Modelling of cumulative groundwater impacts in the Surat CMA: approach and methods

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1 Preamble

Each of the Underground Water Impact Reports (UWIRs) prepared by the Office of Groundwater Impact Assessment (QWC 2012; OGIA 2016a, 2019a, 2021a) has been accompanied by a standalone report containing a detailed description of the regional groundwater model (OGIA 2016b, 2019b; GHD 2012) that underpinned these assessments.

The current UWIR 2021 addresses a new legislative requirement to include coal impacts in the assessment and to assimilate contemporary data and conceptualisation work. While updates of the regional model have built on the significant advances in model development from previous UWIRs, the regional-scale modelling approach has not changed significantly since the UWIR 2019. As such, this report serves as a brief overview of the modelling features that have materially changed and documents the model recalibration and uncertainty analyses undertaken over this period.

2 Modelling objectives and purpose

The primary purpose of modelling undertaken by OGIA is to predict spatio-temporal change in regional groundwater pressures within the Surat Cumulative Management Area (CMA) due to resource development, in both the short and long terms. More specifically, the modelling of cumulative impacts is required to:

- define, for each consolidated aquifer present within the model domain, the Immediately Affected Area (IAA) – the area where water pressures are predicted to decline by more than five metres within the next three years
- define, for each consolidated aquifer present within the model domain, the Long-term Affected Area (LAA) – the area where water levels are predicted to decline by more than five metres at any time in the future
- identify potentially affected springs – springs where the groundwater pressure in aquifers underlying the sites of these springs is predicted to decline by more than 0.2 m at any time in the future
- predict impacts to the rate and volume of groundwater movement between coal formations and key aquifers in the Surat CMA
- estimate the quantity of groundwater that is expected to be extracted by coal seam gas (CSG) and coal mining tenure holders in the CMA.

3 Previous models

OGIA's approach to the assessment of cumulative impacts from CSG has evolved considerably since the UWIR 2012 (Queensland Water Commission 2012) when the first regional groundwater model was developed. This progression reflects expanding data acquisition efforts and enhanced data interrogation that have improved the understanding of key hydrogeological processes operating within the Surat CMA.

The first model iteration in the UWIR 2012 was largely based on information from previous studies. Relatively little primary data interpretation was undertaken and the model was developed by GHD using a standard version of MODFLOW 2005 (GHD 2012).

An entirely new regional groundwater model was constructed as part of the UWIR 2016 using several innovative modelling techniques developed by OGIA, and a revised conceptualisation of the groundwater flow system based largely on primary data interpretation. The MODFLOW-USG code (Harbaugh 2005) was used as the modelling platform for the UWIR 2016, to which numerous revisions were made by OGIA to address the following unique challenges to CSG impact assessment in the Surat CMA:

- simulation of water desaturation due to gas production in coal seams around CSG wells
- dual-porosity formulation for differing hydraulic responses in coal seams and interburden material
- more accurate representation of CSG wells using a descending MODFLOW drain methodology, including cell-to-well conductance calculations that utilise the increased modelled permeability in areas where CSG wells screen multiple coal seams that would otherwise be separated by low permeability interburden
- hydraulic property upscaling of lithological logging and permeability measurement data available for both the CSG target coal reservoir and potentially impacted aquifers using so-called "numerical permeameters"; this information is subsequently used for initial parameterisation of the regional groundwater model
- explicit representation of major faults via (i) layer juxtaposition incurred through stratigraphic displacement and (ii) incorporation of the hydraulic effects associated with inter-formational flow along the fault plane and enhancement of vertical permeabilities within the damage zone adjacent to the fault
- simulation of reinjected CSG water by-product into the Precipice Sandstone.

This work was undertaken by OGIA in collaboration with one of the primary developers of the MODFLOW-USG code. The method developed to simulate water desaturation and the approximation of dual-phase flow in and around CSG wells is described in Herckenrath et al. (Herckenrath, Doherty & Panday 2015).

The third iteration of the regional groundwater flow model in 2019 represented a revision of the UWIR 2016 model and included further refinements to the modelling approach, including modifications to the underlying geological model, revision of the pre-calibration model parameterisation using an updated numerical permeameter workflow, incorporation of additional major faults and simulation of CSG wells partially completed into the Springbok Sandstone.

4 Unique modelling challenges

The primary scope of OGIA's groundwater modelling is to assess potential cumulative impacts to surrounding aquifers in the Surat CMA due to *Petroleum and Gas* (P&G) developments and open cut coal mining. In this context, some of the key challenges associated with modelling impacts are as follows:

- a large domain covering an area of about 650×450 km (almost 300,000 km^2)
- complex multiple layered consolidated aquifer system comprising of more than 20 formations with considerable lateral and vertical heterogeneity, inter-basin contacts and erosional contacts

- allowance for discontinuous, interbedded layering with multiple coal seams that are targeted for CSG production at depths and for coal mining in shallow areas
- significant time period over which CSG and mining development occurs – spanning more than 75 years
- approximation of dual-phase flow effects resulting from coal seam depressurisation
- representation of geological faults that extend into both the Surat and Bowen basins
- definition of upscaled parameters commensurate with the regional scale of the assessment that are conditioned to available borehole measurements
- integration of impacts from stressors occurring at different spatio-temporal scales (CSG extraction and coal mining)
- history-matching the model to a large quantity of monitoring data
- development of numerically efficient ways to represent the potential interactions between near-surface groundwater systems and stressors (CSG extraction and coal mining).

5 Approach for the UWIR 2021 Assessment

Due to the regionally extensive and laterally continuous development of coal seam gas operations in the Surat Basin, the associated impacts are also considered regionally extensive. In comparison, the coal mines in the Surat Basin are discrete and located in shallower parts of the basin (usually targeting the top 100 m or so at outcrop). Thus, the extent and magnitude of coal impacts are likely to be more local in nature – driven by local and shallow processes such as recharge, local connectivity features as well as the details of mine operation (placement of spoil or backfill). These processes are not necessarily relevant to CSG impact modelling and so new approaches are needed to integrate impacts from the two vastly different processes.

Considering the short cycle (18 months) for preparation of the UWIR 2021 compared to the three-year cycle for the previous UWIR, OGIA were primarily focused on an update of the regional model and the integration of coal mining impacts within that framework where appropriate. For those mines in the Surat CMA which are proximate to CSG developments and where overlapping impacts are likely to occur, efforts were made to include these mining stresses in the regional model for the purpose of cumulative impact assessment (i.e., Elimatta, Wandoan Coal Project, the Range, Cameby Downs, Kogan Creek, Wilkie Creek and Commodore). OGIA has also utilised the Acland Groundwater model (SLR 2018) on the basis that there is minimal risk of cumulative impacts at this location given the relative isolation of the New Acland mine from CSG development areas. OGIA reviewed this model and found it to be fit for purpose given the conceptualisation and data that is currently available, however, its suitability will be reassessed for future UWIRs as more site-specific information is collected.

In parallel, OGIA has also started work on prototype groundwater models which will inform the next generation of groundwater modelling. These models are designed to answer specific impact related questions focused on either sub-regional or local scale processes, which are relevant to the modelling of impacts around receptors.

Therefore, to address the above technical challenge, and to balance short (for the UWIR 2021) and long (subsequent UWIRs) term needs, the current OGIA modelling strategy comprises of three streams:

1. regional model update
2. modelling and integration of coal impacts
3. next-gen groundwater modelling for localised impact assessments.

This document provides relevant information for those aspects which underpin the UWIR 2021 assessment while it is anticipated that reports outlining the development of prototype Next-gen models will be published in due course. Consistent with the overall modelling strategy outlined above, the specific modelling approach to underpin the UWIR 2021 involved the use of several model components**.**

An update of the regional groundwater flow model has been undertaken *(the Regional Model 2021*) through assimilation of new information pertaining to improved conceptual knowledge and data, as well as the inclusion of coal mines. As described in section 3, the Regional Model 2021 has undergone several iterations of improvement since 2012 and has been developed for the purpose of assessing regional cumulative groundwater impacts arising from P&G and coal mine developments. A modelling report for the UWIR 2019 model provides a detailed description of model construction, parameterisation, calibration and uncertainty analysis (OGIA 2019b).

Regional Model 2021 is also informed by an updated version of the Condamine groundwater model developed by KCB to assist DNRM with water management of the Condamine Alluvium. This model has been updated by KCB for the purpose of this assessment to include the latest information on groundwater use and recharge. Outputs from this model have been integrated into the regional groundwater model to constrain water levels in the Condamine alluvium.

As mentioned previously, OGIA has also adopted the New Acland groundwater model (the Acland Model) developed by SLR (SLR 2018) for prediction of impacts from existing and proposed development at the New Acland mine. Given the distant proximity the New Acland mine to the CSG impact centre and the modelling results of the Regional Model 2021, overlapping impacts between the Acland coal mine and the CSG operations are expected to be minor. Thus, a superposition approach has been adopted for merging impacts from the Acland Model and OGIA's regional groundwater model. The approach is considered conservative and sufficiently accurate for obtaining the cumulative impact.

Additionally, a prototype model is currently being developed to explore potential impacts from both CSG and coal mining in the near surface. This is a sub-regional groundwater model for the Northern Coal Area (NCA). The sub-regional model is developed as a proof-of-concept for modelling near surface cumulative impacts. As this model is currently under development, a more detailed description of methods and results will be reported following the release of the UWIR 2021.

Figure shows the spatial domain for the above models and Table 5-1 summarises some of the key design features. Further detail on construction and calibration of the Regional Model 2021 and Acland Model can be found in sections 6 and 7, respectively. Note that the NCA model is currently under development, a separate report will be published for this model following the release of the current report. More information on the Condamine Model can be found in (KCB 2011).

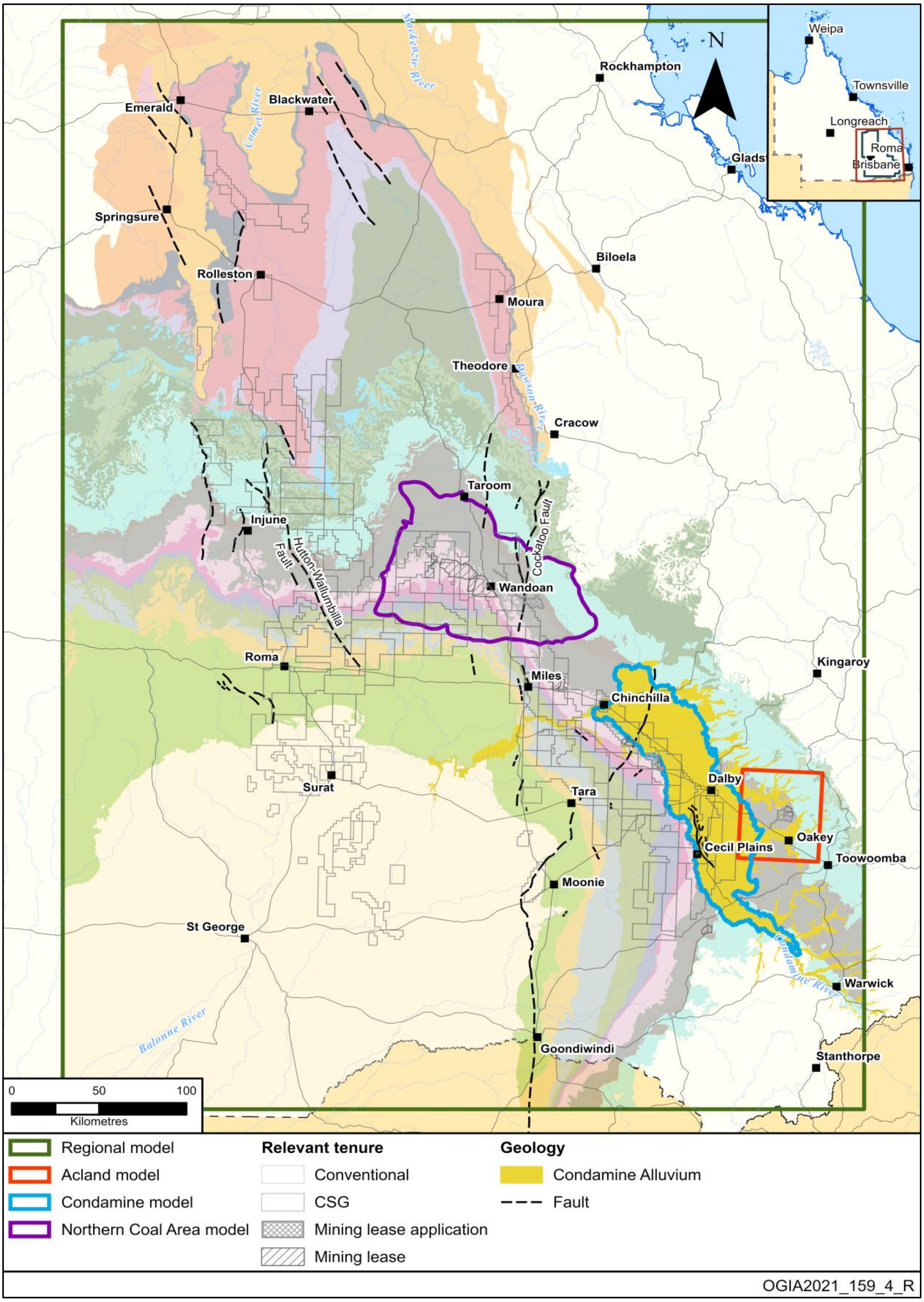

Figure 5-1: Model domains of the suite of models used for UWIR 2021

Table 5-1 Key features of groundwater models used for UWIR 2021

Element	Model			
	Condamine Model	Regional Model 2021	Acland Model	NCA Model
Model Purpose	Assist with water management in the Condamine Alluvium	Predict regional cumulative impacts from Resource development in the Surat CMA	Predict mining only impacts from the New Acland Coal mine	Predict sub-regional cumulative and near-surface impacts
Layering	2 layers Condamine Alluvium	35 layers Cenozoic – Basement	12 layers Alluvium – Hutton Sandstone	8 layers Regolith – Hutton Sandstone
Grid	500×500 m	1,500×1,500 m	100×100 m	250×250 m
Faults	None	35 Regional Faults	6 fault systems	None
Domain	~201×55 km	460×650 km	45×52 km	95×127 km
Modelling code	MODHMS	MODFLOW-USG	MODHMS	MODFLOW-USG

6 Regional model

6.1 Overview

The conceptual framework for the 2021 groundwater flow model remained relatively unchanged since the UWIR 2019, except for a few key updates which will be outlined in this section. Further information on the geological and hydrogeological framework underpinning this model can be found in (OGIA 2021b, 2019c, 2016c).

The regional hydrostratigraphy has been represented numerically using 35 model layers (Figure 6-1). The main change in this regard is the introduction of an additional layer in the Walloon Coal Measures to better represent the geological subdivision of this formation and improve representation of flow between units of the Walloon Coal Measures. This change will assist with the prediction of lateral drawdown impacts in the Walloon Coal Measures, particularly with respect to up-dip propagation of impacts to shallow areas where coal mines are present. This is also a necessary refinement to understand potential cumulative impacts between coal mines and coal seam gas operations. Thickness maps for each of the 35 model layers are provided in Appendix A1.

Key features of the *Regional Model 2021* include the following:

- Geological topology, underpinned by a geological model for the Surat and Southern Bowen basins using 21 layers at 250 m grid resolution derived from lithostratigraphic interpretation of wireline log data from approximately 8,000 wells, surface geological mapping, stratigraphic interpretation of lithological data from nearly 24,500 water bores and seismic survey data (OGIA 2019c).

Model layer	Formation	Basin
1	All Alluvium and Basalt (including Main Range Volcanics)	Cenozoic
2	Upper Cretaceous (Griman Creek Formation & Surat Siltstone) and the Condamine-Walloon transition zone	Surat & Clarence-Moreton basins
3	Wallumbilla Formation	
4	Bungil Formation	
5	Mooga Sandstone	
6	Orallo Formation	
7	Gubberamunda Sandstone	
8	Westbourne Formation	
9	Upper Springbok Sandstone	
10	Lower Springbok Sandstone	
11	Walloon Coal Measures non-productive zone	
12	Upper Juandah Coal Measures - Layer 1	
13	Upper Juandah Coal Measures - Layer 2	
14	Lower Juandah Coal Measures - Layer 1	
15	Lower Juandah Coal Measures - Layer 2	
16	Lower Juandah Coal Measures - Layer 3	
17	Taroom Coal Measures	
18	Durabilla Formation	
19	Upper Hutton Sandstone	
20	Lower Hutton Sandstone	
21	Upper Evergreen Formation	
22	Boxvale Sandstone	
23	Lower Evergreen Formation	
24	Precipice Sandstone	
25	Moolayember Formation	Bowen Basin
26	Clematis Group	
27	Rewan Group	
28	Bandanna Formation non-productive zone	
29	Upper Bandanna Formation	
30	Lower Bandanna Formation	
31	Lower Bowen 1	
32	Cattle Creek Formation non-productive zone	
33	Upper Cattle Creek Formation	
34	Lower Cattle Creek Formation	
35	Lower Bowen 2	

Regional aquifer | Partial aquifer | Tight aquifer | Interbedded aquitard | Tight aquitard

OGIA_017

Figure 6-1: Model layers and formations represented in the regional groundwater flow model

- Geological faults, represented through the inclusion of ‘non-neighbourhood connections’ to simulate flow from one stratigraphic unit to another across the fault plane. The width of the fault core and damage zone was used along with detailed lithology information (from geophysical logs where available) to calculate the likely effective horizontal and vertical resistance created by each fault. Prior to model calibration, application of this methodology generally results in cross-fault resistances that are lower in the horizontal direction than in the vertical direction. Parameters affecting the effective resistance of each fault – in both the vertical and horizontal directions – are considered estimable for the purpose of model calibration.
- An innovative workflow for the estimation of initial aquifer hydraulic parameters originally developed by the OGIA modelling team in 2015, was further refined. These detailed “numerical permeameters” of each stratigraphic unit occupy 21 km x 21 km and are populated by assigning parameters to six lithology types from geophysical logs followed by stochastic permeability modelling. Subsequent numerical computation of horizontal and vertical hydraulic conductivity constituted more than 138,000 model runs.
- Simulation of CSG extraction wells is achieved using the MODFLOW-USG ‘drain’ boundary condition. As each well develops, drains progressively descend over time with an attendant reduction in their bottom hole pressure until their final bottom hole pressure is reached.
- Increase in formation-scale horizontal permeability of the Walloon Coal Measures caused by CSG wells connecting otherwise discontinuous seams. This process is accounted for by modifying the MODFLOW-USG code and providing a supplementary enhanced permeability field for cell-to-well conductance calculation.
- Explicit representation of coal mines, simulated through use of a one-way MODFLOW ‘river’ boundary condition (i.e., the river stage and river bottom elevations are matched to ensure that water can only be exported from the model). The elevations ascribed to each river cell over time represent the progressive excavation from the pre-mined surface down to the base elevation of the open pit for a given development scenario, as provided by industry.
- A separate, calibrated Condamine Model of finer-scale is used to supply the Regional Model 2021 with the hydraulic parameters and time-variant water levels of model layer 1 within the Condamine footprint.
- MODFLOW-USG functionality was introduced as an approximation of dual phase (water and gas) flow to simulate water desaturation in response to a reduction in pressure surrounding CSG wells.
- The hydrogeology of the coal formations is complex in that they comprise highly varied sequences of high and low permeability material. It is not practical to represent the individual coal seams within these coal formations as separate layers in the regional groundwater flow model. This is in part because it is often not possible to correlate individual coal seams across the area. To address this challenge, a dual domain setup has been adopted to represent coal (mobile domain) and interburden (immobile domain) to encourage strong vertical head gradients.
- Partial completion of CSG wells into the lower parts of the Springbok Sandstone, simulated using MODFLOW-USG drains.

- Representation of the thickness and permeability of the non-productive zone (NPZ) of the Walloon Coal Measures, a key control on the transmission of CSG impacts into the overlying Springbok Sandstone.
- Long-term average extractions from the Condamine Alluvium and Main Range Volcanics, simulated using a MODFLOW-USG 'River' boundary condition. Time-variant non-CSG extractions from the remaining formations included in the model have been simulated directly using the MODFLOW-USG 'well' boundary condition.
- Calibration of the groundwater flow model in three stages: 'pre-development' (1947) to replicate conditions that existed prior to the commencement of any groundwater extraction; pre-CSG extraction conditions commensurate with 1995; and a transient simulation to replicate the period from January 1995 to December 2020, during which CSG extraction commenced initially from the Bandanna Formation and then from the Walloon Coal Measures.

