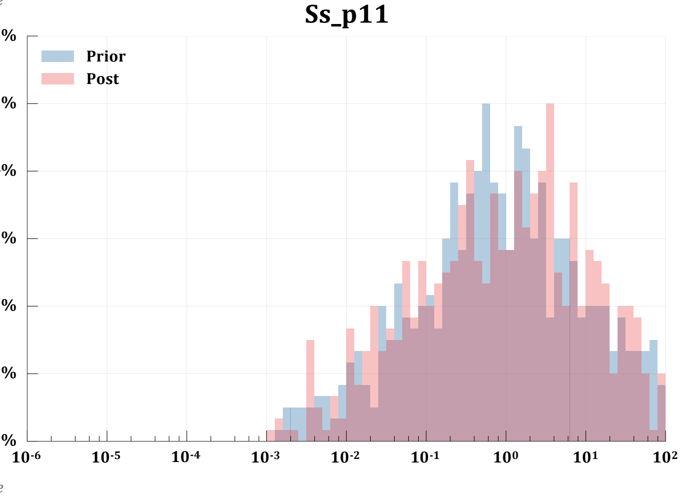
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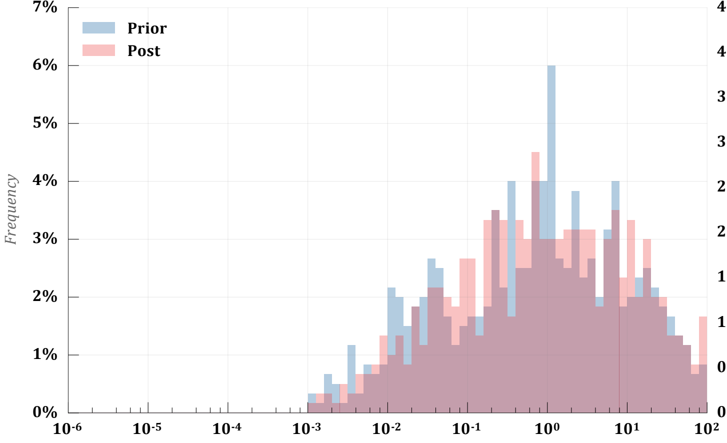

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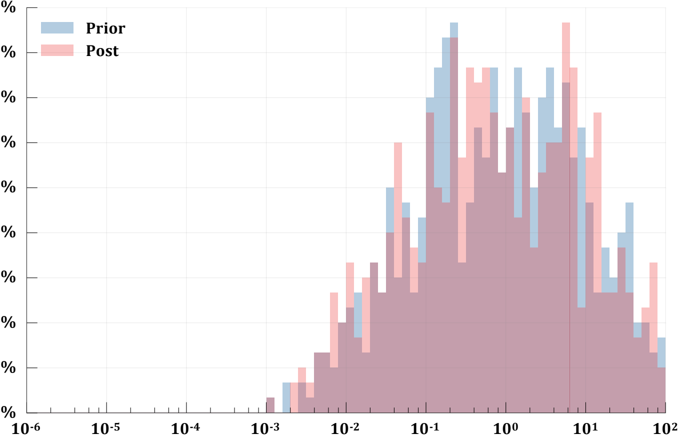

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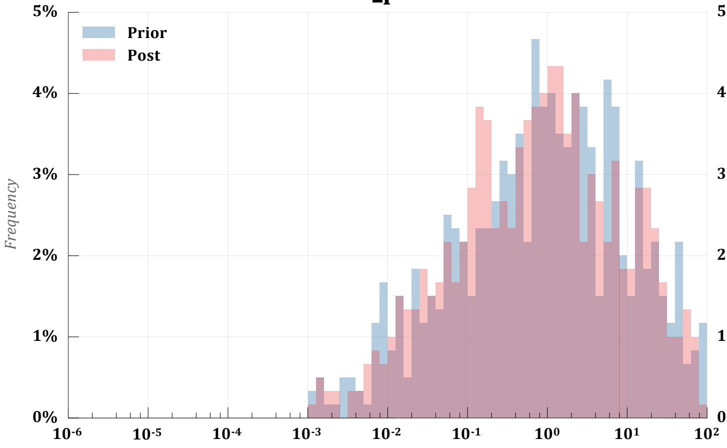

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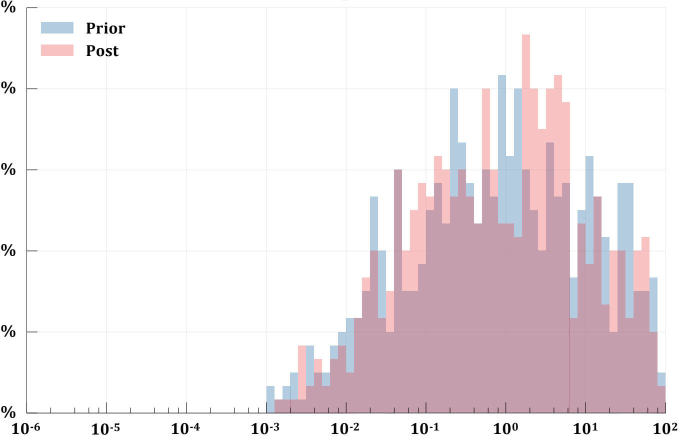

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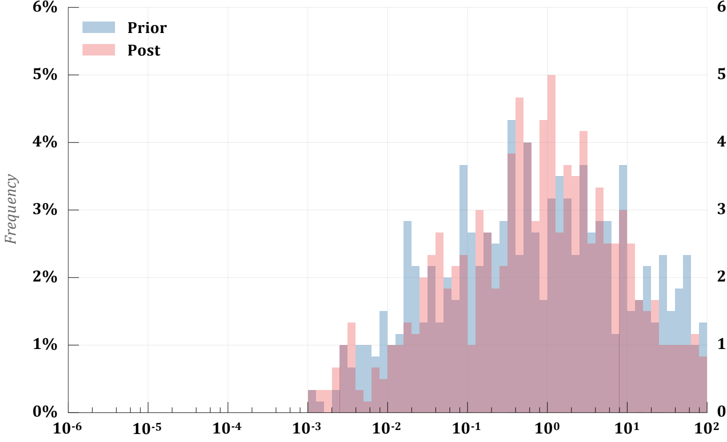

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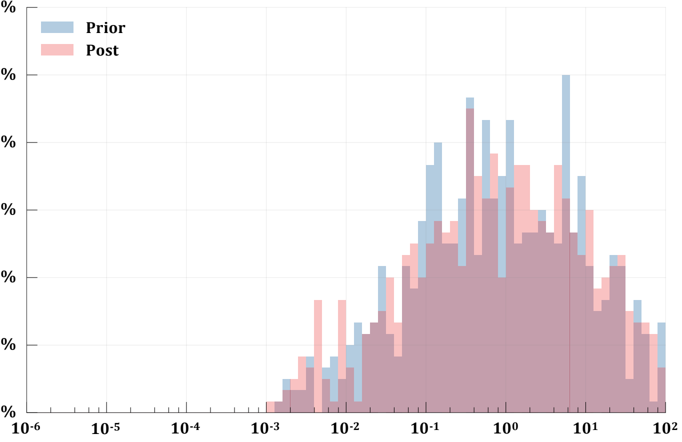

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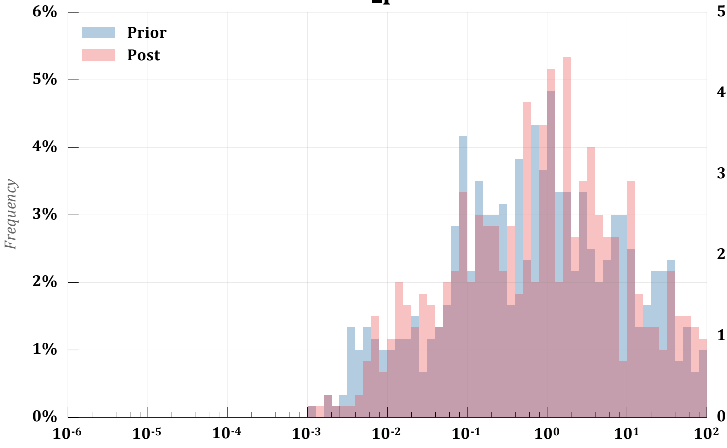

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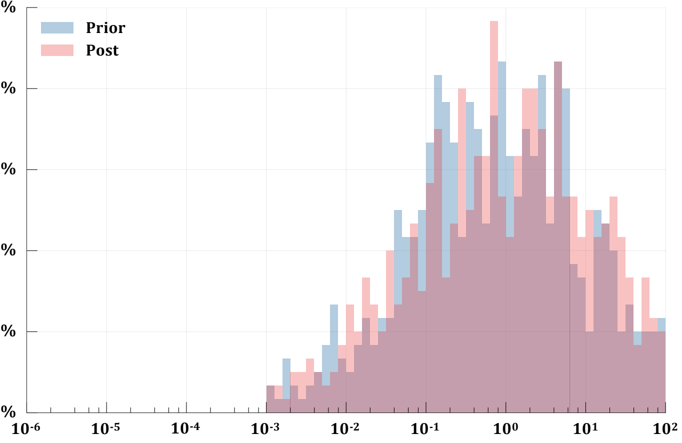
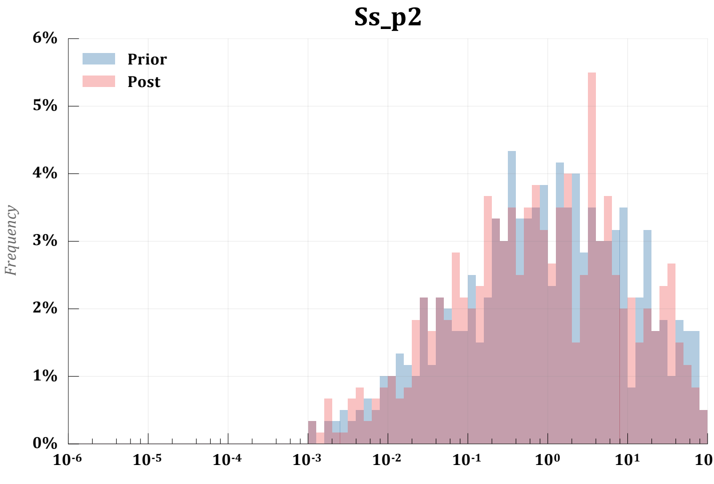


Ss_p19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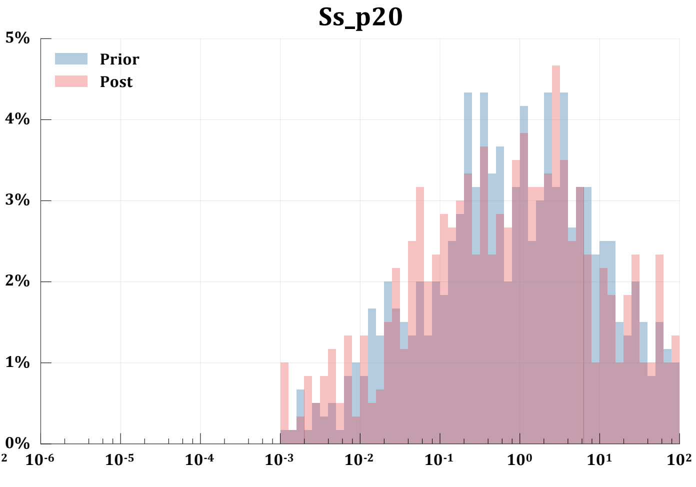
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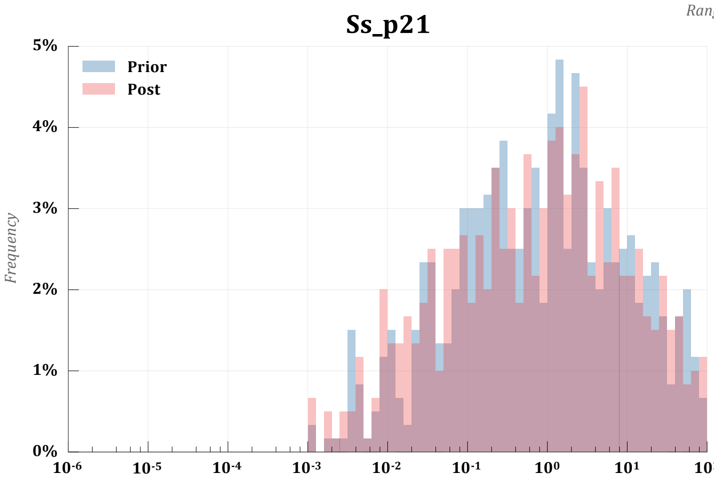
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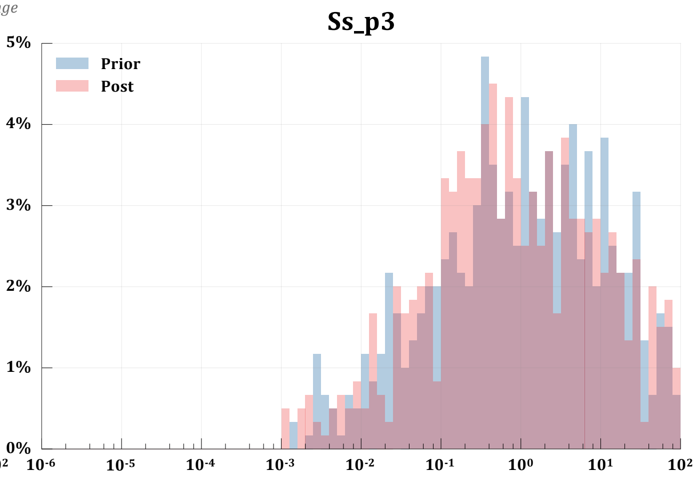
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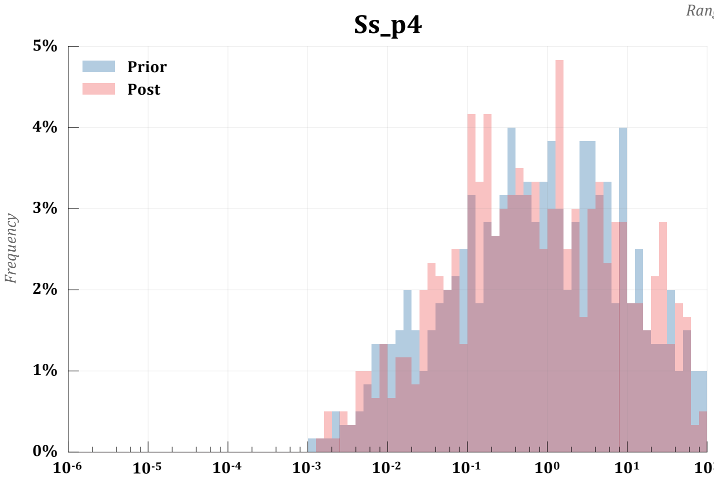
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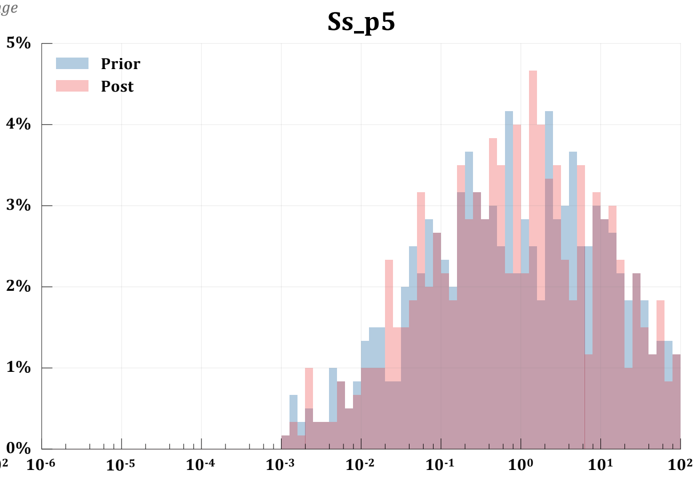
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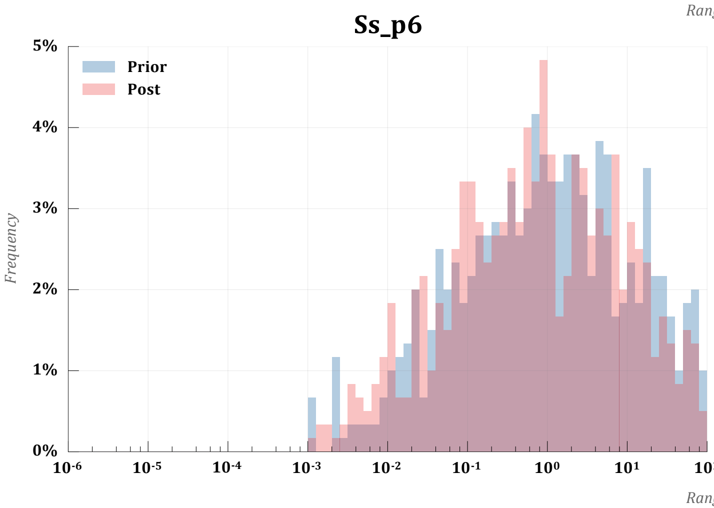
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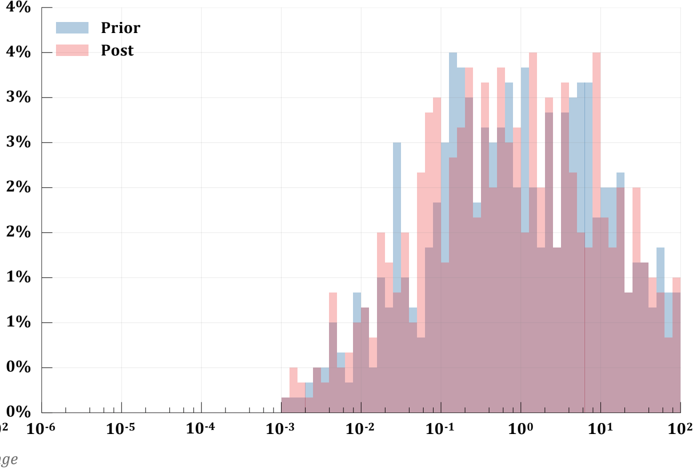
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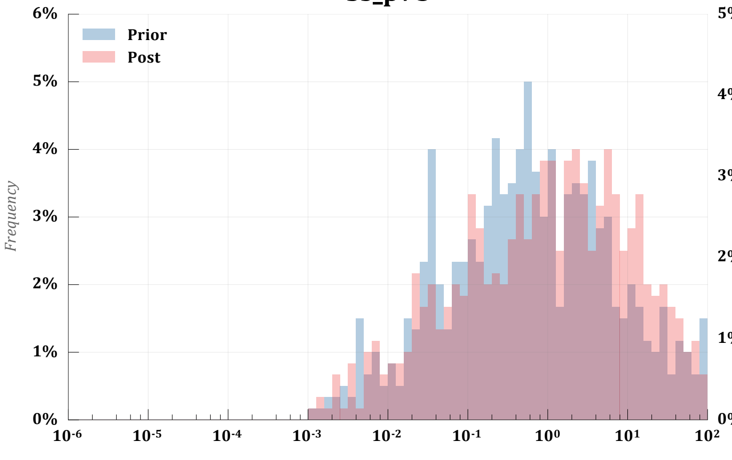
Ss_p75



