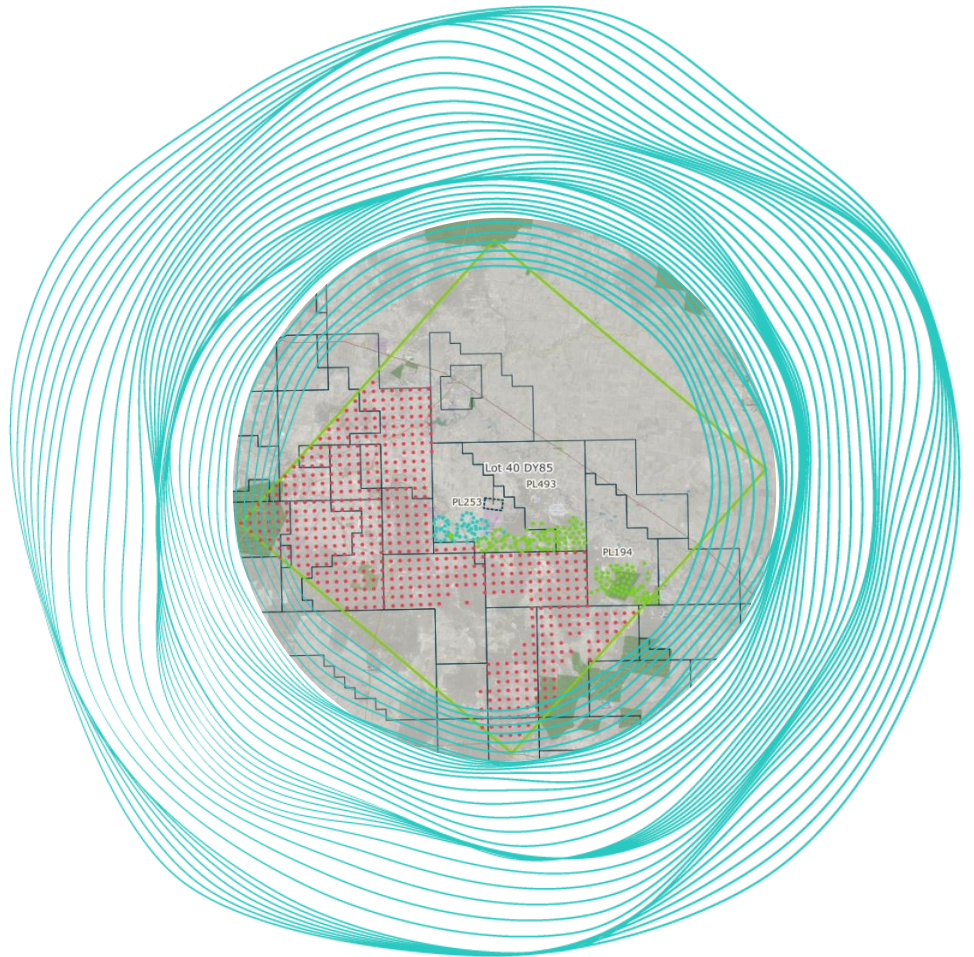


ARROW ENERGY PTY LTD

PL253 Groundwater Impact Assessment - Clynes Road FDP

Document no. Rev 0: 411001-00917-REP-HG-002



29 April 2026

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PROJECT - 411001-00917-REP-HG-002: PL253 Groundwater Impact Assessment - Clynes Road FDP

Rev	Description	Originator	Reviewer	Worley Approver	Revision Date	Customer Approver	Approval Date
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		M. Azadi	G. Jacobs	M. Azadi			
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		M. Azadi	G. Jacobs	M. Azadi			

29 April 2026

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Acronyms and abbreviations

Acronym/abbreviation	Definition
BGL	Below Ground Level
COC	Contaminants of Concern
CSG	Coal Seam Gas
FDP	Field Development Plan
GHB	General Head Boundary
HSU	Hydrostratigraphic Units
LOR	Limit of Reporting
OGIA	Office of Groundwater Impact Assessment
QOI	Quantities of Interest
SCM	Site Conceptual Model
UCG	Underground Coal Gasification
WCM	Walloon Coal Measures

1. Introduction

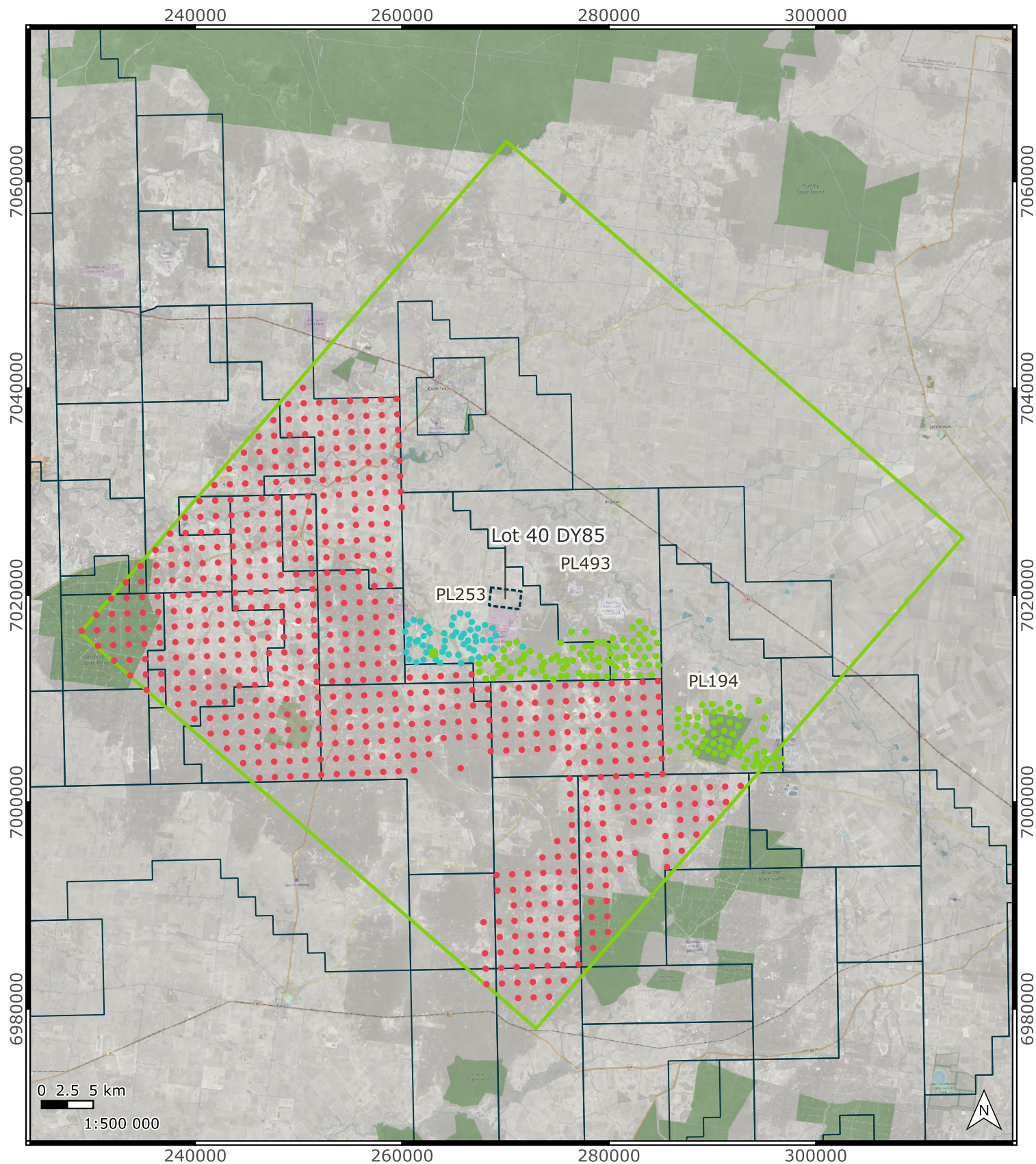
Arrow Energy Pty Ltd (Arrow) proposes to undertake coal seam gas (CSG) production activities within Production Licence 253 (PL253), Queensland. The PL253 area includes the former Hopeland Underground Coal Gasification (UCG) site located on Lot 40 DY85, where historical UCG operations undertaken by Linc Energy resulted in residual hydrocarbon contamination and other UCG by-products within the groundwater system.

Arrow has conducted groundwater monitoring, numerical modelling, and annual reporting in and around the former UCG site since 2018 to characterise groundwater conditions, contaminant behaviour, and potential risks to surrounding receptors. Environmental Authority EA0001401, in effect since November 2023, authorises Stage 1 development activities within PL253, including the drilling and operation of 55 CSG production wells (Kogan Creek development).

Arrow is proposing additional development under an expanded Field Development Plan (FDP) associated with the Jammat project and is seeking regulatory approval for further 55 CSG wells along Clynes Road.

The location of the PL253 project area, the former Hopeland UCG site, and the distribution of Arrow (approved wells and proposed Clynes Road wells) and non-Arrow abstraction wells relevant to this assessment are shown in Figure 1-1.

As part of the Environmental Authority application process, updated groundwater modelling is required to assess the potential impacts of Arrow's proposed activities on groundwater flow, contaminant migration, and long-term groundwater recovery associated with the former Hopeland UCG site. Based on Arrow's previous studies (GHD, 2019; AGE, 2021, 2023; Intera, 2024, 2025), this assessment has been prepared by Worley to support Arrow's application for approval of the proposed expansion.



Legend

- | | |
|---|--|
| Groundwater model extent | Well groups |
| Lot 40 DY85 | ● Approved Arrow wells |
| Petroleum Leases | ● Arrow Clynes Rd wells |
| | ● Non-Arrow abstraction points (from UWIR 2021) |

Project location and distribution of Arrow and non-Arrow wells

Project No.	Client	Figure No.
411001-00917	Arrow	1-1

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References:
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1.1 Scope of work

The scope of work of this study is to assess the potential impacts of Arrow's proposed activities on groundwater flow, contaminant migration, and long-term groundwater recovery associated with the former Hopeland UCG site. The scope includes:

Site conceptual model development

Building on Arrow's previous investigations and modelling studies (GHD, 2019; AGE, 2021, 2023; Intera, 2024, 2025), the Site Conceptual Model (SCM) was updated to incorporate the latest hydrostratigraphic units defined in Arrow's geology model and to refine the understanding of groundwater flow and contaminant behaviour at Lot 40 DY85. The updated SCM integrates groundwater monitoring data from existing bores located both within and beyond Lot 40 DY85 and incorporates current interpretation of residual contaminant source zones associated with historical UCG activities.

The updated SCM was developed to identify potential contaminant mobilisation pathways and to characterise groundwater flow directions and concentration distributions in the vicinity of Lot 40 DY85. This refined conceptualisation provides a robust and informed basis for subsequent numerical model development, history matching, and impact assessment.

Groundwater flow and transport model development

A numerical groundwater flow and contaminant transport model was developed to represent aquifers on and in the vicinity of Lot 40 DY85, with particular focus on the Springbok sandstone and the Macalister coal seam including relevant Walloon Coal Measures (WCM) units. The model was configured to evaluate historical and future changes in groundwater flow directions, and contaminant migration associated with UCG and CSG abstraction. Building on Arrow's most recent PL253 numerical groundwater model (Intera, 2025), the model was updated to incorporate the proposed FDP for the Jammatt project, including the Clynes Road wells.

The numerical simulation period was extended to the end of 2225 (200 years predictive period), to enable assessment of long-term groundwater recovery and potential contaminant migration beyond the abstraction period.

History matching groundwater flow and contaminant transport models

History matching (i.e., calibration) of the groundwater flow and contaminant transport models was undertaken using all available groundwater level data, including monitoring data from Arrow's newly installed Hopeland wells (HL34–HL37).

Particle tracking and contaminant transport modelling

Two approaches were considered to assess the impact of Arrow's proposed FDP on migration of contaminants within PL253, in particular around and within Lot 40 DY85. These include particle tracking and contaminant transport modelling.

First, the particle tracking model was developed based on the history-matched groundwater flow model and used to assess potential contaminant flow paths without including natural attenuation processes, effectively simulating the centre of a plume of a conservative tracer. The contaminant transport model was then developed based on the calibrated groundwater flow model. Unlike particle tracking model, the contaminant transport model includes

mechanical dispersion, molecular diffusion, as well as natural attenuation (sorption and biodegradation/decay) and dual domain mass transfer processes continuously occurring within subsurface.

Particle tracking fulfilled the following objectives:

- Assessed the effect of particle tracking starting in wells that have exhibited elevated UCG contaminants.
- Particles included the following locations:
 - All monitoring bores,
 - All model cells intercepting gasifier locations, and
 - All model cells intercepting Lot 40 DY85 boundaries.
- Assessed particle tracks (travel times, distances and trajectories) to evaluate the impact of Arrow's proposed FDP on migration of contaminants from Lot 40 DY85.

The contaminant transport model, developed based on the SCM and groundwater flow model, incorporates:

- the most recent groundwater quality data for model history matching, and
- dual porosity (or dual permeability) capability to better represent contaminant transport into and out of fractures and low permeability pore spaces that may contain residual contaminant sources.

Predictive uncertainty analysis

An uncertainty analysis was undertaken to evaluate the influence of hydrogeological variability on model predictions.

Impact assessment

Predictive impact assessment were undertaken to evaluate potential future contaminant migration from Lot 40 DY85 during the abstraction period and long-term groundwater recovery associated with the former Hopeland UCG site.

1.2 Study objectives

The overarching objective of this study is to provide a comprehensive understanding of the potential impacts of Arrow's proposed FDP on groundwater flow and contaminant migration associated with the former Hopeland UCG site on Lot 40 DY85.

The outcomes of this study are intended to:

- Support Arrow's Environmental Authority application, ongoing groundwater management, and
- Provide confidence that potential impacts to groundwater resources and receptors are appropriately understood and managed.