6.2 Key datasets

A range of updated input datasets are used to construct and calibrate the model:

- Geological data for around 7,000 CSG wells, 24,500 water bores, over 5,000 seismic lines and 18000 coal holes are used to construct the regional geological model which provides the structure of the groundwater model.
- Newly available seismic data provided by Arrow Energy has been depth converted by UQ and independently interpreted by OGIA and utilised to update the geometry around the Horrane Fault in the eastern Surat basin.
- Recent airborne electromagnetic data acquired by Geoscience Australia and interpreted by OGIA has been used to update fault connections around the Hutton-Wallumbilla fault near the Lucky Last springs.
- Detailed lithology data for around 6,000 CSG wells and 13,000 permeability estimates are used to constrain numerical permeameter calculations and derive initial hydraulic parameter estimates for the model.
- Initial estimates of recharge have been derived from chloride measurements in around 10,100 bores.
- Following review, groundwater level data for almost 10,000 monitoring points was directly used for the history matching of the groundwater model against observed heads, head trends and vertical head differences between formations.
- Monthly volumes of extracted groundwater for each CSG well within the Surat CMA, which have been used to define the active period of CSG in the model and have been used for calibrating the model against total CSG water extraction volumes.
- Groundwater extraction estimates and metered data, described in (OGIA 2021c) for the representation of groundwater extraction, including stock and domestic take, irrigation, and extraction rates for conventional P&G wells.
- Daily records of historic reinjection rates to represent reinjection of water extracted as part of CSG activities into the Precipice Sandstone.

- Mine development plans to inform the representation of open cut coal mines within the *Regional Model 2021*, including their depth and period of operations.

6.3 Model setup

Due to reduced timeframes for delivery of the UWIR 2021, only critical improvements were selected to refine the model architecture. In most cases, these changes have been implemented in such a way as to minimise changes to the architecture of the UWIR 2019 model grid while incorporating tangible improvements with regards to the assimilation of new conceptualisation and data.

This chapter describes how the basic geometry and boundary conditions for the UWIR 2019 model were updated for the UWIR 2021 groundwater model. Specifically, updates are provided on model architecture, process representation as well as calibration and uncertainty analysis.

Further detail on methods used in the construction of the regional groundwater model can be found in (OGIA 2019b).

6.3.1 Model architecture

6.3.1.1 Subdivision of the Walloon Coal Measures

The UWIR 2019 model layering in the Walloon Coal Measures was based on equal proportioning of layers to generate large vertical head differences between coal layers in the Walloon Coal Measures, as is observed in monitoring data. Since the UWIR 2019, OGIA has re-interpreted a large number of LAS files (including new data from coal mines) which have been used to identify geological sub-units of the Walloon Coal Measures(De Jersey & McKellar 2013). These are the Upper Juandah Coal Measures, Lower Juandah Coal Measures and the Taroom Coal Measures respectively. The UWIR 2021 model now reflects the relative proportions of these revised subdivisions, while maintaining the overall thickness of the Walloon Coal Measures. Similar to the UWIR 2019 model, the three units were further subdivided to provide sufficient opportunity to simulate vertical head gradients. In total 7 layers are used to represent the Walloon Coal Measures (including the non-productive zone, which remains unchanged). Figure 6-2 below shows a 3D section of the *Regional Model 2021* with the updated layering in the Walloon Coal Measures.

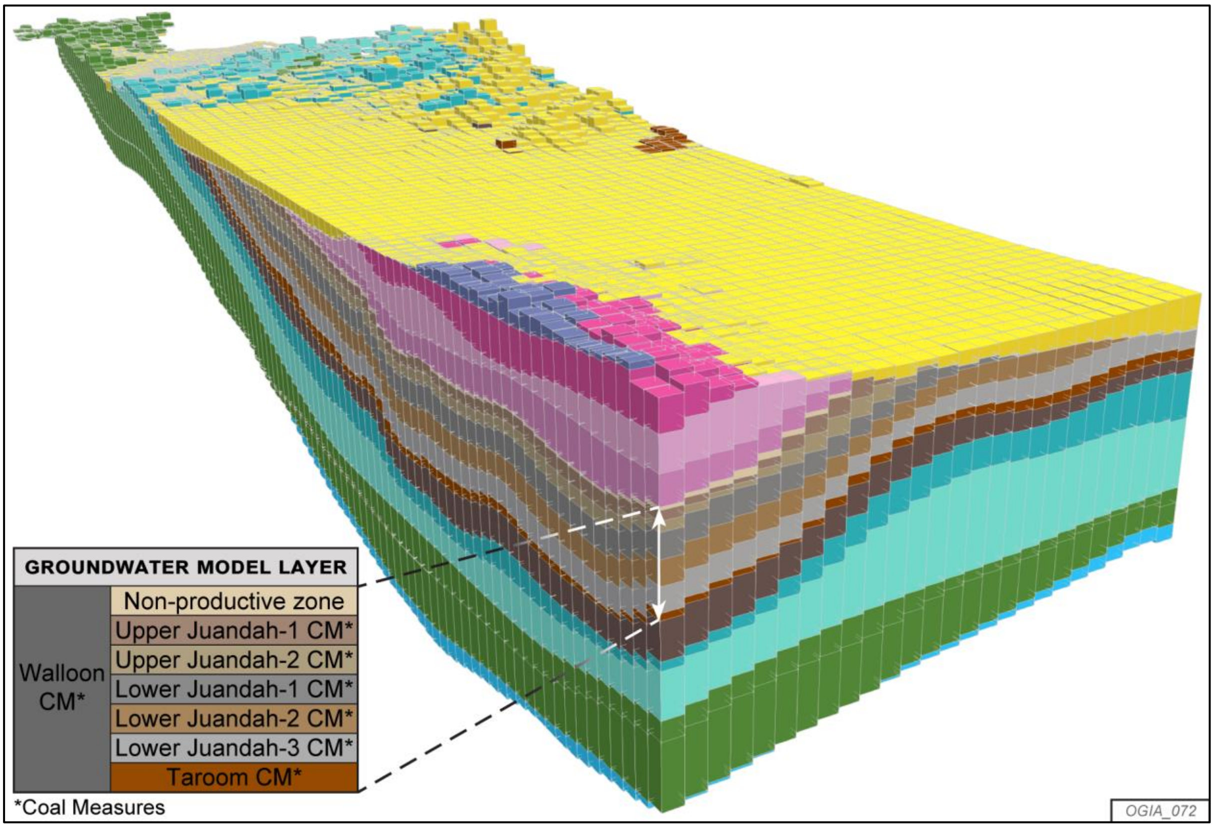

Figure 6-2: 3D representation of the regional groundwater model, showing the revised subdivision of the Walloon Coal Measures

6.3.1.2 Extension of the Horrane Fault

The UWIR 2019 included the discrete representation of a large normal fault in the Surat Basin known as the Horrane Fault. Since then, OGIA has interpreted newly acquired seismic data (provided by Arrow Energy) and updated its representation of this fault both in terms of extent and the modelled displacement. The updated fault extends 20 km further south-east and has improved constraint on the variable displacement along its length (OGIA 2021d), see below Figure 6-3 and Figure 6-4, wherein the fault line is adjusted to align with intersected cell boundaries. In line with the methodology outlined in the UWIR 2019 modelling report, neighbouring/non-neighbouring connections have been updated according to the observed throws along the fault plane.

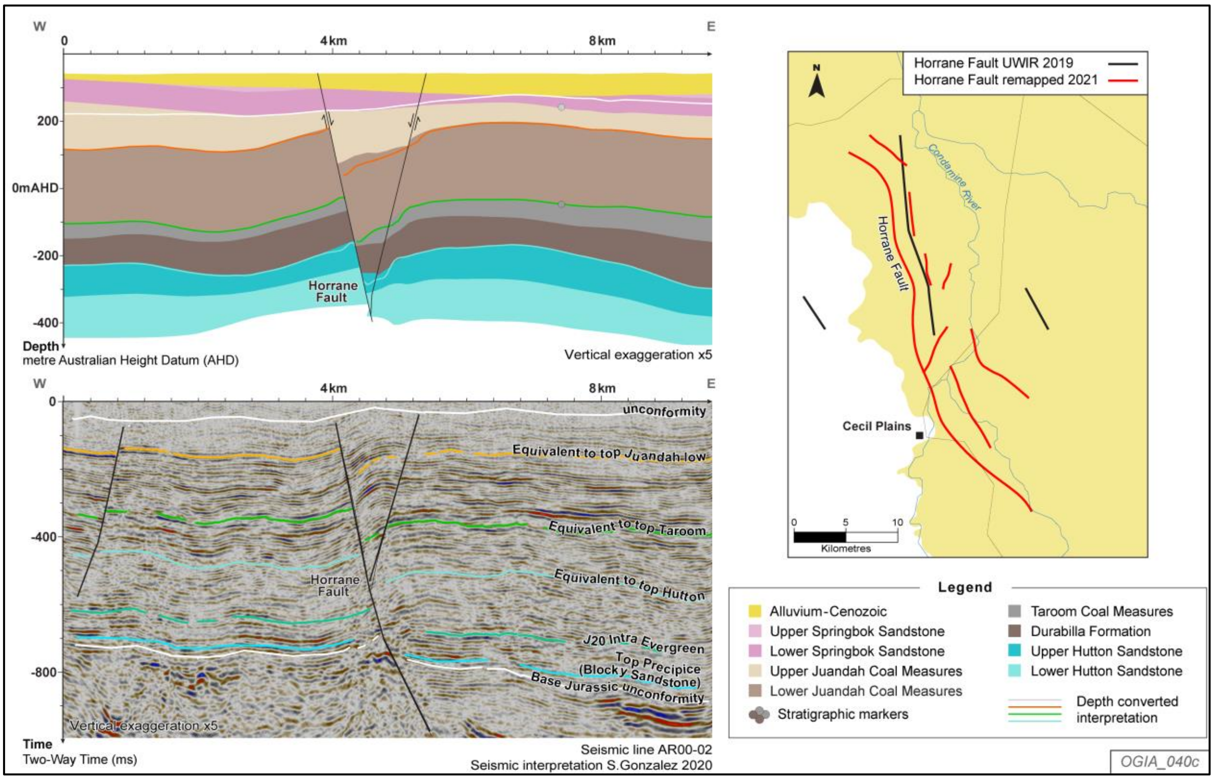

Figure 6-3: Remapping of the Horrane Fault showing a depth converted stratigraphic interpretation (top left), seismic section in Two-Way-Time (bottom left) and the remapped spatial extent (right)

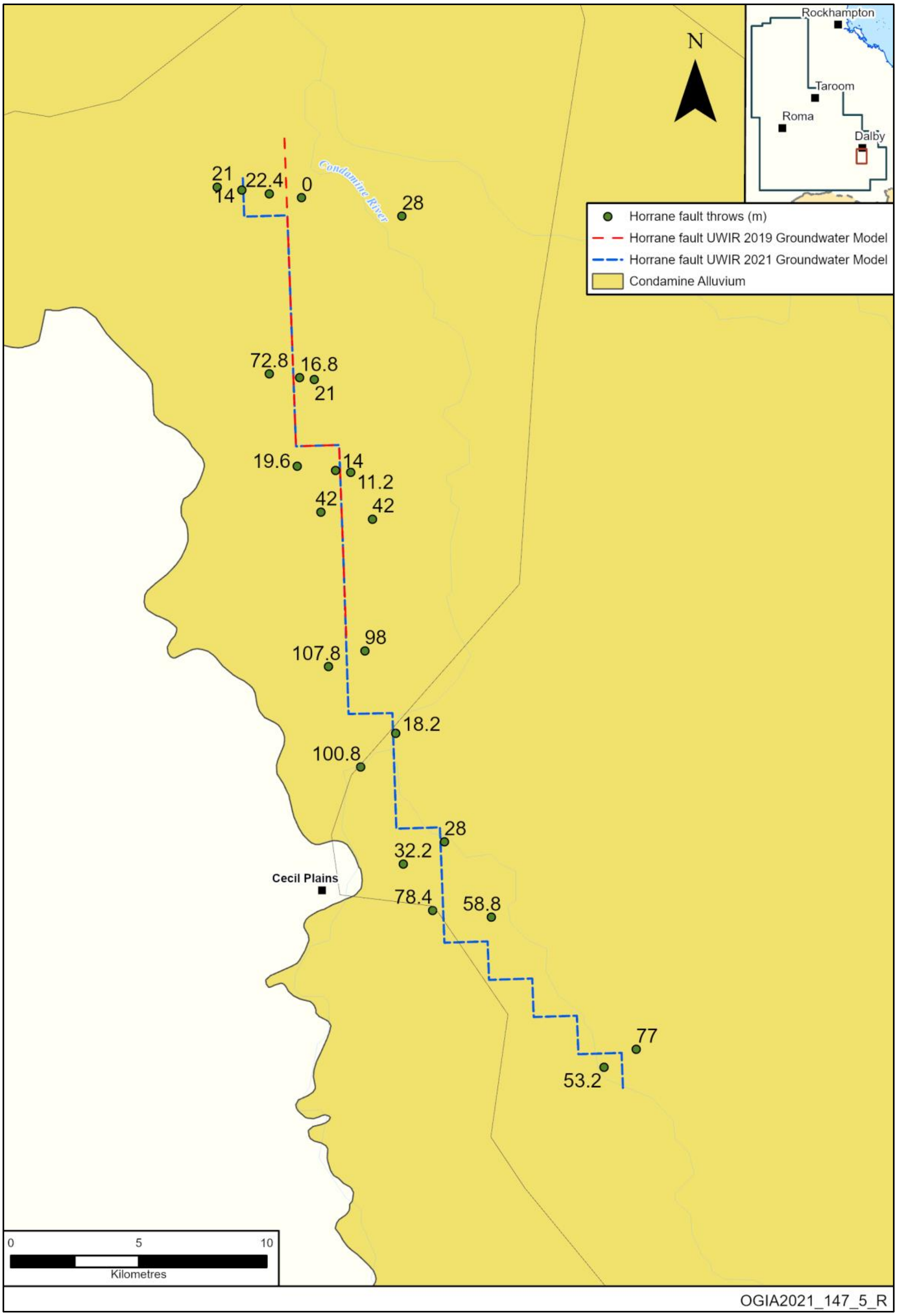

Figure 6-4: Observed Fault intersections with displacement (m) shown in green with modelled fault extents from the UWIR 2019 and UWIR 2021 groundwater models (red and blue, respectively)

6.3.1.3 Adjustment of the Hutton-Wallumbilla Fault

The area around Lucky Last springs has been a continued focus for OGIA in terms of conceptualisation, data gathering and impact modelling. In the previous model, the regionally significant Hutton-Wallumbilla fault has been interpreted to juxtapose the Precipice Sandstone against the source aquifer for the springs in this area (Boxvale Sandstone). This has been interpreted as a potential impact pathway for nearby CSG development in the Bandanna Coal Measures.

Since the UWIR 2019, Geoscience Australia has acquired airborne electromagnetic survey (AEM) data over this area, which has subsequently suggested no obvious juxtaposition between the Precipice and Boxvale Sandstones. Further review of the 250 m Geological model at the same location also corroborated the lack of juxtaposition between the Precipice and Boxvale Sandstones at this location.

As a result, non-neighbour connections have been adjusted around the Hutton-Wallumbilla fault to reflect this information. In the latest model, there are no longer direct non-neighbour connections between the Precipice and Boxvale Sandstones at this location.

6.3.1.4 Refinement of Cenozoic extent in key areas

A limited review of the extent of Cenozoic cover in and around existing coal mines has resulted in the addition of a small number of Cenozoic cells in vicinity of Kogan Creek and Wilkie Creek to better represented the likely impacted formations in these areas.

6.3.2 Process representation

6.3.2.1 Representation of coal mine stresses

The *Regional Model 2021* includes stresses from seven coal mines in the Surat CMA. Four of these are currently in operation (Table 6-1 and Figure 6-5).

Table 6-1: Status and key attributes of coal mines in the Surat CMA[1] (OGIA 2021e)

Operator	Mine	Start	End	Depth (m)	Target formations
Glencore	Wandoan	2024	2056	24–60	Juandah Coal Measures
New Hope Group	Elimatta	2029	2058	50m–150	Juandah Coal Measures
Stanmore Resources	The Range	2027	2051	20–120	Taroom Coal Measures
Yancoal	Cameby Downs	2009	2092	40–110	Upper Juandah Coal Measures
CS Energy	Kogan Creek	2000	2040	40–60	Upper Juandah Coal Measures
Peabody Energy	Wilkie Creek	1995	2015	30–60	Upper Juandah Coal Measures
Intergen	Commodore	2001	2037	15–50	Taroom Coal Measures

[1] New Acland is presented separately in section 7

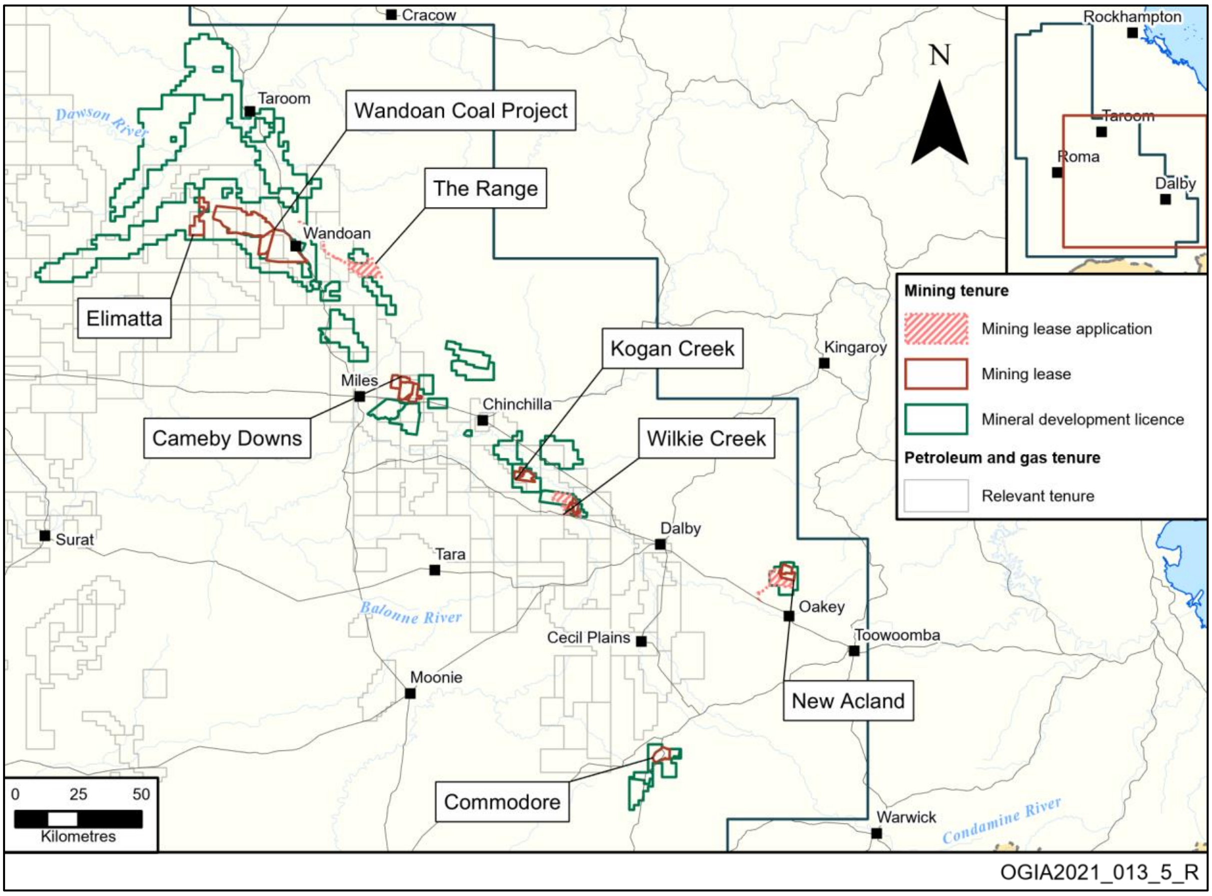

Figure 6-5: Location of coal mines in the Surat CMA

Each of the pits associated with these operations is relatively shallow and the Commodore and New Acland mines are more than 50 km from the nearest CSG fields. However, mines in the Central and Northern Coal Area (NCA) are close to Coal Seam Gas operations and water levels nearby may be influenced by both of these developments. The UWIR 2021 model, therefore, includes representation of each of these open cut operations based on historic mine survey information lodged with the Department of Natural Resources, Mines and Energy. Drainage to each mine pit is simulated over time through the addition of MODFLOW-USG RIV cells in each *Regional Model 2021* cell from the pre-mined surface elevation, down to the minimum elevation of the surveyed pit shell. Figure 6-6 shows time series of minimum pit shell elevation data extracted from the mine survey data and used as input to the UWIR 2021 model transient simulation. As per other surface drainage features, a conductance value of 5,000 m^2/d was assigned to all cells used to simulate coal mining operations. This is high enough to allow easy water outflow, but not so high as to instigate numerical instability.