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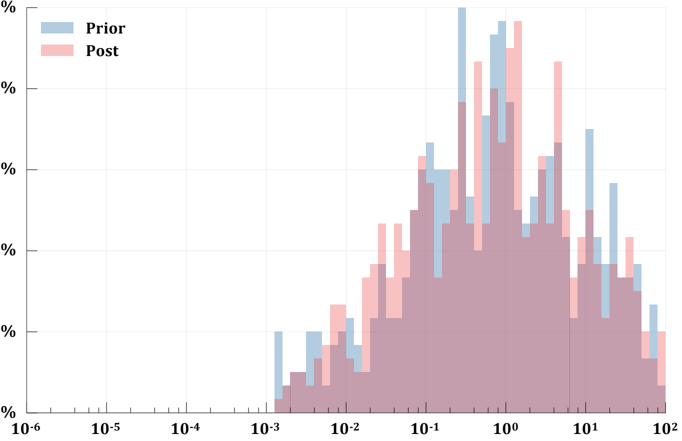
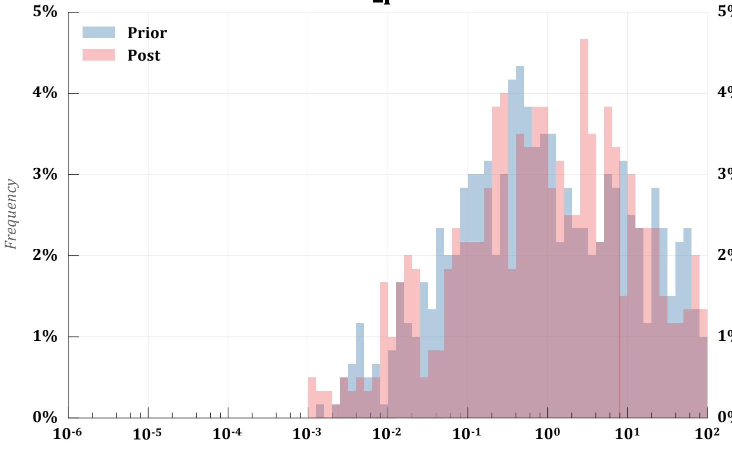
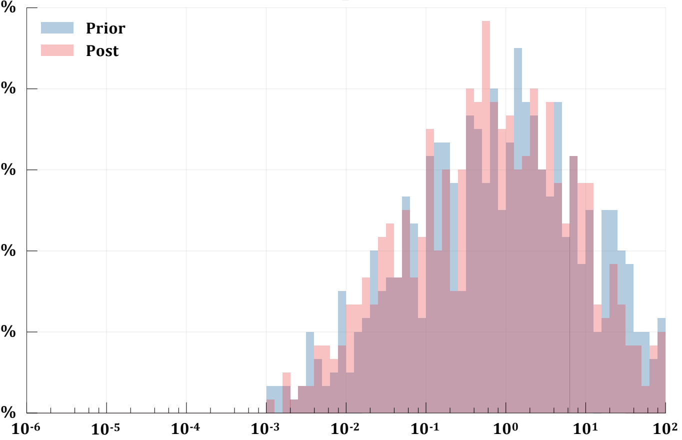


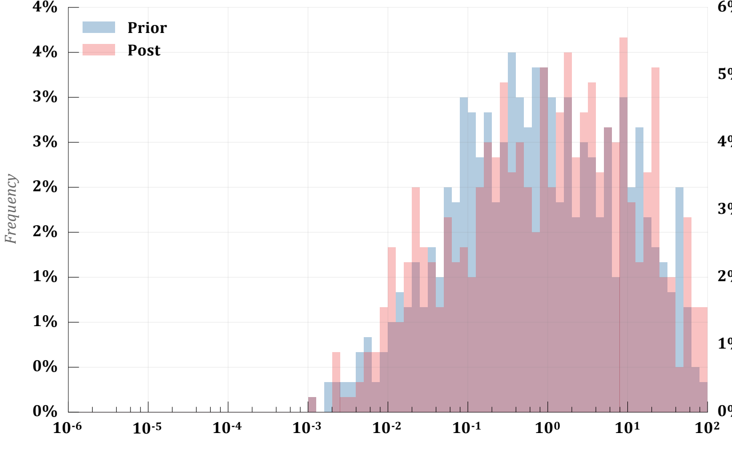
Ss_p78



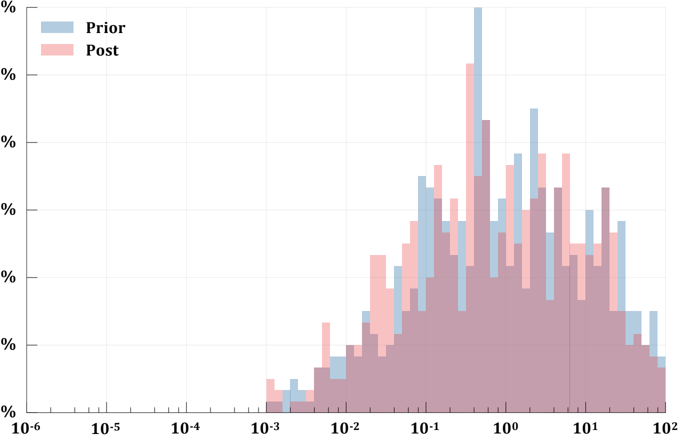
Ss_p79



Ss_p8



Ss_p80



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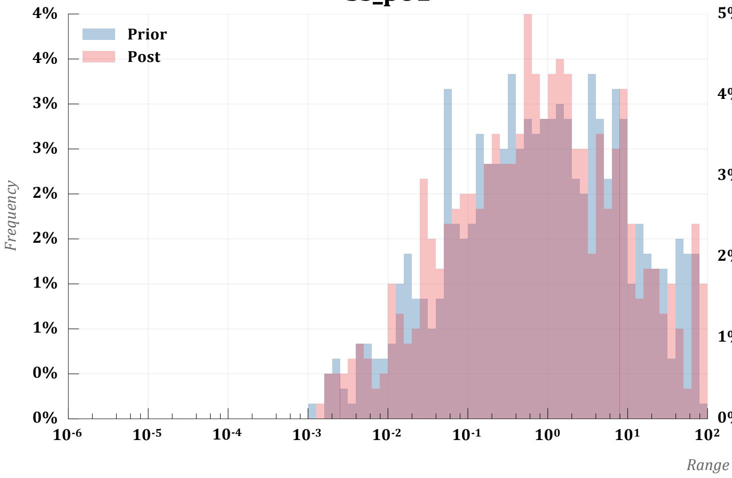
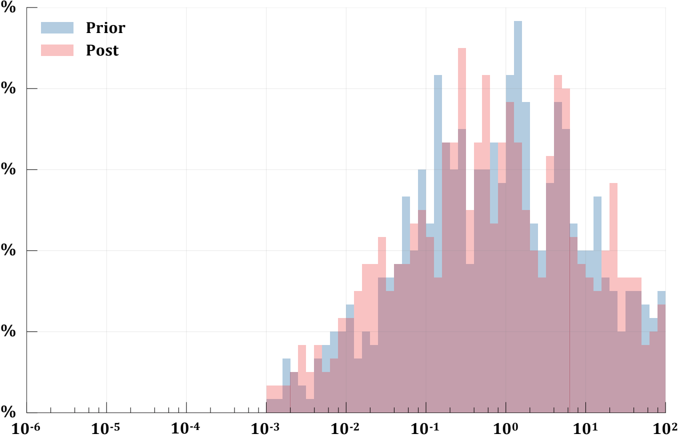
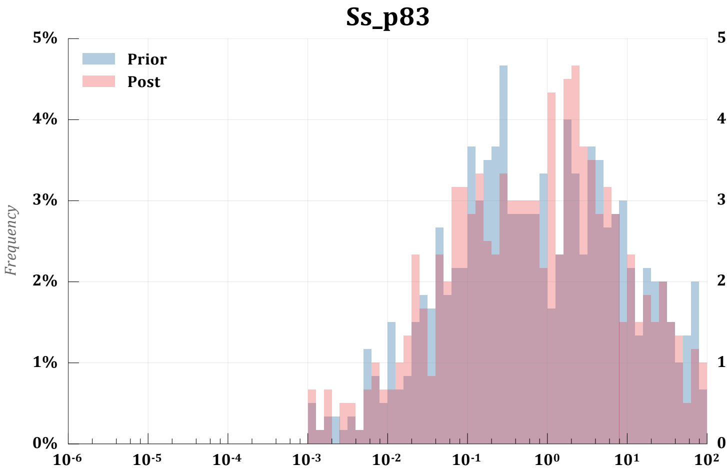