2. Site conceptualisation model

2.1 Previous studies

Hydrogeological understanding of the former Hopeland UCG site and surrounding PL253 area has evolved through a sequence of investigations, conceptual studies and modelling exercises completed since the start of (and informed by) UCG operations. UCG trial activities conducted on Lot 40 DY85 between 1999 and 2013 established the disturbance setting that subsequent studies sought to characterise, including local depressurisation, potential formation fracturing, and hydrocarbon byproducts in groundwater. Early conceptualisation work documented the site setting and identified the Springbok sandstone and the Macalister coal seams as the principal water-bearing horizons of interest, along with potential recharge mechanisms and the influence of historical operations on pressures and groundwater flow pathways. An SCM of contamination sources, groundwater flow pathways and receptors is shown in Figure 2-1 (from Epic, 2020).

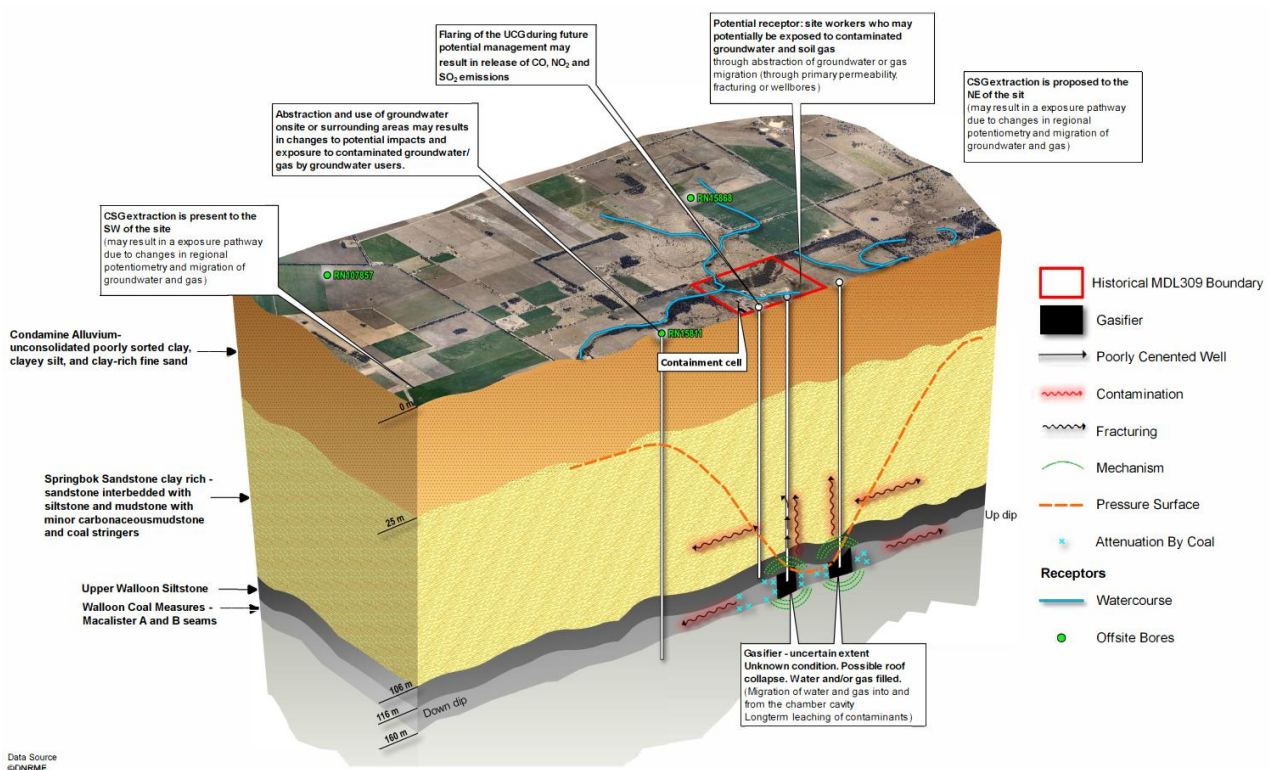


Figure 2-1 Conceptual Site Model of former Hopeland UCG (from Epic, 2020)

Previous hydrogeological studies (GHD, 2019; OGIA, 2021; AGE, 2021, 2023; Intera, 2024, 2025) have progressively integrated regional hydrogeological understanding and datasets, including basin-scale conceptualisation and parameter compilations widely used in the Surat Basin, and groundwater impact assessment studies that represent cumulative CSG influences. These earlier efforts informed the selection of HSUs, parameter ranges and boundary condition approaches used later in numerical groundwater modelling, particularly where regional depressurisation from CSG production governs vertical gradients and flow patterns.

Within PL253 and the immediate Hopeland area, prior groundwater modelling provided the basis for progressively refined representations of stratigraphy, hydraulic properties, and operational stresses. The groundwater modelling studies include earlier models developed by GHD (2019), AGE (2021 and 2023), and Intera (2024 and 2025). These site-focused modelling and assessments aimed to support groundwater monitoring network planning and the evaluation of contaminant mobility under CSG influences. These works collectively established the baseline model domain, local refinement requirements around Lot 40 DY85, and the need to represent UCG-related pressure changes and potential property alterations in and above the gasifier zone.

Detailed hydrogeological conceptualisation of the Surat Basin and PL253 has been reported previously (GHD, 2019; OGIA, 2021a, 2021b; Intera, 2025). The following sections provide a brief overview of the site hydrogeology and summarise relevant updates to date.

2.2 Site setting and geology

The PL253 area is located approximately 20 km south-east of Chinchilla within the Surat Basin. The geological setting comprises Jurassic to Early Cretaceous sedimentary sequences that host multiple aquifers and aquitards relevant to groundwater flow and contaminant transport.

Key HSUs include the Springbok sandstone and the WCM, which are separated by lower-permeability formations that limit vertical groundwater movement. The Macalister coal seam within the WCM was identified as a primary unit of interest due to its association with historical UCG operations and residual contamination. Previous studies (GHD, 2019; AGE, 2021, 2023; Intera, 2024, 2025) used this stratigraphic representation as the basis for numerical model development and conceptualisation.

In these studies, local geological complexity, including heterogeneity within coal seams and interburden units, was incorporated into the groundwater model using pilot point parameterisation. Structural features such as minor faults and fractures were recognised as potential sources of uncertainty but were not considered to form persistent preferential pathways at the site scale.

2.3 Groundwater flow regime

Regional groundwater flow within the Surat Basin is generally directed towards the south to southwest, consistent with basin-scale hydraulic gradients. The localised changes to this regional pattern are influences associated with historical UCG operations and regional CSG production.

Previous modelling works (GHD, 2019; AGE, 2021, 2023; Intera, 2024, 2025) have identified a localised hydraulic depression centred on Lot 40 DY85, reflecting residual effects at the end of UCG activities. Groundwater levels within this area have shown relative stability since the end of UCG activities, with evidence of gradual recovery in some monitoring bores.

Vertical hydraulic gradients are characterised by higher heads in overlying Springbok formation relative to the Macalister coal seam, indicating downward gradients that limit the potential for upward contaminant migration under current conditions.

2.4 Groundwater Monitoring

Groundwater monitoring within and surrounding Lot 40 DY85 has been undertaken over several years to characterise groundwater levels, assess groundwater quality, and track the behaviour of residual contaminants associated with historical UCG activities at Lot 40 DY85. The monitoring network includes bores installed in the Springbok sandstone and WCM, with a particular focus on the Macalister coal seam, reflecting the primary HSUs relevant to contaminant migration risk.

Monitoring data have been collected through a combination of Arrow groundwater monitoring programs, Queensland Government (DETSI/DoR) monitoring, and targeted investigations implemented to satisfy Environmental Authority (EA0001401) requirements. The monitoring framework has been progressively expanded and refined, including installation of additional Springbok sandstone monitoring bores (Hopeland 34 to Hopeland 37), to improve spatial coverage and vertical resolution in the vicinity of the former UCG site and along inferred flow paths.

Groundwater monitoring data has been used to inform groundwater flow directions, assess water quality trends, and support the ongoing history matching of groundwater flow and contaminant transport models, consistent with EA Water Conditions.

2.4.1 Groundwater level

Groundwater level monitoring is undertaken across a network of monitoring bores (including nested bores) screened in the Springbok sandstone and multiple seams within the WCM, including the Macalister coal seam. Regional context indicates that groundwater flow in the Surat Basin is generally towards the south to south-west, with widespread depressurisation of the WCM associated with historical and ongoing CSG production (OGIA, 2021b).

Monitoring data show vertical hydraulic gradients are predominantly directed towards the WCM, indicating downward gradients from the Springbok sandstone and upward gradients from deeper units, consistent with OGIA conceptualisation and reducing the likelihood of vertical contaminant migration out of the coal measures.

Site-specific groundwater level data indicate that, following the end of UCG activities, water levels within the Springbok sandstone and Macalister coal seam have shown partial recovery, with trends stabilising in recent years. Localised variability remains evident near former gasifier locations, reflecting heterogeneity in formation properties and the historical influence of gasifier voids.

Groundwater level observations collected from all monitoring bores up to Q4 2025 were reviewed to remove outlier or non-representative measurements (e.g., data affected by gas interference or incomplete recovery following sampling) prior to use in model history matching. The resulting dataset was used to inform model parameterisation with both absolute head targets and vertical head difference targets, consistent with OGIA (2021a) regional groundwater modelling methodology and Australian Groundwater Modelling Guidelines (Barnett et al., 2012).

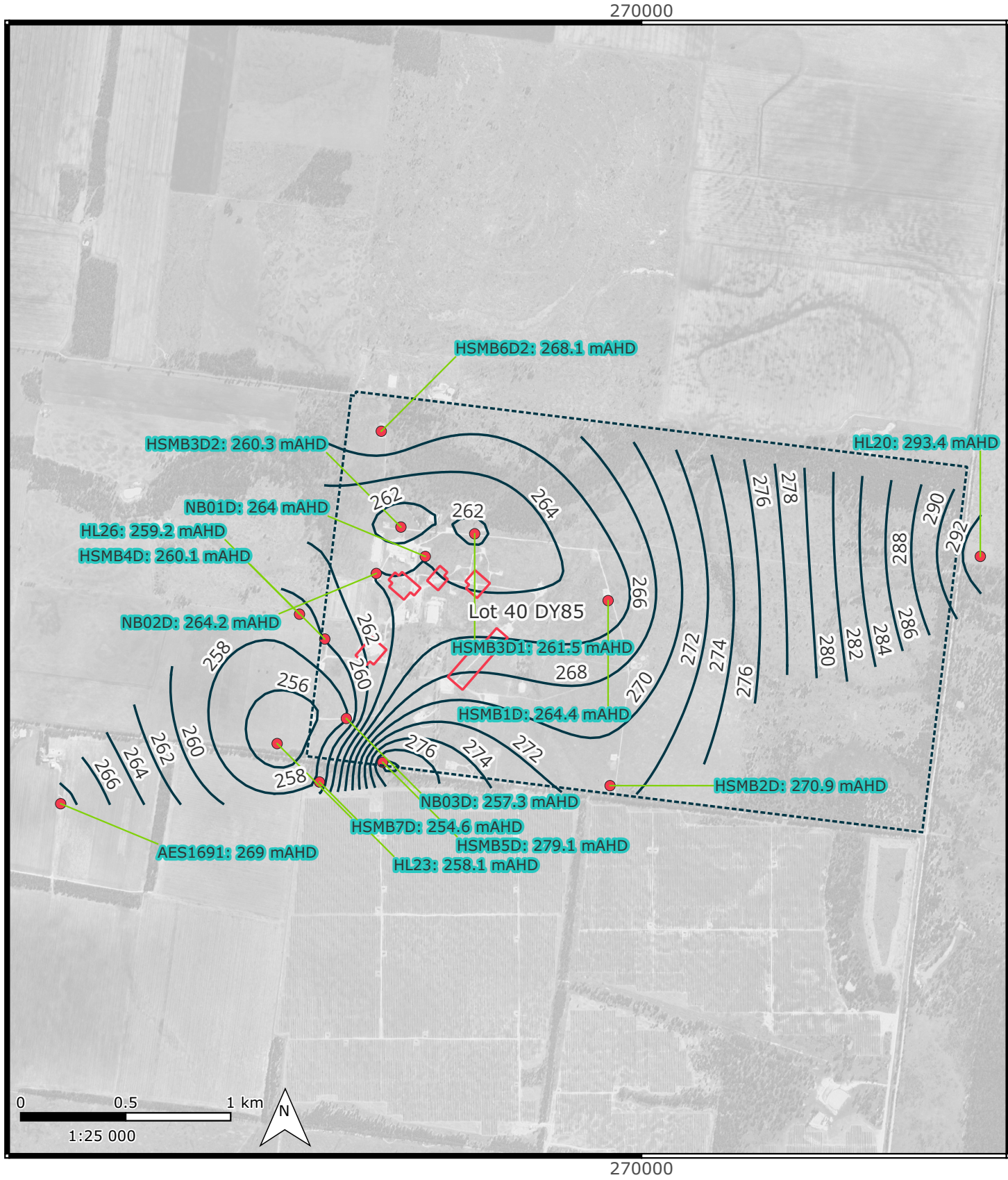
To better represent the most recent groundwater flow directions near Lot 40 DY85, groundwater level contours for the Springbok sandstone and Macalister coal seam were generated using Q3 2025 data. Q3 2025 was selected rather than Q4 2025 because it corresponds to the monitoring period with the greatest number of concurrent groundwater level observations across Lot 40 DY85. These contours (shown in Figure 2-2) provide the most recent estimate of potentiometric conditions and were used to inform interpretation of lateral flow directions and hydraulic gradients in the vicinity of the former UCG site.