To accommodate impacts from New Acland, the Acland Model has been utilised for the impact assessment. The extraction of thermal coal from the lower Walloon Coal Measures at New Acland started in 2002. See section 7 for more information on this model.

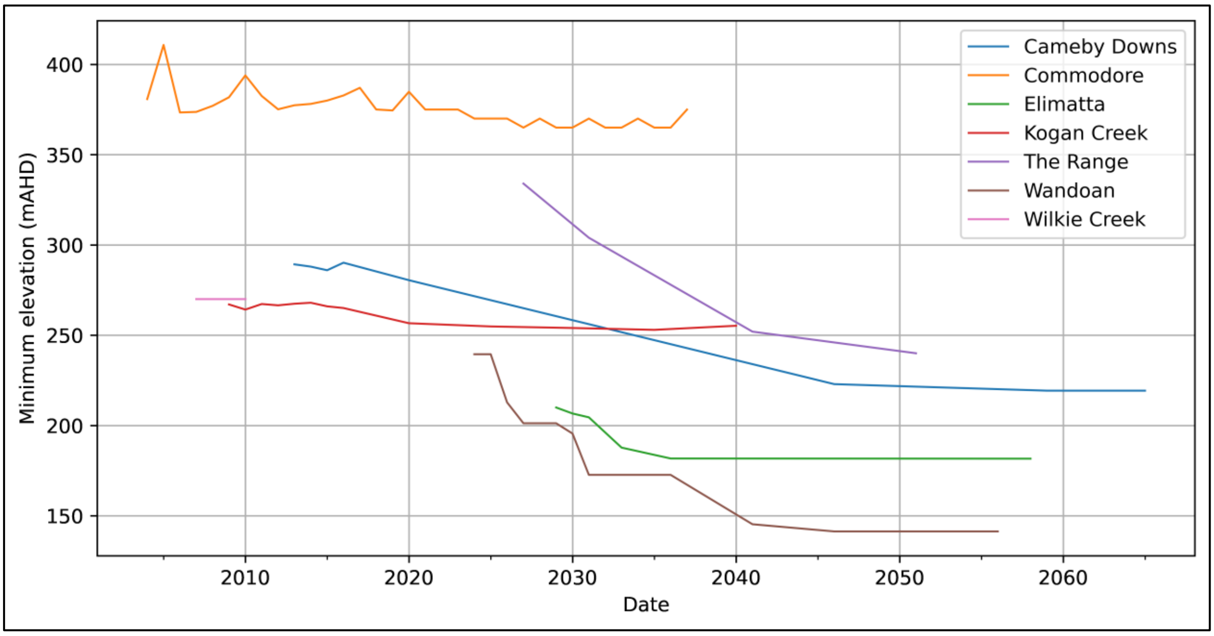

Figure 6-6: Minimum pit shell elevation time-series

6.3.2.2 CSG Extraction

Historic CSG extraction

Information on historic CSG wells during the period January 1995 to December 2019 was obtained from the Queensland Government QDEX database and CSG well information provided to OGIA by individual tenure holders, including well inlet information and monthly actual water extraction volumes for each CSG well. Through comparison of CSG well screen information with stratigraphic picks based on geophysical logs OGIA has also identified that about 16% of existing CSG wells (around 900 wells) may be partially completed into the lower parts of the Springbok Sandstone. This is very similar compared to the numbers reported in 2019.

CSG wells are represented in the groundwater model using the MODFLOW-USG Drain package according to the methodology reported in the UWIR 2019 groundwater modelling report (OGIA 2019b). The model attribution process of drains representing CSG wells is based on well location and inlet information. Where well inlet information is missing, CSG drains are assigned to all layers of the CSG producing formation. This means a maximum of six model layers in the Walloon Coal Measures and a maximum of two model layers in each of the Bandanna and Cattle Creek Formations. A “rule surface” also constrains this default layer assignment in some places of the model area, to account for areas such as the Condamine Alluvium, where CSG well inlets are not typically placed within 150 m of the ground surface.

Figure 6-7 provides the locations of CSG wells that are represented in the model by drain cells assigned to model nodes. Drains are assigned to the relevant target formations (Walloon Coal Measures, Bandanna Formation and Cattle Creek Formation) up to the end of the transient calibration period (i.e. December 2019). Note that a small number of wells are shown outside of current CSG development areas – these pertain to pilot and exploration wells (e.g. the Glenburnie site, located southwest of Cecil Plains). Figure 6-7 also shows the locations of model grid cells with CSG drains assigned to the lower Springbok Sandstone.

Monthly water extraction volumes recorded for CSG wells define whether CSG drains are active and as development of the well takes place, the assigned elevation to the CSG drain is lowered at a rate that reflects a notional bottom hole pressure versus time curve based on data supplied by the tenure holder operating the well. Conductance values for each CSG drain are based on the Peaceman equation (Peaceman 1978). Modifications to MODFLOW-USG made by OGIA automate calculation of the conductance associated with each CSG drain boundary condition. This conductance is calculated internally by MODFLOW-USG based on the CSG well diameter, “enhanced hydraulic conductivity” (coal seam permeability) ascribed to the cell in which each drain is located as well as the water saturation of the cell. Full implementation details are reported in (OGIA 2019b).

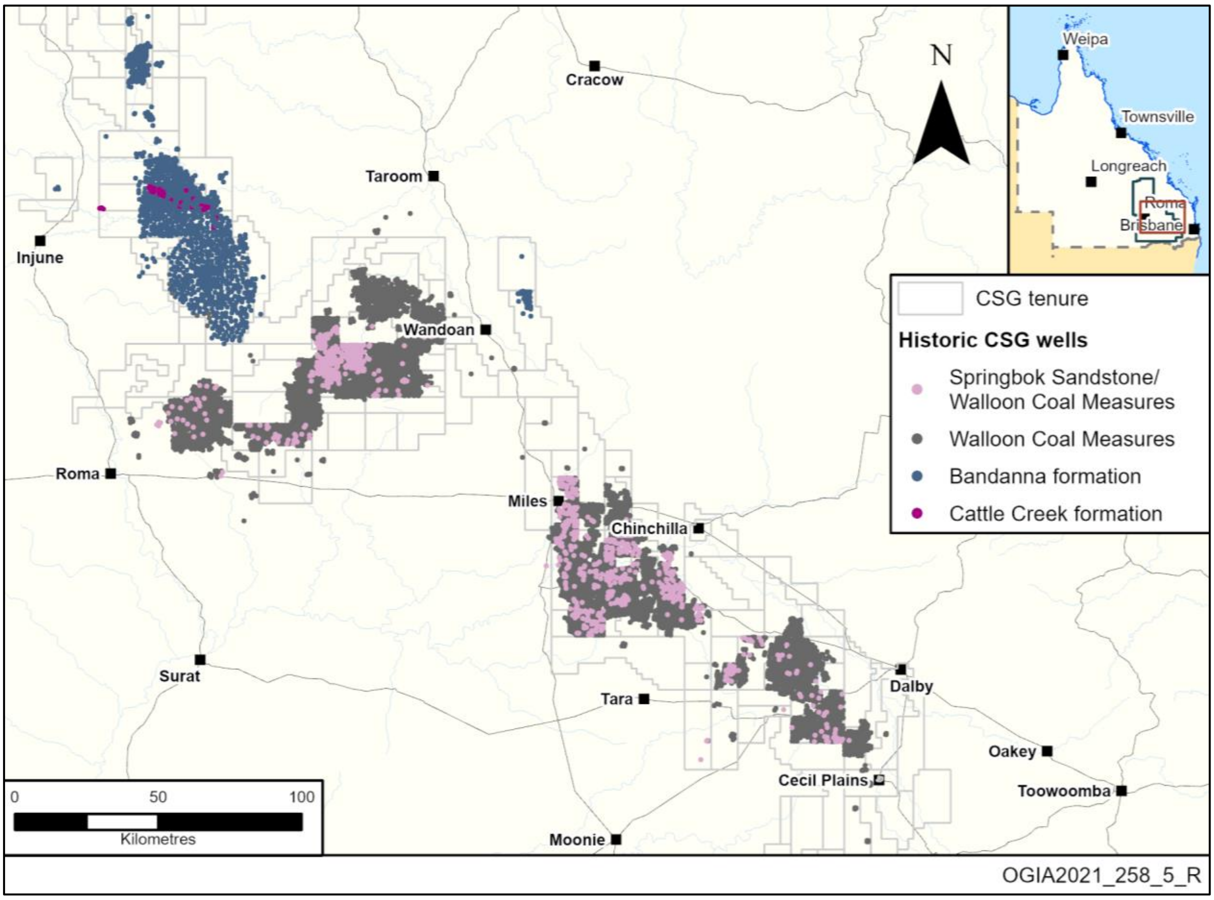

Figure 6-7: Historic CSG well locations included in UWIR 2021 model

Future CSG extraction

Emplacement and activation of future CSG wells in the UWIR 2021 model relies on existing CSG well data and CSG development plans that are provided by each tenure holder as part of this UWIR cycle. This method has been described in the UWIR 2019 modelling report (OGIA 2019b) and consists of creating theoretical locations of CSG wells, which are subsequently modified to accommodate the presence of existing wells. As about 16 percent of existing CSG wells are partially completed into the Springbok Sandstone, including some recently completed wells, a similar percentage of future CSG wells are defined to be tapping into the Springbok Sandstone. CSG wells are activated according to the start and end dates for each CSG development area provided by the tenure holders.

6.3.2.3 Dual-porosity and dual-phase flow approximation

As for the UWIR 2019 model, a dual porosity formulation is used to represent the different properties and responses of coal and interburden (non-coal) material within the CSG reservoir. MODFLOW-USG supports the use of dual porosity media by defining a mobile (coal seams) and immobile domain (interburden) for each dual porosity layer. The two domains are linked through what is called a “dual domain flow transfer rate” (DDFTR), which is further specified in the UWIR 2019 modelling report (OGIA 2019b). CSG drains are only connected to the mobile domain of a dual porosity cell. The fraction of the mobile domain is based on derived coal proportions from available geophysical logs.

The coal seams desaturate when being depressurised due to CSG extraction due to the desorption of gas from a coal matrix and subsequent dual-phase flow of gas and water to CSG wells. This desaturation process of the coal seams is approximated using a modified Richards approach that has been implemented by OGIA in MODFLOW-USG. This approach has been tested, reviewed, and accepted as part of previous UWIR models and is described in detail in the UWIR 2019 modelling report (OGIA 2019b).

6.4 Stochastic model calibration and uncertainty analysis

6.4.1 Methodology

There is a significant difference between a highly parameterised inversion process that produces the “base calibrated model” and uncertainty analyses that generate stochastic samples of the posterior parameter distribution. The former attempts to suppress all parameter heterogeneity that is not required for a model to reproduce historical system response, while ensuring that any heterogeneity that does arise in this process adheres to known geological precepts. Calibration-constrained uncertainty analysis instead attempts to express all heterogeneity in a manner that is geologically sensible provided it remains compatible with historical system response. The extent to which parameter uncertainty is reduced for a particular parameter depends on the information content of the calibration dataset with respect to that parameter.

An approach was taken that combines both approaches using PEST_HP and PESTPP-IES; use of a parameter set that constitutes the minimum error variance may be a helpful precursor to the deployment of uncertainty analyses for the following reasons:

- seeking a single solution to an inverse problem that, by design, departs minimally from that which is deemed to be “most realistic” from an expert knowledge point of view allows for a more nuanced exploration of the most appropriate model structure.
- a calibration process that requires a full Jacobian matrix can often achieve a lower level of model-to-measurement misfit than an inversion process based on a rank-deficient Jacobian matrix. Attainment of a good fit to monitoring data acquired in areas that are most pertinent to impact assessment is advantageous.
- sampling of the posterior parameter probability distribution during uncertainty analysis can sometimes be more numerically efficient if this process begins with random parameter fields that are conditioned by the minimum error variance solution. Under these circumstances PESTPP-IES may require fewer iterations to achieve a good fit with field measurements than if initiated with true samples of the prior parameter probability distribution.

Generation of calibration-constrained parameter realisations for the UWIR model was thus undertaken by:

- using PEST_HP to determine a parameter set of minimum error variance; this encapsulates the heterogeneity “which must exist” to explain observed system behaviour embodied in the calibration dataset.

- randomly sampling from a Gaussian parameter probability distribution that is centred on the calibrated parameter field with standard deviations based on expert hydrogeological knowledge.
- applying the Iterative Ensemble Smoother (IES) method using PESTPP-IES for rigorous Monte Carlo sampling-based uncertainty analysis.

6.4.1.1 Minimum error variance

As noted previously, the first phase of stochastic model calibration and uncertainty analysis was implemented using the PEST_HP suite of software (Doherty 2020). Model calibration constitutes a so-called “inverse problem” in which parameters are adjusted until an acceptable fit is achieved between model outputs and corresponding measurements of system state.

The calibration dataset does not support unique estimation of these parameters. Hence, the inverse problem of model calibration can be mathematically characterised as “ill-posed”. A single parameter set may still be sought for the purpose of obtaining an appropriately calibrated model however, achieved by seeking the parameter set that allows the model to fit the calibration dataset to an acceptable level, while departing from pre-calibration parameter values to only the minimum extent required to achieve this fit. Because pre-calibration parameter values are in part drawn from expert knowledge, the parameter field obtained in this way can claim a status of “minimised error variance”. Of the infinite number of parameter fields which can be found to match a given calibration dataset, this is the parameter field that occupies a central position in parameter space with respect to these other parameter fields. By making its potential for wrongness symmetrical, that potential is thereby minimised.

The PEST_HP calibration step was achieved through highly parameterised inversion in which uniqueness is obtained through enforcement of so-called Tikhonov (Tikhonov 1963a, 1963b) regularisation that operates by seeking a solution to the inverse problem in which parameters, or functions of parameters, depart to the minimum extent possible from a user-defined preferred condition. Therefore, to the extent that departures must occur in order for model outputs to fit the calibration dataset, these departures are constrained to occur in ways that are geologically plausible. In the present case, these were comprised of a suite of additional, user-specified, “observations” (formulated as so-called “prior information” equations) declaring equality of parameters to their initial values. Rules for departure from these values were encapsulated in parameter covariance matrices that suggested, for spatial parameters based on pilot points, collective rather than individual deviations from initial values.

PEST_HP calibration of the *Regional Model 2021* required adjustment of 17,137 parameters for a calibration dataset comprising 72,913 observations; the latter are described in section 6.4.4 and both are summarised in Appendix B1 and B2. A total of 15,156 regularisation equations were also employed for this process.

6.4.1.2 Iterative Ensemble Smoother (IES)

The IES method was implemented via PESTPP-IES, a member of the PEST++ suite. The algorithm is described in Chen and Oliver (Chen & Oliver 2013, 2017) and White (White 2018). PESTPP-IES requires an ensemble of random parameter fields; each of these fields is a sample of the prior (pre-calibration) parameter probability distribution. Then, through a succession of iterations, it modifies these realisations until they become samples of the posterior (post-calibration) parameter probability that expresses residual parameter uncertainty arising from: -

- limited information contained within the calibration dataset, and
- measurement noise associated with this dataset (some of which is, of course, so-called “structural noise” arising from inadequacies of the model as a simulator of real-world behaviour).

The IES approach is attractive because regardless of the number of model parameters, the number of model runs required per iteration is equal to the number of random parameter fields that are being adjusted. The ability to handle large numbers of parameters (far exceeding those which are estimable) ensures that post-calibration predictive uncertainty is not undervalued. Also, the randomised approach to computation of the Jacobian (i.e., a matrix of partial derivatives of the *n* model outputs which correspond to measurements comprising the calibration dataset with respect to the *m* adjustable parameters employed by the model) may prevent entrapment of the inversion process in local objective function minima, adding further to the credibility of posterior parameter and predictive probability distributions that emerge from the process.

6.4.1.3 Prior parameter ensemble

The fewer the number of random parameter fields that comprise an ensemble, the more likely it is that anomalous parameter correlations will arise. For example, in the UWIR regional groundwater model, it is known a priori that the recharge rate for a given model stress period will not affect water levels computed during a previous stress period. Water level responses measured far afield from a given hydraulic model parameter are also likely to be insensitive. While PPEST-IES includes a subjective “localisation” functionality that allows a user to pre-assign values to elements of the Jacobian matrix (mostly values of zero) if the values of these elements are known in advance, this option was not used as the dimensionality of the problem would increase numerical inefficiency. Thus correlations such as those mentioned were not necessarily reflected in the randomised empirical Jacobian matrix. However, Chen and Oliver (Chen & Oliver 2013) note that the importance of this procedure reduces with increasing ensemble size. They recommend a minimum ensemble size commensurate with the number of uniquely identifiable pieces of information in the calibration dataset. This may be approximated by the dimensionality of the solution space for a given inverse problem. Using the PEST utility SUPCALC (Doherty 2018), it was established that the working dimensionality of the calibration solution space of the model is approximately 2,500. PESTPP-IES was subsequently deployed with 3,500 parameter field realisations to ensure that parameter space was adequately sampled.

The PEST utility RANDPAR3 (Doherty 2018) was used to generate 3,500 random parameter realisations using a random number generator algorithm. Gaussian probability distributions were assumed for all parameters natively or for their log-10-transformations. The expected value was centred at the “base” calibrated model parameter value. Parameter-value bounds were respected in all cases.

All parameters other than those associated with pilot points were assumed to show no prior correlation. Under this assumption, their prior uncertainties can be characterised using only their standard deviations (the square of which are their variances). Hence no non-zero off-diagonal elements are required in the prior covariance matrix for these parameters. The standard deviation of each parameter was defined by dividing the difference between the upper and lower bounds adopted for calibration purposes on the assumption that the parameter was Gaussian and the parameter range spanned approximately four standard deviations (thereby representing a 95% confidence limit) up to a maximum of 0.5 in log space. Prior uncertainties for zonal and layer wide parameters are summarised in Appendix G1.

Parameter groups comprising pilot point parameters were assigned a full covariance matrix based on spatially variable variograms, however. For example, for a spatially variable property such as hydraulic conductivity, it expresses both the range of values that this property is likely to take for the different aquifer materials prevailing within the study area, as well as the degree of spatial continuity that is likely to exist for this property.

Statistical correlation was represented by an exponential variogram, and hence was assumed to be a function only of pilot point separation. Covariance relationships implied by the exponential variogram are described by equation (1):

$$C(h) = C(0)[1-e^{-h/a}] \quad (1)$$

where h depicts the separation between any two pilot points and C(0) expresses parameter covariance at zero pilot point separation (the variogram "sill"), this being the innate variance of the parameter, and a is a length parameter or integral scale, which defines a variogram range of approximately 3a (Deutsch & Journel 1992).

For all pilot point parameters, the variogram "a" value was declared as pilot-point-specific. This reflects the fact that pilot points are not capable of representing the prevailing heterogeneity of an aquifer system. Instead, this parameterisation device contains a degree of upscaling, with the extent of upscaling decreasing with increasing spatial density of pilot points. Where pilot point emplacement is dense, short range hydraulic property heterogeneity can be characterised. Alternatively, where it is sparse, only long range hydraulic property heterogeneity can be characterised. The variogram range associated with each pilot point was calculated was thereby formulated in the following manner:

- The average separation between the pilot point to which an "a" value must be assigned and its 8 closest neighbours was calculated.
- The "a" value ascribed to the variogram associated with that pilot point was designated as 25% greater than this average separation.