Ss_p82

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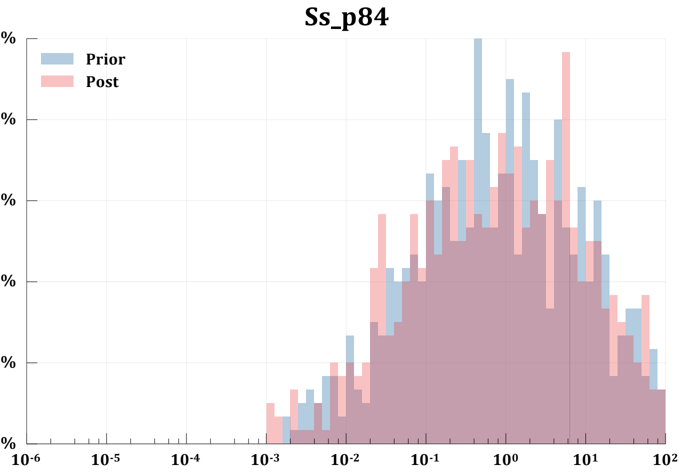
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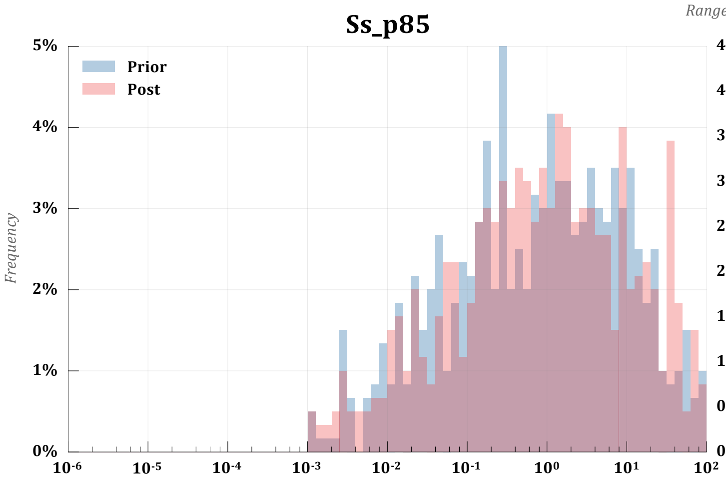
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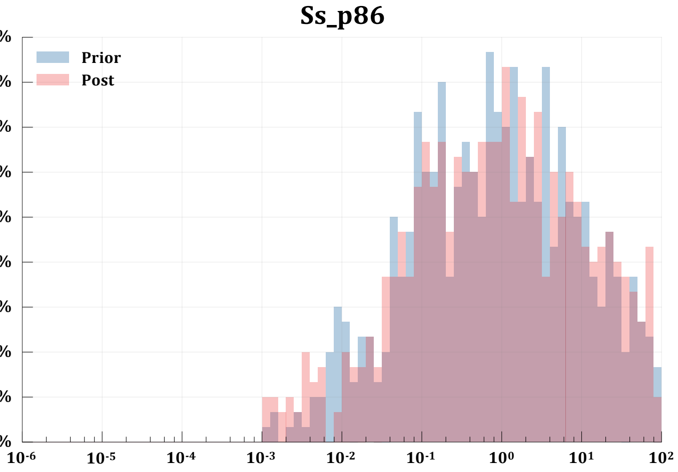
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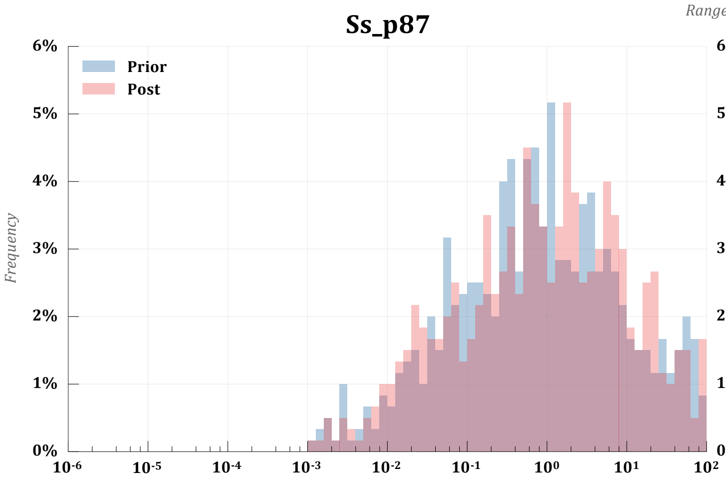
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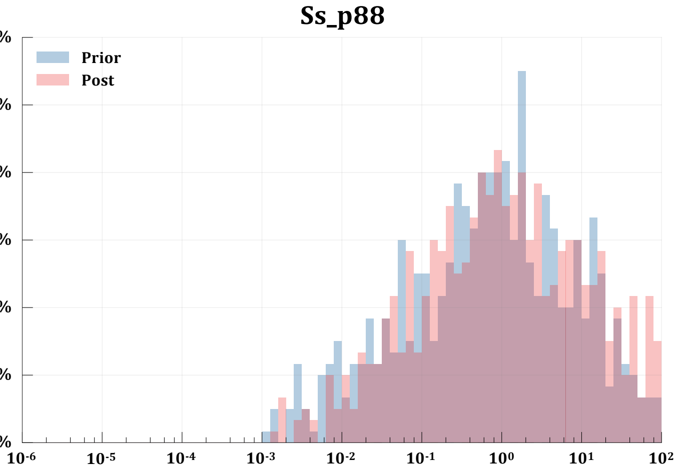
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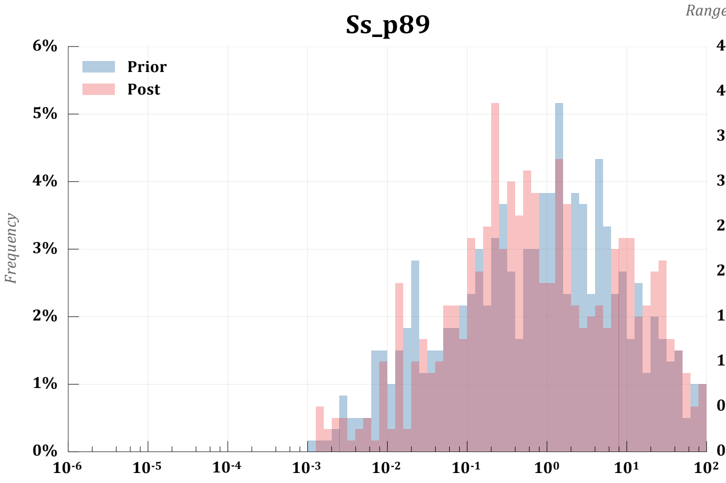
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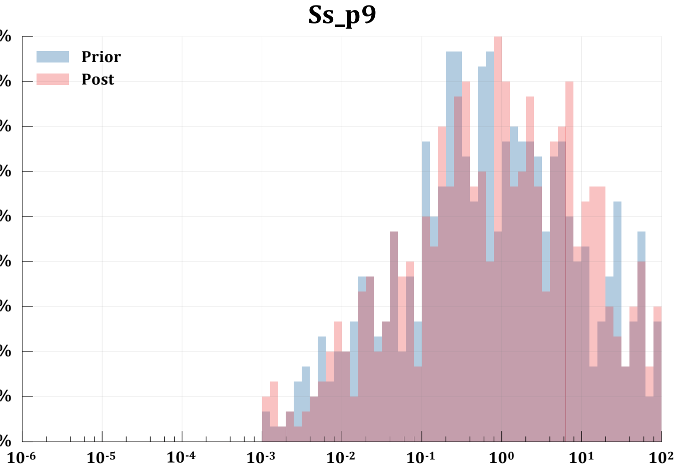
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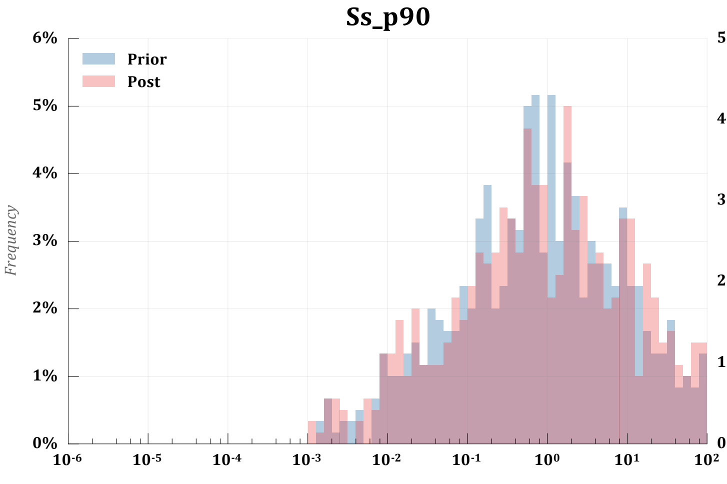
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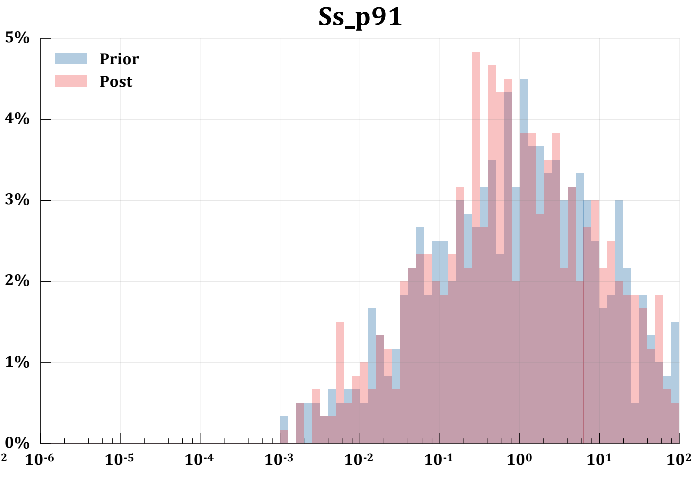
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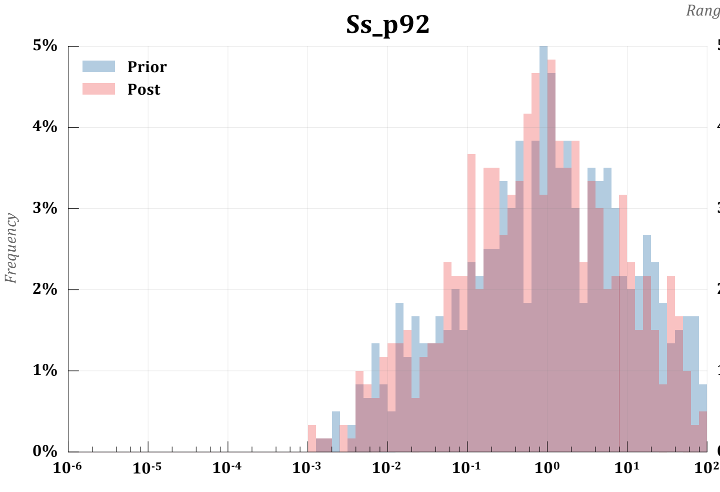
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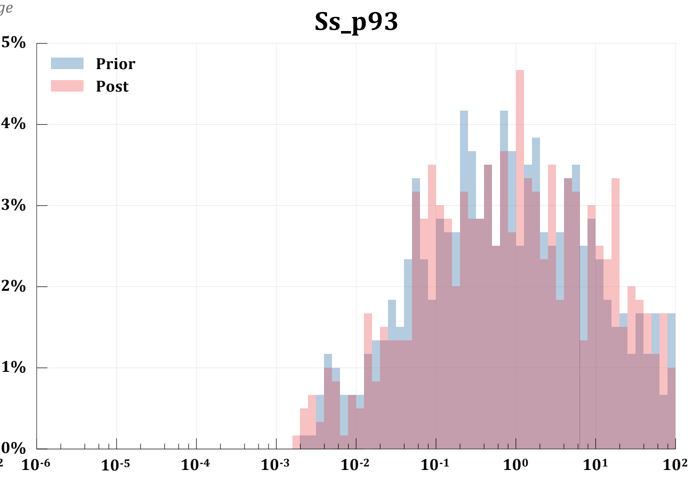
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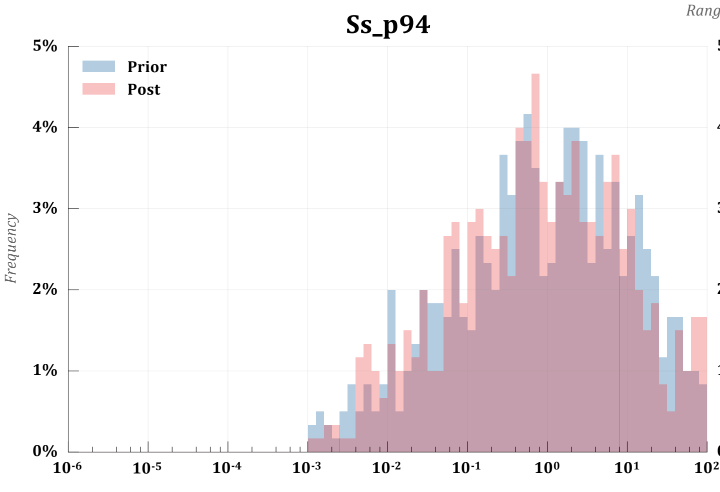
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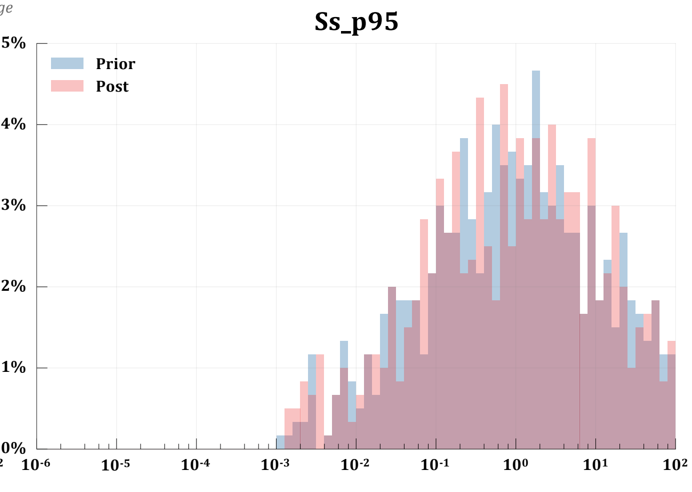
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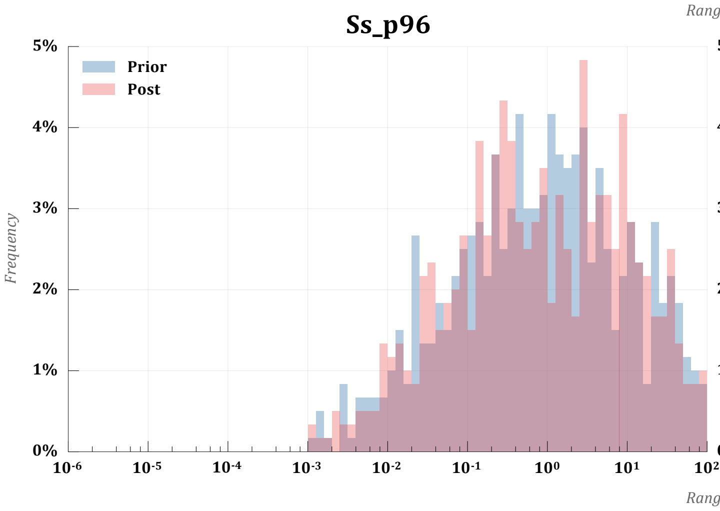
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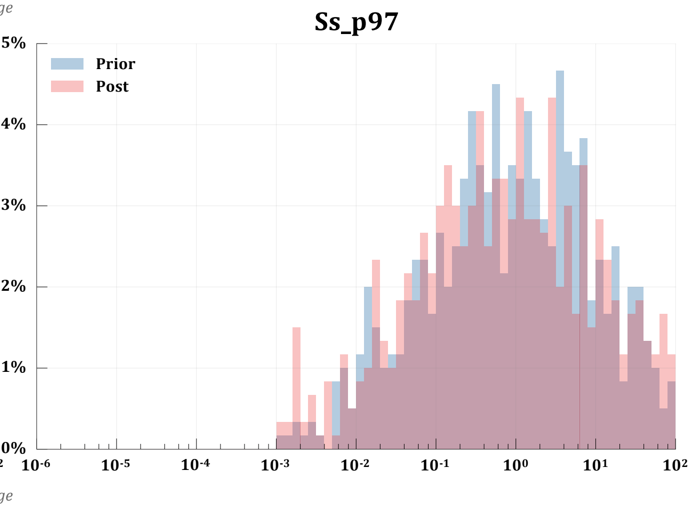
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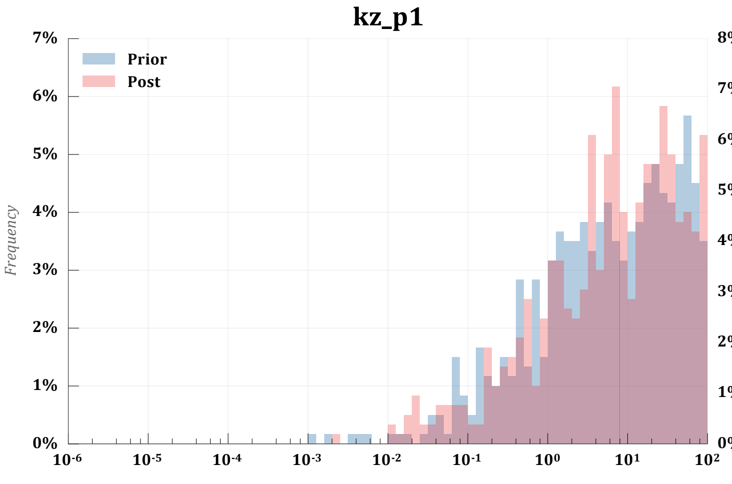
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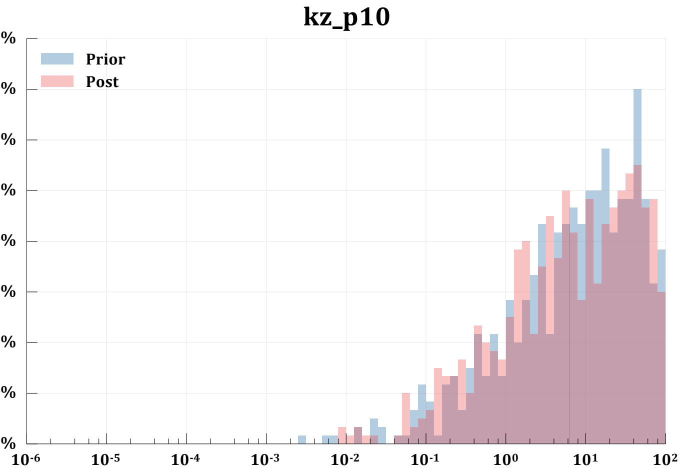
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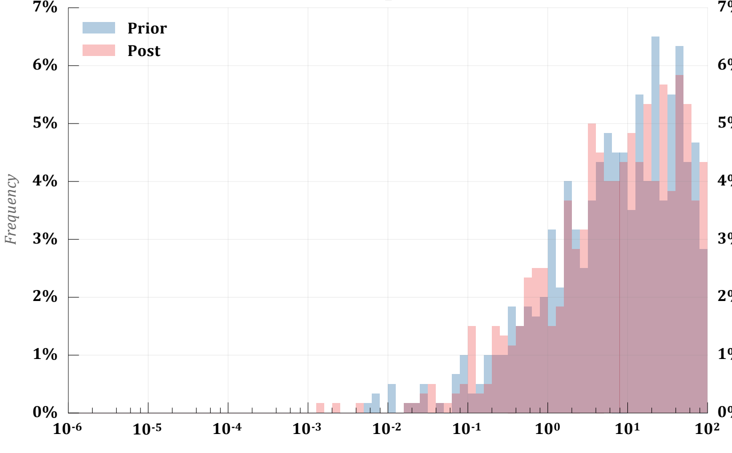
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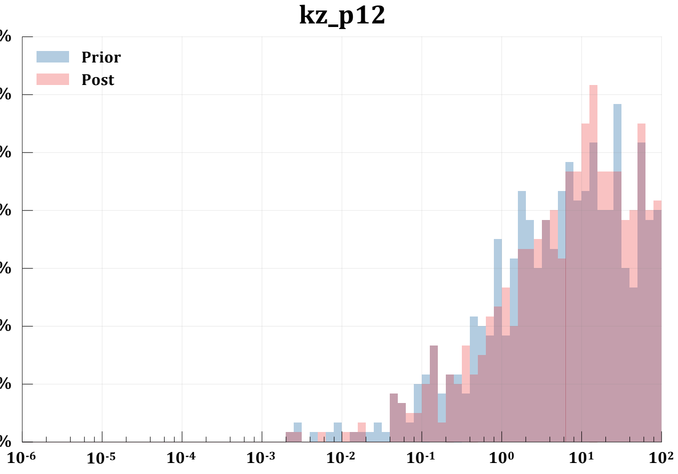
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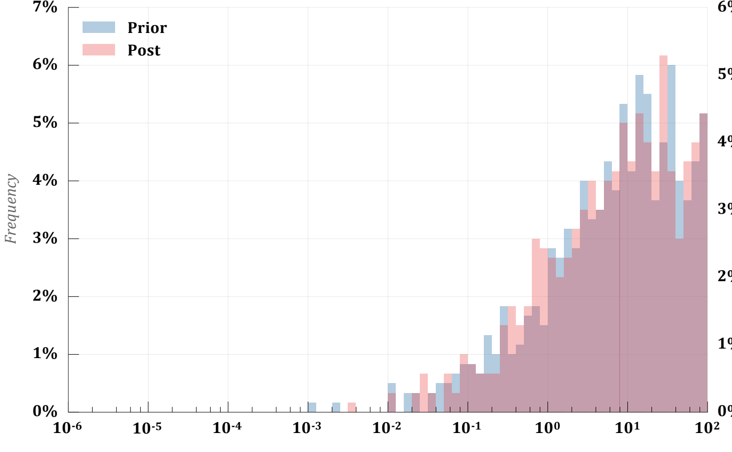
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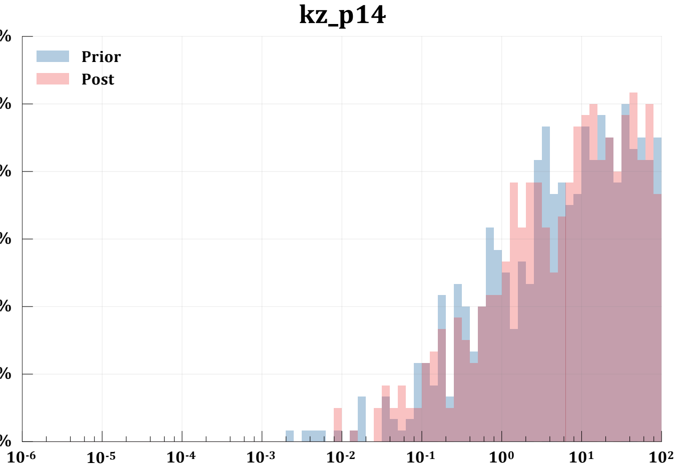
Range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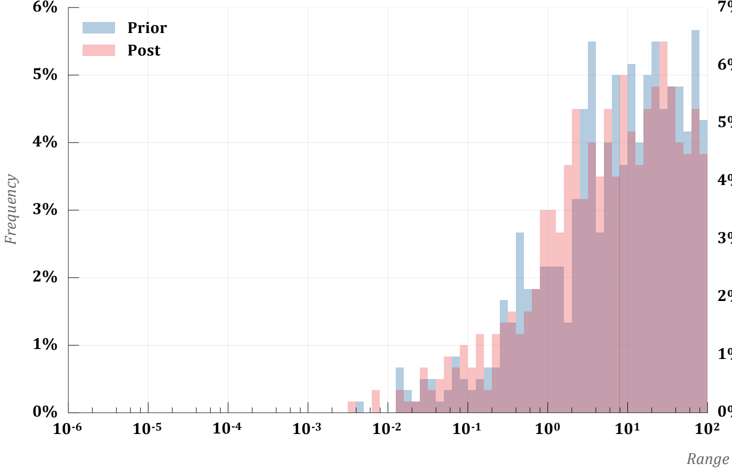
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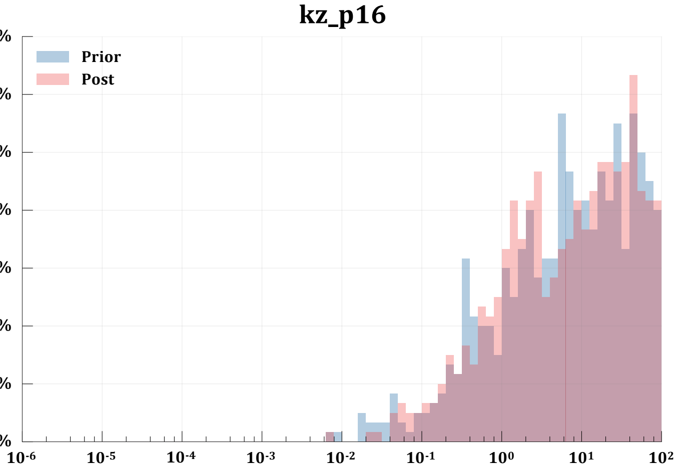
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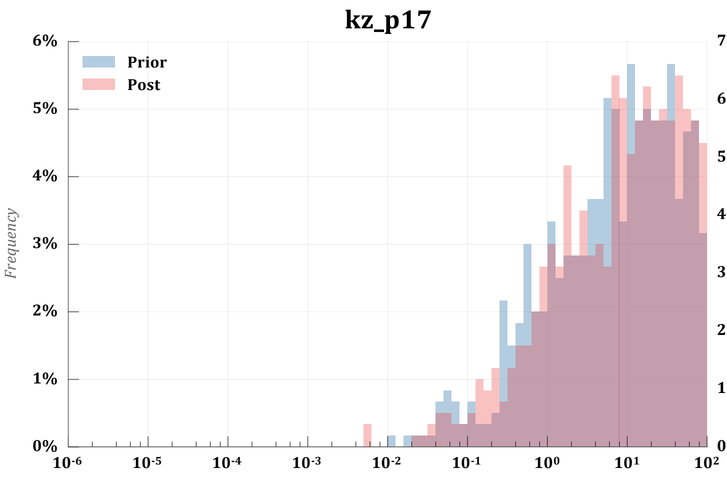
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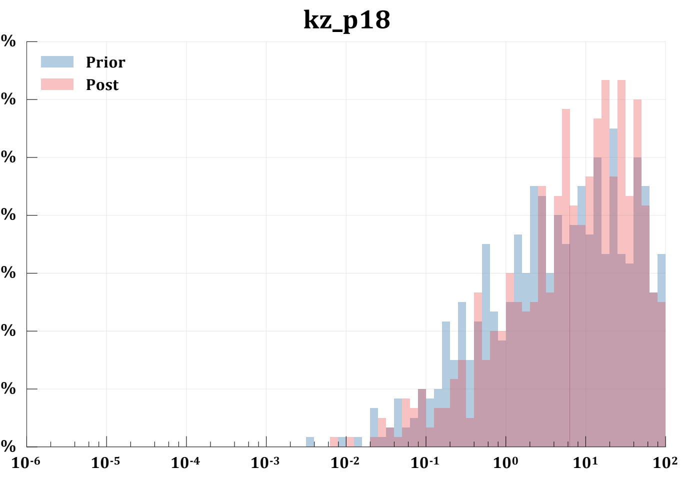
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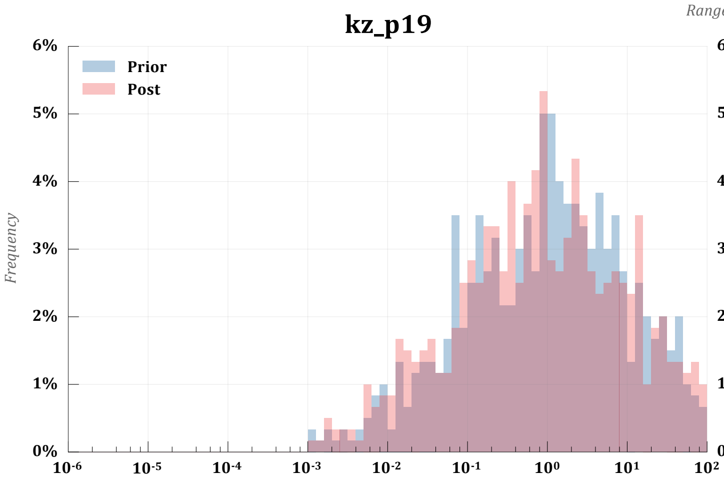
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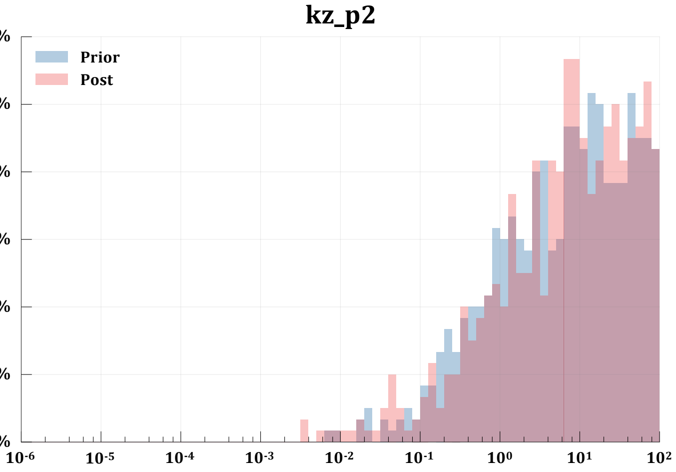
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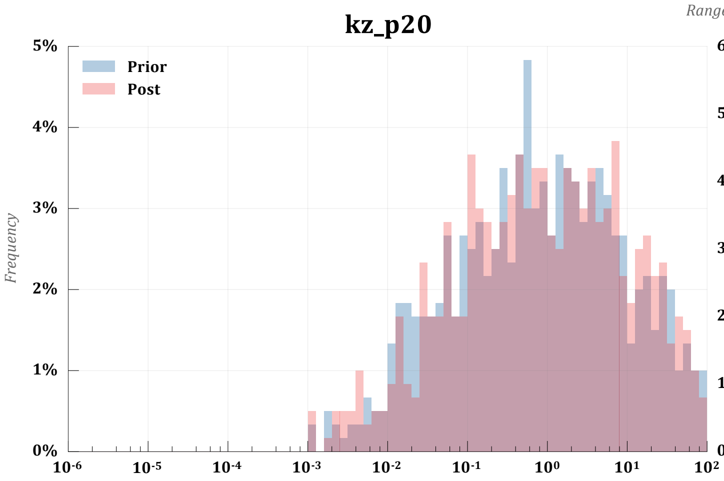
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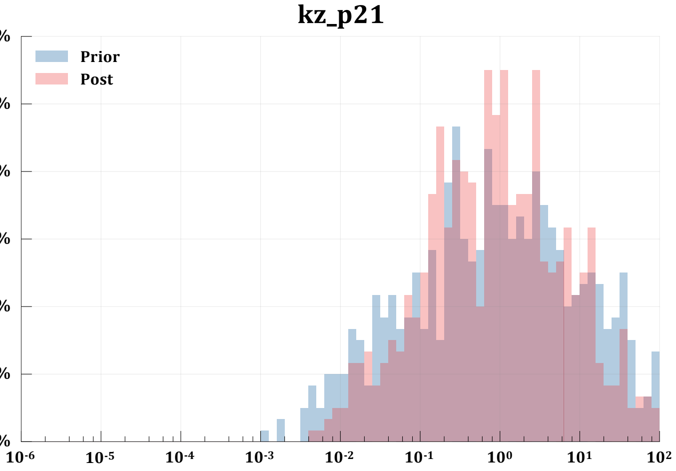
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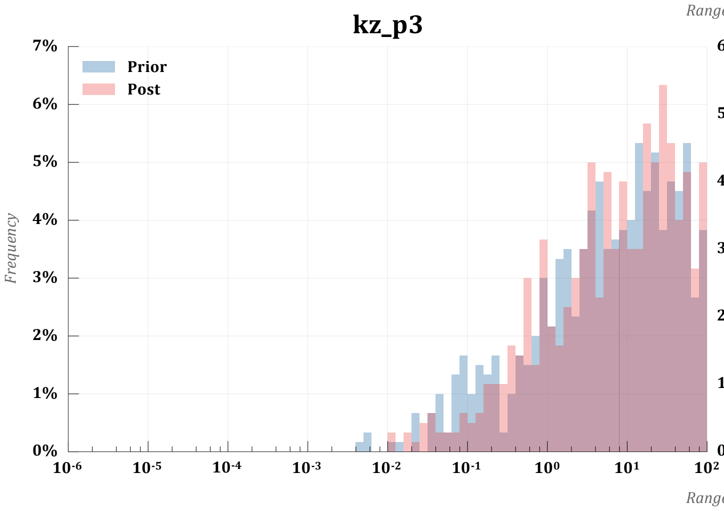
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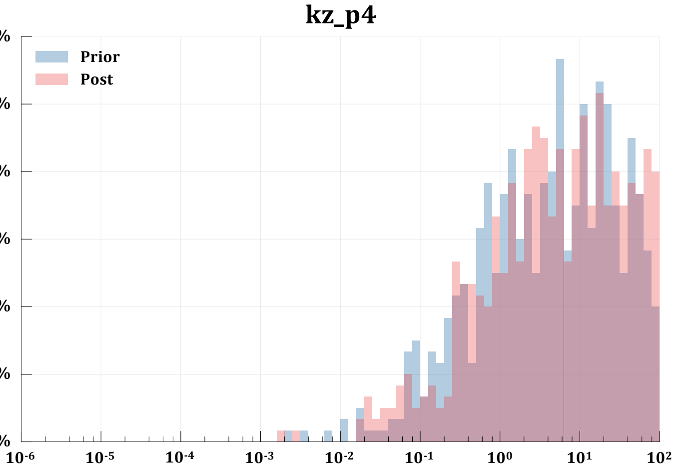
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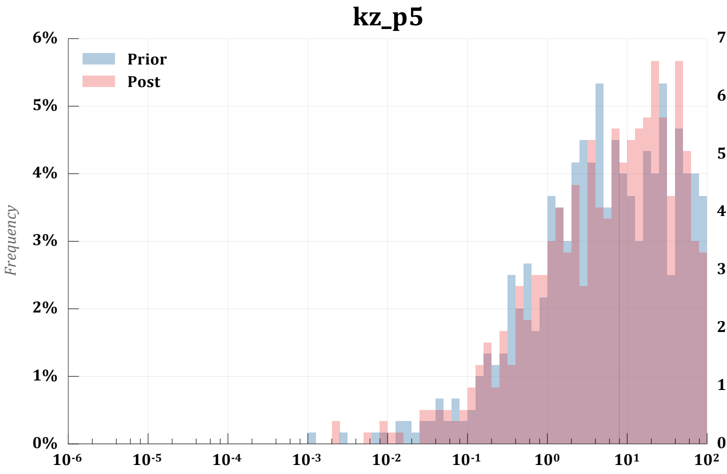
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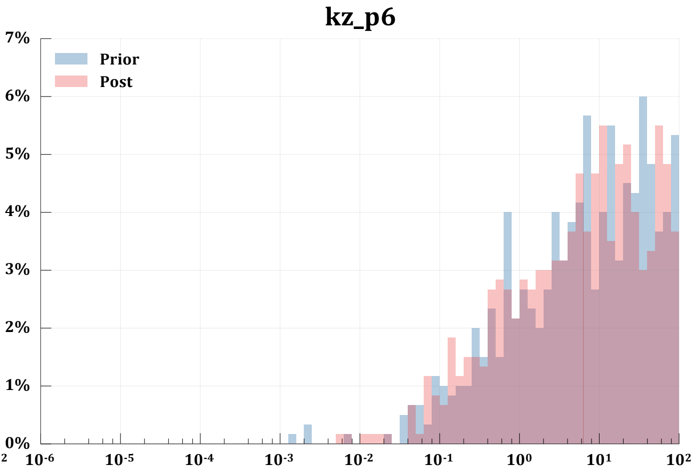
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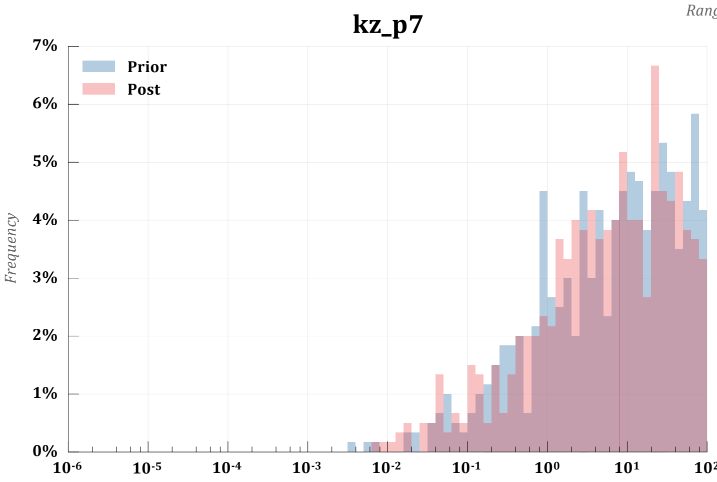
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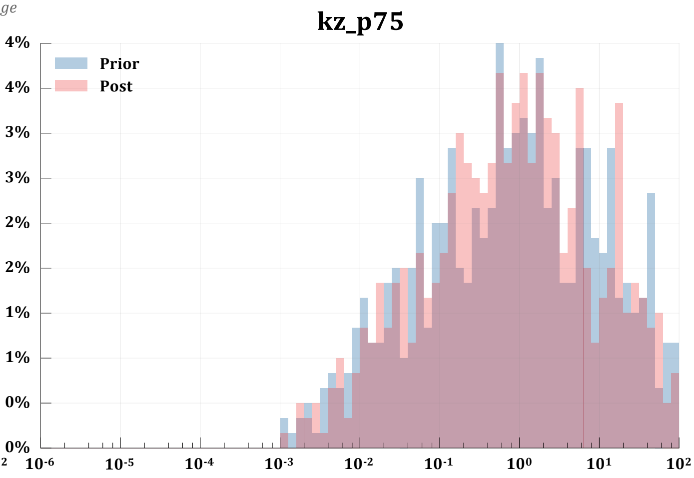
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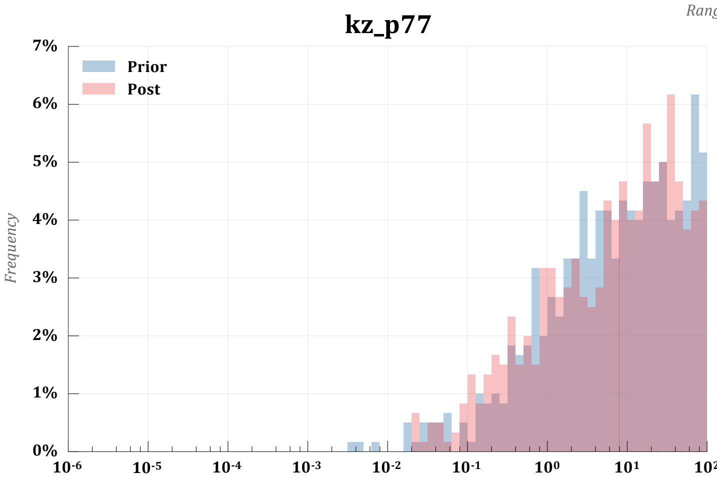
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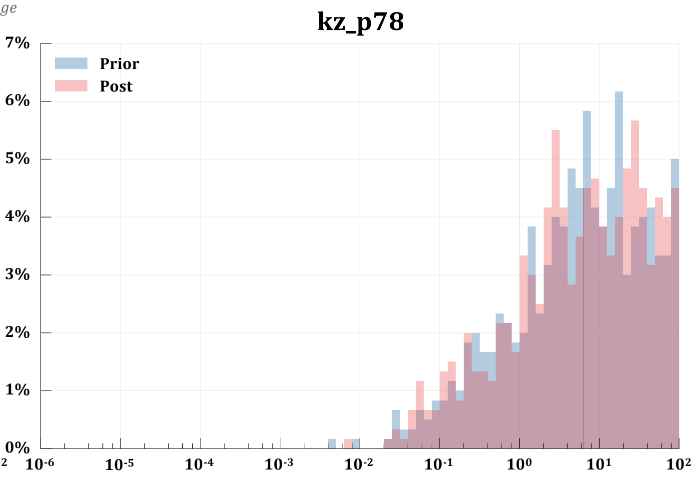
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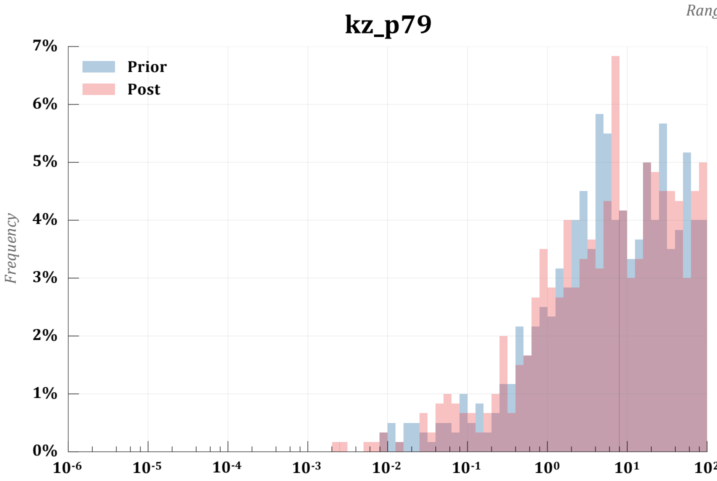
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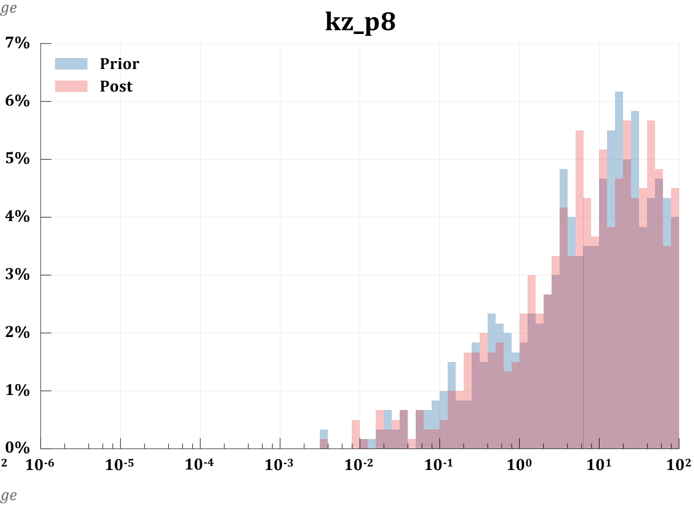
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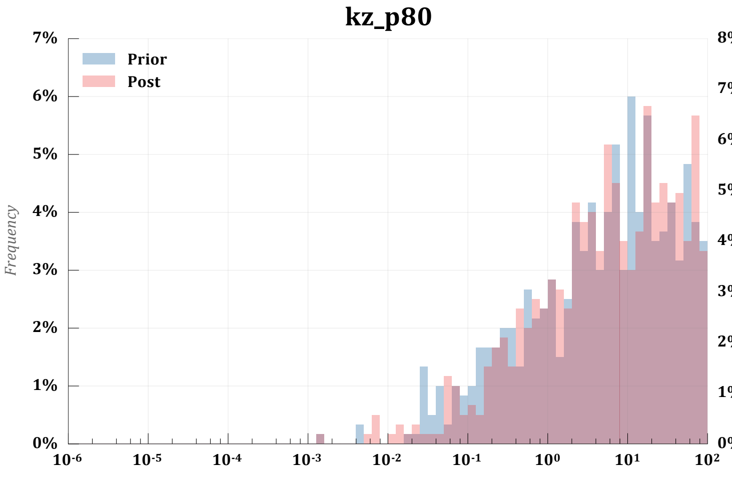
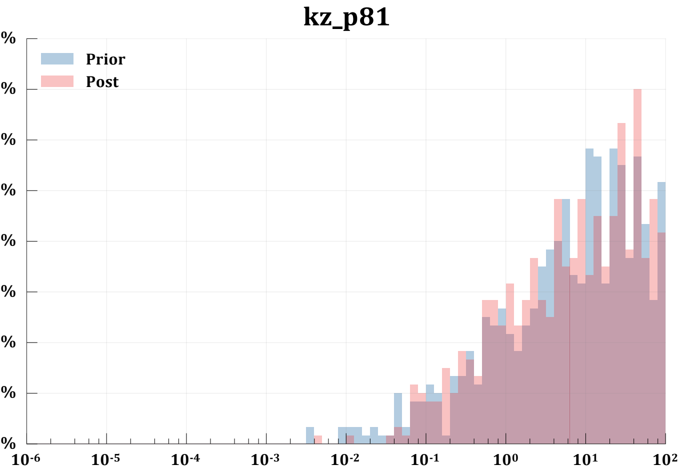