The Q3 2024 groundwater level indicates that hydraulic gradients in the Springbok sandstone directed inward towards Lot 40 DY85, while for Macalister coal seam it is directed to the west and southwest corner of Lot 40 DY85. These variability of hydraulic gradients reflect the continued influence of historical depressurisation associated with UCG activities and regional WCM drawdown.

Springbok sandstone



Macalister coal seam



- Legend
- Lot 40 DY85
 - Gasifiers
 - Monitoring bores
 - Groundwater contours (mAHD)

Simulated groundwater levels in Springbok sandstone and Macalister coal seam for scenario 3 (end of December 2024)

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References:		
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2.4.2 Groundwater quality and contaminants of concern

Similar to previous studies (AGE, 2021, 2023; Intera, 2024, 2025), benzene and naphthalene were selected as representative contaminants of concern (COCs) for the contaminant transport modelling. Benzene, a known carcinogen, is the most mobile of the BTEX (benzene, toluene, ethylbenzene, and xylene) compounds due to its high solubility in water and low adsorption potential (Odermatt, 1994), while naphthalene is the most water-soluble polycyclic aromatic hydrocarbon (PAH) (Bayard et al., 2020). Both compounds exhibited the highest concentrations among their respective groups in the site's chemical dataset. Furthermore, benzene has been shown to degrade more slowly than the other BTEXN compounds (Prommer et al., 2003), making it a reliable indicator of the spatial extent of groundwater contamination.

Elevated concentrations of benzene and naphthalene are generally confined to monitoring bores located on Lot 40 DY85 and in proximity to former gasifier locations. Monitoring data for Springbok sandstone and Macalister coal seam (shown in Figure 2-3 to Figure 2-6) indicate mostly declining concentration trends since 2018, consistent with natural attenuation processes.

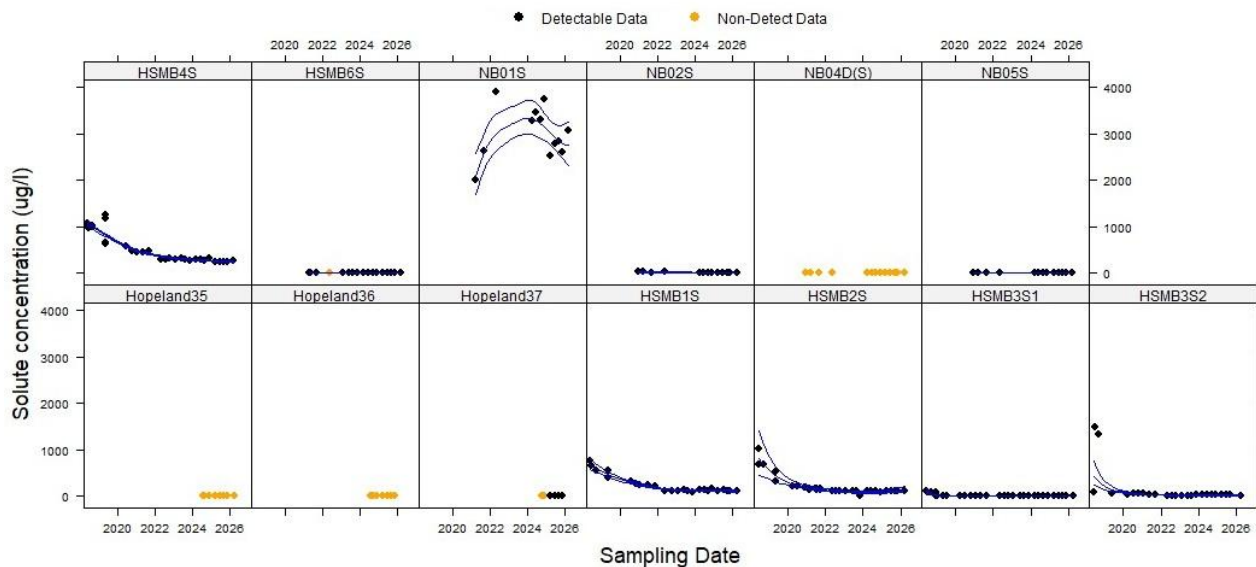
Benzene concentrations are generally higher and more persistent than concentrations of other BTEX compounds. Elevated benzene concentrations have been observed onsite in proximity to Gasifiers 1 and 2 (NB01S). In this location, benzene concentrations have shown relative temporal stability or slow decline, consistent with proximity to residual contaminant sources. Offsite monitoring bores generally show low or non-detectable benzene concentrations.

Naphthalene concentrations are typically lower than benzene and are detected less frequently. Monitoring results indicate that naphthalene concentrations have declined over time across most bores, with many locations now recording concentrations below laboratory Limit of Reporting (LOR). This is due to naphthalene's stronger sorption and attenuation characteristics relative to benzene.

Overall, monitoring data demonstrate a general declining trend in benzene and naphthalene concentrations since approximately 2020, attributable to a combination of natural attenuation processes, limited advective transport due to low groundwater velocities, and the persistence of inward hydraulic gradients for Springbok sandstone towards Lot 40 DY85.

The groundwater quality dataset provides no evidence of progressive offsite migration of benzene or naphthalene under current conditions and supports the conclusion that residual contamination remains localised and effectively contained within the former UCG site area under existing and proposed CSG development scenarios.

(A) Benzene at on-site monitoring bores, Hopeland PL253, Springbok Sandstone



(B) Benzene at off-site monitoring bores, Hopeland PL253, Springbok Sandstone

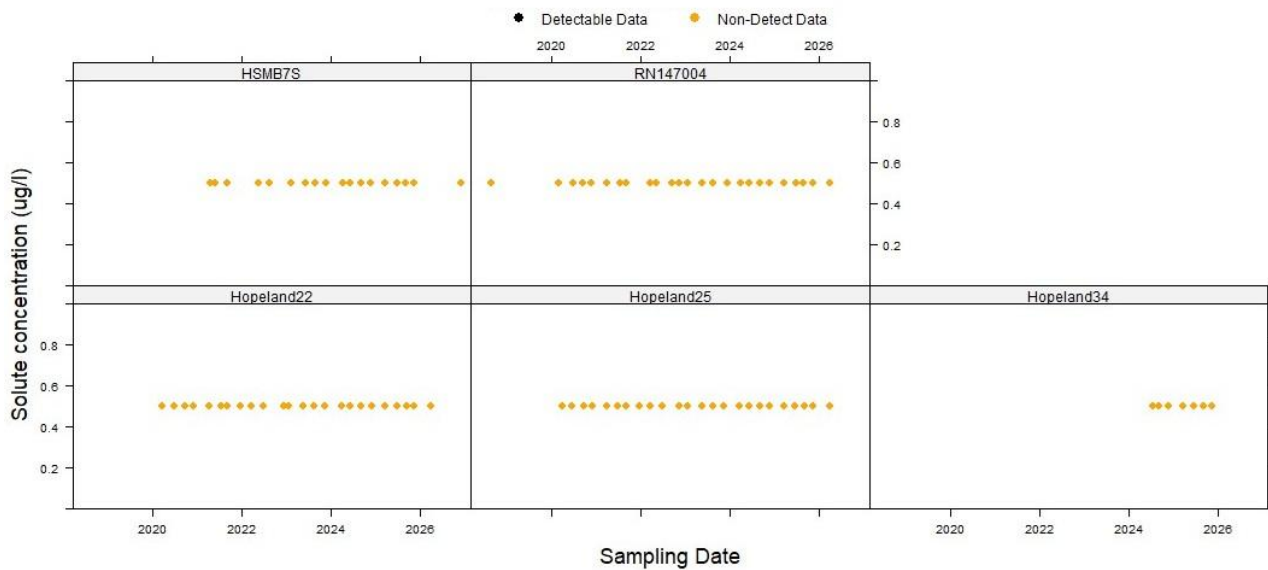
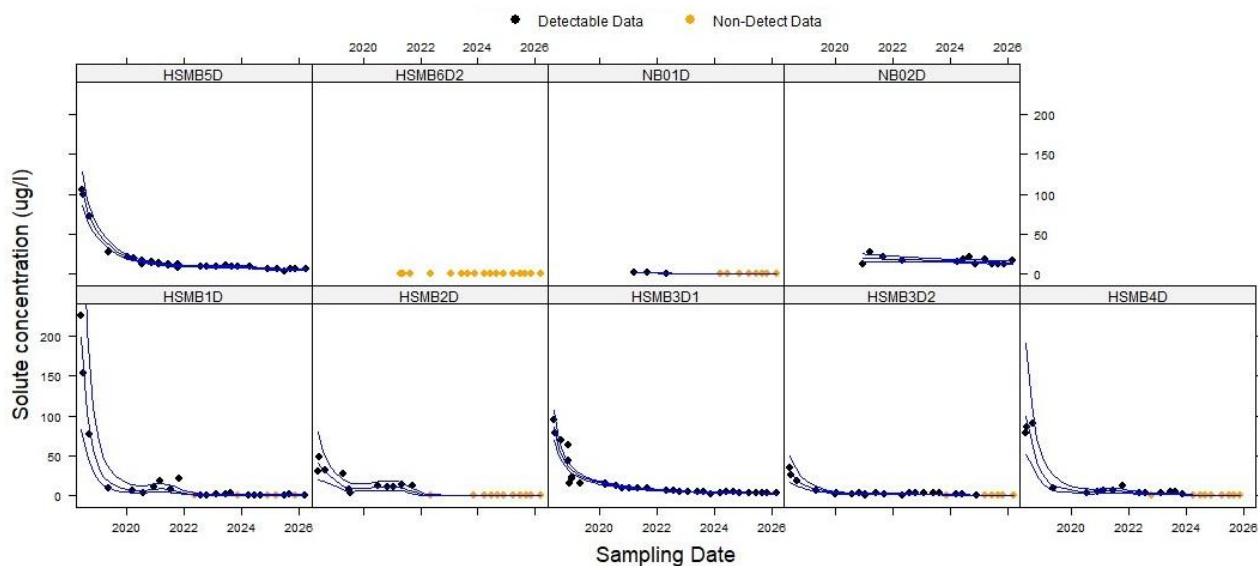


Figure 2-3 Time series benzene concentration for a) on-site and b) off-site bores completed in the Springbok sandstone (provided by Arrow)

(A) Benzene at on-site monitoring bores, Hopeland PL253, Macalister coal seam



(B) Benzene at off-site monitoring bores, Hopeland PL253, Macalister coal seam

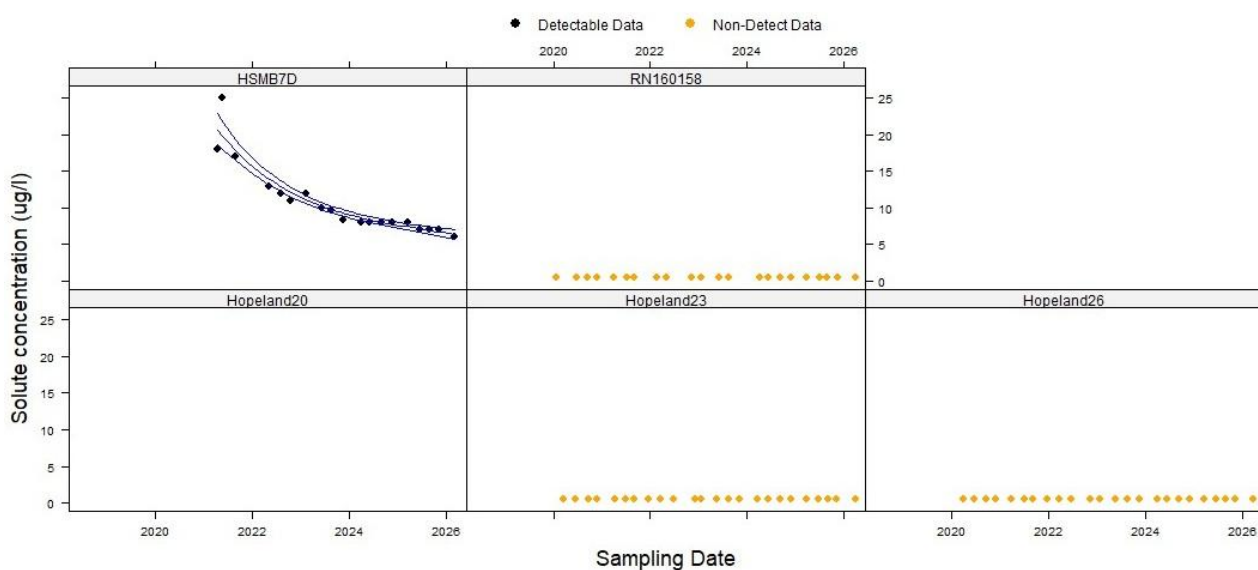
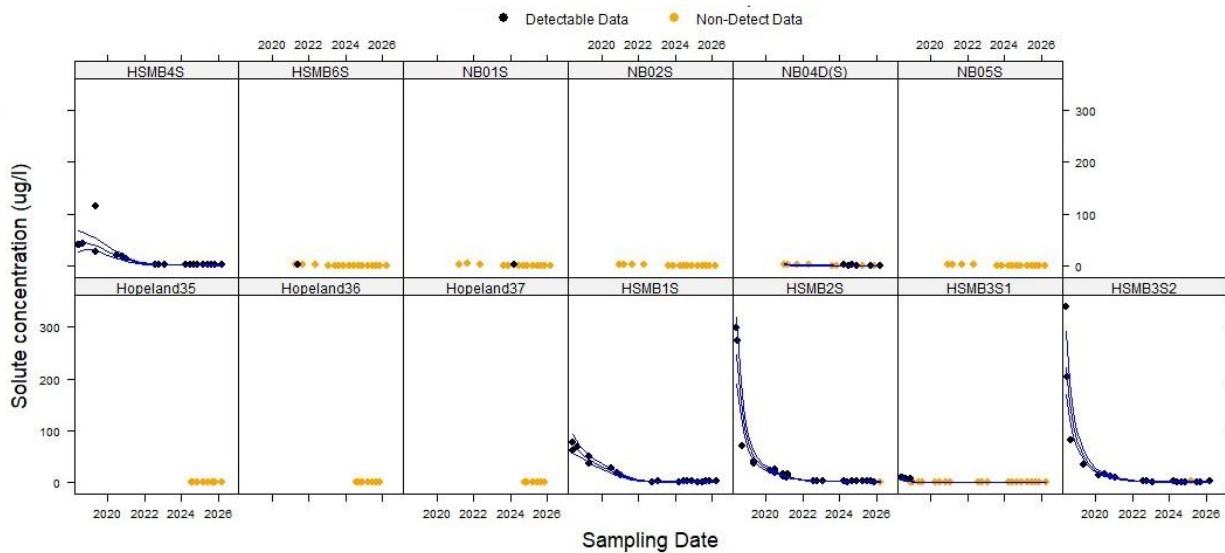