For parameter types represented by pilot points (excluding those associated with western GHB heads), the variogram sill (applied to the logarithm of hydraulic properties associated with pilot points) ranged between 0.01 and 0.25; this implying a standard deviation of parameter variability that could range between 0.1 and 0.5 in log space. The variogram sill for the western GHB head was specified as 100 (i.e. a standard deviation of 10 m in native space). Variograms assigned to all pilot points are isotropic.

6.4.1.4 Observation ensemble

PESTPP-IES also requires 3,500 random observation realisations. Each realisation in the observation ensemble was commensurate with the original observation vector from the PEST control file plus a realisation of measurement noise sampled from the multi-normal distribution defined by the C(ε) matrix. The C(ε) matrix was assumed to be diagonal, and the noise associated with each measurement was assumed to be independent of that associated with all other measurements. The standard deviation of each observation was assumed equal to the inverse of its observation weight. The proportionality constant applied to all weights was such that the measurement objective function is approximately equal to the number of observations comprising the calibration dataset minus the dimensionality of the calibration solution space; refer Doherty (Doherty 2015) for further details.

6.4.2 Calibration stages

The first simulation stage pertains to steady state conditions which existed prior to the commencement of any groundwater extraction from the Surat CMA.

The main purpose of this stage was to allow inclusion in the calibration dataset of a suite of head measurements which are not the outcome of an extraction regime whose pumping details are uncertain. Unfortunately, all measurements of groundwater head within the domain of the UWIR 2019 model postdate the commencement of water extraction from stratigraphic units featured in this model. However, some early measurements of groundwater head are nevertheless relatively unaffected by pumping.

A steady state simulation of hydraulic conditions which existed prior to the commencement of CSG extraction from the Surat and Bowen basins within the CMA in 1995 comprised the second simulation stage. This simulation stage served two purposes, these being as follows:

- it allowed inclusion in the calibration dataset of a further set of observations which were presumed to reflect steady state conditions prior to the commencement of CSG extraction in 1995
- heads calculated through this simulation stage served as initial heads for the ensuing transient model stage.

6.4.3 Parameterisation

No major changes were introduced to the UWIR 2019 parameterisation strategy for calibration and uncertainty analysis (noting that accommodations were made for the altered subdivision of the Walloon Coal Measures). However, minor improvements to hydraulic conductivity and storage parameter bounds were undertaken following a review of field data and supplementary information sources. The parameter bounds for hydraulic conductivity and storage are provided in Appendix C1 and Appendix C2, respectively. For more information on model parameterisation refer the 2019 modelling report (OGIA 2019b)

6.4.4 Observations

6.4.4.1 1947 steady state targets

The below table outlines the stratigraphic distribution of the 1947 steady state calibration dataset. As noted in previous UWIRs, the spatial distribution of observed head data in deeper parts of the basin during this early stage of development are extremely limited.

The total number of observations in this calibration step has decreased from 738 to 651 from the UWIR 2019 to UWIR 2021 with the largest decrease being for Cenozoic Formation targets. The reduction is mainly due to observations being discarded due to quality concerns. See Appendix D1 for locations. Contour maps for simulated water levels during after the 1947 steady state simulation are provided as Appendix E1. Scatter plots of measured versus modelled heads for the 1947 steady state targets, along with maps showing the distribution of residuals (calculated as measured water level subtract modelled water level) are presented as Appendix E2 and E3, respectively.

Table 6-2: Steady state pre-1947 targets by formation

Formation	Layers	UWIR 2019 equivalent	UWIR 2021
Cenozoic Formations	1	267	147
Upper Cretaceous Formations	2	26	27
Wallumbilla Formation	3	30	38
Bungil Formation	4	39	58
Mooga Sandstone	5	83	73
Orallo Formation	6	78	66
Gubberamunda Sandstone	7	51	80
Westbourne Formation	8	0	0
Springbok Sandstone Upper	9	4	8
Springbok Sandstone Lower	10	1	6
Walloon Non-Productive-Zone	11	1	1
Upper Juandah Coal Measures	12, 13	11	7
Lower Juandah Coal Measures	14, 15, 16	21	21
Taroom Coal Measures	17	10	12
Durabilla Formation	18	0	0
Hutton Sandstone Upper	19	69	67
Hutton Sandstone Lower	20	10	10
Upper Evergreen Formation	21	0	0
Boxvale Sandstone	22	0	4
Lower Evergreen Formation	23	0	0
Precipice Sandstone	24	13	14
Moolayember Formation	25	0	0
Clematis Group	26	2	2
Rewan Group	27	0	0
Bandanna Formation Non-Productive-Zone	28	0	0
Bandanna Formation Upper	29	0	0
Bandanna Formation Lower	30	0	0
Upper Permian	31	21	9
Cattle Creek Non-Productive-Zone	32	0	0
Cattle Creek Formation Upper	33	0	0
Cattle Creek Formation Lower	34	0	0
Lower Permian	35	1	1
Total		738	651

Groundwater is conceptualised as flowing parallel to the GHB located along the westernmost extent of the model domain. The locations of GHB cells are shown in Appendix F1. Heads along this boundary are adjustable through the calibration process; as will be discussed below, they are parameterised using pilot points emplaced at 9 km intervals for which a lateral head difference of zero is sought along the E-W direction. These zero gradient observations were introduced in the same layers as those in which the GHB boundary conditions themselves are featured. The total number of zero gradient observations is 341. The locations of paired GHB boundary condition observations are provided as Appendix D2.

6.4.4.2 1995 steady state targets

6.4.4.3 Heads – Condamine Alluvium and Main Range Volcanics

1995 steady state heads experienced in the Condamine Alluvium and Main Range Volcanics were obtained from the Condamine Alluvium Model (KCB 2011) in the former case, and through spatial interpolation of observed water levels in the latter case. These were then ascribed directly to MODFLOW-USG drains assigned to all model cells which comprise this part of the model domain.

In order to ensure that water levels within these cells actually rise to the drainage surface, these heads were also introduced to the calibration dataset as observations. Heads cannot rise above the drainage surface due to the action of the drains. This resulted in 278 head observations for the Condamine Alluvium footprint of the UWIR 2021 model and 386 head observations for the footprint of the Main Range Volcanics. See Appendix D3 for locations of these calibration targets.

Scatter plots of modelled versus observed water levels at these targets illustrate the restriction applied to the modelled water levels preventing them from exceeding measured water levels (i.e. the drain elevation), see Appendix E4.

6.4.4.4 Heads – other stratigraphic units

Following processing of groundwater head data, a total of 5,888 measurements were available for use in the calibration dataset in conjunction with the 1995 steady state simulation (compared to 5,099 in the previous UWIR model). Their disposition with respect to model layers and stratigraphic units is listed in Table 6-3.

Values of ΔH computed for each head observation were used to identify those observations for which the departure from the steady state assumption was likely to be greatest. The ΔH values of greater than 5 m were assumed to be significant.

Observations for which ΔH exceeded this threshold were placed into a "penalty" group. Asymmetric residual calculation was employed for each member of this group, where a residual is the value of an observation minus its model-calculated counterpart. The asymmetric residual was designed to forgive model-calculated heads which are less than their observed counterparts but to penalise those which are above their observed counterparts. This acknowledges the fact that steady state water levels (as computed by the model) will be lower than transient water levels (which are observed) in a context where steady state conditions in response to gradually increasing groundwater extraction have not yet been achieved.

Let h_0 denote the observed head for a member of the penalty group. Let h_m denote the model-generated counterpart to this observation. A zero residual is calculated if h_m is between h_0 and $h_0 - \Delta H$. Hence, if h_o is 300 mAHD and ΔH is 10 m, then model-to-measurement misfit is deemed to be zero if the simulated head falls in the range 290 to 300 mAHD. Where h_m is less than ($h_o - \Delta H$), the residual (r) is calculated as

$r = -[h_m - (h_o - \Delta H)]$ (5.1)

Alternatively, if h_m is greater than h_0 then the residual is calculated in the conventional way, i.e. as (h_o – h_m)..

Water level observations for which the ΔH value is less than 5 m were placed into the "traditional" group. Residuals were calculated in the usual way for members of this group, that is as (h_o – h_m).

Simulated water level contour maps for the end of the 1995 steady state period are presented as Appendix E5. Appendix D4 and D5 show the locations of these partitioned observations for the traditional and penalty groups, respectively. Scatter plots of observed and modelled groundwater levels and residual maps are provided as Appendix E6 and E7, for the traditional group, and Appendix E8 and E9 for the penalty group of observations.

Table 6-3: Steady state 1995 targets by formation

Formation	Layers	UWIR 2019 equivalent	UWIR 2021
Cenozoic Formations	1	1,027	1,483
Upper Cretaceous Formations	2	93	116
Wallumbilla Formation	3	79	94
Bungil Formation	4	160	180
Mooga Sandstone	5	430	398
Orallo Formation	6	396	340
Gubberamunda Sandstone	7	346	448
Westbourne Formation	8		
Springbok Sandstone Upper	9	81	102
Springbok Sandstone Lower	10	32	47
Walloon Non-Productive-Zone	11	5	9
Upper Juandah Coal Measures	12, 13	148	121
Lower Juandah Coal Measures	14, 15, 16	283	312
Taroom Coal Measures	17	183	187
Durabilla Formation	18		
Hutton Sandstone Upper	19	949	1,045
Hutton Sandstone Lower	20	273	249
Upper Evergreen Formation	21		
Boxvale Sandstone	22	28	36
Lower Evergreen Formation	23		
Precipice Sandstone	24	202	227
Moolayember Formation	25		
Clematis Group	26	99	122
Rewan Group	27		
Bandanna Formation Non-Productive-Zone	28		1
Bandanna Formation Upper	29	19	42
Bandanna Formation Lower	30	8	10

Formation	Layers	UWIR 2019 equivalent	UWIR 2021
Upper Permian	31	149	186
Cattle Creek Non-Productive-Zone	32		
Cattle Creek Formation Upper	33	1	5
Cattle Creek Formation Lower	34		
Lower Permian	35	108	128
Basement	36		
Total		5,099	5,888

6.4.4.5 Other Targets

The following calibration targets were also included in the current model as per UWIR 2019 (OGIA 2019b):

- Vertical inter-aquifer head differences (see Appendix D6 for locations and Appendix E10 for residual map)
- Condamine water flux exchange

6.4.4.6 1995-2019 transient targets

6.4.4.7 Consumptive groundwater extraction

Like the UWIR 2019 model, simulation of groundwater extraction for purposes other than CSG production is undertaken using the MODFLOW-USG well (WEL) package. Each well is set up to extract water at its metered rate or a proportion of its estimated “licensed” or full entitlement rate. Extraction rates assigned to conventional P&G wells are based on metered information. However, for all simulated groundwater extraction wells this rate is automatically reduced (also referred to as “derating)” if the head in the well falls below a user-specified elevation. This elevation is defined by either the top of the well screen or the top elevation of the cell in which the well is emplaced.

To prevent unrealistic derating of extraction (e.g. by underestimation of local hydraulic conductivity), the transient calibration dataset was supplemented with time series of estimated groundwater extraction rates for each of the main aquifers that are represented by the groundwater model.

For each of the key water supply aquifers, a non-zero residual is calculated if the total modelled groundwater extraction falls below 80% of the estimated actual extraction. For the Walloon Coal Measures a threshold of 50% was used. The computed residual is then equal to the extraction deficit below this value. These cut-offs are less than 100% given the knowledge base is far smaller for groundwater extractions than those derived from surface water. Information inadequacies are exacerbated where flow metering has been made in only a few wells, and where these measurements do not extend far back in time. Assumptions are therefore required to estimate historical usage. Table 5 shows the target extraction at the end of the transient historic simulation period, i.e. Dec 2019. Figure 6-8 shows the total extraction rate from all formations for the transient historic simulation period.

Table 6-4: Estimated and targeted groundwater extraction rates for Dec-2019

Stratigraphic unit (model layer/s)	Extraction (ML/yr) Estimated actual	Targeted
Gubberamunda Sandstone (layer 7)	10,010	8,008
Springbok Sandstone (layers 9 and 10)	767	614
Walloon Coal Measures (layers 11 to 17)	4946	2,473
Hutton Sandstone (layers 19 and 20)	22,265	17,812
Boxvale Sandstone (layer 22)	148	118
Clematis Sandstone (layer 26)	1,166	933

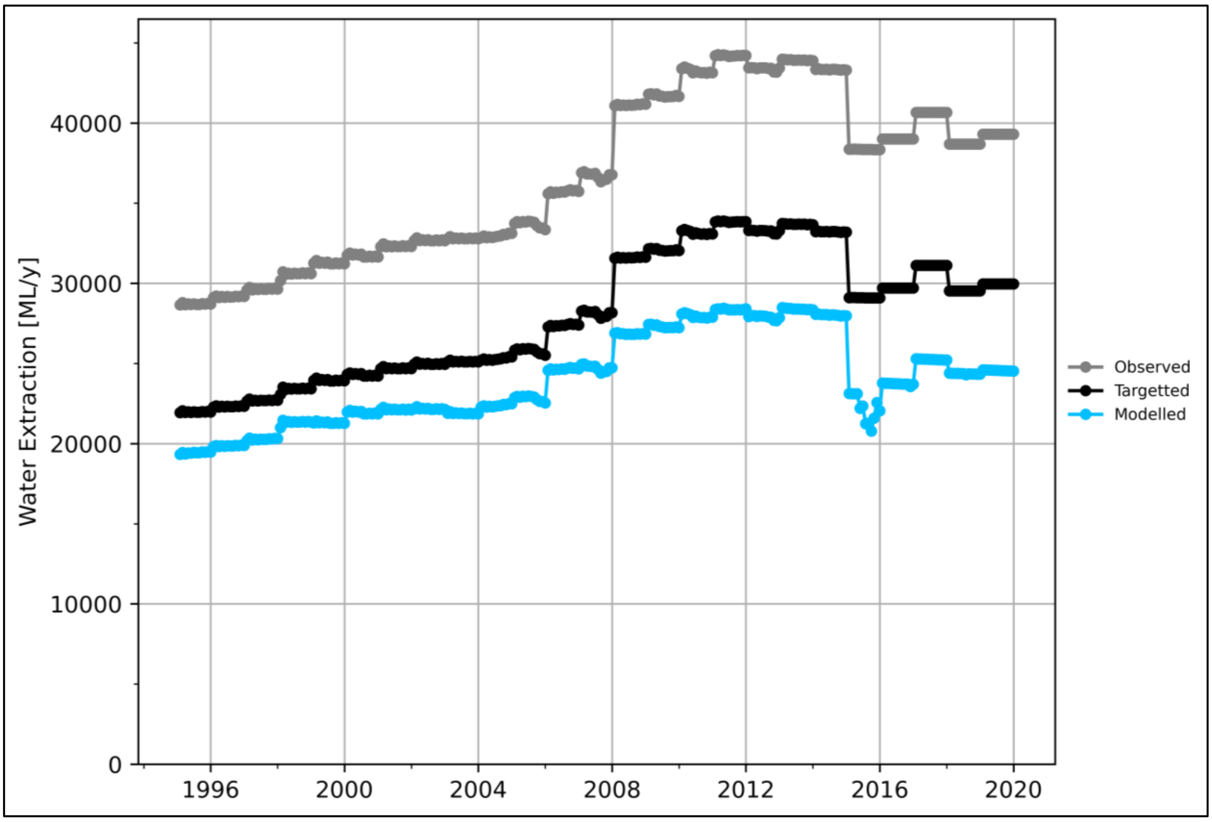

Figure 6-8: Total transient historic non-CSG extraction (1995 to 2019)

6.4.4.8 Measured CSG water extraction rates

Monthly records of extracted groundwater volumes are available for all active CSG wells in the Surat CMA. This dataset has been used to history match the *Regional Model 2021* against time-series of total CSG groundwater extraction for the following CSG formations:

1. Walloon Coal Measures
2. Bandanna Coal Measures
3. Cattle Creek Formation.

Furthermore, history matching was undertaken against total CSG extraction volumes for 25 CSG development areas. These are listed in Table 6-5, together with their observed CSG production volume for December 2019. Timeseries plots for modelled and observed CSG extraction rates by formation as well as by development area are provided as Appendix E11.

Table 6-5: CSG development areas and CSG groundwater extraction rates for Dec-2019

Development area	Extraction (ML/yr)	
	Measured	Modelled
Alfredson	501	115
Arcadia	371	363
Atlas	470	460
CDA	8,537	6,996
Combabula	5,992	7,424
Condabri	3,071	1,908
Daandine	2,071	2,064
Development Area 2	0	0
Development Area 5	23	163
Development Area 8	292	246
Fairview Bandanna	4,494	3,044
Fairview Cattle Creek	85	122
Kia Ora	0	0
Kogan	194	94
NDA	5,301	9,454
Outside	60	527
Peat	38	1
Riley	50	43
Roma	3,629	1,961
Scotia	61	68
SDA	4,921	4,812
Spring Gully Bandanna	3,112	635
Talinga Orana	9,879	7,351
Tipton	1,011	754
Western Surat Gas Project	401	219

6.4.4.9 Transient head observations and observed temporal trends

Head observations in key units form a substantial part of the 2021 transient calibration dataset. After a thorough QA/QC process to verify aquifer attribution and the representativeness of water level measurements, the following criteria were applied to further select monitoring locations for inclusion in the transient calibration dataset:

- time series with records between 1995 and 2019

- a minimum of 4 head measurement records
- at least one year of data
- attributed to one of the following formations: Alluvium (layer 1), Springbok Sandstone (layers 9 and 10), Walloon Coal Measures (layers 12-17), Hutton Sandstone (layers 19 and 20), Boxvale Sandstone (layer 22), Precipice Sandstone (layer 24) and Bandanna Coal Measures (layers 29 and 30).

Table 6-6 summarizes the number of monitoring locations for each of the afore mentioned formations that have been used for the history matching of the transient groundwater model, which amounted to a total of 19,652 measurements for 487 monitoring locations. This is an increase by 17 monitoring locations compared to the dataset used for the calibration of the UWIR 2019 model. Also note that the *Regional Model 2021* is calibrated against groundwater level data up to December 2019, whereas the UWIR 2019 model has been calibrated against data until December 2017.

Consistent with the calibration approach adopted for the UWIR 2019 model, temporal head differences have been calculated for each observation point using the first head observation at each monitoring point as reference head. This generated a further 19,165 temporal head change observations relating to the 487 monitoring locations with transient head data used for model calibration. These are introduced to emphasize the importance of replicating temporal trends, such as observed drawdown in the Walloon Coal Measures, Springbok Sandstone and Hutton Sandstone. See Appendix D7 for locations.

Ground water level contours representing conditions at the end of the transient calibration period (December 2019) are provided as Appendix E12 for every model layer. Scatter plots of observed versus modelled groundwater levels are provided as Appendix E13. Modelled and observed heads and head change hydrographs for all transient calibration points are provided as Appendix E14.

Similar to the UWIR 2019 model, groundwater level observation groups for the Walloon Coal Measures and Precipice Sandstone have been further subdivided. For the Upper Juandah Coal Measures, Lower Juandah Coal Measures and Taroom Coal Measures, monitoring points were assigned to separate observation groups depending on their proximity to CSG activities. This subdivision has been made to improve the calibration against more subtle temporal head trends further away from CSG areas compared to the large observed drawdown within active CSG extraction areas. For the Precipice Sandstone a similar subdivision has been made to distinguish between monitoring points that are showing increasing groundwater levels due to their proximity to aquifer reinjection sites.