kz_p80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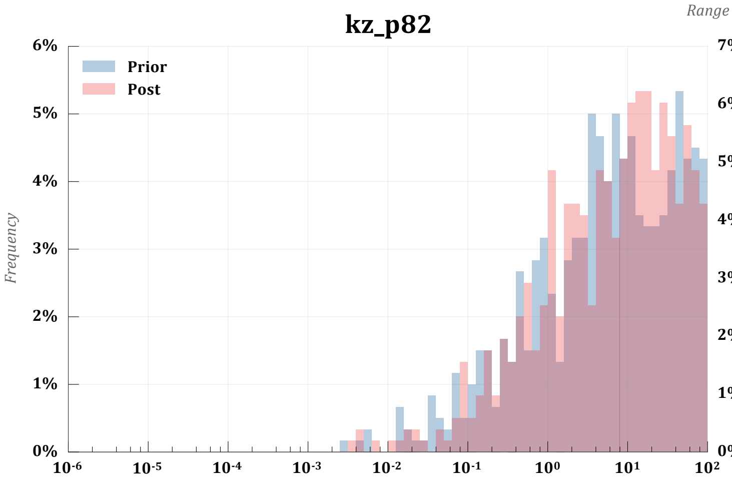
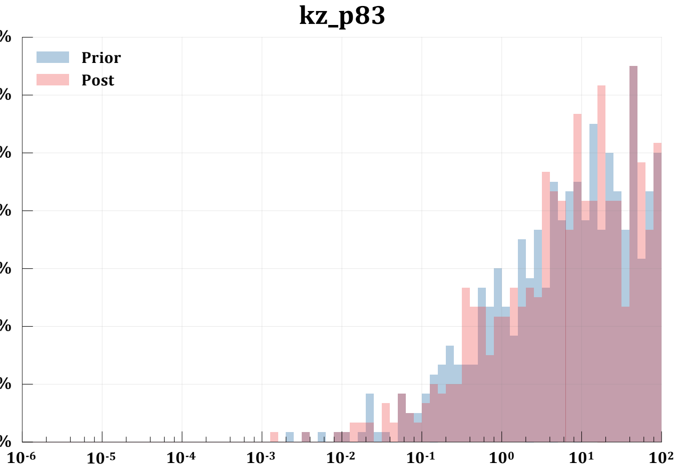
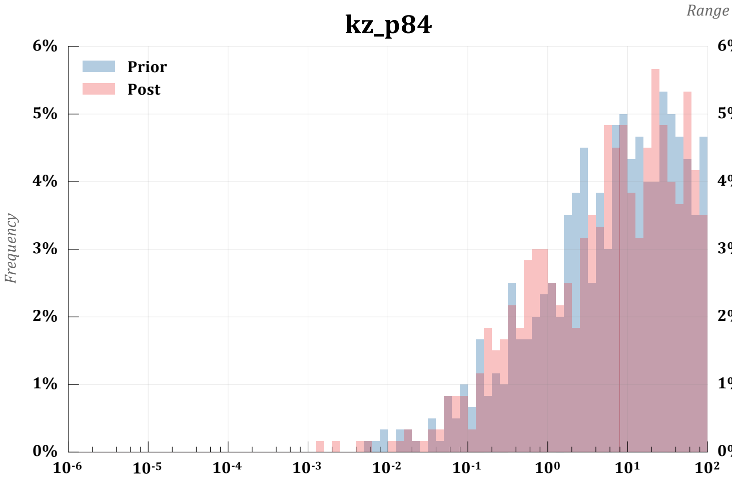