Figure 2-4 Time series benzene concentration for a) on-site and b) off-site bores completed in the Macalister coal seam (provided by Arrow)

(A) Naphthalene at on-site monitoring bores, Hopeland PL253, Springbok Sandstone



(B) Naphthalene at off-site monitoring bores, Hopeland PL253, Springbok Sandstone

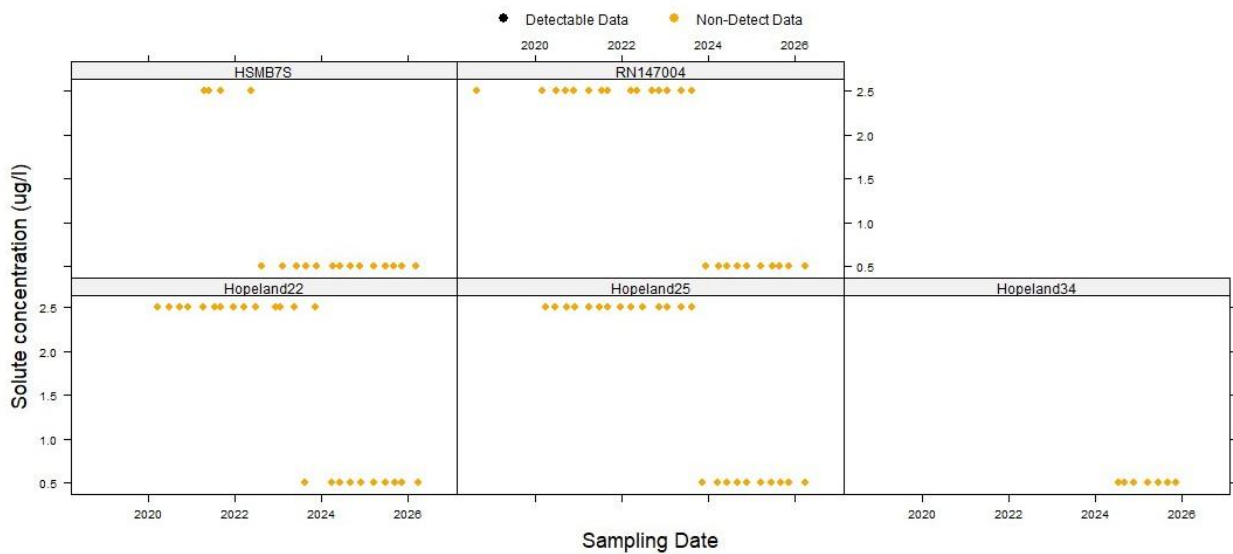
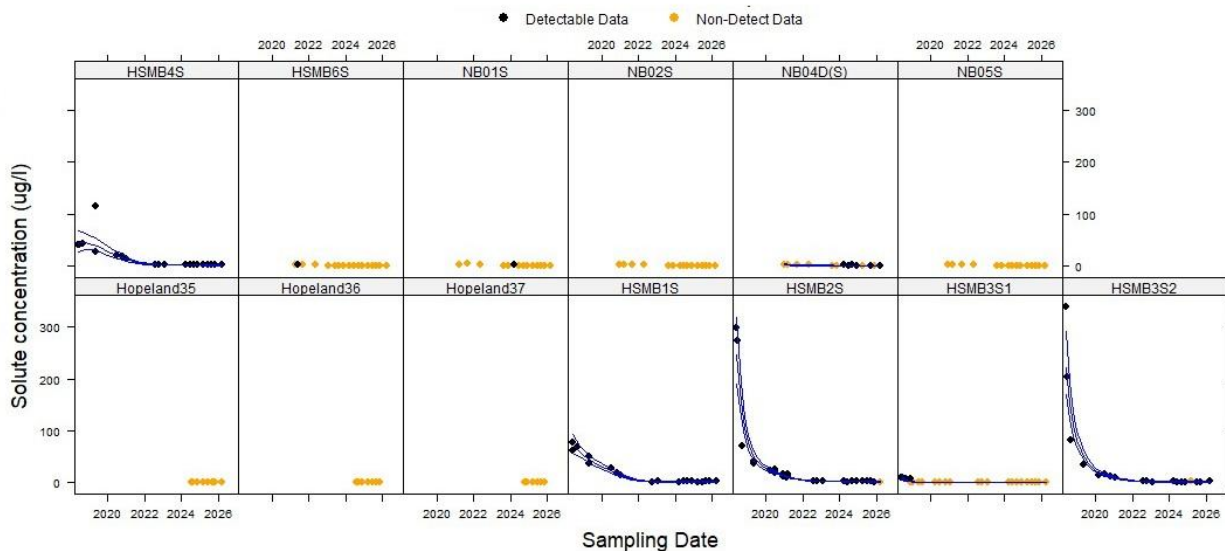


Figure 2-5 Time series naphthalene concentration for a) on-site and b) off-site bores completed in the Springbok sandstone (provided by Arrow)

(A) Naphthalene at on-site monitoring bores, Hopeland PL253, Springbok Sandstone



(B) Naphthalene at off-site monitoring bores, Hopeland PL253, Springbok Sandstone

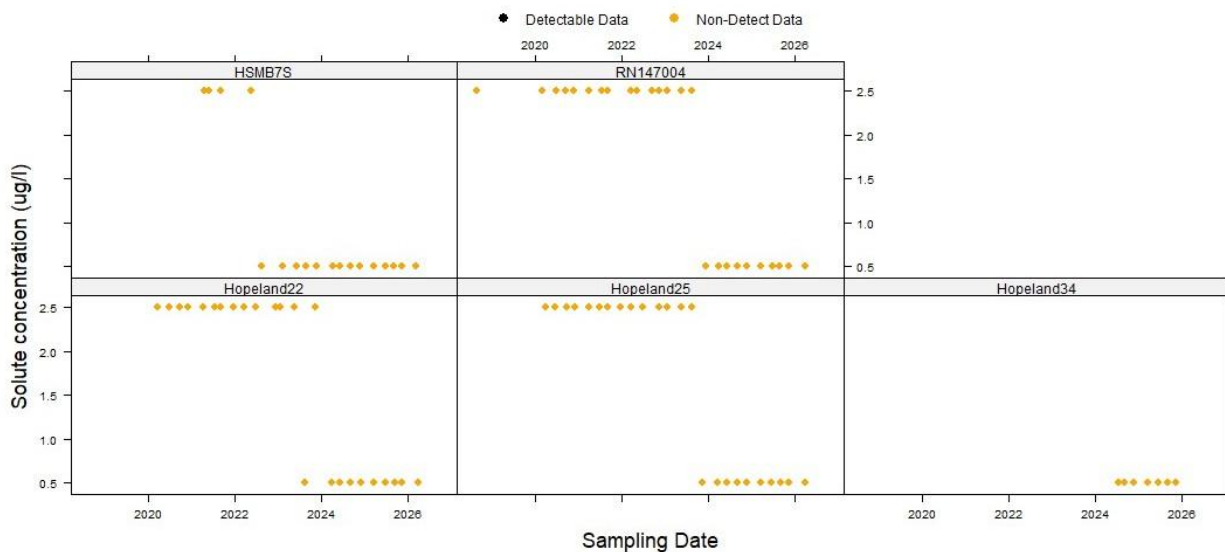


Figure 2-6 Time series naphthalene concentration for a) on-site and b) off-site bores completed in the Macalister coal seam (provided by Arrow)

2.4.2.1 Contaminant source depletion at gasifiers

The contaminant transport model incorporates a time-varying source depletion term to represent the gradual reduction in residual contaminant mass available for dissolution from the gasifiers. Source depletion was implemented to capture long-term declines in contaminant concentrations attributable to natural attenuation processes (i.e., sorption, and degradation). Rather than assuming a constant or infinite source, this approach provides a more realistic

representation of contaminant behaviour, while allowing for the continued release of residual contaminants from dead-end pores.

The source depletion formulation was defined using the most comprehensive available groundwater quality dataset. For each compound and HSU (Springbok sandstone and Macalister coal seam), the highest observed concentration from all monitoring bores at each sampling event was extracted from the full time-series record as shown in Figure 2-7 and Figure 2-8 for benzene and naphthalene, respectively. This upper-envelope dataset was used conservatively to derive an exponential decay relationship describing the temporal reduction in source concentration. The fitted exponential functions were then used to define time-varying source boundary conditions in the contaminant transport model.

For benzene, the extracted maximum concentration time series shows a gradual but persistent decline over time across monitoring bores screened in the Springbok sandstone and Macalister coal seam. An exception is elevated concentrations observed in monitoring bore NB01S within the Springbok sandstone (blue points above the fitted exponential decay curve in Figure 2-7). The elevated benzene concentrations at NB01S, which is proximal to former gasifier areas, are interpreted to represent a localised and spatially confined source. This interpretation is supported by groundwater monitoring data from surrounding bores (HSMB3S1, HSMB3S2, and NB02S), which indicate substantially lower concentrations consistent with the broader monitoring network.

Given the localised nature of the elevated benzene concentrations at NB01S, an ongoing source term with a constant concentration was adopted within a 50 m radius of this bore and assessed separately within the contaminant transport model. This approach allows the broader, data-derived source depletion term to be applied across Lot 40 DY85, while explicitly accounting for localised residual contamination in the vicinity of NB01S.

An exponential decay function was fitted to the upper-envelope benzene dataset for all the remaining monitoring bores, representing the depletion of benzene source as shown in equations (1) and (2) for springbok sandstone and Macalister coal seam, respectively:

$$C(t) = 1750 e^{-0.00065 t} \quad (1)$$

$$C(t) = 375 e^{-0.001 t} \quad (2)$$

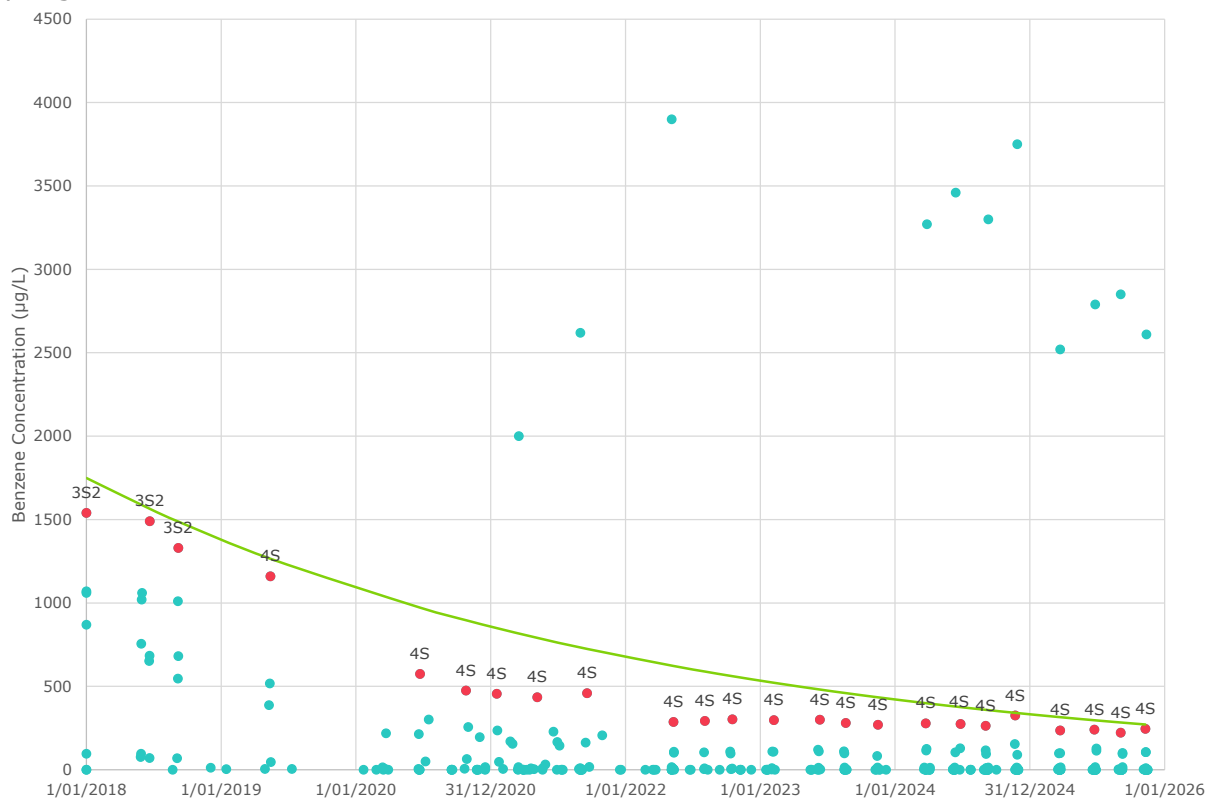
where $C(t)$ is source concentration term in ($\mu\text{g/L}$), and t is the number of days from the first day of contaminant transport simulation on 1/1/2018.