Table 6-6: Groundwater level monitoring sites by formation used for transient model calibration

Formation	Layers	UWIR 2019 equivalent	UWIR 2021
Alluvium	1	0	2
Upper Springbok Sandstone	9	30	29
Lower Springbok Sandstone	10	23	27
Upper Juandah Coal Measures	12, 13	53	79
Lower Juandah Coal Measures	14, 15, 16	108	84

Formation	Layers	UWIR 2019 equivalent	UWIR 2021
Taroom Coal Measures	17	56	77
Upper Hutton Sandstone	19	78	91
Lower Hutton Sandstone	20	27	14
Boxvale Sandstone	22	0	1
Precipice Sandstone	24	83	68
Upper Bandanna Formation	29	5	6
Lower Bandanna Formation	30	7	8
Total		470	487

6.4.4.10 Transient vertical head difference observations

Based on the observed head data, a dataset of interlayer vertical head differences has also been generated and added to the transient calibration dataset. As discussed in Doherty and Hunt (Doherty & Hunt 2010) this can be an important type of information to estimate vertical hydraulic conductivities. Observed vertical head differences to constrain the vertical hydraulic conductivity of these layers are based on pairs of monitoring points that are situated above and below the afore-mentioned aquitard layers and within 1 km of each other. In most cases, the selected observation points are within 100 m of each other. Table 6-7 below shows the vertical head pairs and targeted parameters for the UWIR 2021 model. See Appendix D8 for locations of vertical head difference calibration targets used in the transient calibration.

An example of observed vertical head differences is provided in Figure 6-9 for nested monitoring site 160759A_160951A, showing observed and modelled vertical head difference based on head monitoring information for the Taroom Coal Measures and Hutton Sandstone. The data for this site shows a vertical head difference of more than 200 metres, which is important information to constrain the vertical hydraulic conductivities between these two formations in the *Regional Model 2021*. Timeseries plots for modelled and observed vertical head differences at all nested monitoring sites included in the transient calibration period are provided as Appendix E15.

Table 6-7: Transient vertical head difference targets by formation

Stratigraphic unit pair	Targeted parameter	Model layer		Number of observation locations
		Upper	Lower	
Condamine Alluvium-GAB	Kv Condamine transition zone (layer 2)	1	10,12,13,14, 15,16,17	8
Gubberamunda Sandstone – Upper Springbok Sandstone	Kv Westbourne Formation (layer 8)	7	9	5
Lower Springbok Sandstone – Upper Walloon Coal Measures	Kv Walloon non-productive zone (layer 11)	10	12	15
Internal Walloon Coal Measures	Kv Walloon Coal Measures (layers 12 to 17)	12	13,14,15,16, 17	20

Stratigraphic unit pair	Targeted parameter	Model layer		Number of observation locations
		Upper	Lower	
Lower Walloon Coal Measures – Upper Hutton Sandstone	Kv Durabilla Formation (layer 17)	17	19	22
Upper – Lower Hutton Sandstone	Kv Hutton Sandstone (layers 18 and 19)	18	19	3
Boxvale Sandstone – Precipice Sandstone	Kv Lower Evergreen Formation (layer 23)	22	24	1
Precipice Sandstone – Bandanna Formation	Kv Precipice & Bandanna Formation	24	29	1
Total				76

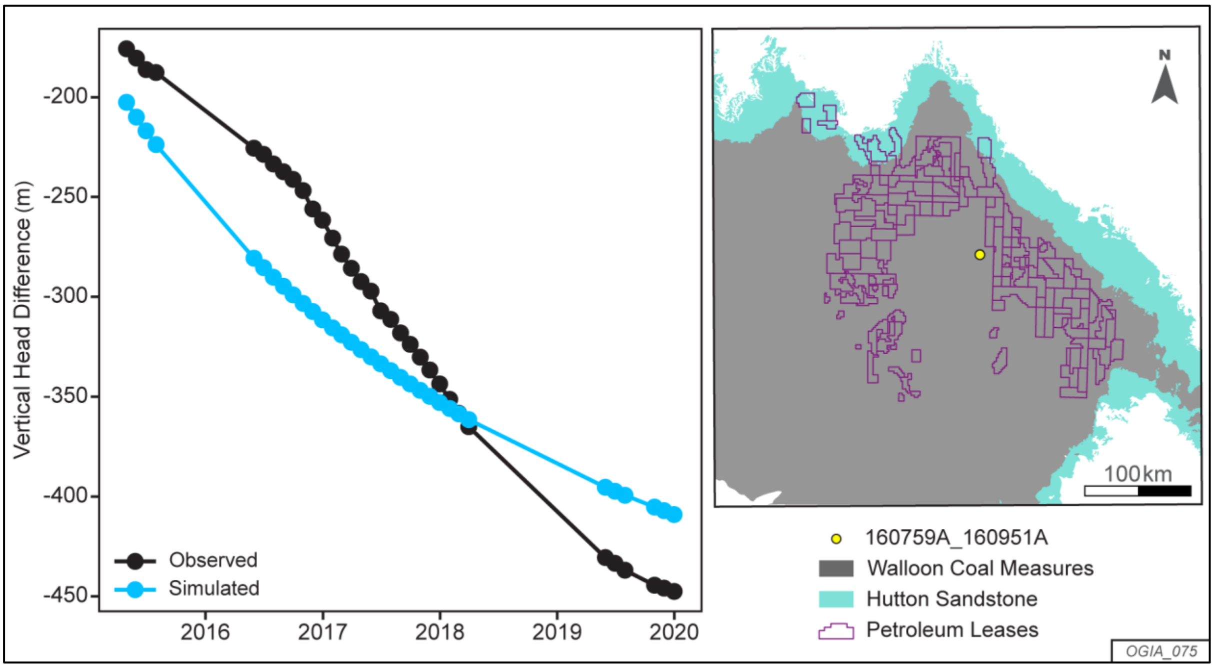

Figure 6-9: Transient vertical head difference between the upper Hutton and Taroom Coal Measures (left), location of monitoring point with other observations in the same layer (right)

6.4.4.11 Other targets

The following additional targets have been used for the *Regional Model 2021*:

- Vertical head differences and water saturation within coal-bearing layers in active CSG extraction areas. See Appendix E16 and E17, respectively.
- Measured reinjection rates for Precipice Sandstone reinjection areas and head targets for reinjection areas to prevent heads exceeding surface elevation that would lead to zero reinjection rates in the model (and subsequent model insensitivity to observed reinjection rates).

- Heads, vertical head differences and water saturation based on existing dual phase CSG reservoir models developed by CSG companies. See Appendix E18 through E20.

6.4.5 Calibration performance

A statistical summary of the overall performance of the initial PEST_HP calibrated transient groundwater levels (totalling 24,496 weighted observations) in the key stratigraphic units for impact assessment is provided in Table 6-8. Inferential statistics used to quantify the levels of model-to-measurement misfit include the scaled rooted mean square (SRMS), scaled mean sum of residuals (SMSR) and the Pearson's R correlation coefficient (R); refer Middlemis et al (Middlemis, H., Merrick, N., Ross, J., and Rozlapa 2001) for further details on these statistics in the groundwater modelling context.

Given that the SRMS and SMSR are well below 5% and the correlation coefficients approaches unity for all units collectively, the calibration of historic water level behaviour was deemed appropriate for conditioning the prior parameter distribution.

Table 6-8: Calibration performance statistics for transient groundwater levels

Stratigraphic unit / model layer	SRMS (%)	SMSR (%)	Pearson's R
Springbok Sandstone (layers 9 and 10)	6.0	4.6	0.75
Walloon Coal Measures (layers 12 to 17)	3.9	1.9	0.93
Upper Juandah Coal Measures (layers 12 to 13)	*8.9*	*4.9*	*0.82*
Lower Juandah Coal Measures (layers 14 to 16)	*6.9*	*4.2*	*0.92*
Taroom Coal Measures (layer 17)	*5.0*	*2.8*	*0.97*
Hutton Sandstone (layers 19 and 20)	2.4	1.1	0.98
Precipice Sandstone (layer 24)	5.0	2.2	0.92
Bandanna (layers 29 and 30)	6.3	4.3	0.93
All units	**3.1**	**1.3**	**0.94**

The progression of the ensemble objective functions per number of model runs is shown in terms of the mean and standard deviation in Figure 6-10 and Figure 6-11 respectively. Note that the objective function values for the "base" realisation are compared against the former. For further reference, the distribution of the objective functions for the parameter ensembles is provided in Figure 6-12 for various PESTPP-IES iterations.

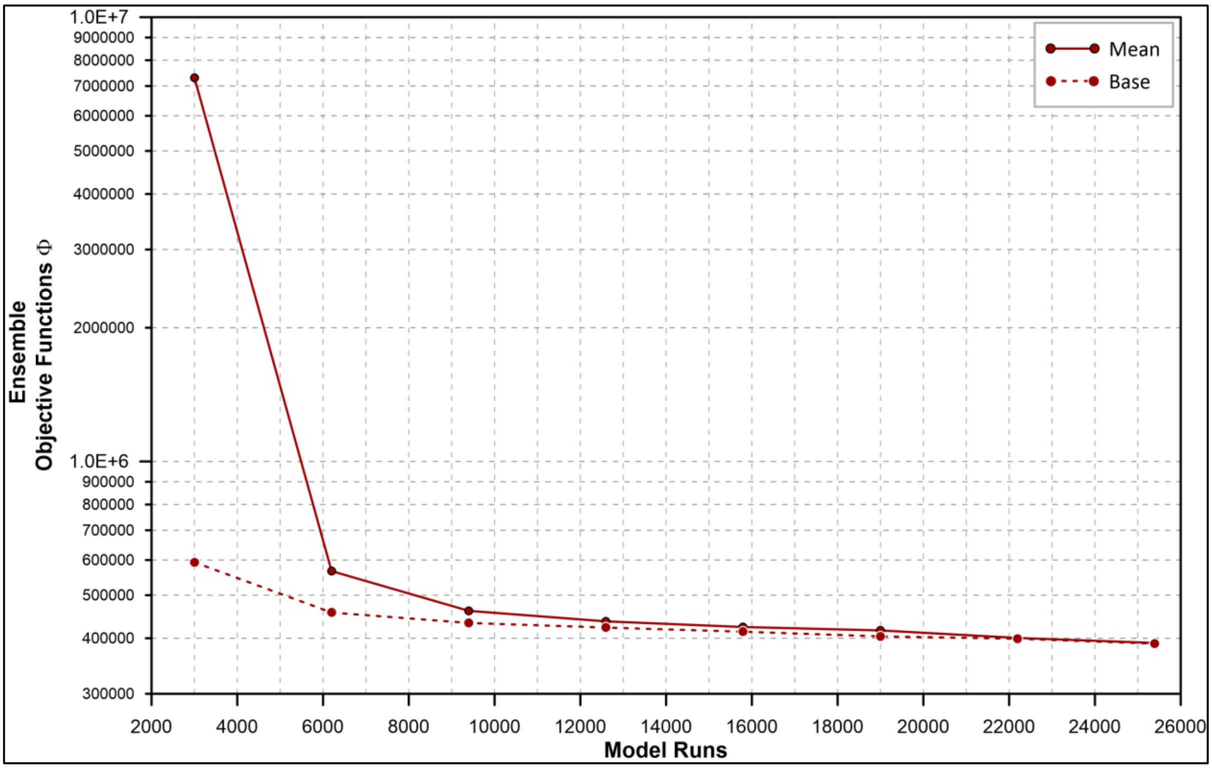

Figure 6-10: Mean of objective function for parameter ensemble and the "base" parameter set versus number of model runs

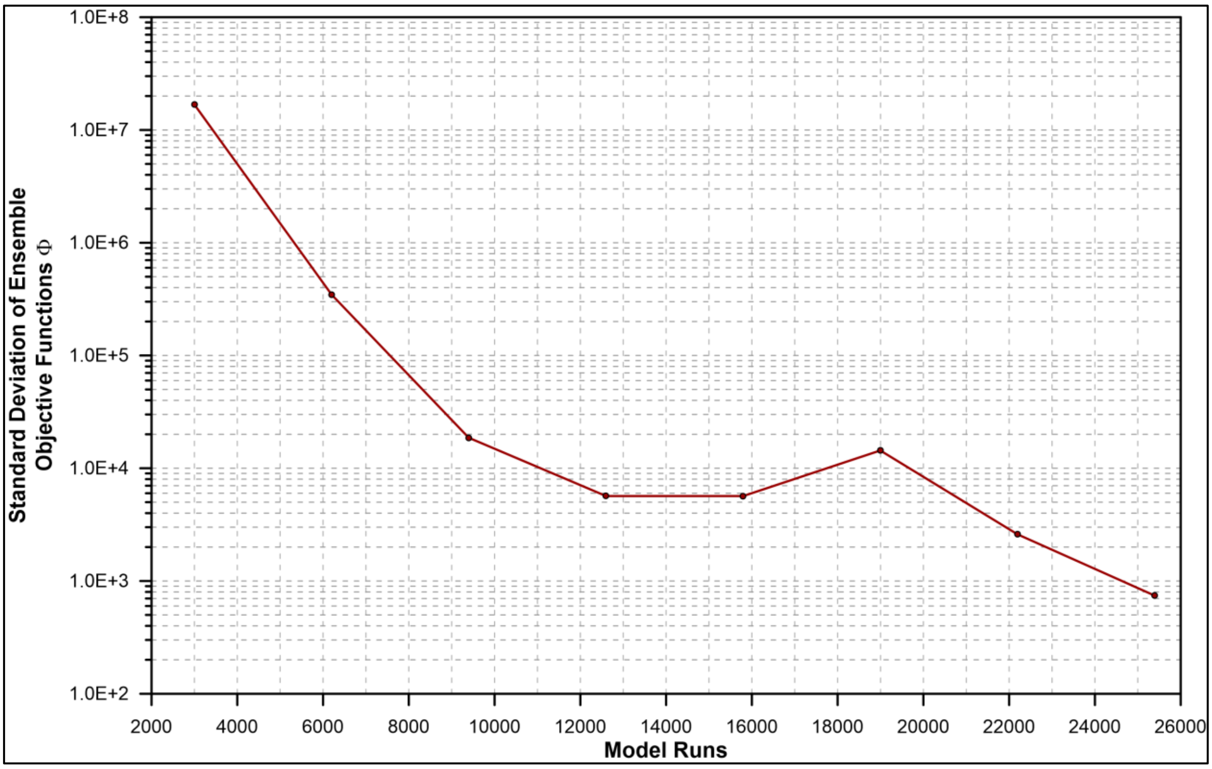

Figure 6-11: Standard deviation of objective function for parameter ensemble and the "base" parameter set versus number of model runs

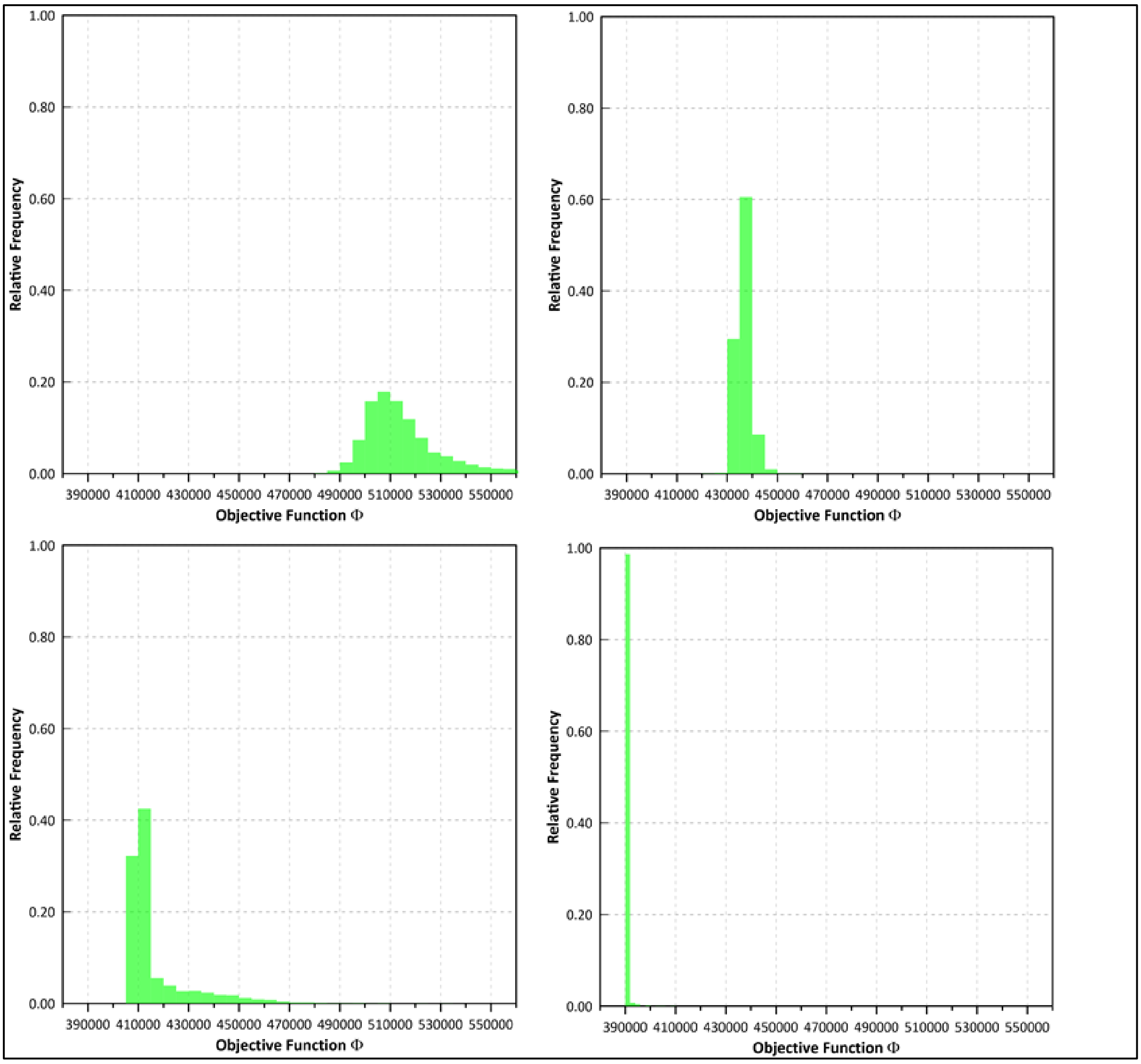

Figure 6-12: Distribution of the ensemble objective functions for (upper-left) 1, (upper-right) 3, (lower-left) 5 and (lower-right) 7 iterations of PPEST-IES.

These figures show most realisations achieve an acceptable fit within approximately 9,000 model runs (3 iterations) as indicated by the substantial decrease in the mean and standard deviation of the objective function by this stage. By iteration number 7 the spread of the objective functions has largely stabilised around 3.9E+05. This is also an indication of ensemble “collapse”, whereby the parameter sets become nearly indistinguishable and the range of uncertainty may be underestimated. Therefore, the parameter ensemble pertaining to the third iteration was chosen for use in subsequent predictive uncertainty analyses.

6.4.6 Calibrated parameters

The aggregate of the objective function groups for calibration targets associated with stratigraphic units and/or observation types deemed most pertinent for CSG impact assessment for each parameter ensemble were ranked and the lowest 550 were considered to comprise samples of the posterior parameter probability distribution. While this narrows the bandwidth of the posterior parameters marginally, it was also important to include parameter fields for which model-to-measurement misfit was lowest for datasets most pertinent to the impact source. The range of the total objective function remained similar to that recorded for the full ensemble. Collectively, these fields can be used to characterise the statistical properties of any model parameter. For example, histograms of posterior probability distributions for zonal and layer-wide parameter types are provided in Appendix G1.

Spatial variability of the statistical properties associated with a pilot point parameter can be represented by mapping a given statistic to the location of its corresponding model parameter. Appendices G2 through G8 show the geographical distribution of the “base” calibrated value of the pilot point parameter. The following appendices (G9 through G15) show the geographical distribution of the standard deviation of log (to base 10) of the pilot point parameter, i.e. the posterior uncertainty diagnostic.

6.5 Model predictions

Posterior probability distributions for selected predictions can then be amassed by running the predictive model using the 550 calibration-constrained parameter fields. From these outputs, uncertainty statistics and the resultant “bandwidth” of the prediction can be displayed graphically as histograms and cumulative probability distributions, for example. To interpret this abundance of outputs a statistical approach was adopted, whereby the 5th percentile (P5), 50th percentile (P50) and 95th percentile (P95) of a given output at every grid cell (or interpolated to points of interest) were computed from the 550 realisations. The values outside the P5 and the P95 are considered ‘outliers’. Such an approach is common practice in probabilistic risk assessments, where a range of outcomes are produced that meet a prescribed set of risk criterion for a representative sample population. A percentile is the value of a variable (e.g., a water level) below which a given percentage of values for that variable fall. So, the P95 is the value below which 95% of the values for that variable may be found (and 5% are greater). Similarly, the P5 represents the value below which only 5% of the values for that variable reside (and 95% are greater).