kz_p82


kz_p83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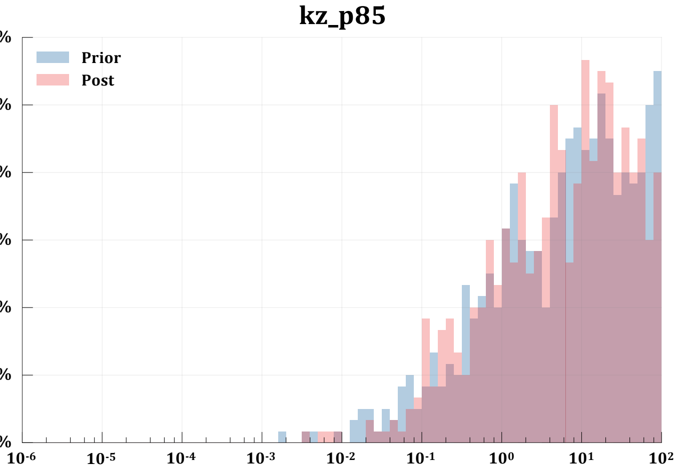
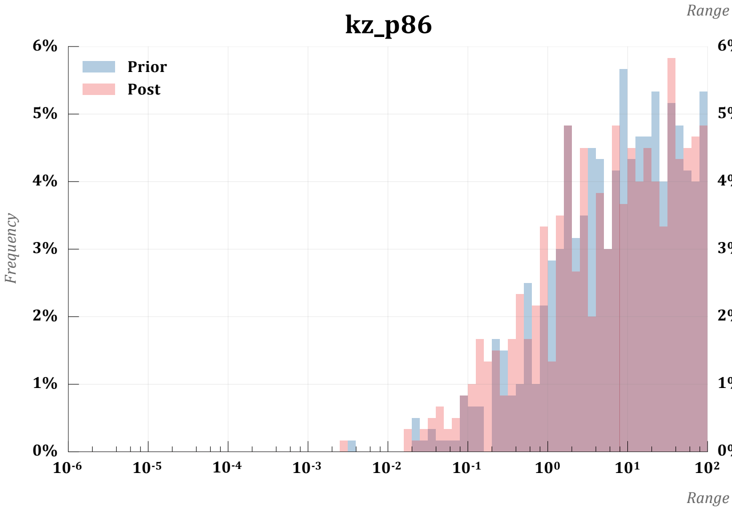

kz_p85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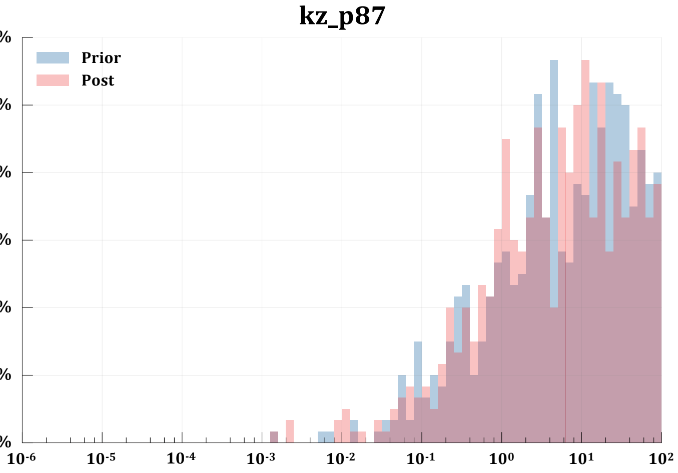
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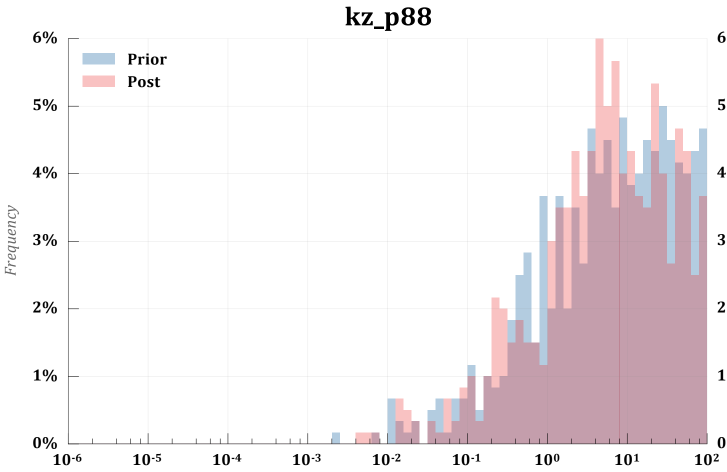
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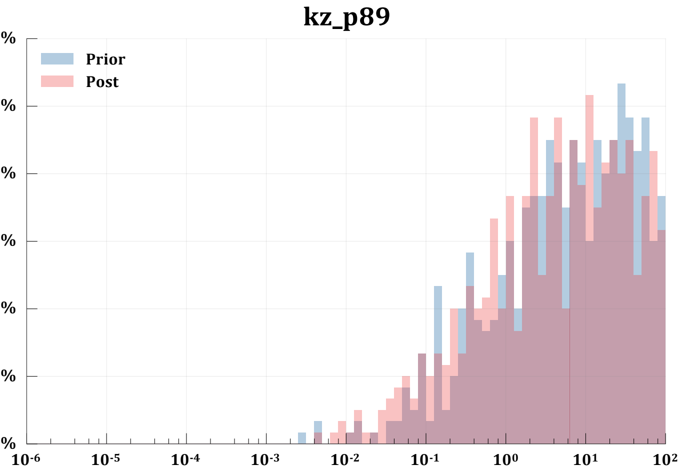
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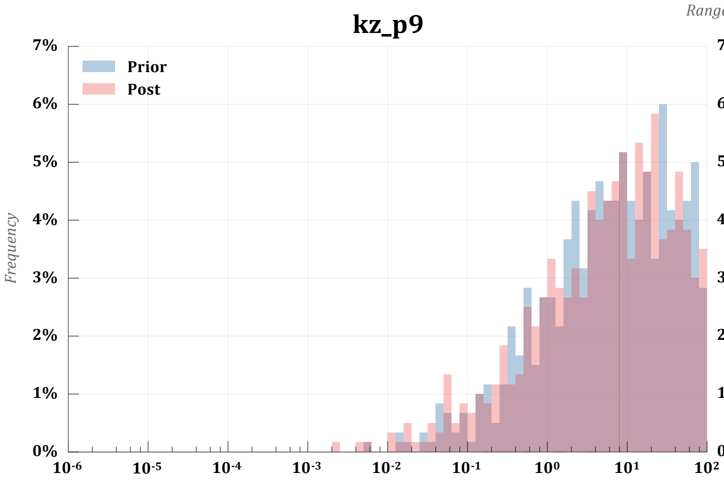
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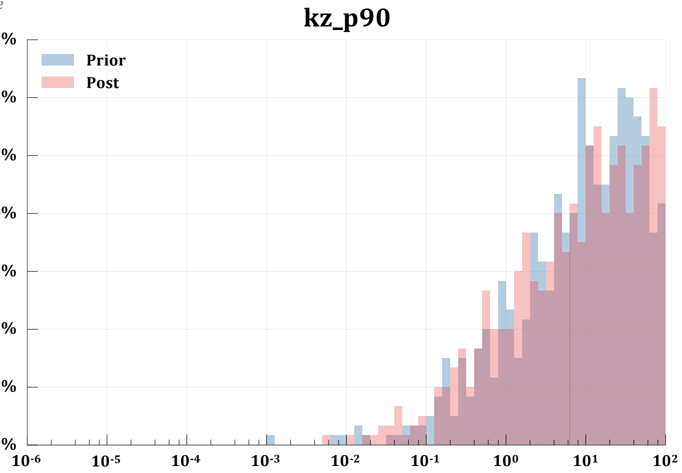
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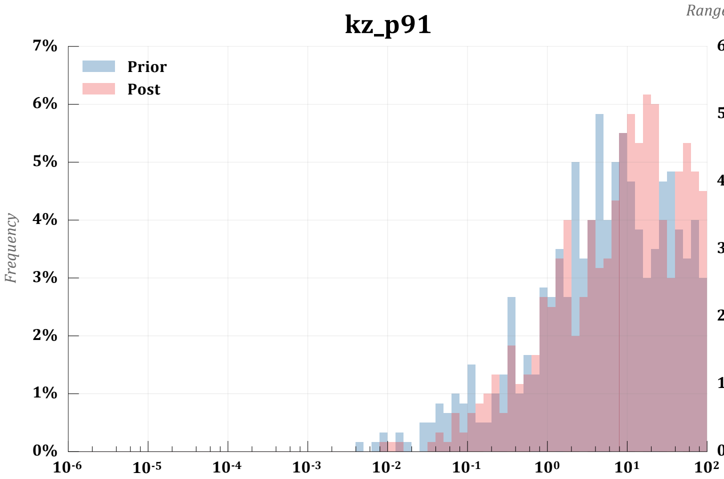
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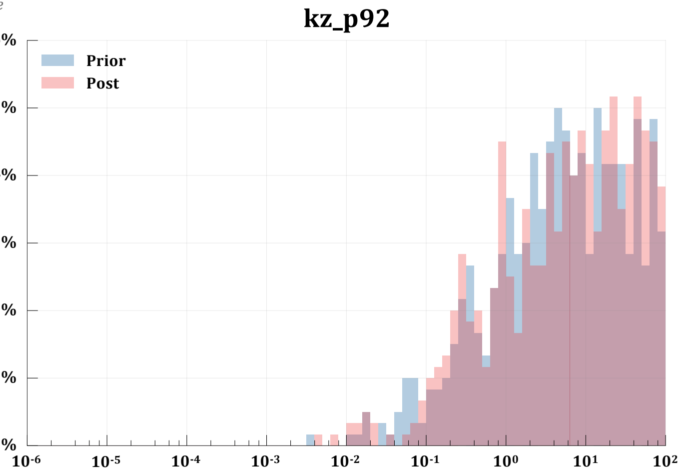
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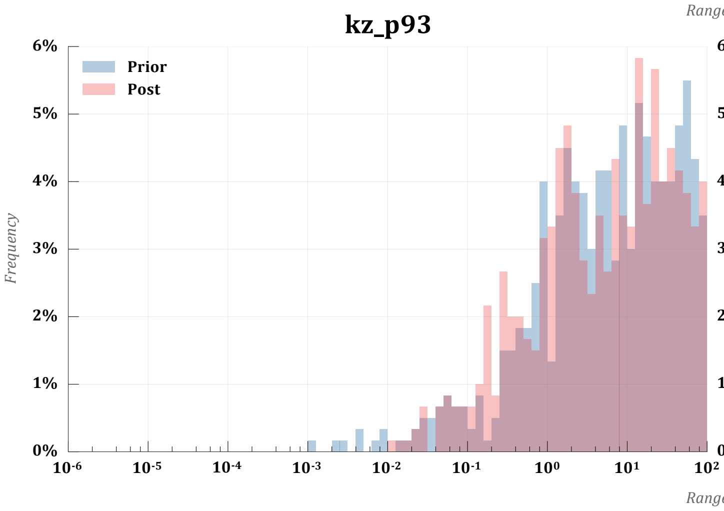
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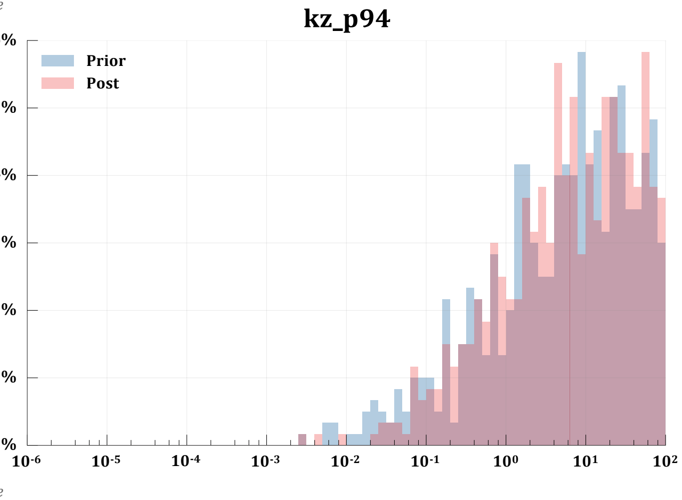
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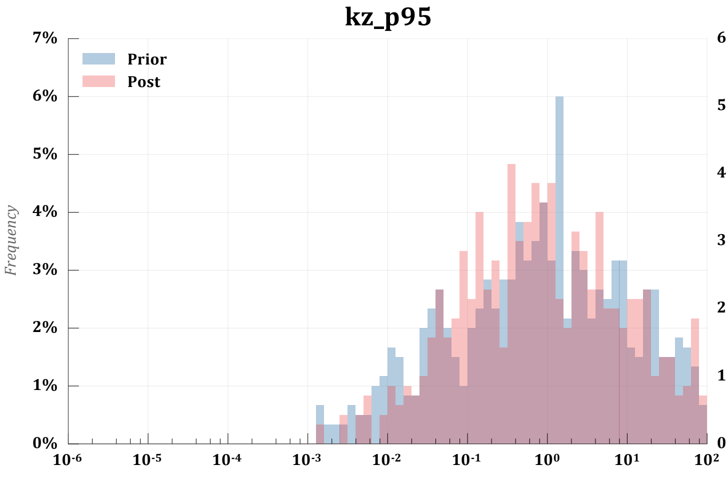
Range



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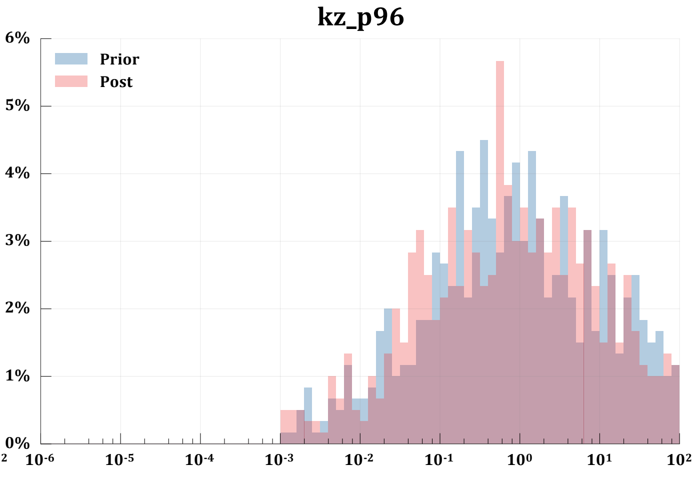

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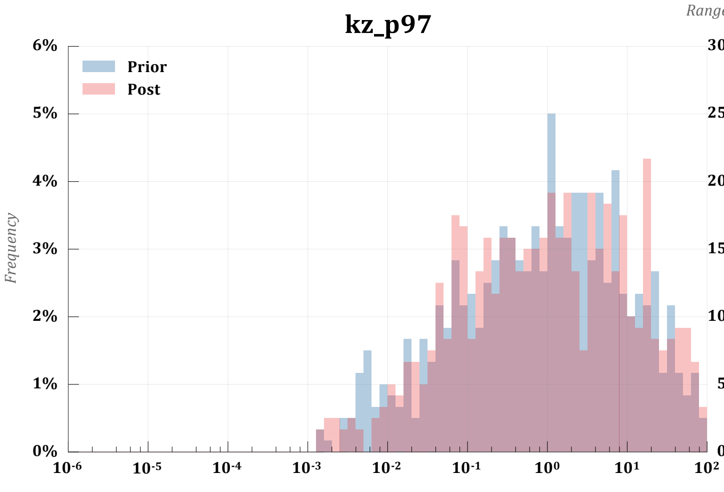