Naphthalene monitoring data indicate lower maximum concentrations and a more rapid decline relative to benzene, consistent with stronger sorption and attenuation characteristics. The same upper-envelope methodology was applied, with maximum naphthalene concentrations extracted from all monitoring bore records and fitted with an exponential decay function. The resulting relationship was used to define the naphthalene source depletion term in the transport model as shown in equations (3) and (4) for springbok sandstone and Macalister coal seam, respectively:

$$C(t) = 500 e^{-0.0019 t} \quad (3)$$

$$C(t) = 75 e^{-0.0019 t} \quad (4)$$

Springbok sandstone



Macalister coal seam

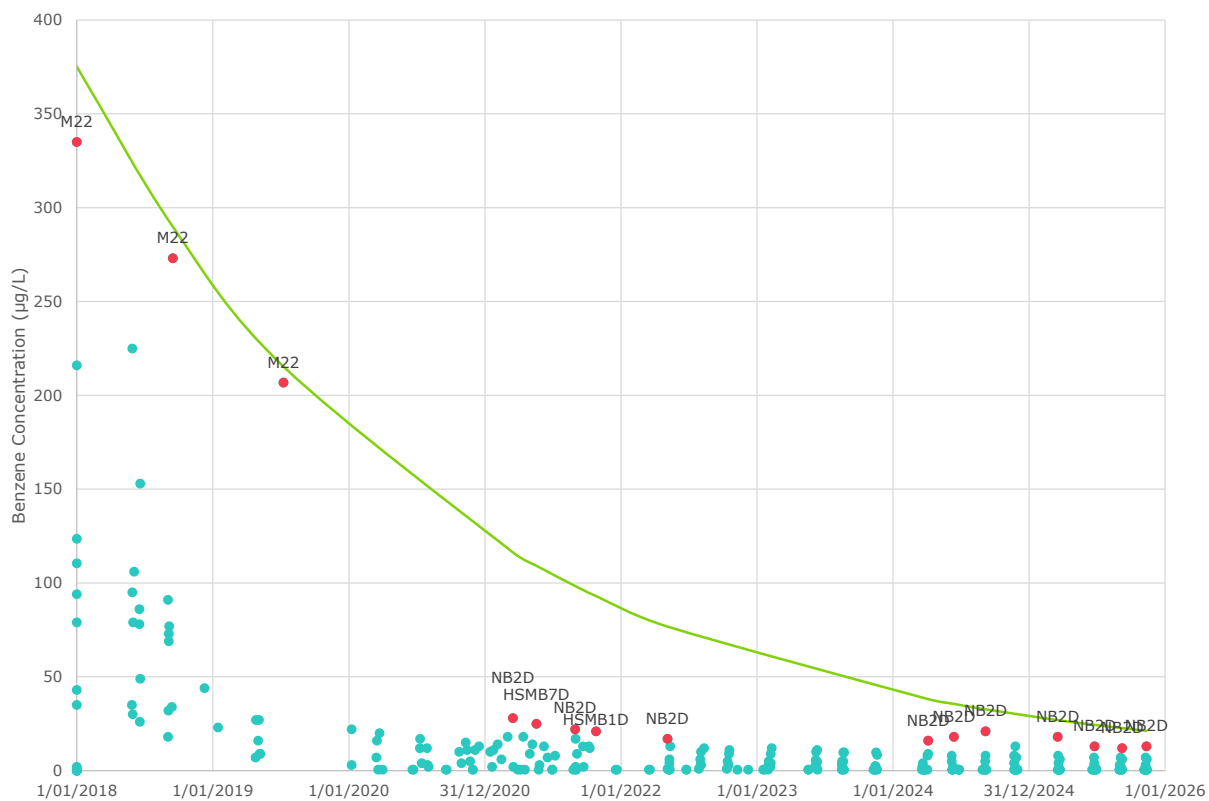
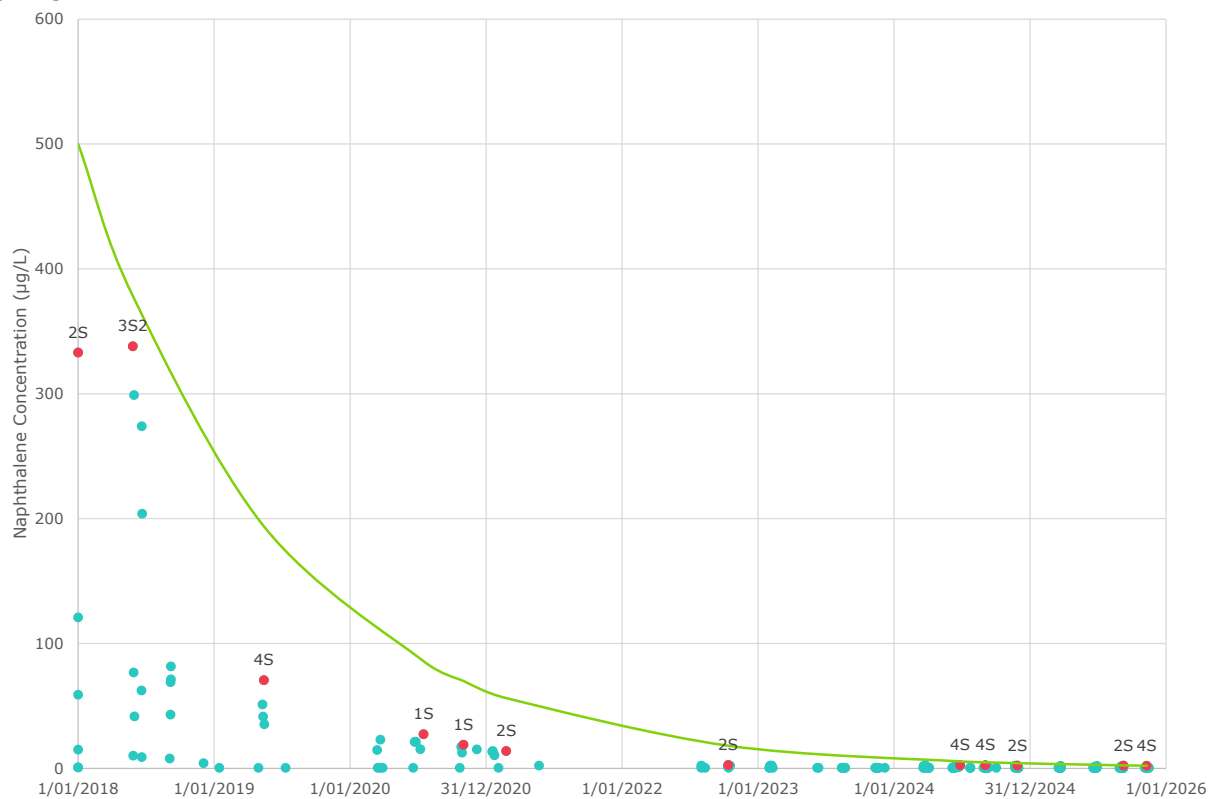


Figure 2-7 Benzene concentration for all monitoring bores compared with exponential curve of source depletion term for a) Springbok sandstone and b) Macalister coal seam

Springbok sandstone



Macalister coal seam

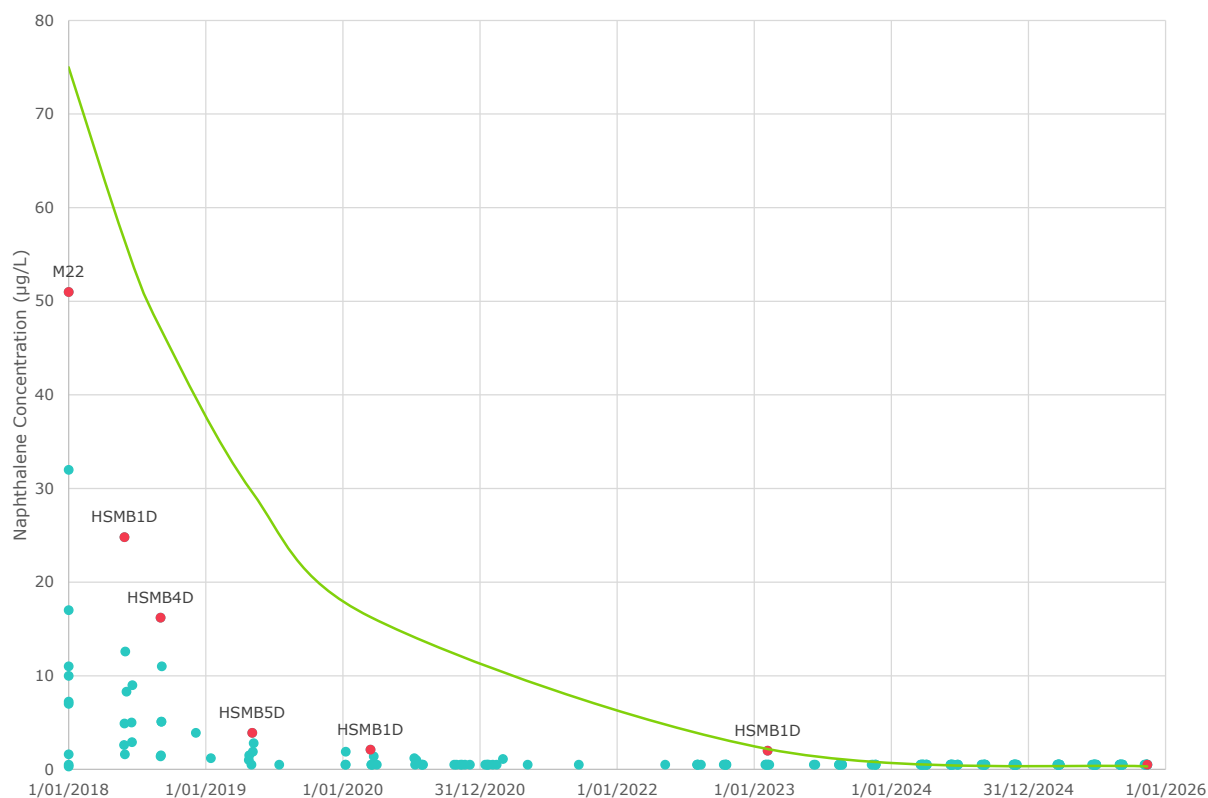


Figure 2-8 Naphthalene concentration for all monitoring bores compared with exponential curve of source depletion term for a) Springbok sandstone and b) Macalister coal seam

3. Groundwater modelling

3.1 Groundwater flow model

Building on Arrow's recent PL253 numerical groundwater model (INTERA, 2025), a numerical groundwater model was developed to assess the impacts of Arrow's proposed FDP for the Clynes Road wells. The model focuses on aquifers on and surrounding Lot 40 DY85, including the Springbok sandstone and the Macalister coal seam and associated aquifers within the WCM. The groundwater model is developed to evaluate and predict potential changes in contaminant transport, groundwater flow directions, and drawdown resulting from development of the Clynes Road wells.

The groundwater model extent (Figure 1-1), is consistent with the area adopted by previous studies (e.g., GHD, 2019, 2020; AGE, 2021, 2023; INTERA, 2024, 2025). It encompasses an approximately 20-km radius around Lot 40 DY85 and includes PLs 253, 493 and 185, as well as adjacent areas, ensuring the model captures key hydrogeological stresses and their zones of influence during past and future activities.

The rectangular model domain (Figure 1-1) was rotated so that the northeastern boundary aligns with the extent of WCM, while the northwest and southeastern boundaries are roughly parallel to the strata dip and regional groundwater flow direction. From a numerical modelling perspective, the boundaries were defined to minimise potential boundary effects and ensure that all relevant flow pathways can be fully simulated within the required timeframes.

Consistent with the most recent groundwater model (INTERA 2025, shown in Figure 3-1), the updated model is developed in MODFLOW 6 incorporating local grid refinement around Lot 40 DY85, with 18 layers representing the key HSUs in the area. The use of MODFLOW 6 introduced improvements in modelling assumptions and boundary condition representation (e.g. incorporation of dual-porosity processes). However, the predictive model remained subject to a wide range of uncertainty in some aspects of the predictions. Accordingly, while maintaining the MODFLOW 6 modelling platform, a comprehensive review of the previous modelling work was undertaken, and key boundary conditions and HSU representation were revised. This approach enabled incorporation of hydrogeological information to revise the model boundary conditions, while retaining the strengths of the MODFLOW 6 platform in the current groundwater model.

Boundary conditions (presented in this chapter) represent regional groundwater influences, historical UCG depressurisation, and CSG abstraction from Arrow and non-Arrow wells. Time-varying hydraulic properties are used to reflect changes associated with UCG operations.

The prediction period extends to the end of 2225 (200 years), well beyond the groundwater abstraction period, when off-site contaminant migration may become possible.