6.5.1 Steady-state water balance

The water balance for the 1947 and 1995 steady state simulations are provided in Table 6-9 and Table 6-10 respectively. These correspond to the “base” calibrated parameter set only for ease of interpretation. Also note that net flux into the layer is positive.

Consistent with previous iterations of the regional model, both the pre-development (1947) and pre-CSG development (1995) water balances suggest only relatively minor outflows along the southern model boundary to the remainder of the GAB; these are 3,238 and 1,253 and ML/yr respectively. This outflow estimate represents no greater than 1% of the applied recharge; the remainder being discharged locally to shallow groundwater systems from where it may be lost as evaporation or provides baseflow to surface water courses. Once steady state conditions are established the non-CSG groundwater extraction demand of around 30,000 ML/yr will predominantly met by a reduction in the volume of water discharged to shallow systems.

6.5.2 Transient water balance for the Walloon Coal Measures

Transient water balance results for the period January 1995 through to the end of the historic simulation period in December 2019 for the Walloon Coal Measures are shown in Figure 6-13. These are provided for the “base” calibrated parameter set only. This plot suggests that most of the additional extraction demand of the CSG industry is currently being met from storage in the Walloon Coal Measures, with only minor increases in inflows from adjacent strata or reductions in other outflows (to surface or along the southern model boundary).

Table 6-9: Water balance in each model layer for the 1947 steady state simulation (“base” calibrated parameters)

Stratigraphic unit(s)	Model layer	Recharge (ML/yr)	Non-CSG extraction (ML/yr)	Surficial drainage (ML/yr)	Net GHB flux (ML/yr)	Net interlayer flux (ML/yr)	% Error
Alluvia, Basalt and Cenozoic Sediments	1	328,891	0	338,539	0	9,648	0
Upper Cretaceous	2	1,745	0	1,896	0	151	0
Wallumbilla Formation	3	12,425	0	7,648	0	-4,777	0
Bungil Formation	4	4,484	0	2,318	280	-2,446	0
Mooga Sandstone	5	12,447	0	5,904	-1,219	-5,325	0
Orallo Formation	6	11,708	0	6,246	0	-5,462	0
Gubberamunda Sandstone	7	2,225	0	2,149	-853	777	0
Westbourne Formation	8	2,883	0	2,707	0	-177	0
Upper Springbok Sandstone	9	10,186	0	9,962	-7	-216	0
Lower Springbok Sandstone	10	1,126	0	1,169	-16	59	0
Walloon Coal Measures non-productive zone	11	0	0	0	0	0	0
Upper Juandah-1 Coal Measures	12	1,625	0	1,714	0	89	0
Upper Juandah-2 Coal Measures	13	240	0	252	-2	14	0
Lower Juandah-1 Coal Measures	14	1,040	0	981	-6	-53	0
Lower Juandah-2 Coal Measures	15	587	0	579	-5	-4	0
Lower Juandah-3 Coal Measures	16	552	0	536	-5	-11	0
Taroom Coal Measures	17	752	0	680	-5	-67	0
Durabilla Formation	18	1,331	0	1,005	0	-326	0
Upper Hutton Sandstone	19	31,298	0	34,911	-185	3,799	0
Lower Hutton Sandstone	20	677	0	699	-84	106	0
Upper Evergreen	21	27,261	0	27,156	0	-105	0
Boxvale Sandstone	22	446	0	438	-1	-8	0
Lower Evergreen	23	21,115	0	20,449	0	-666	0
Precipice Sandstone	24	63,640	0	66,696	-1,131	4,187	0
Moolayember Formation	25	14,550	0	15,482	0	931	0
Clematis Sandstone	26	123,113	0	122,530	0	-583	0
Rewan Group	27	220	0	525	0	305	0
Bandanna Formation non-productive zone	28	0	0	0	0	0	0
Upper Bandanna Formation	29	1,247	0	1,235	0	-12	0
Lower Bandanna Formation	30	0	0	0	0	0	0
Undifferentiated Bowen Basin strata	31	2,581	0	2,560	0	-21	0
Cattle Creek Formation non-productive zone	32	0	0	0	0	0	0
Upper Cattle Creek Formation	33	0	0	0	0	0	0
Lower Cattle Creek Formation	34	0	0	0	0	0	0
Undifferentiated Bowen Basin strata	35	680	0	872	0	193	0
Totals		**681,076**	**0**	**677,838**	**-3,238**	**0**	

Table 6-10: Water balance in each model layer for the 1995 steady state simulation ("base" calibrated parameters)

Stratigraphic unit(s)	Model layer	Recharge (ML/yr)	Non-CSG extraction (ML/yr)	Surficial drainage (ML/yr)	Net GHB flux (ML/yr)	Net interlayer flux (ML/yr)	% Error
Alluvia, Basalt and Cenozoic Sediments	1	329,091	0	330,083	0	992	0
Upper Cretaceous	2	1,745	973	1,316	0	545	0
Wallumbilla Formation	3	12,425	391	6,024	0	-6,011	0
Bungil Formation	4	4,484	701	1,513	592	-2,860	0
Mooga Sandstone	5	12,447	2,986	4,177	-116	-5,168	0
Orallo Formation	6	11,708	2,579	4,977	0	-4,152	0
Gubberamunda Sandstone	7	2,225	6,581	1,915	-520	6,791	0
Westbourne Formation	8	2,883	0	2,640	0	-243	0
Upper Springbok Sandstone	9	10,186	260	9,744	1	-184	0
Lower Springbok Sandstone	10	1,126	117	1,162	-10	163	0
Walloon Coal Measures non-productive zone	11	0	33	0	0	33	0
Upper Juandah-1 Coal Measures	12	1,625	122	1,606	0	103	0
Upper Juandah-2 Coal Measures	13	240	171	230	-1	162	0
Lower Juandah-1 Coal Measures	14	1,040	143	898	-4	5	0
Lower Juandah-2 Coal Measures	15	587	222	502	-2	139	0
Lower Juandah-3 Coal Measures	16	552	293	462	-3	205	0
Taroom Coal Measures	17	752	254	525	-3	30	0
Durabilla Formation	18	1,331	0	983	0	-349	0
Upper Hutton Sandstone	19	31,298	6,075	29,128	-106	4,011	0
Lower Hutton Sandstone	20	677	1,078	682	-33	1,116	0
Upper Evergreen	21	27,261	0	27,128	0	-133	0
Boxvale Sandstone	22	446	209	427	0	189	0
Lower Evergreen	23	21,115	0	20,419	0	-696	0
Precipice Sandstone	24	63,640	4,911	62,014	-1,048	4,333	0
Moolayember Formation	25	14,550	0	15,450	0	899	0
Clematis Sandstone	26	123,113	1,649	121,018	0	-445	0
Rewan Group	27	220	0	513	0	293	0
Bandanna Formation non-productive zone	28	0	6	0	0	6	0
Upper Bandanna Formation	29	1,247	46	1,210	0	9	0
Lower Bandanna Formation	30	0	17	0	0	17	0
Undifferentiated Bowen Basin strata	31	2,581	0	2,545	0	-36	0
Cattle Creek Formation non-productive zone	32	0	1	0	0	1	0
Upper Cattle Creek Formation	33	0	13	0	0	13	0
Lower Cattle Creek Formation	34	0	32	0	0	32	0
Undifferentiated Bowen Basin strata	35	680	0	871	0	191	0
Totals		**681,276**	**29,861**	**650,162**	**-1,253**	**0**	

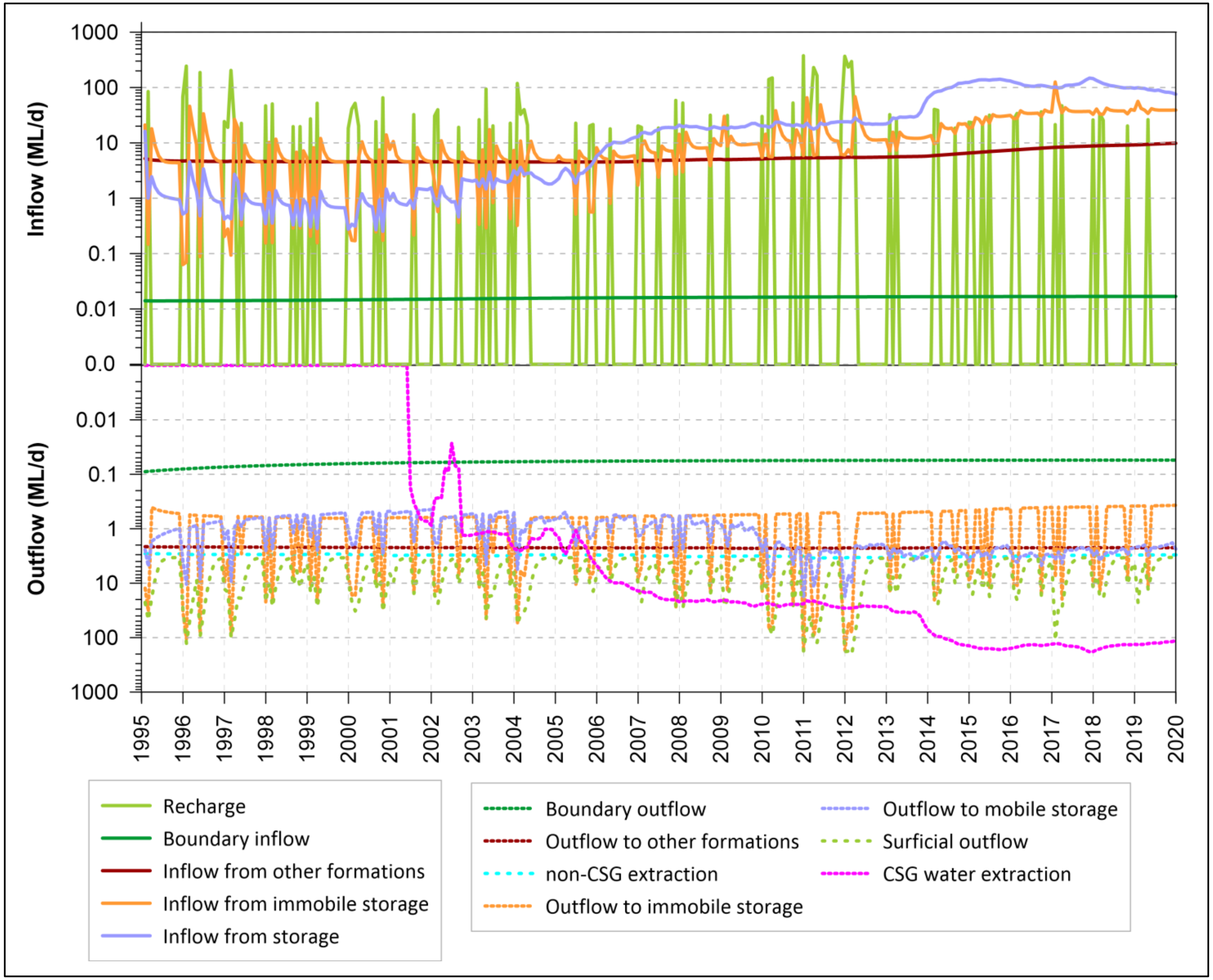

Figure 6-13: Water balance of the Walloon Coal Measures for the transient calibration period ("base" calibrated parameters)

6.5.3 Drawdown Impacts

As outlined in section 2, one of the primary purposes of this model is to assess regional drawdown impacts arising from CSG and coal mining developments. Drawdown impacts are defined as the difference in simulated groundwater level between a no development scenario (including consumptive water use only) and a development scenario (including P&G and coal mining). Each aquifer has an associated trigger threshold above which bores in the respective aquifer are deemed to be impacted (2 or 5 m for unconsolidated and consolidated aquifers, respectively).

Consistent with the methodology described in 6.4.1, 550 model simulations were used to explore the uncertainty of drawdown impacts. Maps showing the P5, P50 and P95 for the maximum all time impact can be found in Appendix G16. Time series of predicted impacts at selected locations are provided as Appendix G17.

Table 6-11 below provides the statistics of the area predicted to experience drawdowns greater than the relevant threshold at any time in the future for each formation.

Table 6-11: Area of maximum all-time impact drawdown by formation

Stratigraphic units	Model layers	Trigger threshold (m)	Area (km^2)		
			P5	P50	P95
Cenozoic aged units	1	2	54.00	94.50	114.75
Main Range Volcanics	1	5	24.75	29.25	33.75
Upper Cretaceous aged units	2	5	22.50	216.00	735.75
Wallumbilla Formation	3	5	0.00	0.00	0.00
Bungil Formation	4	5	0.00	0.00	0.00
Mooga Sandstone	5	5	0.00	0.00	0.00
Orallo Formation	6	5	0.00	0.00	0.00
Gubberamunda Sandstone	7	5	0.00	0.00	0.00
Westbourne Formation	8	5	1755.00	3618.00	5436.00
Upper Springbok Sandstone	9	5	9022.50	11083.50	13236.75
Lower Springbok Sandstone	10	5	11781.00	13898.25	16042.50
Walloon Coal Measures non-productive zone	11	5	12102.75	14224.50	16350.75
Upper Juandah	12 and 13	5	17048.25	18886.50	21195.00
Lower Juandah	14 to 16	5	20139.75	22614.75	25789.50
Taroom Coal Measures	17	5	19793.25	22176.00	25177.50
Durabilla Formation	18	5	13493.25	16564.50	19635.75
Hutton Formation	19, 20	5	1937.25	3267.00	5928.75
Upper Evergreen Formation	21	5	92.25	130.50	418.50
Boxvale Sandstone	22	5	15.75	42.75	119.25
Lower Evergreen Formation	23	5	13.50	49.50	119.25

Stratigraphic units	Model layers	Trigger threshold (m)	Area (km^2)		
			P5	P50	P95
Precipice Sandstone	24	5	3629.25	4563.00	6117.75
Moolayember Formation	25	5	132.75	231.75	731.25
Clematis Sandstone	26	5	182.25	326.25	886.50
Rewan Group	27	5	1804.50	3573.00	6594.75
Bandanna non-productive zone	28	5	13932.00	19215.00	25947.00
Upper Bandanna Formation	29	5	14413.50	19431.00	26217.00
Lower Bandanna Formation	30	5	15090.75	20074.50	27355.50
Lower Bowen 1	31	5	38.25	648.00	2349.00
Cattle Creek Formation non-productive zone	32	5	929.25	1154.25	1604.25
Upper Cattle Creek Formation	33	5	931.50	1167.75	1635.75
Lower Cattle Creek Formation	34	5	985.50	1226.25	1656.00
Lower Bowen 2	35	5	924.75	1100.25	1671.75

6.5.4 Net flux impacts to the Condamine Alluvium

A key predicative output for the impact assessment is the CSG induced flux between the Condamine Alluvium and the underlying Great Artesian Basin. For the *Regional Model 2021* this is obtained through differencing of the net zonal fluxes for the development and no-development scenario, referred to as the Condamine differential net-flux. Concordant with the spatio-temporal depressurisation underneath the Condamine Alluvium, the differential net-flux peaks around the year 2060; this ranges between 1,700 and 2,200 ML/yr stochastically (P5 and P95), with a P50 of 1,979 ML/yr. The differential net-flux then begins to reduce as groundwater levels recover after the end CSG development. The 100-year average of differential net-flux starting at 2011 is predicted to be between 1,088 and 1,431 ML/yr (P5 - P95), with a P50 of 1,272 ML/yr (Figure 6-14).

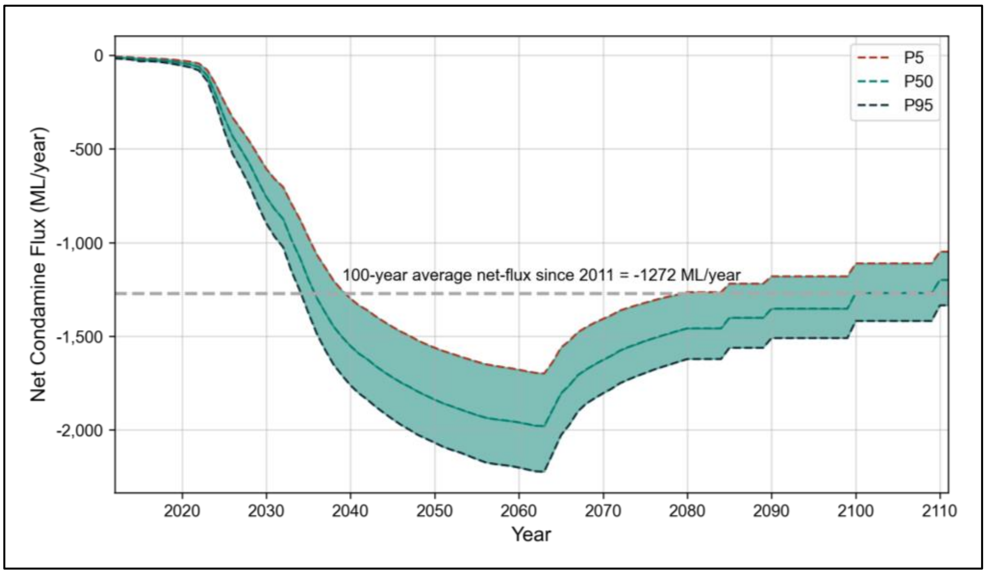

Figure 6-14: CSG-induced differential net flux for the Condamine Alluvium

6.5.5 CSG water extraction

Predicted total CSG water extraction from the Walloon Coal Measures, Bandanna Formation and Cattle Creek formations are shown in Figure 6-15 featuring the P5, P50 and P95 statistics based on 550 predicted realisations.

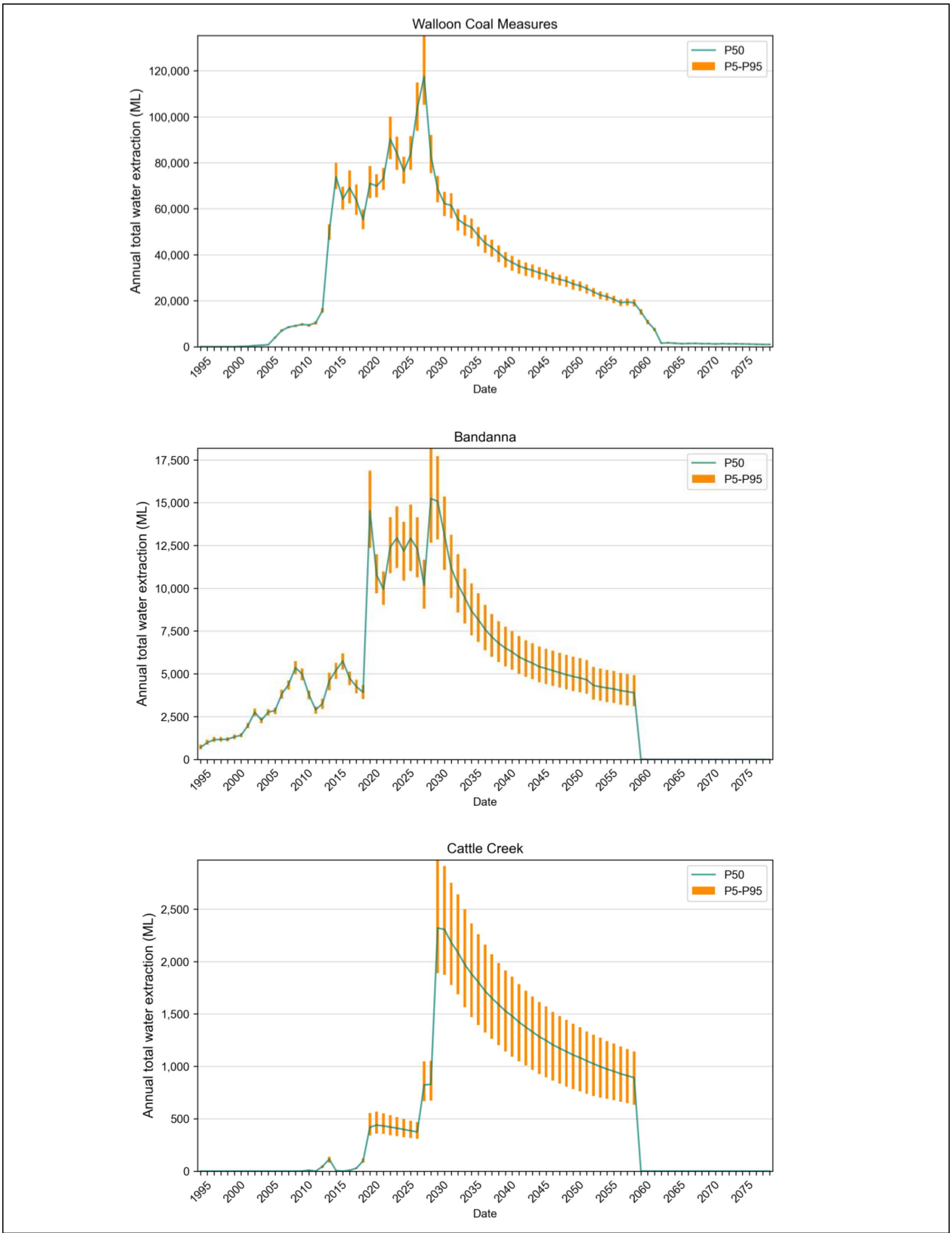

Figure 6-15: Modelled CSG water extraction with uncertainty

For the Walloon Coal Measured the predicted range in volumes is relatively narrow reflecting the large amount of history-matching data available for this unit. Higher uncertainties are associated with water extraction for the Bandanna and Cattle Creek formations, reflecting the relatively scant data available for these deeper CSG reservoirs.