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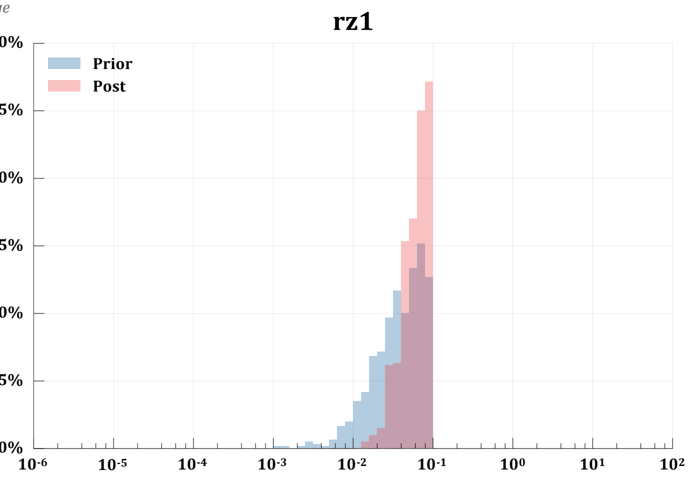

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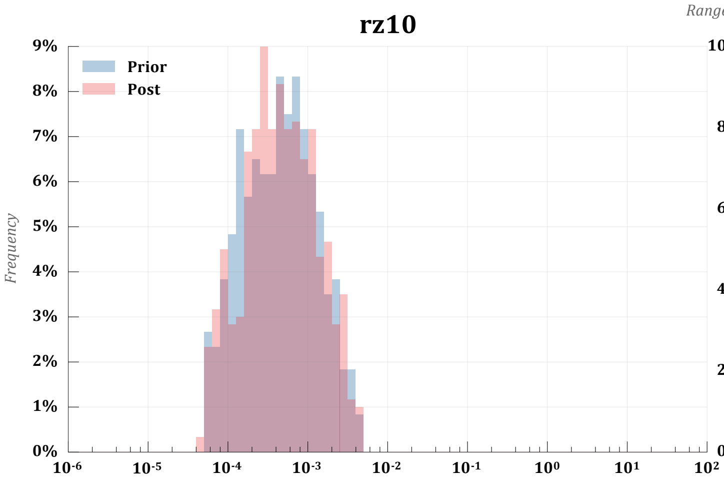

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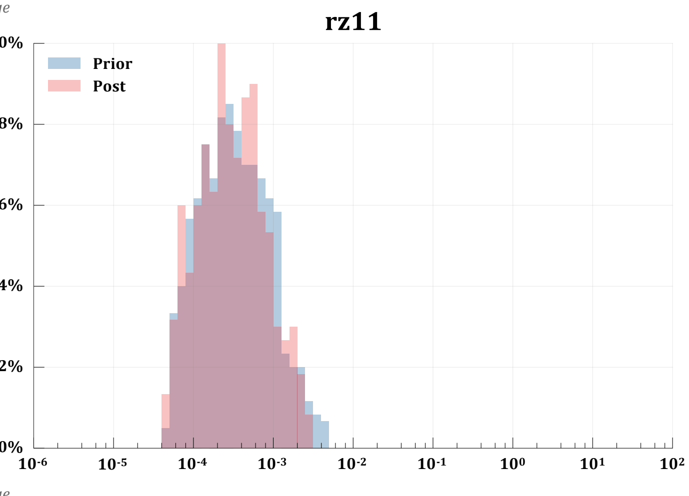

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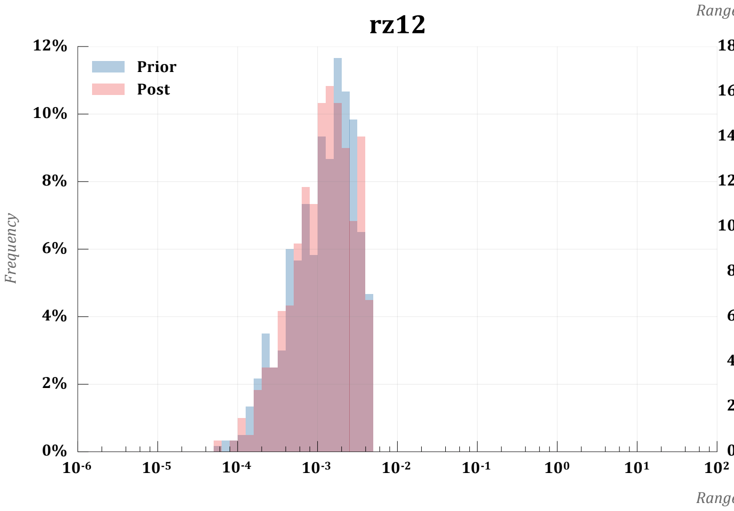

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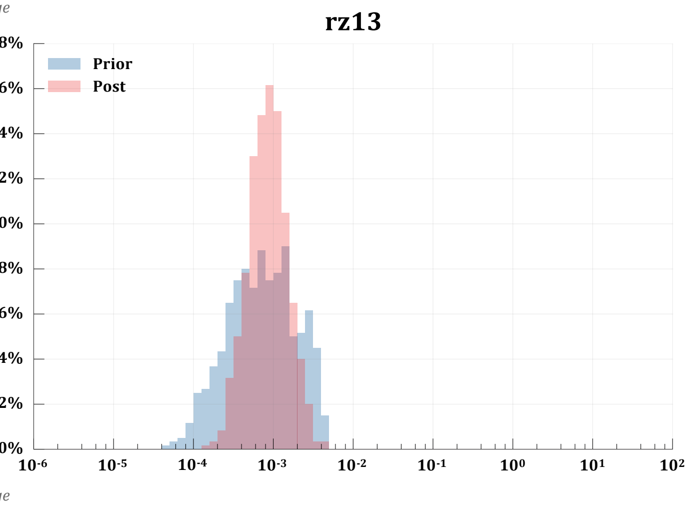

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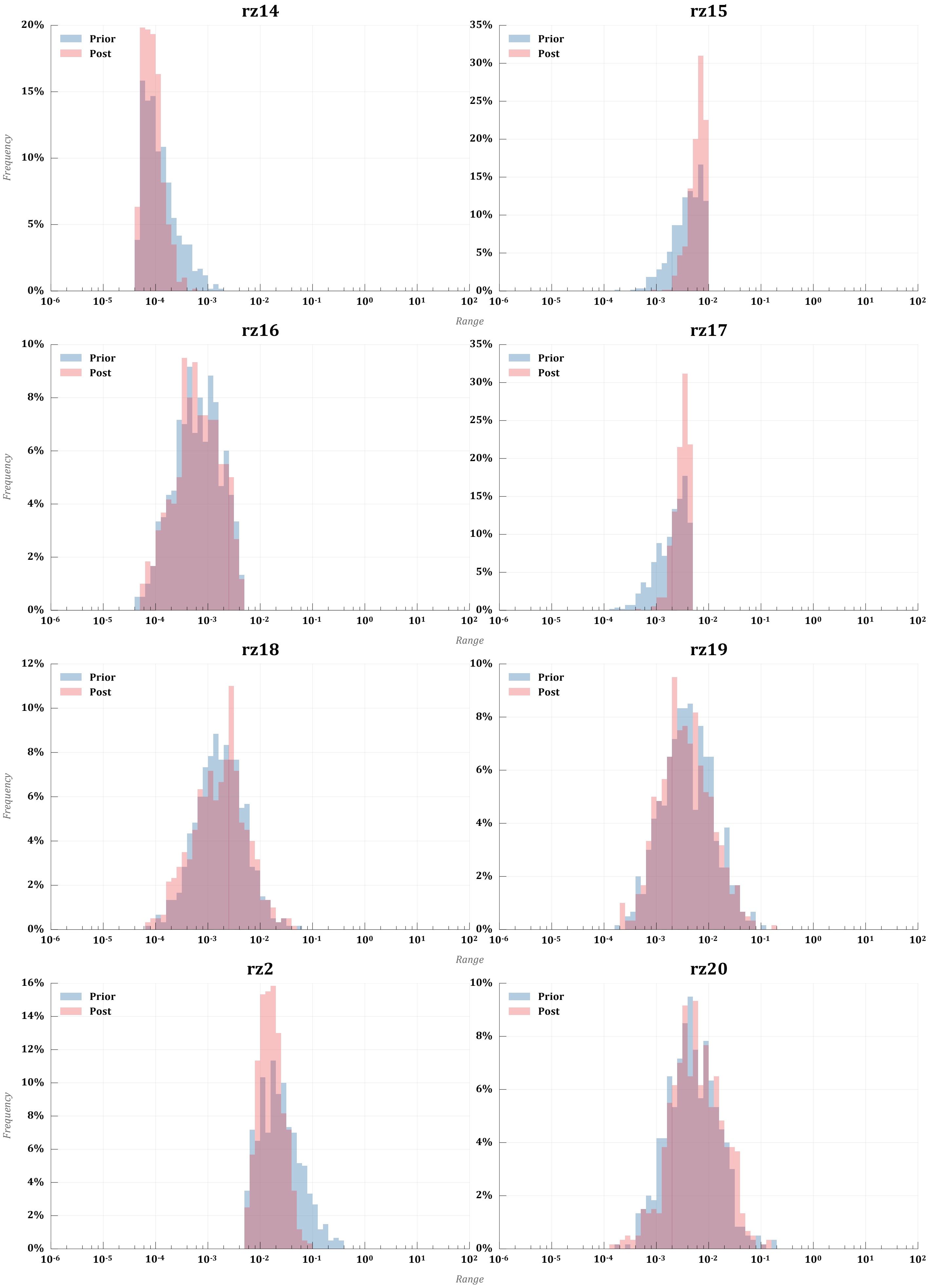
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rz15
Prior
Post
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25%
20%
15%
10%
5%
0%
10^{-6}
10^{-5}
10^{-4}
10^{-3}
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10^{0}
10^{1}
10^{2}
Range
rz16
Prior
Post
Frequency
10%
8%
6%
4%
2%
0%
rz17
Prior
Post
35%
30%
25%
20%
15%
10%
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Range
rz18
Prior
Post
Frequency
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rz19
Prior
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Range
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Prior
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12%
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rz20
Prior
Post
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8%
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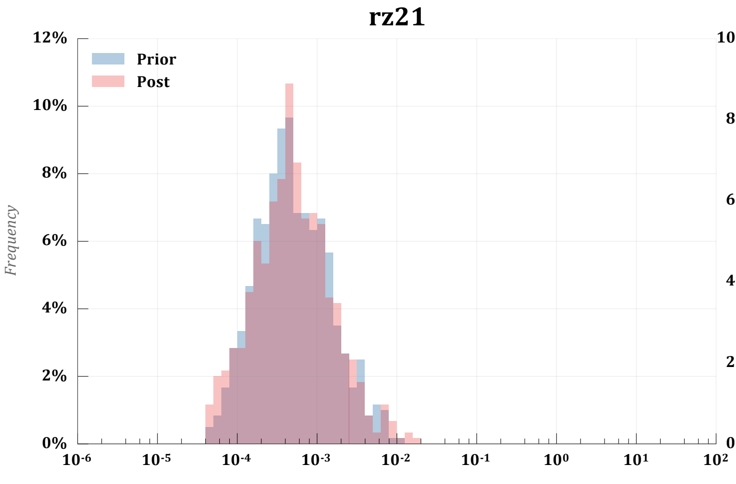
2%
0%
Range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10⁻⁵
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10⁻³
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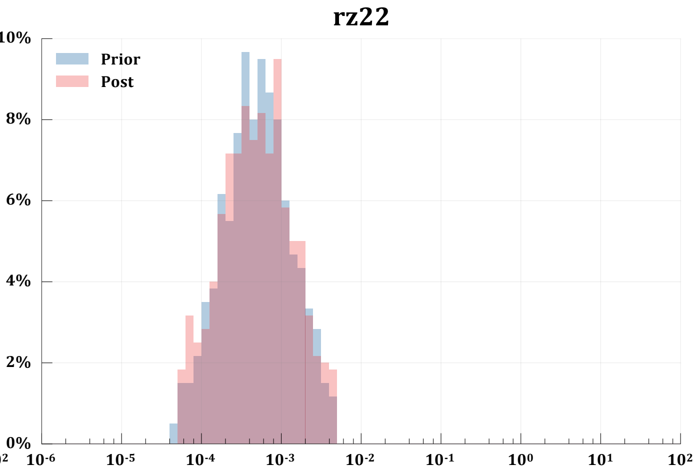
10⁻¹
10⁰
10¹
10²
Range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10⁻¹
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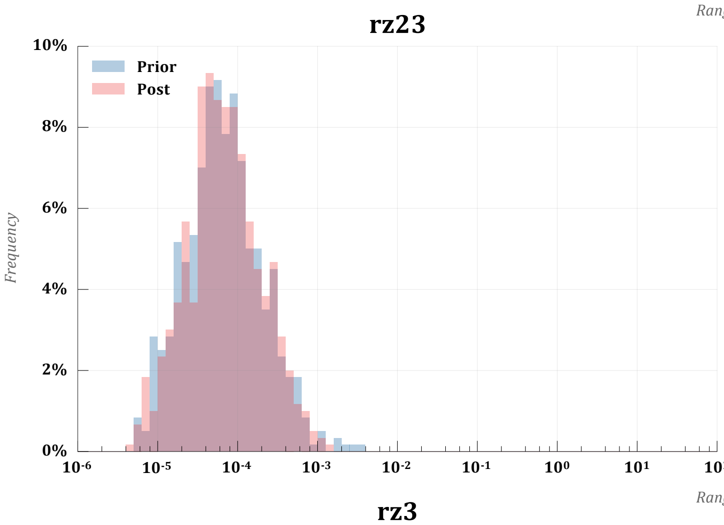
10¹
10²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Prior
Post
Frequency
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8%
6%
4%
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0%
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10⁻⁵
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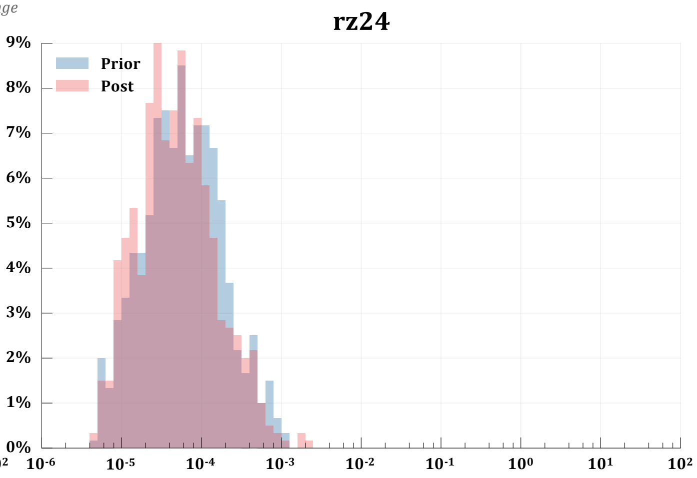
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
Range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10⁻³
10⁻²
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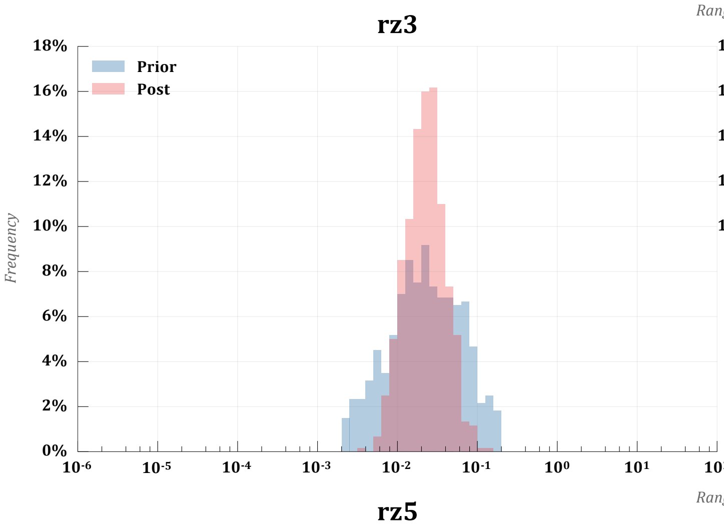
10²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Frequency
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10⁻⁴
10⁻³
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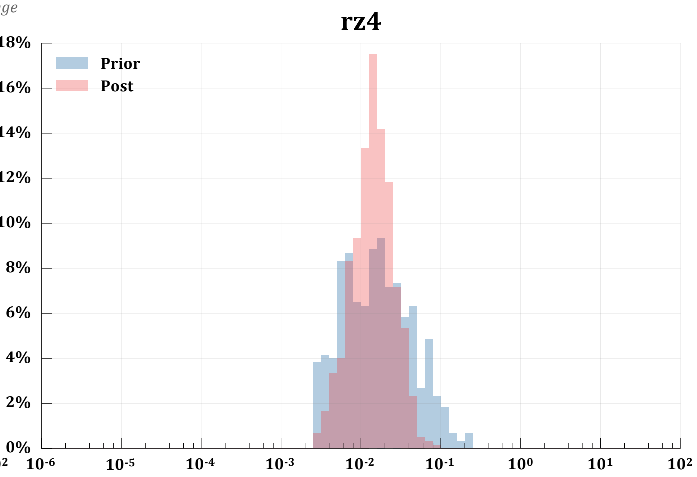
10⁻¹
10⁰
10¹
10²
Range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6%
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0%
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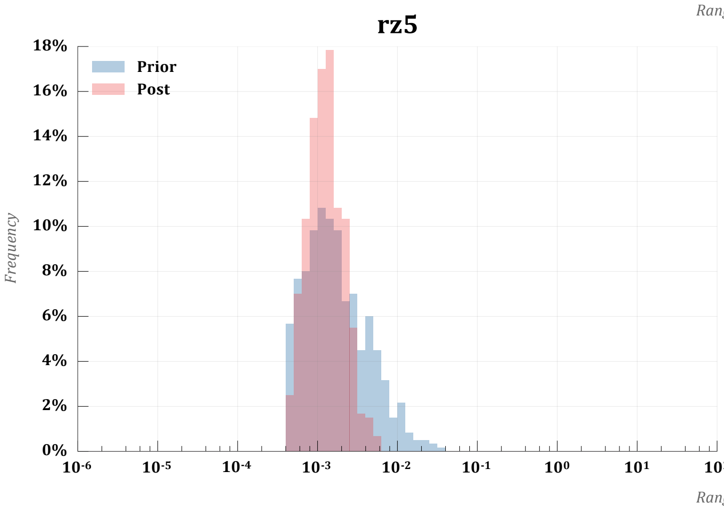
10⁻¹
10⁰
10¹
10²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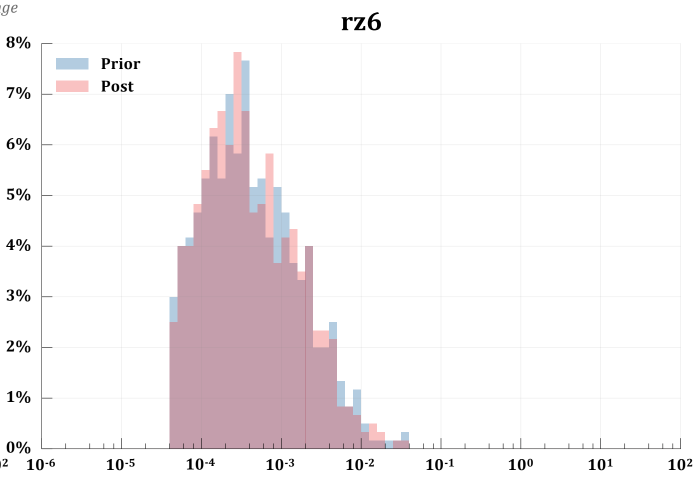
Range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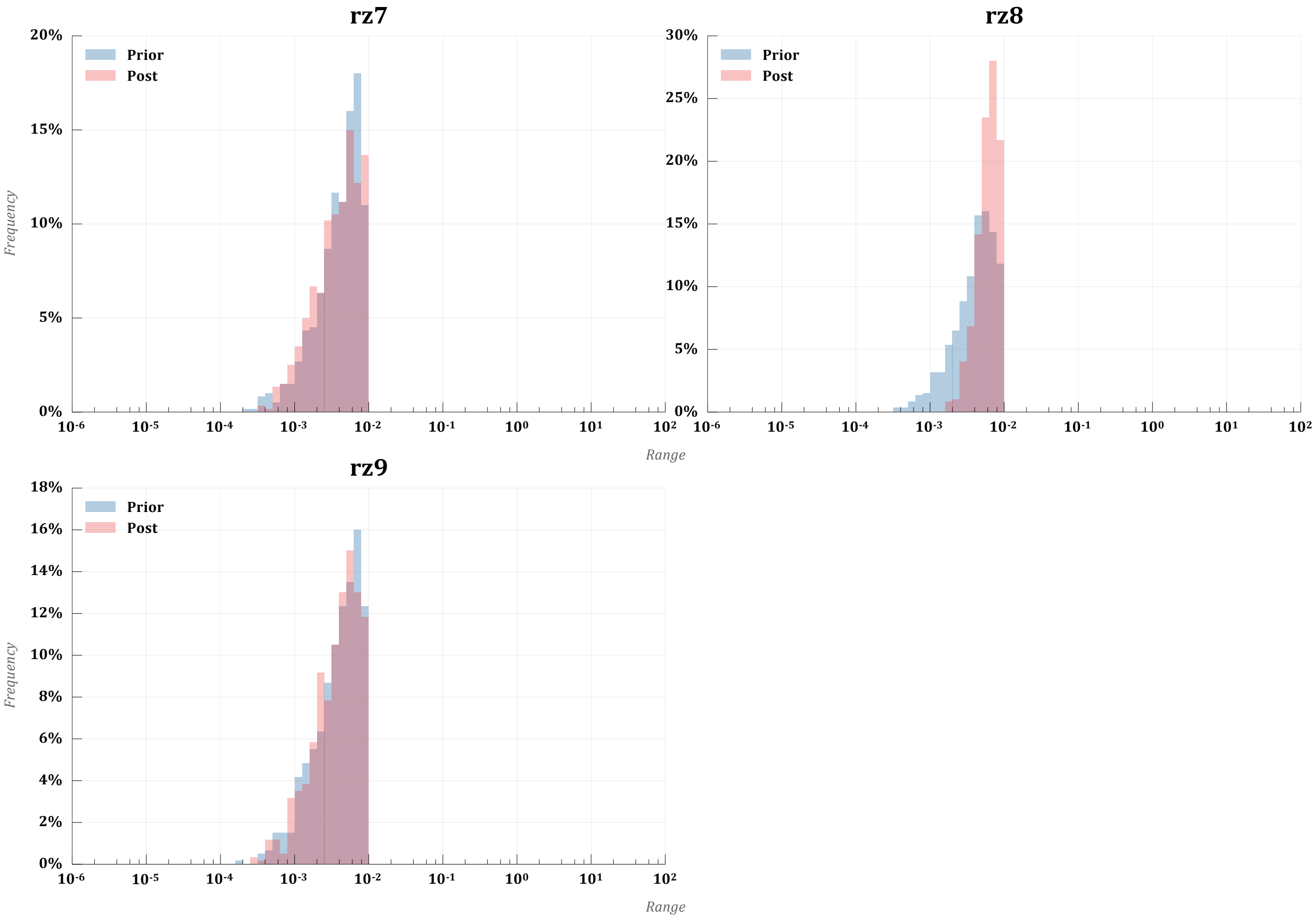
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Frequency
Prior
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10^{1}
10^{2}
Range
rz8
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25%
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Prior
Post
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10^{2}
rz9
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4%
2%
0%
Frequency
Prior
Post
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10^{-5}
10^{-4}
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10^{-1}
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10^{1}
10^{2}
Range