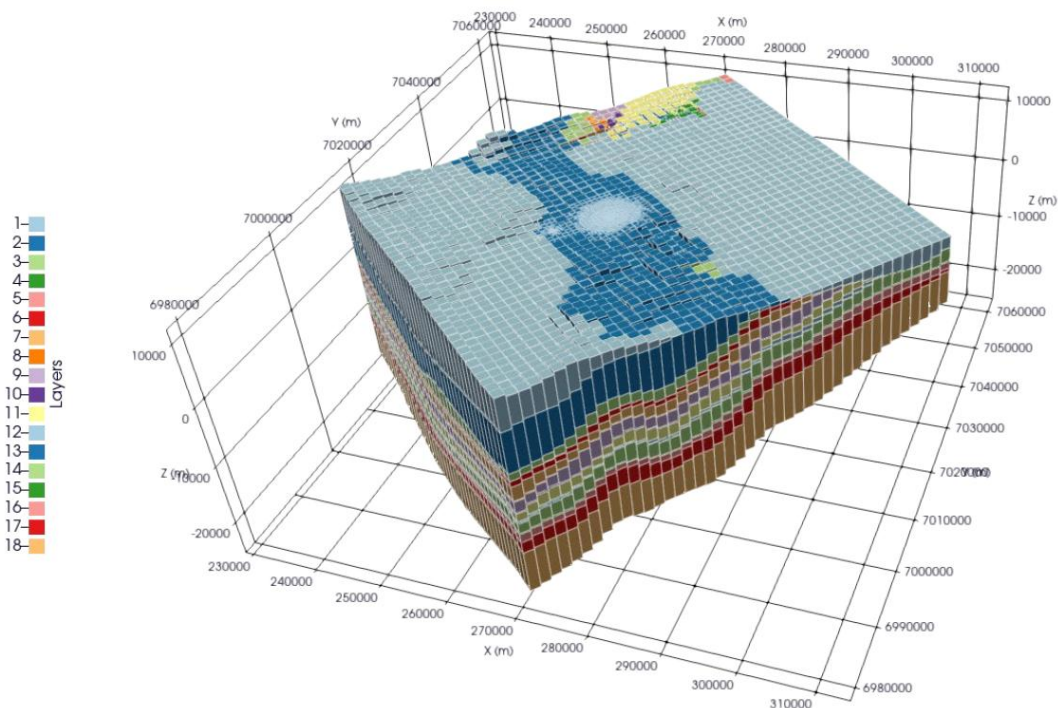


Figure 3-1 3D groundwater model with 30x vertical exaggeration (from Intera, 2025)

Key updates incorporated in the current numerical groundwater flow model include:

- Updated HSUs based on the latest geology model developed by Arrow.
- The General Head Boundary (GHB) conditions were extracted from the OGIA 2021 cumulative groundwater model and assigned to model boundary layers ensuring alignment between the two model layers. Additionally, excessively high conductance values used at the model boundaries in the previous model (INTERA, 2025) were updated based on the individual cells' hydraulic conductivity and thickness.
- The drain (DRN) package elevations were extracted from the OGIA 2021 cumulative groundwater model for simulation of CSG abstraction. The extracted elevation time series were assigned to the groundwater model layers ensuring alignment between the two model layers. Additionally, conductance values were calculated based on the individual cells' hydraulic conductivity, thickness and a multiplier factor informed during history matching.
- Simulation solver settings were updated to ensure the numerical model converges in all the model time steps aligned with Australian Groundwater Modelling Guidelines (Barnett et al 2012). If the model does not converge during a specific time step, the simulation stops and does not proceed further.
- Unlike the previous model (INTERA, 2025), which used the Drain Package to simulate groundwater abstraction under FDP scenarios (with and without the Clynes Road wells), the current model uses the WEL Package. This approach avoids estimation errors associated with converting well flow rates to drain elevations in the drain boundary condition. Model inputs include bore locations, screened intervals, and time-series pumping rates.
- Updated groundwater level datasets to inform both steady-state and transient history matching and incorporated current groundwater flow directions into the calibration targets.
- Refinement of pilot points location to capture spatial heterogeneity in hydraulic parameterisation of the aquifer system based on a conceptual understanding of groundwater flow directions and monitoring bore locations.

- A review and revision of the other modelled boundary conditions (e.g. recharge, and multi-aquifer well boundary conditions) in the previous model (INTERA, 2025) to improve the simulation of groundwater flow regimes consistent with the hydrogeological conceptualisation.
- Model calibration, predictive simulations and uncertainty analysis using the combined Ensemble Space Inversion¹ (PEST-ENSI) and Iterative Ensemble Smoother (PESTPP-IES, White, 2018) methods to replicate historical groundwater flow systems and understand the probability envelope associated with environmental impacts within PL253.

3.1.1 Model layers

Model layers are built based on HSU geometry from Arrow's geological model. The lithological contacts were discretised using Intera's model grid to construct the updated model layers and are aligned with the previous groundwater models as presented in Table 3-1 and shown in Figure 3-2.

Table 3-1 Model layers

Hydrogeological Domain	Average thickness (m)	Model Layer
Condamine alluvium/Gubberamunda sandstone	43.8	1
Westbourne formation	56.7	2
Springbok sandstone	96.3	3
WCM Kogan coal seam	1.2	4
WCM Kogan interburden	11.9	5
WCM Macalister coal seam	9.5	6
WCM Macalister interburden	54.9	7
WCM Wambo coal seam	3.7	8
WCM Wambo interburden	60.3	9
WCM Argyle coal seam	3.5	10
WCM Argyle interburden	50.8	11
WCM Tangalooma sandstone	8.7	12
WCM Upper Taroom coal seam	4.0	13
WCM Upper Taroom interburden	88.5	14
WCM Condamine coal seam	5.5	15
WCM Condamine interburden	43.3	16
Eurombah formation	81.0	17
Hutton sandstone	197.1	18

¹ <https://gmdsi.org/blog/ensemble-space-inversion/>

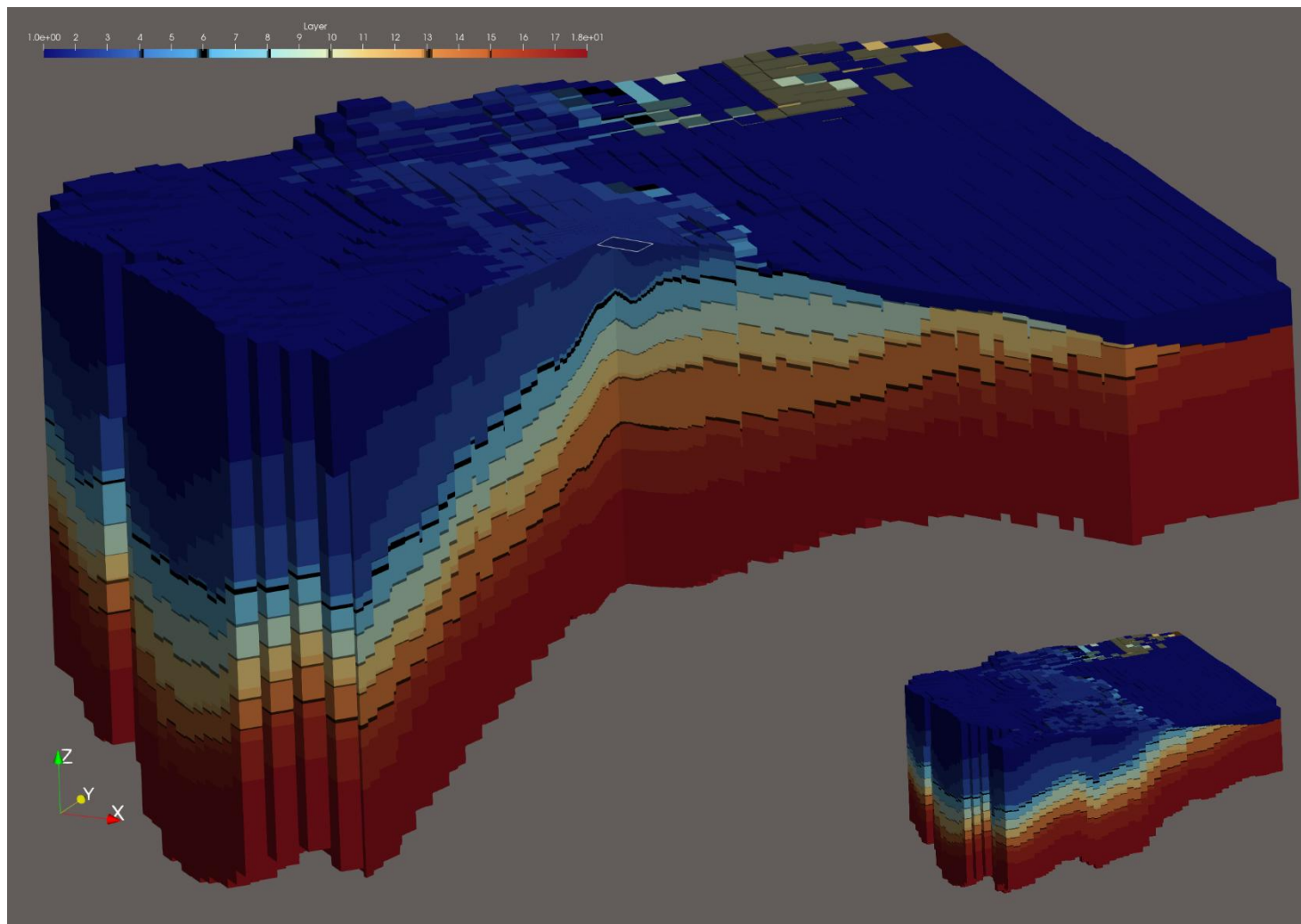


Figure 3-2 PL253 3D groundwater model (with 30x vertical exaggeration of the 3D model and cross-sections)

3.1.2 Hydraulic properties

Initial hydraulic properties were assigned as a single value across each model zone based on the learnings from the previous groundwater model history matching (Intera, 2025 and AGE, 2023). The initial horizontal hydraulic conductivity (k_h), vertical to horizontal hydraulic conductivity ratio (k_v/k_h), specific storage (S_s), and specific yield (S_y) values assigned in each model layer is presented in Table 3-2.

Once the parameter zones were initialised with a hydraulic property value, a 2D distribution of hydraulic properties of each zone was generated using the pilot points with multipliers. This allows for improved data assimilation by extracting information from measured observations in scenarios where the use of a single value for hydraulic properties within a zone is not sufficient to interpret the groundwater level variability or trends in bores located close to each other.

Other details of the parameterisation approach will be discussed further in Section 4.2.

Table 3-2 Summary of initial hydraulic properties

Hydrogeological Domain	Layer	K_h (m/day)	K_v/K_h	S_s (m ⁻¹)	S_y (%)
Condamine alluvium	1	2.6E+01	1.0E-01	2.3E-05	10
Gubberamunda sandstone	1	1.3E-01	1.0E-02	5.0E-06	2.5
Westbourne formation	2	8.9E-04	1.0E-03	2.3E-05	2.5
Springbok sandstone	3	1.6E-02	5.0E-03	1.0E-05	5
WCM Kogan coal seam	4	6.9E-02	1.0E-01	1.0E-05	1
WCM Kogan interburden	5	2.8E-02	1.0E-03	5.0E-06	1
WCM Macalister coal seam	6	4.0E-02	1.0E-01	5.0E-06	1
WCM Macalister interburden	7	4.9E-03	1.0E-03	5.0E-06	1
WCM Wambo coal seam	8	1.3E-01	1.0E-01	2.3E-05	1
WCM Wambo interburden	9	4.2E-03	1.0E-03	5.0E-06	1
WCM Argyle coal seam	10	1.4E-01	1.0E-01	2.3E-05	1
WCM Argyle interburden	11	5.2E-03	1.0E-03	1.0E-05	1
WCM Tangalooma sandstone	12	9.6E-03	1.0E-03	1.0E-05	1
WCM Upper Taroom coal seam	13	1.7E-01	1.0E-01	5.0E-06	1
WCM Upper Taroom interburden	14	1.7E-02	1.0E-03	5.0E-06	1
WCM Condamine coal seam	15	1.5E-01	1.0E-01	5.0E-06	1
WCM Condamine interburden	16	3.1E-02	1.0E-03	2.3E-05	2.5
Eurombah formation	17	1.8E-04	1.0E-03	5.0E-06	2.5
Hutton sandstone	18	3.4E-02	1.0E-03	2.3E-05	2.5

3.1.3 Boundary conditions

The MODFLOW 6 boundary packages are used to assign the boundary conditions and simulate relevant flow exchange processes. The assigned boundary conditions for PL253 groundwater model are presented in sections 3.1.3.1 to 3.1.3.7.

3.1.3.1 Recharge

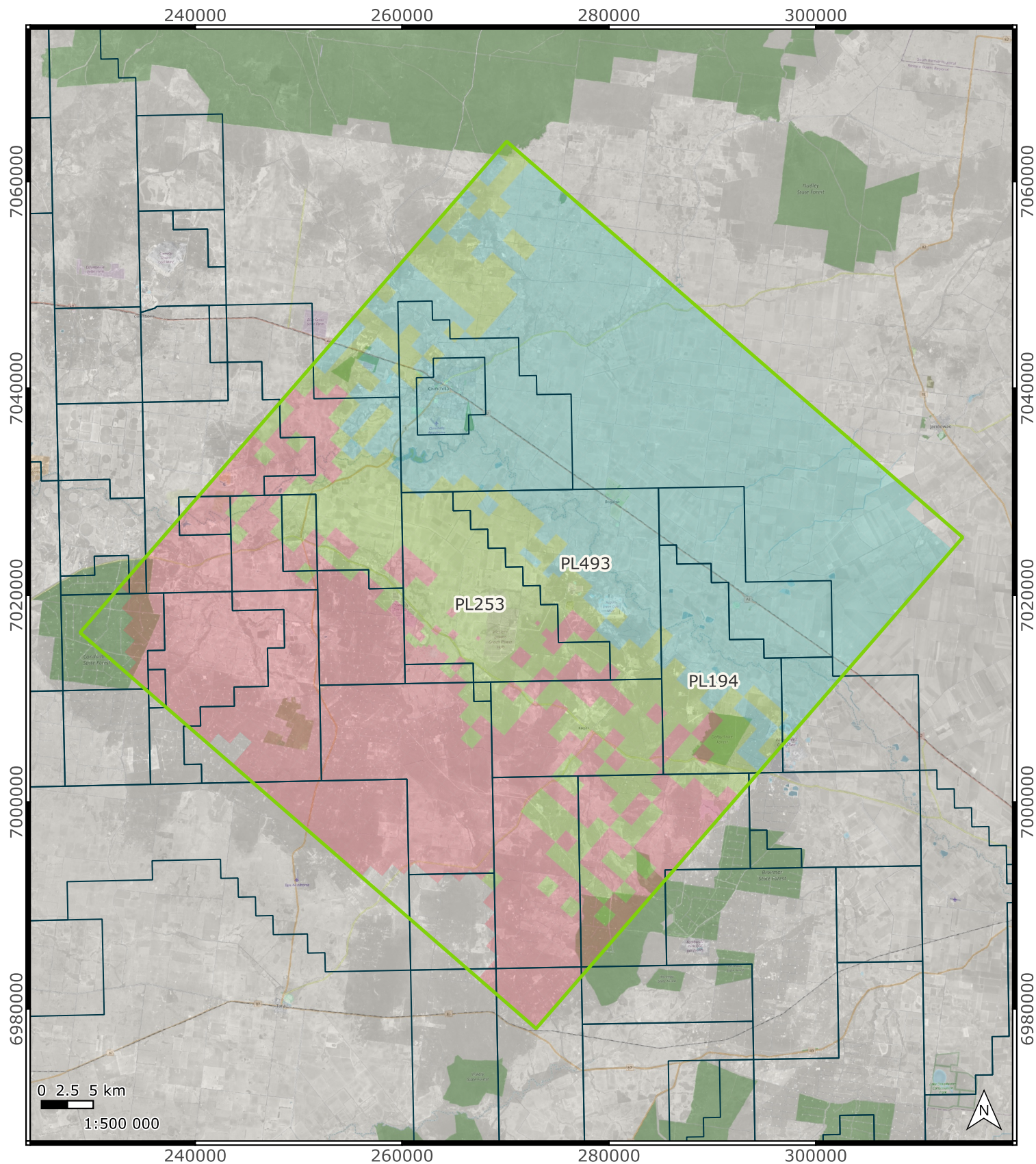
Recharge to the groundwater system is represented by setting up three distinct recharge zones (shown in Figure 3-3) including:

- Condamine alluvium,
- Gubberamunda sandstone, and
- Westbourne formation and outcropping layers.