It should be emphasised that these stochastic envelopes are based on a single CSG company development profile scenario and so do not include uncertainties associated with changes in the development plan. Potential uncertainties in the predictive scenario have instead been investigated by running an additional maximum development scenario.

6.5.6 Pit Inflows

While the model was not calibrated to historic associated water-use from coal mining operations, model predictions of pit-related inflows were obtained for information purposes; refer Figure 6-16 below. The range of total water extraction from coal mines in the year 2020 is predicted to be less than 1,000 ML, which is consistent with analytical estimates undertaken by OGIA (OGIA 2021c). The relative magnitude of water extracted is a minor proportion of the cumulative water extraction from CSG and coal developments. For comparison, CSG operations in the Walloon Coal Measures extracted approximately 54,000 ML/yr in 2020.

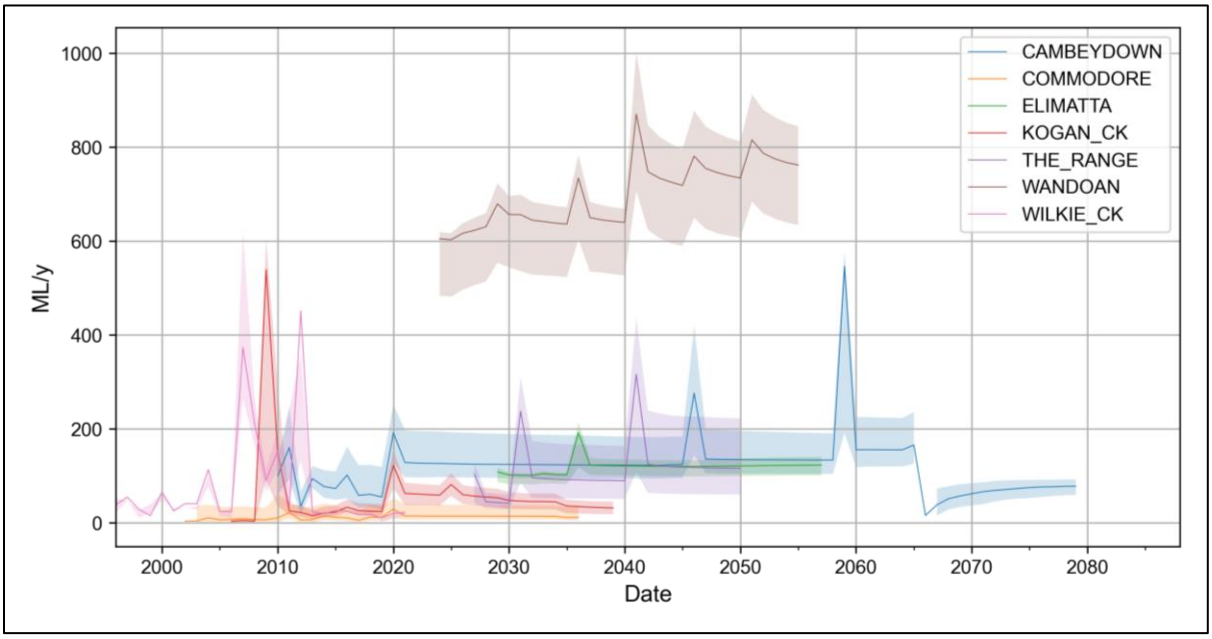

Figure 6-16: Predicted pit inflows for various mines in the Surat CMA

7 New Acland groundwater model

7.1 Overview

OGIA has reviewed the previous investigations by New Hope Group (NHG), including those presented in their application for an Associated Water License (SLR 2018), and have also considered various external and expert reviews in relation to NHG's groundwater impact assessments. OGIA also undertook primary interpretation of the geological data and remodelled the geology in the area, mapped faults, assessed fault connectivity, reassessed pit inflows and evaluated monitoring data. Based on this collective assessment and review, OGIA has formed the view that:

- The hydrogeological conceptualisation in relation to potential propagation of groundwater pressure impacts from the existing (Stage 1 & 2) and proposed mining (Stage 3) is fit for purpose and is broadly consistent with the available data.
- If the Balgowan coal sequence is intersected during mining, then this may likely cause some hydraulic connection between the Taroom Coal Measures and the Marburg Sandstone (via faults). This pathway would result in impacts in the Marburg Sandstone that are greater than predicted.
- Availability of additional monitoring and investigation data would progressively improve the conceptualisation of impact pathways at New Acland Mine.
- In the future, OGIA is considering carrying out an airborne electromagnetic (EM) geophysical survey to collect additional data in the vicinity of New Acland Mine. This geophysical data, combined with on-going monitoring data, would assist with the development of the groundwater conceptualisation and impact pathways and future iterations of the Surat CMA UWIR.

Additionally, the most recent numerical groundwater model (SLR 2018) is currently considered by OGIA to be fit for purpose to assess groundwater pressure impacts in the area surrounding New Acland Mine. As such, this model has been adopted for the UWIR 2021 to facilitate the prediction of impacts arising from the NHG development. As OGIA's conceptualisation of the site evolves as new datasets are collected and interpreted, the modelling strategy will be revisited and refined where needed.

This section outlines some of the key design features of the Acland Model. However, a detailed description of the conceptualisation, model setup, parameterisation, calibration and uncertainty analysis can be found in (SLR 2018).

7.2 Model architecture

A three-dimensional finite difference model was created by SLR using MODFLOW-SURFACT (Version 4) (Panday and Huyakorn 2008) to accommodate the efficient solution of variably saturated flow conditions using adaptive time-stepping with an advanced solver routine. The model covers an approximate area of 46 km x 53 km spatially discretised into uniform 100 m x 100 m cells. It comprises 12 layers, extending from the Alluvium down to the Marburg Sandstone (Hutton Sandstone Equivalent). The model also incorporates coal and interburden layers in the Walloon Coal Measures (Figure 7-1).

Layer	Primary Stratigraphic Unit\Formation	Lithology	Indicative Thickness
1	Alluvium	Gravels, sands, silts and clays	
2	Main Range Volcanics	Alkaline basalt	Up to 250m
3	Miscellaneous Walloon Coal Measures	Interbedded fine grained sandstone, siltstone and coal	Variable
4	Wonkers Coal Sequence	Interbedded fine grained sandstone, siltstone and coal	Average of 35m
5	Interburden	Mudstone, siltstone, and fine grained sandstone	Average of 24m
6	Waipanna Coal Sequence	Interbedded fine grained sandstone, siltstone and coal	Average of 33m
7	Interburden	Mudstone, siltstone, and fine grained sandstone	Average of 36m
8	Acland Coal Sequence	Interbedded fine grained sandstone, siltstone and coal	Average of 50m
9	Interburden	Mudstone, siltstone, and fine grained sandstone	Average of 24m
10	Balgowan Coal Sequence	Interbedded fine grained sandstone, siltstone and coal	Average of 35m
11	Durabilla Formation	Mudstone, siltstone, and fine grained sandstone	Average of 25m
12	Marburg Sandstone	Sandstone interbedded with siltstone, shale, and minor mudstone	Average of 250m

Figure 7-1: Layering for the Acland Model (taken from SLR 2018)

7.3 Process representation

7.3.1 Faults

Several geological faults have been mapped in the area by NHG. Based on the available data, these faults act as partial flow barriers primarily because of displacement across the faults. They are included in the model as horizontal flow barriers (MODFLOW HFB package) with the horizontal hydraulic conductivity of the barriers a function of the vertical hydraulic conductivity of the intervening interburden material and the estimated displacement. This approach bears some similarity with that adopted by OGIA for the *Regional Model 2021*, however, the potential for enhanced vertical flow has not been accounted for in the Acland Model.

7.3.2 Recharge and surficial processes

A chloride mass balance approach was undertaken for estimation of recharge in the study area. Calculated recharge rates generally ranged from 1 to 7 mm/yr, with the highest values in the Main Range Volcanics and the lowest values in the Walloon Coal Measures. Throughout the mining operations the recharge rate to the pits is assumed to be zero. Upon cessation, recharge to areas within the pit voids is assumed to be 100% of average annual rainfall. For all backfilled areas the recharge is assumed to be 1% of average annual rainfall.

Evapotranspiration is expected to be a significant driver of groundwater outflow from the model and has been simulated using the MODFLOW EVT package. For areas undisturbed by mining, the maximum rate of EVT was allowed to range between 700 and 1,100 mm/yr at ground level, linearly decreasing to zero at 3 m below the surface. For areas of active mining, this was reduced to 0.5 m below the surface given the drawdown cone around the pit. For the disturbed material within pit voids, a higher rate of 1,560 mm/yr was adopted given the greater likelihood of open water, with 900 mm/yr applied in (mounded) backfilled areas.

Additionally, the MODFLOW River (RIV) package was employed in cells along water courses within the model domain that were deemed to potentially provide recharge to the groundwater system at least 50% of the time. This also provided the capability to exfiltrate groundwater to these watercourses if/when groundwater levels rose episodically.

7.3.3 Consumptive water use

Groundwater extraction from almost 2,500 wells is simulated within the model using the Fracture Well Package (FWL4). This allows for automatic derating of the extraction rate when water levels fall below the bottom elevation of a pumped cell. Extraction rates were derived from estimates of consumptive water use provided by OGIA from the UWIR 2016 assessment; parallel conceptualisation work undertaken by SLR supported the scaling down of these estimates for the modelling study.

7.3.4 Coal mining

The MODFLOW drain (DRN) package was used to replicate the sequential excavation of the pit in accordance with the mine development plan. The elevations ascribed to active drain cells were therefore adjusted as the pit shell expanded and deepened over time. Drain conductance was also set suitably high to ensure only a minimal head drop as water is removed from the groundwater system. Additionally, the Time-varying Material Property (TMP) package was employed to simulate increases to the hydraulic conductivity and storage of disturbed materials (i.e., voids or deposited backfill).

7.4 Calibration and uncertainty analysis

SLR undertook stochastic model calibration based on a quantitative and qualitative approach that shared a similar philosophy to “Bayesian rejection sampling”. This involved the following steps:

- Collation of over 870 randomly generated “prior” parameter realisations constrained by measured data (such as hydraulic conductivity estimated from pumping tests) and expert knowledge
- Model simulations undertaken using “prior” parameter sets for the calibration period
- Comparison of model results to calibration targets, including historical groundwater levels, Oakey Creek baseflows and estimated pit inflows, where available
- 58 “posterior” parameter realisations were selected for use in predictive modelling based on their performance against historical data

7.5 Scenarios

Two scenarios have been used by OGIA for the UWIR 2021 impact assessment at New Acland:

1. No Mining – accounts for all system stresses except historical and proposed mining activities
2. Proposed – as above with the addition of all historical and proposed mining activities

Some modifications were made to the non-CSG extractions in the No Mining scenario provided by SLR. As the UWIR 2021 is only assessing the impacts of associated water use, this ensured that impact predictions were not influenced by non-associated water use provisions enacted by NHG. The integrated impact predictions are presented in below.

8 Integration of impacts for UWIR 2021

As discussed in section 5 of this document, a suite of models was utilised for impact assessment in UWIR 2021. The *Regional Model 2021* was used for the prediction of cumulative impacts from CSG, conventional gas and coal mines in the Northern and Central areas as well as the Commodore mine in the South (see 6). Impact predictions at the New Acland mine were produced separately via the Acland Model (see 7). Overall cumulative impacts where thereby obtained through superposition of the cumulative impact predictions from the *Regional Model 2021* and the Acland model impacts. Although the concept is derived from linear systems, it can also be used for mildly nonlinear systems with acceptable errors (Reilly et al., 1987). For nonlinear systems, the composite impact from the superposition is therefore an approximation of the actual accumulative impact. Furthermore, given the distant proximity the New Acland mine, overlapping impacts with CSG operations are expected to be minor and so the above approach is considered suitable for obtaining cumulative impact estimates.

More specifically, stochastic time-series of impact (P5, P50, P95) from the *Regional Model 2021* were combined with the stochastic time-series of impact (P5, P50, P95) from the Acland Model. The approach for the superposition of impacts involved two main steps:

1. Resampling of time series output in the Acland Model to that of the *Regional Model 2021*
2. Merging of impacts using nearest neighbour interpolation and bilinear interpolation

For the first step, each output time step from the Acland Model was re-assigned the closest *Regional Model 2021* output time step. Next, layers of the Acland Model with analogous representation in the *Regional Model 2021* were assigned to their counterpart layer in the *Regional Model 2021*.

In the second step, for each model time-step and layer, cell-based impacts computed by the Acland Model were assigned to *Regional Model 2021* cells using nearest neighbour interpolation. Where multiple layers in the *Regional Model 2021* corresponded to a single layer of the Acland Model, the maximum impact from a relevant *Regional Model 2021* layer was selected for superposition. So, for cumulative impacts at water bores, bilinear interpolation of cell-based impacts from both the *Regional Model 2021* and Acland Model to each bore location was performed and the impacts combined. An example of this is shown in the figure below.

Figure 8-1 presents a pair of impact time-series from the *Regional Model 2021* and Acland Model for a location in the Taroom Coal measures. This plot shows the result of the superposition of each impact time-series, with the cumulative impact equal to their sum.

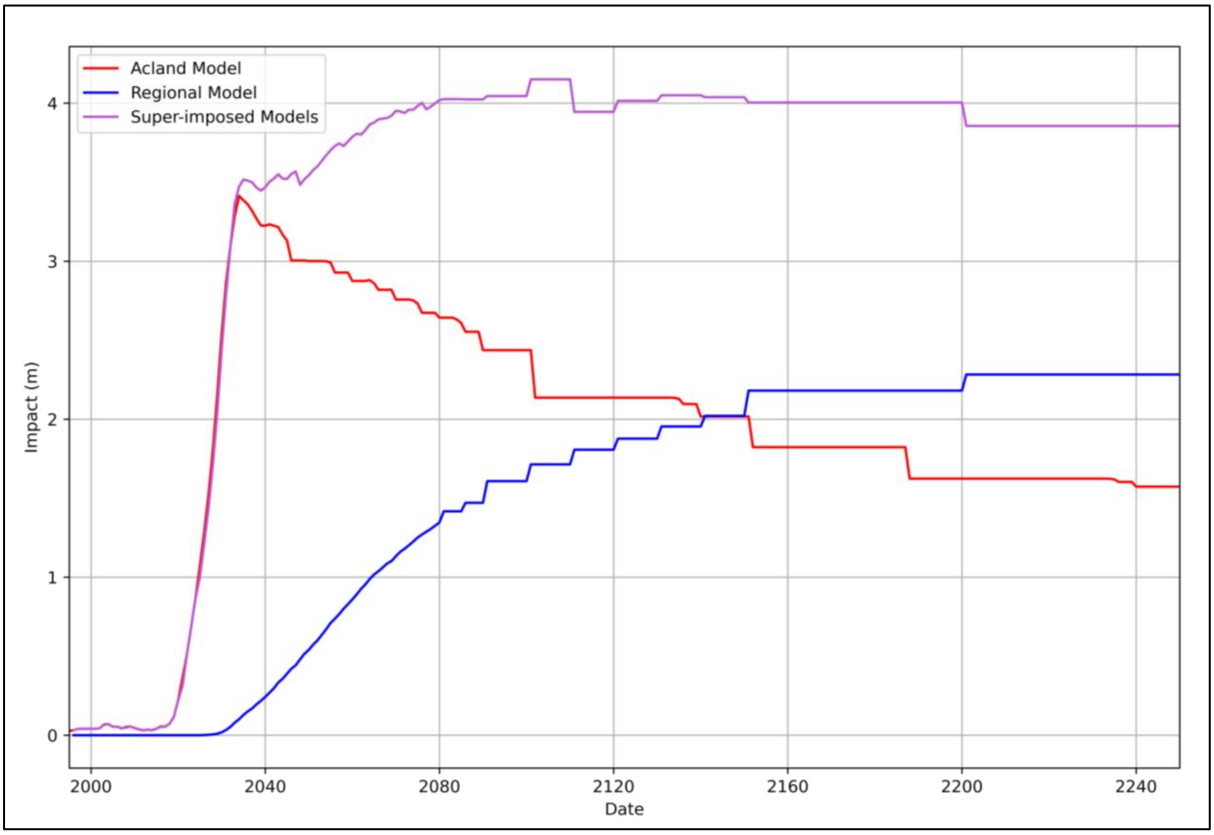

Figure 8-1: Superposition of regional and local impact time-series

The IAA reported in the UWIR 2021 has been calculated from superposition of the respective impacts for December 2024 while the LAA was similarly calculated using the maximum all time impacts in each model cell. Results are interpolated to the same 1500 m grid resolution as the regional groundwater model. Maps showing the Merged P5, P50, P95 for the maximum all time impact can be found in Appendix G16

Figure 8-2 shows three IAA impact heatmaps for the Taroom Coal Measures. The top map presents the cumulative model impacts, while the lower left and right present the *Regional Model 2021* and Acland Model impacts, respectively. The three maps also indicate the position of the example time-series used in Figure 8-1. It is apparent from Figure 8-2 that impacts from the New Acland mine and nearby CSG development do not coalesce in the next three years. Figure 8-3 shows the corresponding LAA maps for the Taroom Coal Measures, where cumulative impacts become relevant.

LAA impacts may occur at fringe areas between the two models, however no receptors have been identified that are not predicted to be impacted by either model independently. This further supports the simplified approach taken for the merging of impacts between the two models.