Appendix C Comparison of AGE 2018 and Norwest model parameters

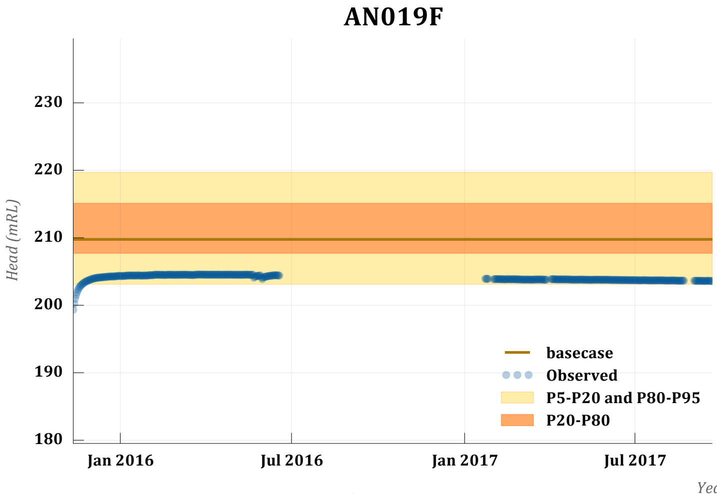
Table C.1 Hydraulic conductivity values for AGE 2018 model and Norwest model

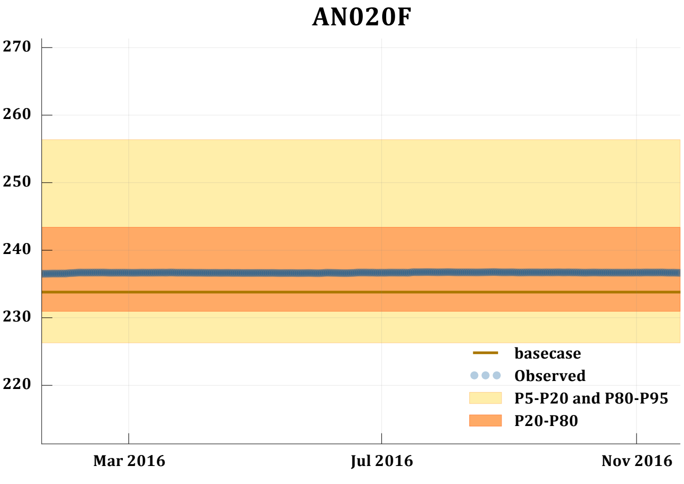
Geological Unit			AGE 2018 model			Norwest model	
Age	**Primary Formation**	**Key Material type**	**Depth interval**	**Kh (m/d)**	**Kv(m/d)**	**Kh(m/d)**	**Kv(m/day)**
Quaternary	Floodplain Alluvium	Alluvium	------	1 to 15	0.1 to 5	1 to 40	0.1 to 2
Quaternary	Other sediments and alluvium, alluvial fans, high terraces	Alluvium	------	1 to 15	0.1 to 5	1 to 40	0.1 to 2
Tertiary	Suttor Fm	Sedimentary Rocks	------	1	0.1	1	0.1
Tertiary	Basalt Flows	Basalt	------	0.14	0.09	0.05	0.005
Tertiary	Duaringa Fm	Sedimentary Rocks	------	0.08	0.009	0.05	0.005
Tertiary	Emerald Fm	Sedimentary Rocks	------	0.05	0.005	0.05	0.005
Tertiary	Moolayember Fm	Sedimentary Rocks	------	6.1E-4	1.9E-5	7.5E-4	1.0E-5
Triassic	Clematis Group	Sedimentary Rocks	------	0.04	0.013	0.05	0.005
Triassic	Rewan Fm	Sedimentary Rocks	------	8.4E-4	1.1E-7	7.5E-4	1.0E-7
Late Permian	Rangal Coal Measures (RCM)	Main Coal Seams	0-100	1.00E-01	3.68E-02	0.15 to 5E-3	0.03 to 1.1E-6
			100-250	4.43E-02	9.02E-03		
			250-500	3.25E-03	6.51E-04		
			500-1500	2.76E-05	5.54E-06		
		Interburden	------	1.0E-4	1.0e-8	1.0E-4	1.0E-8
Late Permian	Fort Cooper Coal Measures (FCCM)	Sedimentary Rocks	------	4.0E-3 to 1.0E-4	7.0E-5 to 1.0E-8	0.044 to 1.0E-4	8.0E-5 to 1.0E-8
Late Permian	Moranbah Measures (MCM)	Main Coal Seams	0-100	1.00E-01	2.96E-02	0.16 to 5.3E-5	0.03 to 1.0E-5
			100-250	4.75E-02	1.02E-02		
			250-500	4.64E-03	1.06E-03		
			500-1500	5.39E-05	1.14E-05		
		Interburden	------	1.0E-4 to 1.0E-6	6.0e-8	1.0E-4	1.0E-8
Middle Permian	Back Creek Group	Sedimentary Rocks		0.0004	8.8E-6	0.0004	8.8E-6

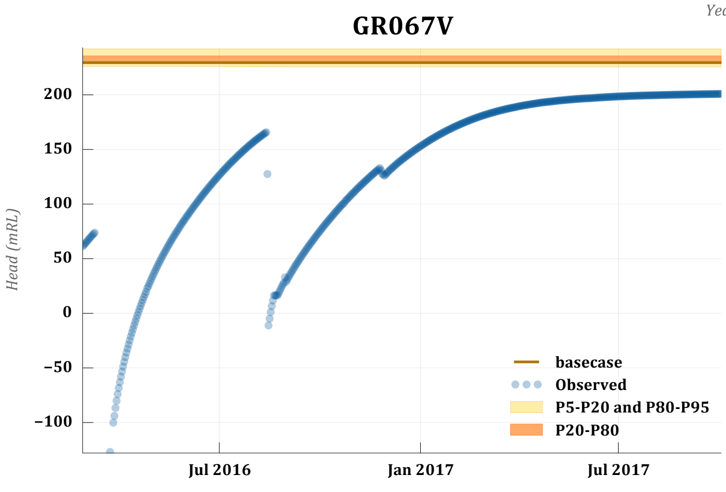
Table C.2 Storage values for AGE 2018 model and Norwest model

Geological Unit			AGE 2018 model		Norwest model	
Age	**Primary Formation**	**Key Material type**	**Ss (m^{-1})**	**Sy**	**Ss (m^{-1})**	**Sy**
Quaternary	Floodplain Alluvium	Alluvium	5.0E-4	0.05-0.18	5.0E-4	0.05 to 0.18
Quaternary	Other sediments and alluvium, alluvial fans, high terraces	Alluvium	5.0E-4	0.05-0.18	5.0E-4	0.05 to 0.18
Tertiary	Suttor Fm	Sedimentary Rocks	5.0E-5	0.2	5.0E-5	0.2
Tertiary	Basalt Flows	Basalt	5.0E-6	0.13	5.0E-5	0.13
Tertiary	Duaringa Fm	Sedimentary Rocks	5.0E-5	0.12	5.0E-5	0.12
Tertiary	Emerald Fm	Sedimentary Rocks	5.0E-5	0.12	5.0E-5	0.12
Tertiary	Moolayember Fm	Sedimentary Rocks	5.0E-5	0.12	5.0E-5	0.12
Triassic	Clematis Group	Sedimentary Rocks	5.0E-5	0.17	5.0E-5	0.17
Triassic	Rewan Fm	Sedimentary Rocks	5.0E-5	0.06	5.0E-5	0.18
Late Permian	Rangal Coal Measures (RCM)	Main Coal Seams	8.5E-5	0.05	8.5E-5	0.075
		Interburden	8.5E-5	0.06	8.5E-6	0.05
Late Permian	Fort Cooper Coal Measures (FCCM)	Sedimentary Rocks	8.5E-5	0.05	8.0E-6 to 5.0E-5	0.05 to 0.06
Late Permian	Moranbah Measures (MCM)	Main Coal Seams	8.3E-5	0.05	8.5E-5	0.075
		Interburden	8.5E-6	0.05	8.5E-6	0.05
Middle Permian	Back Creek Group	Sedimentary Rocks	5.0E-5	0.06	5.0E-5	0.12

Appendix D Calibration uncertainty hydrographs


AN019F
Head (mRL)
180
190
200
210
220
230
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


AN020F
220
230
240
250
260
270
Mar 2016
Jul 2016
Nov 2016
basecase
Observed
P5-P20 and P80-P95
P20-P80


GR067V
Head (mRL)
−100
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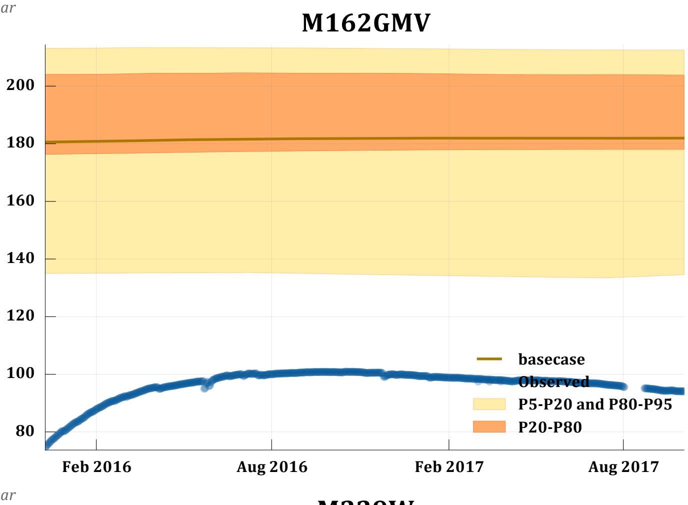
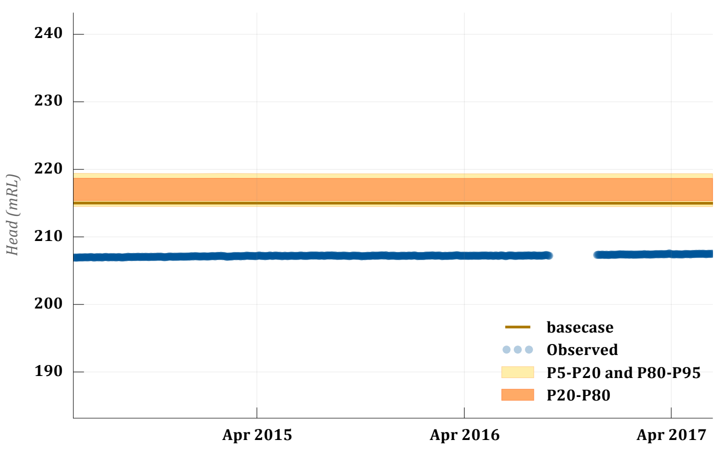
0
50
100
150
200
Jul 2016
Jan 2017
Jul 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


M162GMV
80
100
120
140
160
180
200
Feb 2016
Aug 2016
Feb 2017
Aug 2017
basecase
Observed
P5-P20 and P80-P95
P20-P80


M225W
Head (mRL)
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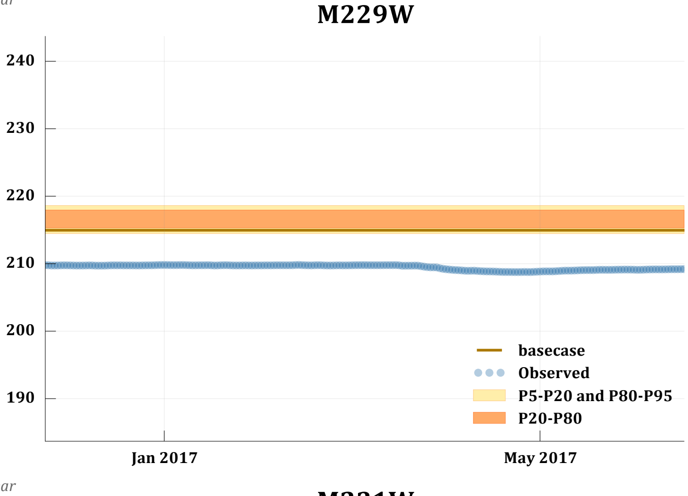
200
210
220
230
240
Apr 2015
Apr 2016
Apr 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