The initial annual recharge rates for each zone, adapted from previous studies (AGE, 2023; INTERA, 2025), are presented in Table 3-3. A recharge factor for each zone was defined and allowed to be adjusted during the model calibration.

Table 3-3 Initial annual recharge rate for each zone

Recharge zone	Initial annual recharge, mm/year
Condamine alluvium	3.5
Gubberamunda sandstone	1.0
Westbourne formation and outcropping layers	0.2



Legend

 Groundwater model extent	Recharge zones
 Petroleum Leases	 Condamine alluvium
	 Gubberamunda sandstone
	 Westbourne formation and outcropping layers

Simulated recharge zones

Project No. 411001-00917	Client Arrow	Figure No. 3-3
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3.1.3.2 Surface drainage

Surface drainage was simulated using drain (DRN) boundary conditions assigned to the uppermost active model cells, with drain elevations set to the model top (land-surface elevation). This allows groundwater discharge when simulated heads exceed land surface. This head-dependent approach representing surface drainage provides a numerically stable representation of topographically controlled groundwater discharge without imposing fixed hydraulic constraints.

3.1.3.3 General head boundaries

Time series of GHB elevations were extracted from the OGIA (2021) regional groundwater model and assigned to boundary cells in the updated HSUs, with careful alignment of layer elevations between the regional OGIA and PL253 models. Inferred hydraulic heads were obtained for the following units:

- Gubberamunda sandstone,
- Westbourne formation,
- Springbok formation,
- WCM Kogan interburden,
- WCM Macalister coal seam,
- WCM Wambo coal seam,
- WCM Argyle coal seam, and
- WCM Condamine coal seam.

During calibration, GHB head values were allowed to vary through vertical shifting of the prescribed head time series, while boundary conductance was adjusted using multiplier factors. This approach enabled adjustment of the quantitative influence of regional boundary conditions on simulated groundwater flow while preserving the temporal structure of the heads extracted from OGIA (2021) model. All remaining boundary cells, including the northeastern model boundary, were represented as no-flow boundaries.

3.1.3.4 Non-Arrow CSG wells

In the current model, non-Arrow CSG wells included in the OGIA (2021) regional groundwater model were simulated using drain (DRN) boundary conditions. Drain elevation time series were extracted directly from the corresponding OGIA (2021) model layers and assigned to the PL253 model to ensure consistency with the regional depressurisation conceptualisation. Drain conductance for each cell was calculated based on the product of horizontal hydraulic conductivity and individual cell thickness and scaled by a dimensionless multiplier. This multiplier was informed through history matching of observed regional groundwater responses and subsequently assessed during uncertainty analysis. This provides a simplified yet physically consistent representation of non-Arrow CSG extraction impacts while maintaining alignment with OGIA regional groundwater flow directions.

3.1.3.5 FDP abstraction scenarios

In order to quantify the impact of Arrow's proposed FDP (Clynes Road development) on groundwater flow and migration of contaminants, the following groundwater abstraction scenarios were initially considered in the current study:

- **Scenario 1:** this includes all non-Arrow production wells in proximity of PL253 (within the modelled domain).
- **Scenario 2:** this corresponds to the six existing Hopeland pilot wells and the soon to be installed 55 Kogan Creek CSG wells approved under the current EA for PL253 (green points in Figure 1-1), together with approved wells in Arrow's neighbouring tenure. This scenario reflects Arrow's currently authorised Field Development Plan (FDP).
- **Scenario 3:** this includes all wells from Scenario 2, plus the additional 55 Clynes Road wells for which Arrow is seeking approval.

Assessing incremental changes between scenario 2 and scenario 3 will provide insight into understanding impacts from Lot 40 DY85 attributable to Arrow's proposed Clynes Road FDP for the expansion project.

The abstraction rates for Arrow wells scenarios 2 and scenario 3 (simulated using the WEL package), are shown in Figure 3-4.

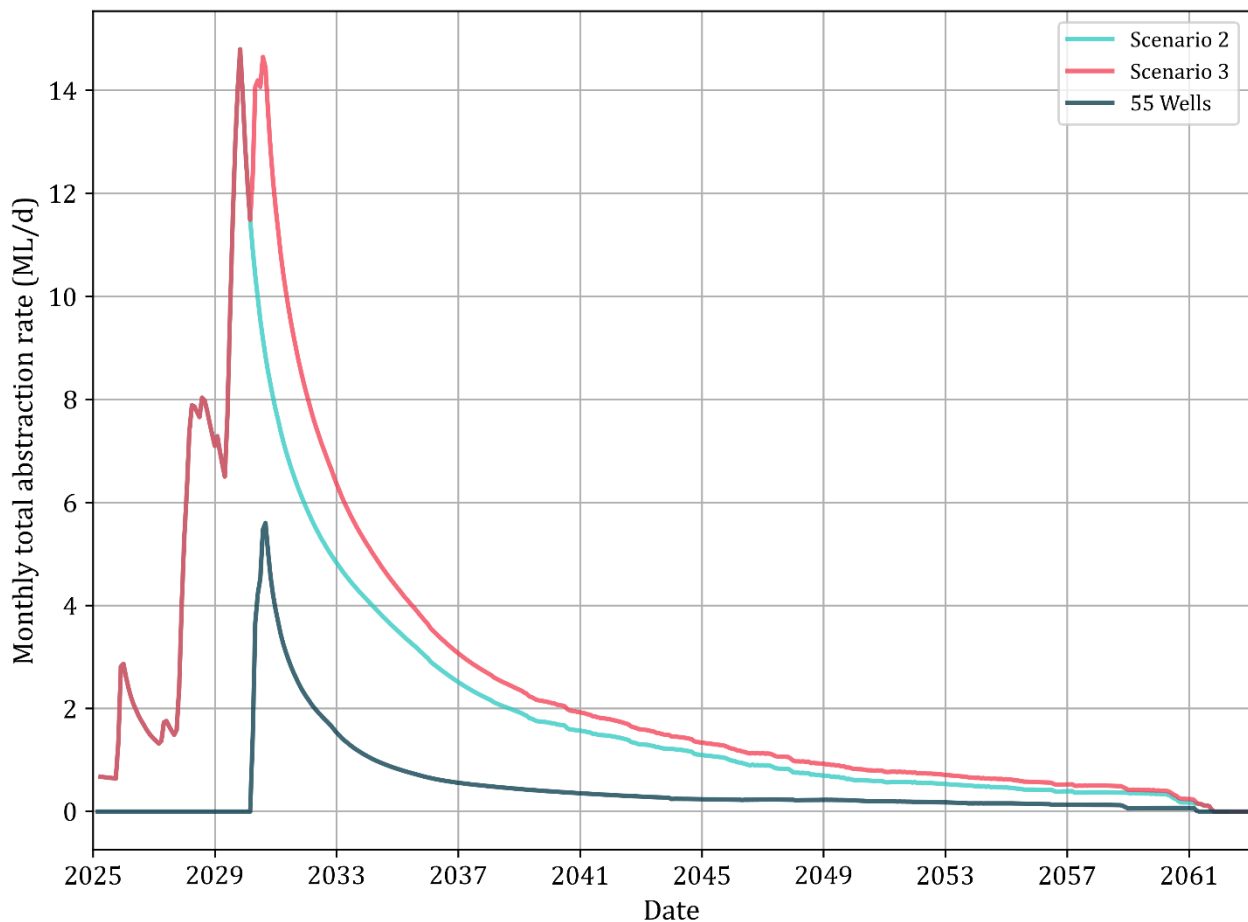


Figure 3-4 Monthly total abstraction rates for FDP scenarios 2 and 3

Extraction from existing and proposed Arrow CSG wells was distributed across multiple WCM layers using a transmissivity-weighted approach. Using this approach, the total abstraction rate from each well is apportioned based on the relative hydraulic conductivity and thickness of the intersected model layers. This ensures that groundwater extraction is preferentially assigned to more transmissive coal seams, consistent with the conceptual understanding of multi-seam CSG production in the Surat Basin.

3.1.3.6 Hopeland pilot wells

Hopeland pilot wells were explicitly simulated in the groundwater flow model to represent multi-seam extraction and to reproduce observed groundwater level responses associated with historical pilot testing at the Hopeland site. The pilot wells are located approximately 8 km southwest of Lot 40 DY85 and comprise six authorised CSG bores completed across several WCM coal seams. Given the vertical extent of well completions and the importance of simulating groundwater level responses to abstraction during pilot tests, these wells were represented using the MODFLOW 6 Multi-Aquifer Well (MAW) package.

Use of the MAW boundary condition allows abstraction to be distributed dynamically along the well as a function of layer transmissivity and simulated hydraulic heads, providing a physically realistic representation of vertical flow within multi-seam CSG wells. The MAW formulation enables interaction between the well and multiple WCM model layers providing improved simulation of observed drawdown behaviour recorded in pilot wells and monitoring bore HL17. Parameters controlling MAW behaviour, including well conductance and scaling height above the pump elevation, were subject to calibration and uncertainty analysis.

3.1.3.7 Historical UCG activities

Historical UCG activities were explicitly simulated over their respective operational periods using drain (DRN) boundary conditions. Combustion processes and subsequent collapse of gasifier voids may have induced broader-scale fracturing beyond the target coal seams, with fractures propagating upward into overlying formations. This secondary fracturing could locally enhance hydraulic connectivity and influence post-UCG groundwater flow and contaminant migration pathways.

The DRN package was used to represent depressurisation and enhanced groundwater discharge associated with gasifier operation. Drain elevations were assigned consistent with the affected HSUs and UCG activities at each gasifier, allowing groundwater discharge to occur. The drain elevation and conductance were allowed to be adjusted during history matching and uncertainty analysis.

To account for changes in hydraulic properties induced by gasification processes, time-varying hydraulic properties were applied to HSUs affected by UCG activities, including the Macalister coal seam, Kogan interburden, and the Springbok sandstone. UCG-related fracturing, material removal, and permeability enhancement were represented by modifying hydraulic conductivity and storage properties during defined gasification periods. Allowing hydraulic property changes in the layers overlying Macalister coal seam provides a conservative representation of the

potential for vertical migration of contaminants into or out of overlying units, including the Springbok sandstone.

Time-varying hydraulic conductivity (TVK) and time-varying storage (TVS) parameters were applied on a gasifier-specific basis, enabling localised impacts to be simulated independently for each gasifier footprint. Spatial variability in fracturing intensity and material alteration was allowed to be adjusted during history matching, uncertainty analysis, and predictive assessment under post-UCG recovery and CSG development scenarios.

3.1.4 Temporal discretisation

The groundwater model simulation starts with a steady state stress period to simulate the “steady-state” groundwater flow regime, reflecting the chosen parameterisation and boundary conditions, before progressing to a transient model.

The combined steady-state and transient model simulations are divided into 215 stress periods for historical matching (calibration) and prediction periods. The number and duration of transient stress periods are tailored based on the dates associated with the recorded groundwater levels, and former UCG activities as follows:

- History-matching period (159 stress periods):
 - 1 steady-state stress period,
 - 14 annual stress periods from 1/1/2000 to 1/1/2014, and
 - 144 quarterly stress periods from 1/1/2014 to 1/1/2026.
- Prediction period (56 stress periods):
 - 40 annual stress periods from 1/1/2026 to 1/1/2066, and
 - 16 10-year stress periods from 1/1/2066 to 1/1/2226.

3.1.5 Metric systems

The groundwater flow model uses units of meters and days. The geographic coordinate system used is the Geographic Datum of Australia 1994 (GDA94), and the projection used is the Map Grid of Australia (MGA) zone 56.

3.2 Particle tracking

Particle tracking was undertaken to assess potential groundwater flow pathways and provide a conservative assessment of advective contaminant migration (compared with contaminant transport model) under approved and proposed coal seam gas (CSG) development scenarios. The particle tracking analysis was designed to evaluate groundwater flow directions, travel distances, and relative changes in migration behaviour, independent of chemical processes such as sorption, decay, or dispersion, thereby providing a conservative representation of potential solute movement.

Particles were released in 2019 at locations representative of residual contaminant source areas (gasifiers), Lot 40 DY85 boundaries, and key monitoring points (shown in Figure 3-5) within the Springbok sandstone and the Macalister coal seam. Release locations were selected

to reflect both the former UCG footprint and bore locations where elevated benzene and naphthalene concentrations have been historically observed. Particle releases were distributed both laterally and vertically within the groundwater model to adequately capture local flow variability. The density and placement of particles were selected to ensure consistent coverage of potential transport pathways and to support interpretation of site-scale flow patterns.