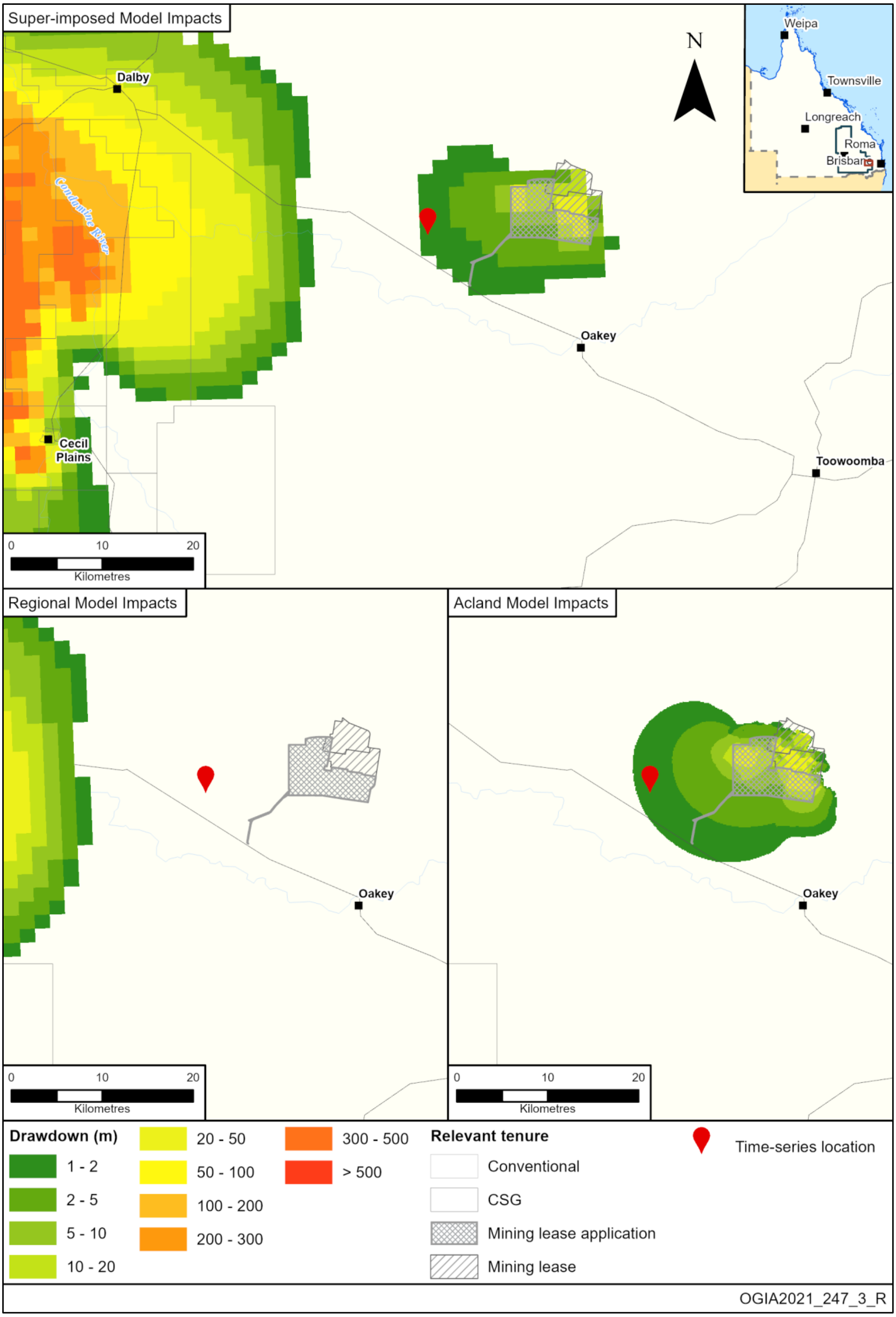

Figure 8-2: IAA (December 2024) impact based on superposition

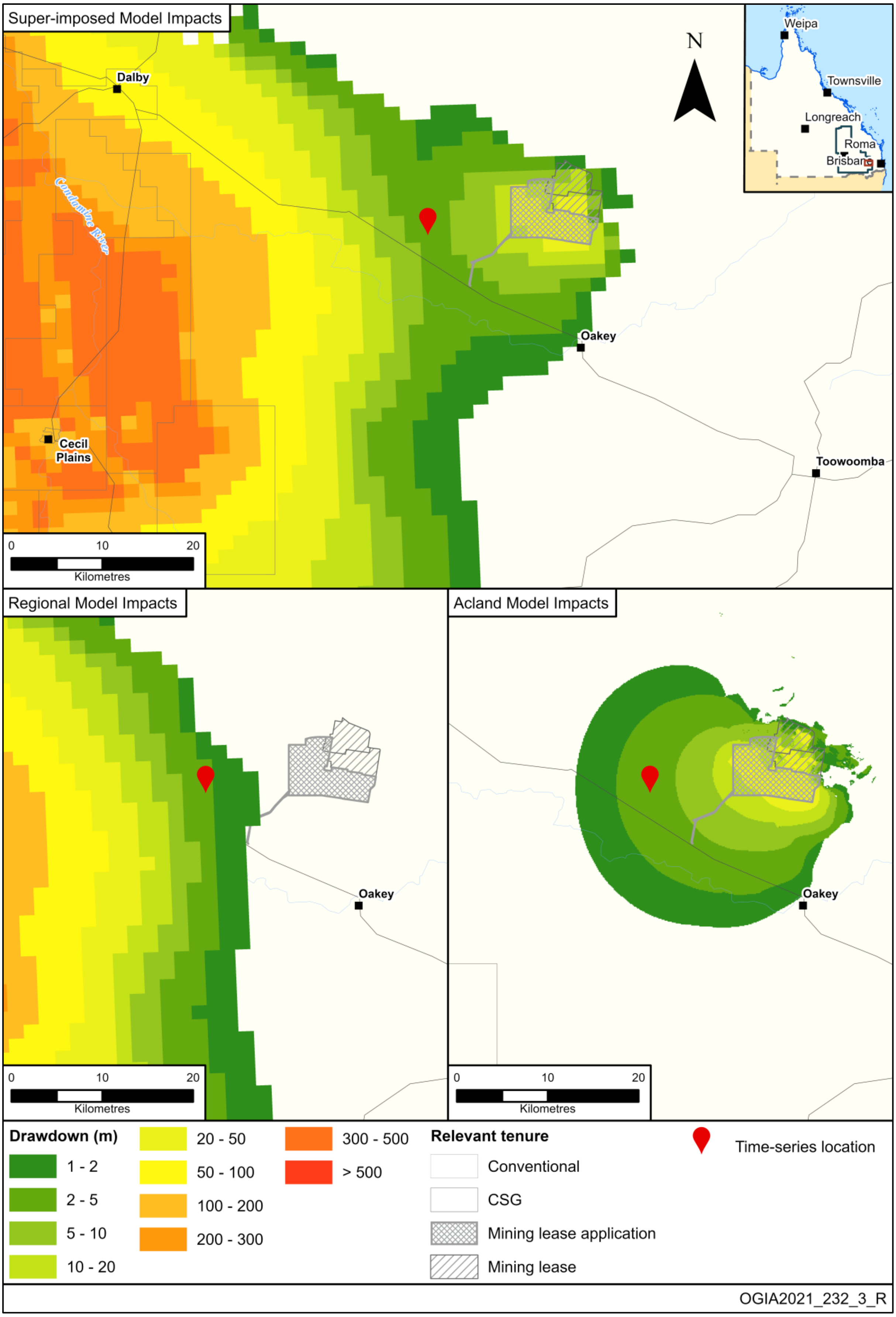

Figure 8-3: LAA impact based on superposition

9 Conclusions and approach to next-generation modelling

9.1 Key improvements to modelling approach

The key improvements in impact modelling for the UWIR 2021 compared to the UWIR 2019 are:

- refinement of underlying regional geology model with new data, representation of Walloon Coal Measures subdivisions and development of a detailed geological model in the NCA
- refinement of the Horrane and Hutton-Wallumbilla faults based on new geological data
- updated and extended calibration dataset with two additional years of data
- inclusion of coal mines in the regional cumulative impact model
- integration of the Acland groundwater model
- improved efficient of calibration and uncertainty methodology using PEST++ IES
- utilisation of improved computational capacity to explore predictive uncertainty.

9.2 Next-generation groundwater modelling

OGIA aspires to continuously improve the cumulative modelling on three parallel fronts:

- ongoing improvements to the regional groundwater flow model
- further development and exploration of sub-regional models in specific areas of interest
- researching and testing new methods.

OGIA plans to put considerable effort in researching and testing new methods as summarised below.

9.2.1 New-generation modelling philosophy

Up until now, the approach to CSG impact assessment modelling has been to build a large-scale model first and then predict impacts at different locations concurrently. This is particularly useful for assessing broad-scale cumulative drawdown in the CSG reservoirs, quantifying the rates of water and gas extraction therein, and estimating time to recovery (as long-term predictions require a large model domain). However, potential impacts at a spring, a water production bore, or another environmental asset are likely to be sensitive to geological conditions near both the stressor and the receptor. As a consequence, the uncertainty in these predictions will be dominated by such geological detail.

OGIA has therefore commenced researching and exploring a different philosophy, in that it will attempt to “start at the problem and work backwards”. As such, it is proposed that for any given location or sub-region where impact is desired, a model will be purpose-built to predict that impact. Moreover, different models must be specifically designed to serve different purposes. Such a philosophical shift will require a degree of abstractification to account for a wide variety of impact pathways, signal sources and geological constructs. However, it is envisaged that such models will be calibrated against local drawdown (as opposed to absolute heads) to predict future impact and extract the maximum information content pertinent to future local impact. There may also be opportunities for geographical transferability between similar model “types”.

“Local-scale” modelling requires more than just a finer grid, however. Detailed “local-scale” models allow geology to be represented more realistically. This requires many model layers and realisations of possible causative features to be embedded – including lithological layering, alluvial channels, offsetting faults, etc. Given the primary aim is to reduce the uncertainty of predictions of CSG and coal mining impact, it should also support the refinement of stochastic permeability modelling and/or allow a reduction of the uncertainties of demonstrably conservative regionally upscaled hydraulic properties through appropriate history-matching. While the existence and properties of these geologically realistic small-scale features are difficult to calibrate, hypothesis-testing can be used to accept or reject whether observed drawdowns can be reproduced with stochastic realisations of causative geology.

It is anticipated that modelling to be undertaken to assess impact at a range of "location categories" will have certain features in common, including the following:

- In contrast to the *Regional Model 2021*, these new-generation models will aim to better represent local geology, lithology and structure commensurate with the scale relevant to the receptor.
- These representations must, by necessity, be stochastic and conditioned by local data, such as those available from borehole lithology and geophysical logs.
- Stochastic realisations of lithology must accommodate the presence of faults (where appropriate) which offset strata both within the WCM and in neighbouring layers. Representation of the effects of faulting must also be stochastic. Conditioning information will include nearby seismic traces.
- Stochastic realisations of lithology will be populated with stochastic realisations of hydraulic properties as they pertain to lithologies and depth of burial.
- Where modelling near-surface impact, stochastic hydraulic properties assigned to different lithologies must take account of their shallow burial and their weathered status.

9.2.2 Some challenges and opportunities

9.2.2.1 Surficial processes

The inclusion of coal mining and the associated impact of CSG extraction on surficial systems when the CSG pressure front reaches the surface must consider the following:

- The nuances of the surface take on greater relevancy, including recharge processes and topographically driven drainage pathways.
- The properties of surficial materials are unknown and highly variable; a "permeability model" for these is required.
- Cumulative impact cannot be ignored, with some of the impact coming from an existing OGIA model which, by necessity, represents surficial processes quite simplistically.

A modelling framework was subsequently developed to predict cumulative groundwater impacts arising from comingled CSG and coal mine stressors. This has been deployed in the sub-regional groundwater model for the NCA. Key features of this model include:

- explicit representation of a surficial regolith zone
- incorporation of consumptive and associated water use
- "calibration" under both steady state and transient conditions

- stochastic parameterisation methodology for both calibration and predictive uncertainty.

9.2.2.2 Faults

To date, impact data suggests that the role of faults is more in its juxtapositioning of the WCM against Springbok and Hutton sandstone strata than through its provision of local conduits that induce inter-formational flow. Alternatively, if faults do indeed provide conduits, these are not of great length; they tend to be blocked with distance into the Hutton or Springbok sandstone through clay smearing, swelling of clays and mineralisation of fault surfaces. These conclusions follow from the observation that impact appears to be restricted to those locations that are in vertical proximity to the WCM, and that impact is location-specific (and sometimes explicitly traceable to strata juxtapositioning) rather than ubiquitous. Models are required that consider the following mechanisms for assessment of CSG impact:

- lithology-offsetting faults
- one or more formation-juxtapositioning faults
- one or more conduit-hosting faults
- one or more disused, formation-linking bores.

9.2.2.3 Condamine Alluvium

There are local processes that may affect drawdown impact on the Condamine Alluvium, such as horizontal propagation of drawdown through discontinuous coal seams and vertical propagation of drawdown through a heterogeneous and weathered Springbok Formation along the Horrane fault. A detailed model would include existing and future CSG extraction, as well as the subcrop of the WCM against the Condamine Alluvium to optimally leverage existing qualitative and quantitative measurements to constrain what must be conservative predictions based on stochastic lithology realisations.

9.2.2.4 Baseflow depletion

While most recharge supplied to outcropping stratigraphic units is rejected at present, less will be rejected if CSG-induced drawdown propagates vertically upwards through sub-cropping coal seams at the Springbok Sandstone or laterally up-dip to outcrop areas, to then interact with local systems at or near the surface. This could result in reduced run-off and river/creek baseflow depending on the season, and surficial water that would otherwise contribute to river/creek baseflow may instead move laterally to the source of drawdown. As baseflow may form a significant component of the flow in these watercourses, particularly under low-flow conditions, small local transient models may be needed in coal measure outcrop areas. Lessons learned from the Condamine-proximal modelling may indicate whether upward propagation of drawdown is predominantly along coal seams, or whether it is more diffuse than this. Shallow transient modelling in areas where there are high-quality observation wells and stream gauges will help OGIA to explore issues such as the dynamics of shallow system “top-up” following a large rainfall event and consequently, the extent that dry season baseflow is likely to be impacted by upwardly propagating CSG drawdown.

9.2.2.5 Signal separation

The information that best informs prediction of future impact is impact that has already (or not) happened. The rich and extensive head data that has been gathered from monitoring wells contains signals from which information can be extracted both qualitatively and quantitatively using models of different types. Potential signals of CSG-induced impact are often small and buried in other signals composed of the following:

- Pressure responses that reflect rainfall cycles and large rainfall events in outcrop areas. It is generally assumed that many of the seasonal and multi-seasonal variations evident in observation wells are the result of recharge in stratigraphic outcrop areas; however, there is a need to investigate how a “recharge signal” travels from an outcrop area, and how much the high-frequency components of this signal diminish with travel.
- Hydraulic loading in the Springbok Sandstone caused by higher water levels in surficial aquifers following large rain events. The “climatic signal” in some deeper observation wells may therefore require two components to be disaggregated – a hydraulic loading signal that follows rainfall quite closely and a lower frequency, delayed, recharge signal.
- Non-CSG pumping from a water supply aquifer. Monitoring the temporal details of nearby extractive sources will allow an exploration of how different frequencies get attenuated after the high-frequency filter of transmission through a permeable medium is taken into account.
- Hydraulic unloading effects on the Hutton Sandstone emanating from spatially restricted unloading of an overlying aquifer (i.e. CSG extraction in the WCM).

Investigation of sophisticated signal separation methodologies so that a “CSG impact signal” (probably accompanied by a high degree of uncertainty) becomes available to compare with, or calibrate against, model-calculated water levels is an important next step. This may involve an assemblage of models representative of each signal type that operate simultaneously, from which a real CSG signal is separated from other signals via a parameter estimation exercise.

Work on the next-generation modelling has commenced and is anticipated to be the prime focus in the post-UWIR 2021 period.

References

Chen, Y & Oliver, DS 2013, ‘Levenberg-Marquardt forms of the iterative ensemble smoother for efficient history matching and uncertainty quantification’, *Computational Geosciences*, vol. 17, no. 4, pp. 689–703, accessed from <https://doi.org/10.1007/s10596-013-9351-5>.

Chen, Y & Oliver, DS 2017, ‘Localization and regularization for iterative ensemble smoothers’, *Computational Geosciences*, vol. 21, no. 1, pp. 13–30.

Deutsch, C V. & Journel, AG 1992, ‘GSLIB: Geostatistical Software Library and User’s Guide’, , p. 340.

Doherty, J 2015, *Calibration and uncertainty analysis for complex environmental models*, Watermark Numerical Computing, Brisbane, Australia, accessed from <Downloadable from www.pesthomepage.org>.

Doherty, J 2018, ‘PEST: Model-Independent Parameter Estimation User Manual Part II: PEST Utility Support Software (7th Edition)’, accessed from <Downloadable from www.pesthomepage.org>.

Doherty, J 2020, *PEST_HP, PEST for Highly Parallelized Computing Environments*,.

Doherty, J & Hunt, R 2010, *Approaches to Highly Parameterized Inversion: A Guide to Using PEST for Groundwater-Model Calibration*, accessed May 29, 2019, from <https://pubs.usgs.gov/sir/2010/5169/pdf/GWPEST_sir2010-5169.pdf>.

GHD 2012, *Report for Queensland Water Commission (QWC), Stage 2 Surat Cumulative Management Area Groundwater Model Report*, Office of Groundwater Impact Assessment, Brisbane.

Harbaugh, AW 2005, ‘MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process’, , p. 253, accessed from <https://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf>.

Herckenrath, D, Doherty, J & Panday, S 2015, ‘Incorporating the effect of gas in modelling the impact of CBM extraction on regional groundwater systems’, *Journal of Hydrology*, vol. 523, pp. 587–601.

De Jersey, NJ & McKellar, JL 2013, ‘The palynology of the Triassic-Jurassic transition in southeastern Queensland, Australia, and correlation with New Zealand’, *Palynology*, vol. 37, pp. 77–114.

KCB 2011, *Central Condamine Alluvium, Stage IV - Numerical Modelling, Final Report*, Brisbane.

Middlemis, H., Merrick, N., Ross, J., and Rozlapa, K 2001, *groundwater Flow Modelling Guideline*, Perth, Australia.

OGIA 2016a, ‘Underground Water Impact Report for the Surat Cumulative Management Area’, , p. 270, accessed from <https://www.dnrm.qld.gov.au/__data/assets/pdf_file/0003/409359/uwir-submission-summary.pdf>.

OGIA 2016b, *Groundwater modelling report for the Surat Cumulative Management Area*, Brisbane, Queensland.

OGIA 2016c, *Hydrogeological Conceptualisation Report for the Surat Cumulative Management Area*, OGIA, Department of Natural Resources and Mines, Brisbane, accessed from <https://drive.google.com/file/d/0B5u2TKAmnh_iaWsydHlfZVR0VVk/view>.

OGIA 2019a, *Underground Water Impact Report for the Surat Cumulative Management Area*, Brisbane, Queensland, accessed from <https://www.dnrme.qld.gov.au/__data/assets/pdf_file/0020/1461242/uwir-main-report.pdf>.

OGIA 2019b, *Groundwater Modelling Report - Surat Cumulative Management Area*, Brisbane, Queensland, accessed from <https://drive.google.com/file/d/0B5u2TKAmnh_iRlo4T0ZMOTB3WE0/view>.

OGIA 2019c, *Updated Geology and Geological Model for the Surat Cumulative Management Area*, Brisbane, Queensland.

OGIA 2021a, *Underground Water Impact Report 2021 for the Surat Cumulative Management Area*, Brisbane, Australia, accessed from <https://www.resources.qld.gov.au/__data/assets/pdf_file/0008/1584728/draft-uwir-2021-report.pdf>.

OGIA 2021b, *Geological modelling - source data, information and method (OGIA21CD03)*, Brisbane, Queensland, accessed from <https://www.business.qld.gov.au/ogia>.

OGIA 2021c, *Estimation of groundwater use in the Surat Basin (OGIA21CD12)*, Brisbane, Queensland, accessed from <https://www.business.qld.gov.au/ogia>.

OGIA 2021d, *Hydrogeological characterisation of faults in the Surat CMA (OGIA21CD18)*, Brisbane, Queensland, accessed from <https://www.business.qld.gov.au/ogia>.

OGIA 2021e, *Existing and proposed coal mining in the Surat Basin (OGIA21CD02)*, Brisbane, Queensland, accessed from <https://www.business.qld.gov.au/ogia>.

Peaceman, DW 1978, 'Interpretation of Well-Block Pressures in Numerical Reservoir Simulation.', *Soc Pet Eng AIME J*, vol. 18, no. 3, pp. 183–194.

Queensland Water Commission 2012, *Underground water impact report for the Surat Cumulative Management Area*, Queensland Water Commission, Brisbane, accessed from <https://www.dnrm.qld.gov.au/__data/assets/pdf_file/0016/31327/underground-water-impact-report.pdf>.

QWC 2012, *Underground Water Impact Report for the Surat Cumulative Management Area*, Brisbane, Queensland.

SLR 2018, *New Acland Stage 3 2017-2018 Groundwater Model Update*,.

Tikhonov, AN 1963a, 'Solution of incorrectly formulated problems and the regularization method', *Soviet Mathematics Doklady*, vol. 4.

Tikhonov, AN 1963b, 'Regularization of Incorrectly Posed Problems', *Soviet Mathematics Doklady*, vol. 4, no. 6.

White, JT 2018, 'A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions', *Environmental Modelling & Software*, vol. 109.

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