M229W
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200
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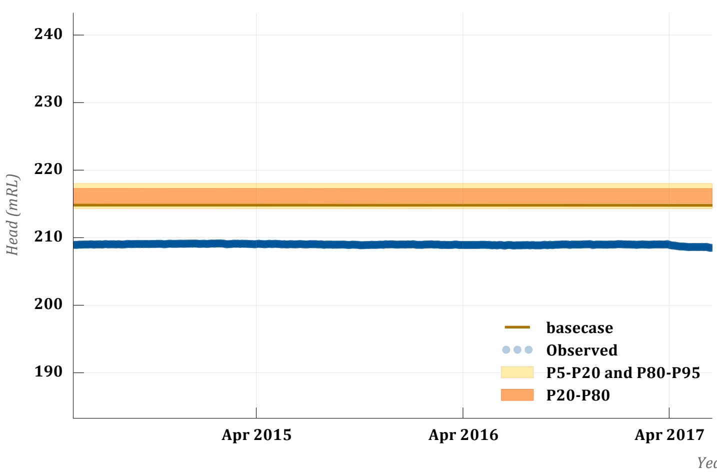
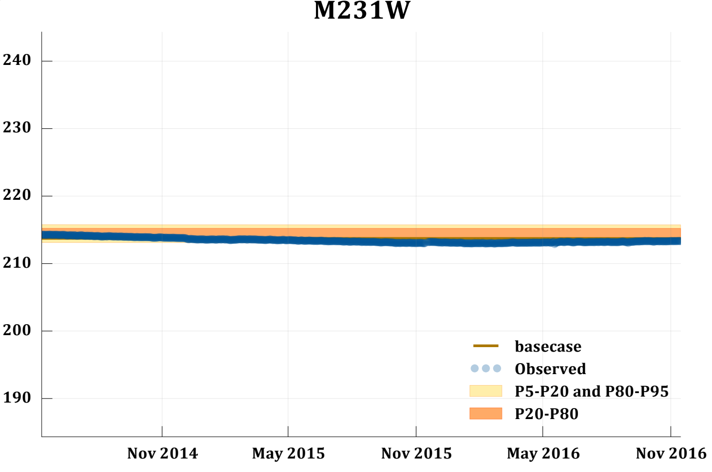
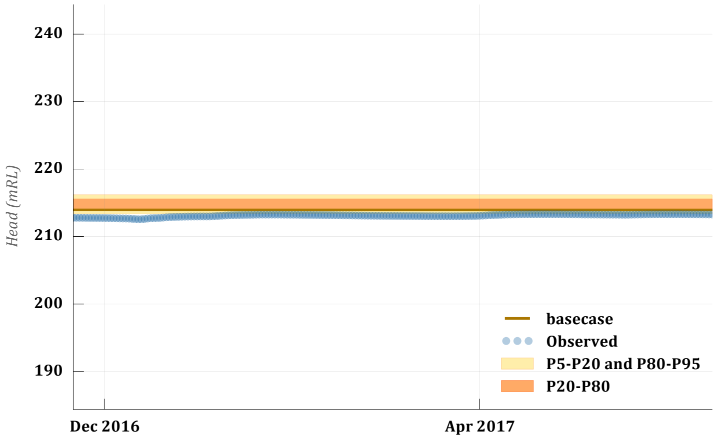
220
230
240
Jan 2017
May 2017
basecase
Observed
P5-P20 and P80-P95
P20-P80

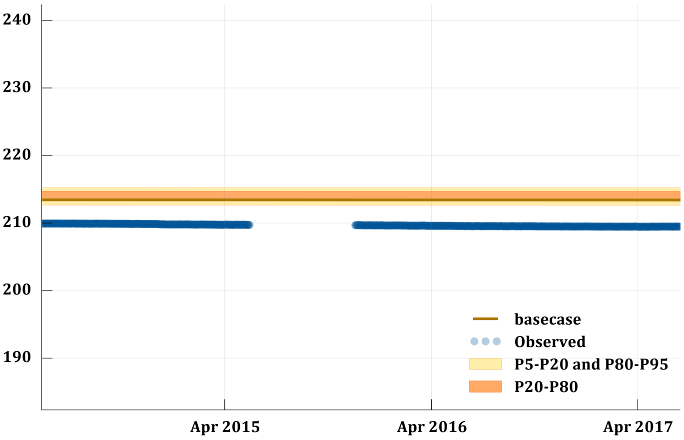

M230W
Head (mRL)
190
200
210
220
230
240
Apr 2015
Apr 2016
Apr 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


M231W
190
200
210
220
230
240
Nov 2014
May 2015
Nov 2015
May 2016
Nov 2016
basecase
Observed
P5-P20 and P80-P95
P20-P80

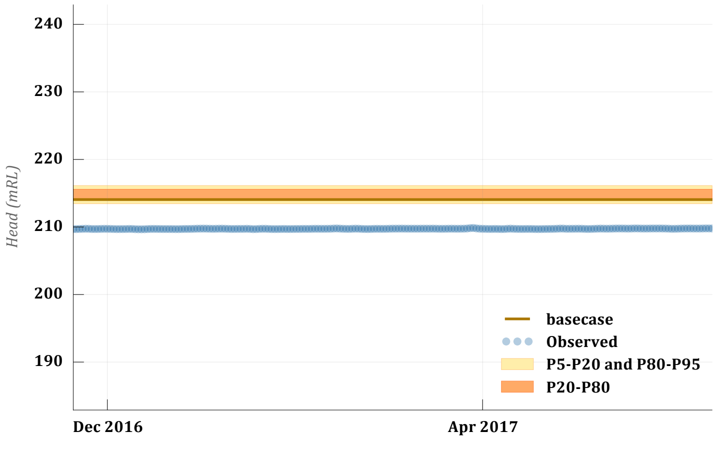
M232W



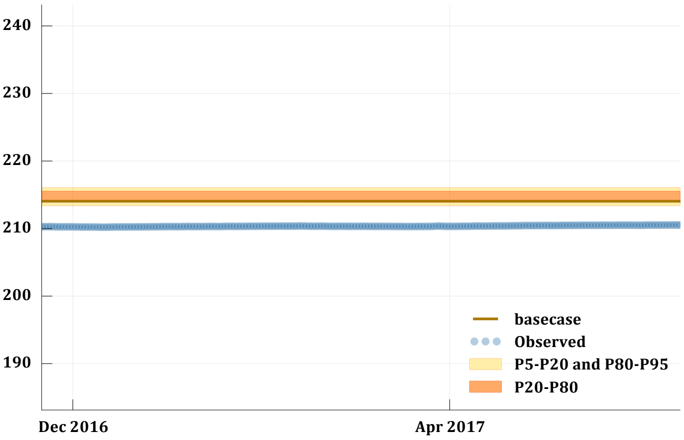
M234W



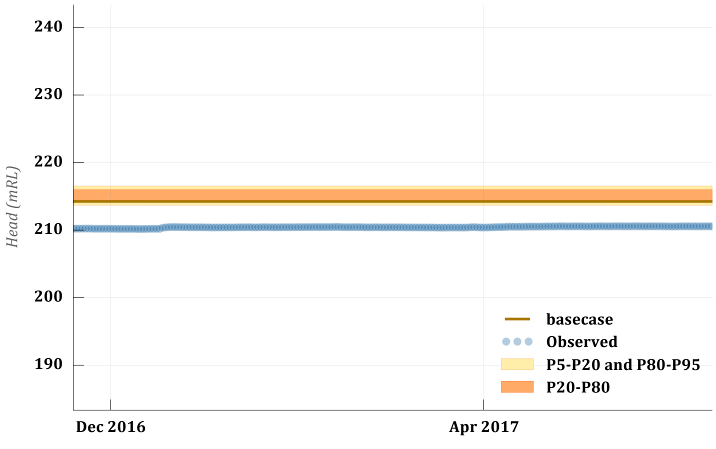
M235W



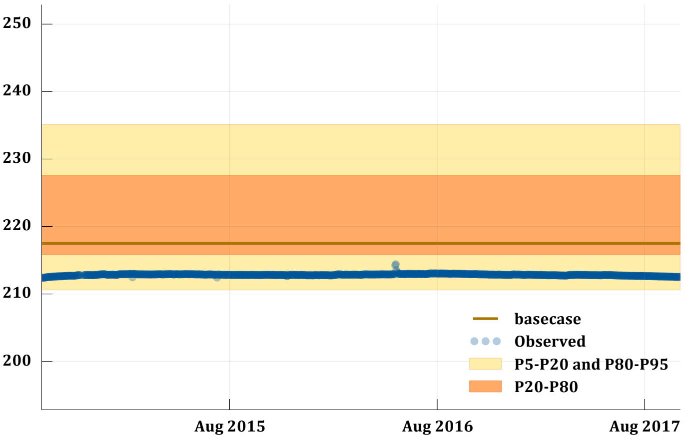
M236W



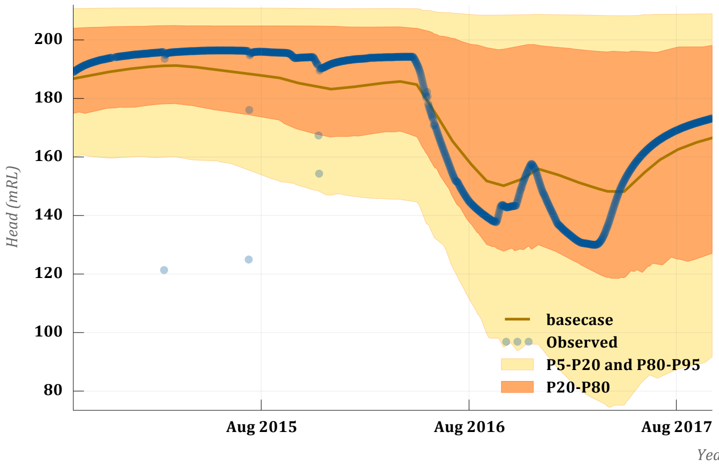
M237W



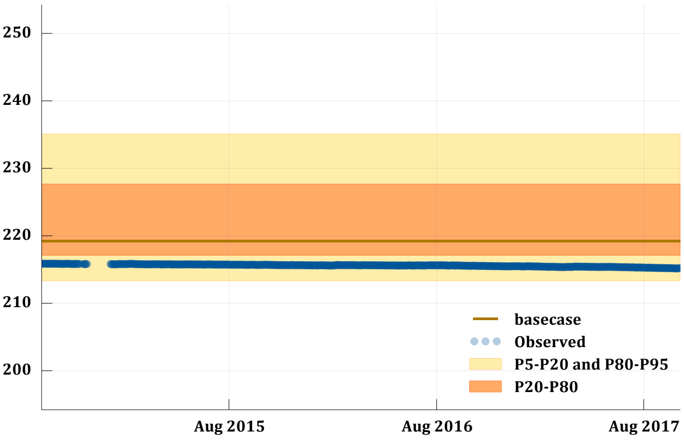
M313_BK_1P

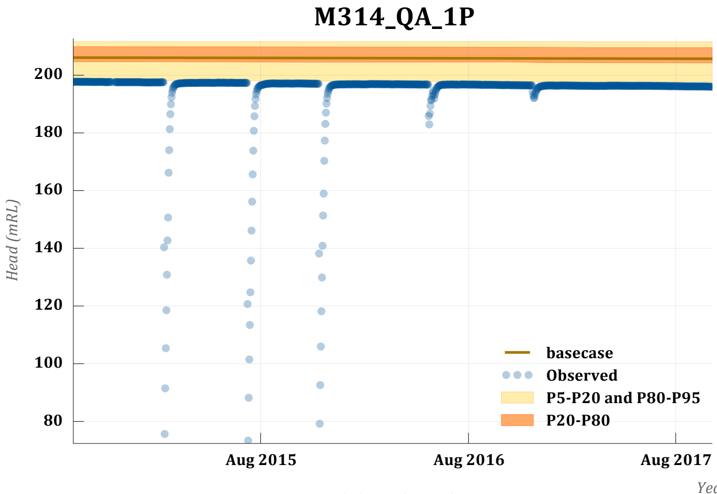


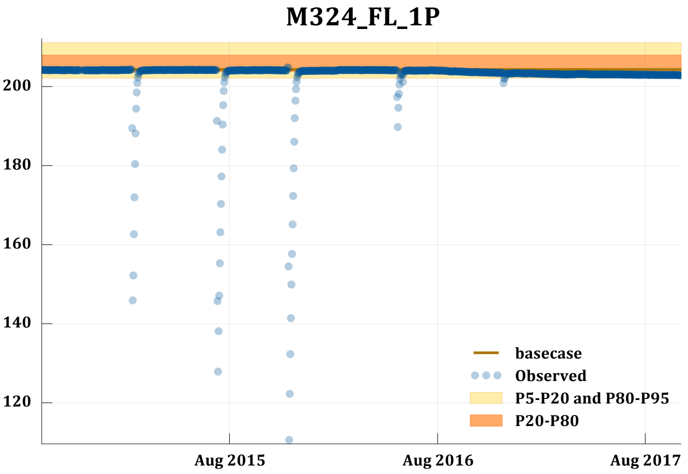
M313_GM_1P

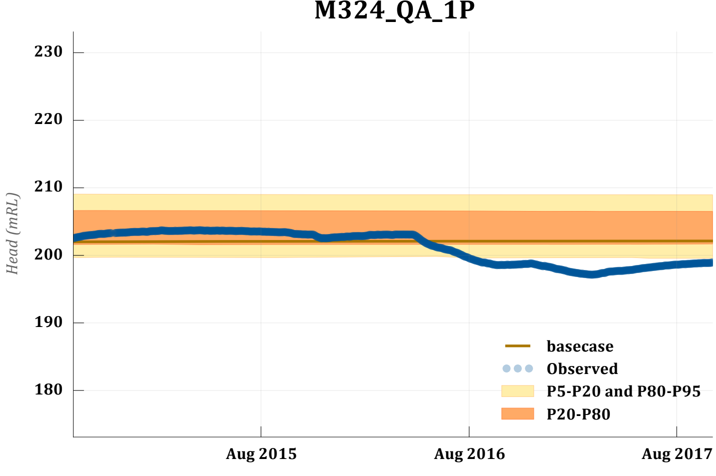


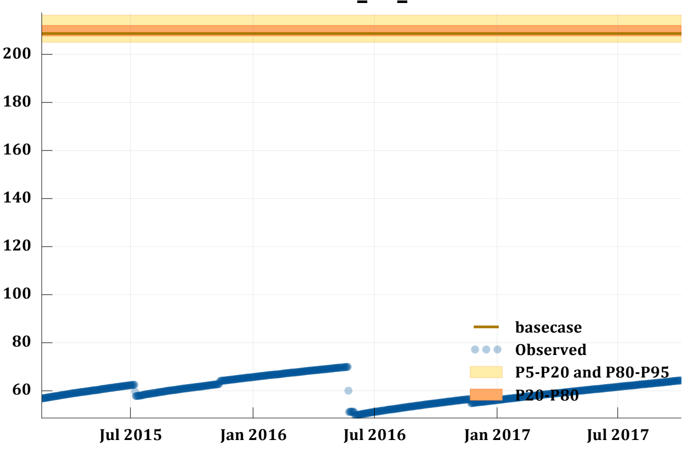
M314_BK_1P

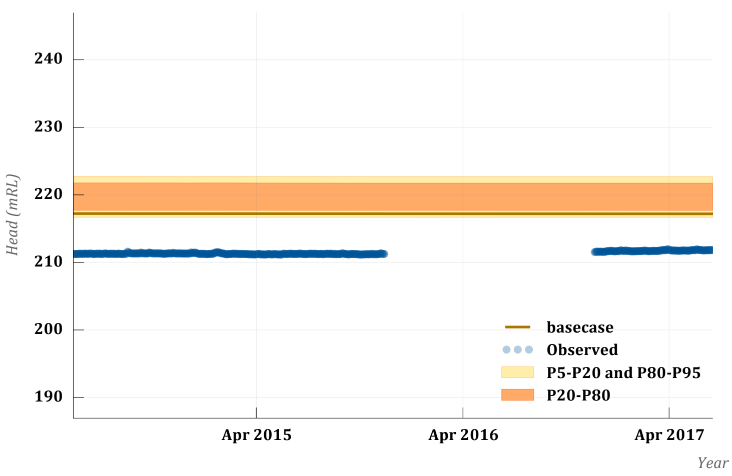



M314_QA_1P
Head (mRL)
200
180
160
140
120
100
80
Aug 2015
Aug 2016
Aug 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


M324_FL_1P
200
180
160
140
120
Aug 2015
Aug 2016
Aug 2017
basecase
Observed
P5-P20 and P80-P95
P20-P80


M324_QA_1P
Head (mRL)
230
220
210
200
190
180
Aug 2015
Aug 2016
Aug 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80


M325_FL_1P
200
180
160
140
120
100
80
60
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
basecase
Observed
P5-P20 and P80-P95
P20-P80


M345W
Head (mRL)
240
230
220
210
200
190
Apr 2015
Apr 2016
Apr 2017
Year
basecase
Observed
P5-P20 and P80-P95
P20-P80

Appendix D – MGP - Groundwater Monitoring Network Status

Bore Name	Location	Target Aquifer	Easting	Northing	Installed & Completed	On Monitoring	12 months of water level/pressure collected	12 months of biannual water quality collected	Baseline groundwater dataset established
			(GDA94 Zone 55)	(GDA94 Zone 55)					
M339W	PL191	Weathered Tertiary Basalt	603458.6	7572763.8	Yes	Yes	Yes	Yes	Yes
M225W	PL191	Weathered Tertiary Basalt	604808.3	7569885.6	Yes	Yes	Yes	Yes	Yes
M340W	PL191	Weathered Tertiary Basalt	604902.6	7572726.2	Yes	Yes	Yes	Yes	Yes
M230W	PL191	Weathered Tertiary Basalt	605635.9	7570996.3	Yes	Yes	Yes	Yes	Yes
M250W	PL191	Tertiary Sediment	608184.9	7582504.6	Yes	Yes	Yes	Yes	Yes
M224W	PL191	Quaternary Alluvium	611154.8	7567225.1	Yes	Yes	Yes	Yes	Yes
M222W	PL224	Weathered FCCM	611810.7	7566589.4	Yes	Yes	Yes	Yes	Yes
M313W	PL196	MCM & BCG	614824.9	7562084.1	Yes	Yes	Yes	Yes	Yes
M314W	PL196	MCM & BCG	614323.7	7566534.8	Yes	Yes	Yes	Yes	Yes
M324W	PL196	MCM & FCCM	614827.6	7562105.6	Yes	Yes	Yes	Yes	Yes
M325W	PL196	MCM & FCCM	614342.8	7566541.7	Yes	Yes	Yes	Yes	Yes
GR067V	PL191	MCM	612820.6	7582153.4	Yes	Yes	Yes	Yes	Yes
M162V	PL191	MCM	603364.7	7573356.2	Yes	Yes	Yes	Yes	Yes
AN019F	PL223	FCCM	623219.2	7569209.2	Yes	Yes	Yes	Yes	Yes
AN020F	PL223	Rewan	623192.1	7569069.6	Yes	Yes	Yes	Yes	Yes
AN021F*	PL223	Tertiary	623296.6	7569127.6	Yes	No	No	No	No

** AN021F has been dry since the drilling was completed*