Particle tracking simulations were carried out using groundwater flow fields generated by the calibrated numerical model for both FDP scenarios. The analysis focused on both relative differences between scenarios and absolute travel distance, while recognising uncertainty associated with effective porosity and residual multi-phase effects following UCG operations. Particle tracking simulations were treated as a conservative tool to inform risk assessment rather than a predictive representation of contaminant concentrations.

Porosity values adopted for the particle tracking simulations were derived from the calibrated specific yield values, obtained from the groundwater flow model, with the addition of a layer-wide specific retention component. This approach ensures consistency between the simulated groundwater flow field and particle velocities while accounting for spatially varying storage behaviour within coal seams and interburden lithologies. A range of specific retention between 1% and 10% was explored as part of history matching and uncertainty analysis to assess particle travel distances and trajectories with a plausible variability in porosity.



Legend

- Groundwater model extent
- Lot 40 DY85
- Particles released at:**
 - Monitoring bores
 - Gasifiers
 - Lot 40 DY 85 boundaries

Particle release locations

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3.3 Contaminant transport model

The contaminant transport model was developed to simulate the fate and transport of dissolved benzene and naphthalene within the Springbok sandstone and the Macalister coal seam. The model was configured to represent key processes controlling contaminant migration and attenuation following historic UCG activities, and to assess potential changes under the approved and proposed FDP scenarios.

The transport model focuses on reproducing observed concentration trends and predicting potential future behaviour rather than predicting exact concentrations at individual monitoring locations. Model setup and parameterisation were informed by available monitoring data, previous contaminant transport modelling for PL253, and the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), providing a risk-based impact assessment.

3.3.1 Transport model coupling

In the present study, the contaminant transport model is coupled with the calibrated groundwater flow model, using the transient simulated flow field to represent advective transport processes. The spatial discretisation, layering, and groundwater flow boundary conditions are consistent between the flow and transport models, ensuring internal coherence between groundwater flows and contaminant migration.

Coupling the transport model to the flow model allows changes in hydraulic gradients and groundwater velocities arising from different development scenarios to be directly reflected in simulated contaminant behaviour. This provides a consistent and interconnected basis for assessing migration pathways in both the Springbok sandstone and the Macalister coal seam.

3.3.2 Initial condition

Initial conditions for benzene and naphthalene were defined using groundwater quality monitoring data from Arrow and DoR operated monitoring bores. Similar to the approach used in the previous groundwater modelling studies (AGE, 2023; Intera, 2025), concentrations were spatially assigned to represent residual dissolved contamination associated with former UCG activities, commencing on 1/1/2018.

The initial concentration distributions for benzene and naphthalene within the Springbok sandstone and Macalister coal seam reflect the best available estimate of groundwater quality conditions post-UCG activities and were adjusted to be conservative where uncertainty exists. This approach ensures that subsequent transport simulations evaluate conservative impacts over the assessment period.

Initial contaminant concentration distributions and transient source depletion release at gasifiers (discussed in section 2.4.2.1) were both implemented using the MODFLOW 6 Constant Concentration (CNC) package. Initial concentrations for benzene and naphthalene were defined to represent residual dissolved impacts within Lot 40 DY85 and in the vicinity of former gasifier locations within the Springbok sandstone and Macalister coal seam. Time-varying source boundary conditions at these locations were assigned through compound-specific exponential

depletion equations (1) to (4) derived from the upper-envelope groundwater monitoring datasets within the Springbok sandstone and Macalister coal seam.

3.3.3 Boundary condition

Contaminant transport model was coupled with the calibrated groundwater flow model to ensure that predicted concentrations and plume evolution appropriately reflect the simulated flow regime and contaminant transport parameters. The transport response is therefore governed partially by transport boundary conditions defined by formation physical properties (porosity and bulk density), source representation, and key transport processes such as dispersivity, dual-domain porosity, and natural attenuation (sorption and degradation).

A summary of the parameters used in the transport model with the initial value, lower bound and upper bounds considered in the transport model history matching is summarised in Table 3-4 Contaminant transport parameters. The transport boundary conditions are described in the following sections.

Table 3-4 Contaminant transport parameters

Transport parameter	Unit	Compound	Layer	Initial	Min	Max	Reference
Effective molecular diffusion-coefficient	m ² /d	Benzene	All	1.1E-05	3.9E-06	1.9E-05	Gustafson & Dickhut (1994)
Effective molecular diffusion-coefficient	m ² /d	Naphthalene	All	8.4E-06	3.0E-06	1.4E-05	Gustafson & Dickhut (1994)
Longitudinal dispersivity	m	All	Non-coal	5.0E+00	1.0E+00	1.0E+01	Gelhar et al. (1992), Schulze-Makuch (2005), Bjerg et al. (2025)
Longitudinal dispersivity	m	All	Coal	1.0E+01	5.0E+00	3.0E+01	Gelhar et al. (1992), Schulze-Makuch (2005), Dong et al. (2018)
Transverse horizon-al dispersivity	m	All	Non-coal	5.0E-01	1.0E-01	1.0E+00	Gelhar et al. (1992), Schulze-Makuch (2005), Bjerg et al. (2025)
Transverse horizon-al dispersivity	m	All	Coal	1.0E+00	5.0E-01	3.0E+00	Gelhar et al. (1992), Schulze-Makuch (2005), Dong et al. (2018)
Transverse vertical dispersivity	m	All	Non-coal	5.0E-02	1.0E-02	1.0E-01	Gelhar et al. (1992), Schulze-Makuch (2005), Bjerg et al. (2025)
Transverse vertical dispersivity	m	All	Coal	1.0E-02	1.0E-03	5.0E-02	Gelhar et al. (1992), Grathwohl et al. (2000)
First-Order Decay Rate Coefficients	1/day	Benzene	Non-coal	1.0E-03	1.0E-04	1.0E-02	US EPA (1999), Newell et al. (2002), Zhang et al. (2005)
First-Order Decay Rate Coefficients	1/day	Naphthalene	Non-coal	7.5E-03	5.0E-05	5.0E-02	Anderson & Lovley (1998), Wiedemeier et al. (1999), ATSDR (2022)
First-Order Decay Rate Coefficients	1/day	Benzene	Coal	5.0E-04	1.0E-06	1.0E-03	API (1998), US EPA (1999); Anderson et al. (1998)
First-Order Decay Rate Coefficients	1/day	Naphthalene	Coal	5.0E-03	1.0E-06	1.0E-02	Wiedemeier et al. (1999), Bjerg et al. (1999), Musat et al. (2008)
Immobile First-Order Decay Rate Coefficients	1/day	Benzene	Non-coal	1.0E-04	3.0E-05	1.0E-03	US EPA (1999) Newell et al. (2002); Anderson & Lovley (1998)
Immobile First-Order Decay Rate Coefficients	1/day	Naphthalene	Non-coal	1.0E-03	2.5E-06	1.5E-02	Anderson & Lovley (1998), Wiedemeier et al. (1999), Bjerg et al. (1999), Musat et al. (2008)
Immobile First-Order Decay Rate Coefficients	1/day	Benzene	Coal	5.0E-04	3.0E-07	1.0E-03	US EPA (1999), Newell et al. (2002), Anderson & Lovley (1998)
Immobile First-Order Decay Rate Coefficients	1/day	Naphthalene	Coal	1.0E-04	5.0E-08	3.0E-03	Anderson & Lovley (1998), Wiedemeier et al. (1999), Bjerg et al. (1999), Musat et al. (2008)
Freundlich coefficient	m ³ /kg	Benzene	Non-coal	1.0E-04	5.0E-05	3.0E-04	Shi et al. (2020), U.S. EPA (1996), ECETOC (2013)
Freundlich coefficient	m ³ /kg	Naphthalene	Non-coal	7.5E-03	2.0E-04	1.0E-02	Osagie & Owabor (2015), Shi et al. (2020), ECETOC (2013)
Freundlich coefficient	m ³ /kg	Benzene	Coal	1.0E-03	5.0E-04	3.0E-03	ECETOC (2013), U.S. EPA (1996)
Freundlich coefficient	m ³ /kg	Naphthalene	Coal	5.0E-02	2.0E-03	1.0E-01	Ahangar (2010), Ukalska-Jaruga & Smreczak (2020), Osagie & Owabor (2015), ECETOC (2013)
Non-linearity exponent	-	Benzene	Non-coal	9.5E-01	9.0E-01	1.0E+00	Shi et al. (2020), U.S. EPA (1996), ECETOC (2013)
Non-linearity exponent	-	Naphthalene	Non-coal	9.5E-01	9.5E-01	1.0E+00	Osagie & Owabor (2015), Shi et al. (2020), ECETOC (2013)
Non-linearity exponent	-	Benzene	Coal	9.0E-01	8.5E-01	1.0E+00	ECETOC (2013), U.S. EPA (1996)
Non-linearity exponent	-	Naphthalene	Coal	9.5E-01	9.5E-01	1.0E+00	Ahangar (2010), Ukalska-Jaruga & Smreczak (2020), Osagie & Owabor (2015), ECETOC
Immobile non-linearity exponent	-	Benzene	Non-coal	9.0E-01	8.5E-01	9.5E-01	Shi et al. (2020), U.S. EPA (1996), ECETOC (2013)
Immobile non-linearity exponent	-	Naphthalene	Non-coal	8.5E-01	7.5E-01	9.0E-01	Osagie & Owabor (2015), Shi et al. (2020), ECETOC (2013)
Immobile non-linearity exponent	-	Benzene	Coal	8.0E-01	7.0E-01	8.5E-01	ECETOC (2013), U.S. EPA (1996)
Immobile non-linearity exponent	-	Naphthalene	Coal	7.0E-01	5.0E-01	8.5E-01	Ahangar (2010), Ukalska-Jaruga & Smreczak (2020), Osagie & Owabor (2015), ECETOC (2013)
Immobile domain fraction	-	All	Non-coal	2.0E-01	1.0E-02	3.0E-01	Warren & Root (1963), Aguilera (2004), Langevin et al. (2022)
Immobile domain fraction	-	All	Coal	7.0E-01	6.0E-01	8.5E-01	King & Ertekin (1988), Pruess & Narasimhan (1985)
Mass transfer rate coefficient	1/day	All	Non-coal	5.0E-04	1.0E-04	1.0E-03	Warren & Root (1963), Pruess & Narasimhan (1985), Langevin et al. (2022)
Mass transfer rate coefficient	1/day	All	Coal	1.0E-05	1.0E-06	1.0E-04	King & Ertekin (1988)

3.3.3.1 Dispersivity

Dispersivity describes the spreading of dissolved contaminants in groundwater arising from variations in groundwater velocity at different spatial scales and is a key process controlling solute transport behaviour. Contaminant plume dispersion occurs both along the direction of groundwater flow (longitudinal dispersivity) and perpendicular to flow in the horizontal and vertical directions (transverse horizontal and transverse vertical dispersivity), reflecting aquifer heterogeneity, pore-scale velocity differences, and preferential flow pathways. In addition to mechanical dispersion, solute spreading is influenced by molecular diffusion, which governs mass transfer driven by concentration gradients, particularly in low-velocity or low-permeability zones. Together, these processes control plume shape, extent, and dilution over time. MODFLOW 6 Dispersion (DSP) package was used in the contaminant transport model to simulate mechanical dispersion and molecular diffusion. The input parameters included longitudinal, transverse horizontal, and transverse vertical dispersivity (Table 3-4) defined on a layer-specific basis and effective molecular diffusion-coefficient defined on a compound-specific basis. All these input parameters were adjusted during history matching of the transport model.

3.3.3.2 Natural attenuation

Natural attenuation processes were incorporated in the contaminant transport model to represent the reduction in contaminant mobility and mass through physicochemical and biological mechanisms occurring within the subsurface. For benzene and naphthalene, natural attenuation was represented through equilibrium-controlled sorption and first-order degradation processes, which together influence plume migration, and long-term concentration trends.

MODFLOW 6 Mobile Storage and Transfer (MST) package was used in the contaminant transport model to simulate natural attenuation processes. This included both first-order degradation processes, as outlined above, and equilibrium-controlled sorption described using a Freundlich isotherm formulation. These processes were applied to simulate reduction in contaminant mass and mobility for benzene and naphthalene within the mobile groundwater domain. The input parameters included porosity, bulk density of the layer, first-order decay rate coefficient, Freundlich coefficient and mobile non-linearity exponent (Table 3-4) defined on a layer-specific basis and adjusted during history matching of the transport model.

3.3.3.3 Dual-Domain Porosity

Dual-porosity behaviour was simulated in the contaminant transport model to represent mass exchange between mobile groundwater flowing through fracture-dominated pathways and immobile pore water stored within low-permeability micropore domains. Solute mass can transfer from the fracture-scale flow system into the rock matrix and micro-porosity, and subsequently diffuse back into the mobile domain over time. This bidirectional mass transfer mechanism allows contaminant mass to be temporarily retained or released depending on concentration gradients, influencing plume persistence and long-term concentration trends.

Representation of immobile-mobile mass transfer is particularly relevant for coal seams and fine-grained sandstone units, where pore structure heterogeneity and sorptive surfaces can result in delayed contaminant breakthrough. MODFLOW 6 Immobile Storage and Transfer (IST) package was used in the transport model to simulate dual-domain porosity and associated mass exchange processes. This boundary condition allows for diffusion-controlled mass transfer between micro-pores and fracture-scale flow. The input parameters included porosity, bulk density of the layer, immobile domain fraction, mass transfer rate coefficient, first-order decay rate coefficient, Freundlich coefficient and immobile non-linearity exponent (Table 3-4) defined on a layer-specific basis and adjusted during history matching of the transport model.