Department of Environment and Science

EA0001401 – Hopelands Groundwater Technical Assessment

18 March 2021 - FINAL

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Limitations

The interpretations in this report are based on the data and references identified.

Statement of Interest

RDM Hydro Pty Ltd is subcontracted to provide hydrogeological advice to Brad May of Epic Environmental Pty Ltd as the Contaminated Land Auditor for the Hopeland site for the Department of Environment and Science, and technical advisor to the Department of Resources.

1. Introduction

RDM Hydro Pty Ltd (RDM Hydro) was engaged by the Department of Environment and Science (DES) to undertake a technical review of Arrow Energy's (Arrow) application to amend Environmental Authority EA0001401 (the EA) to enable coal seam gas (CSG) production from petroleum lease (PL) 253, known as Hopelands. PL253 surrounds the former Linc Energy (Linc) underground coal gasification (UCG) trial site located on former mineral development license (MDL) 309 (the site) which is in the southwestern corner of Lot 40 Plan DY85 (Figure 1). The site is considered to be contaminated due to the operation of the UCG trials.

The overarching objective of the review is to *establish the level of risk associated with Arrow Energy's proposal including gas and contaminant migration, and impacts to environmental values to inform the department's assessment against the requirements of the Environmental Protection Act 1994 (the Act).*

The scope of work requested by DES was to:

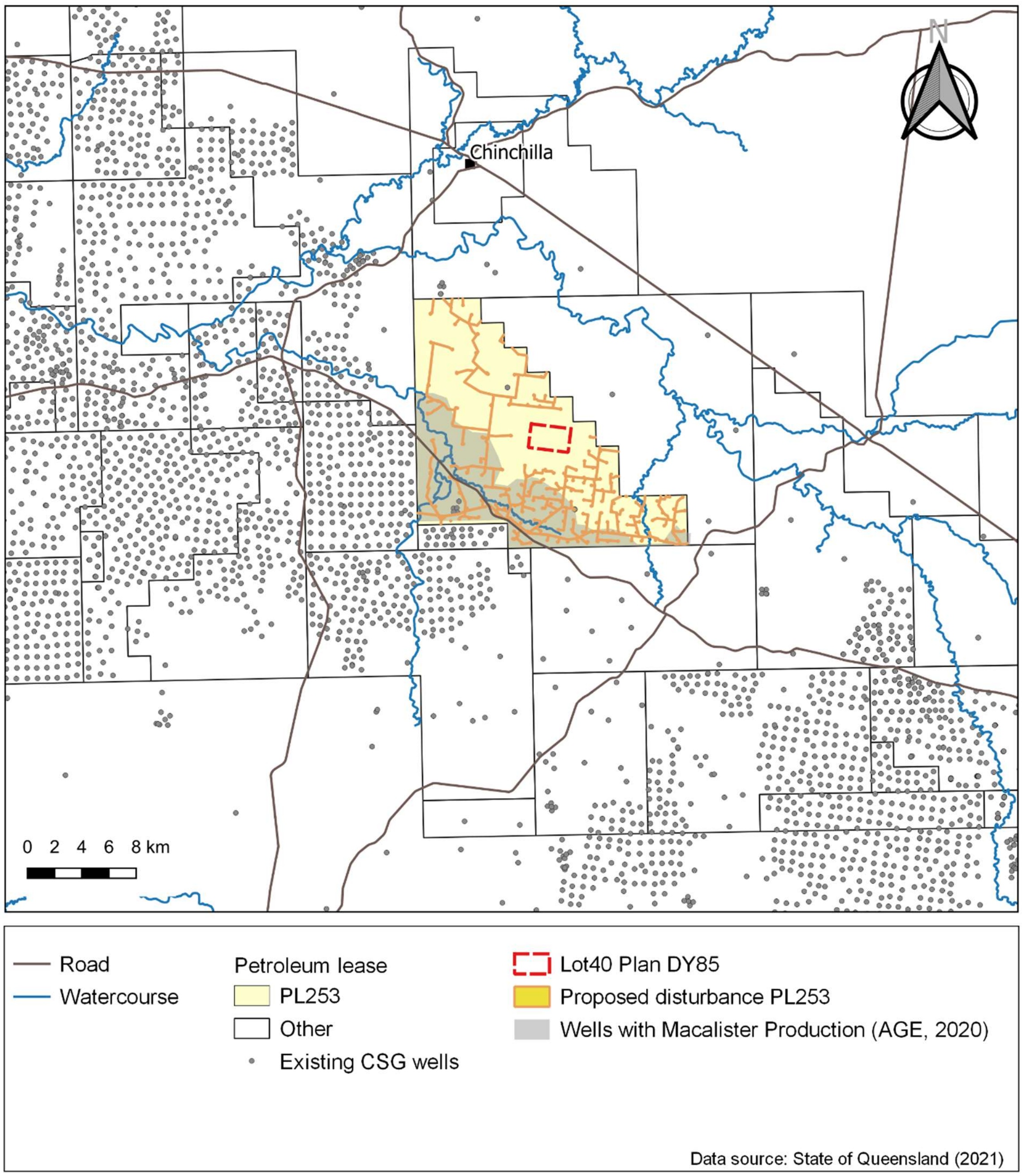
1. Review the information provided and deliver concise advice regarding risk as follows:
    a. Whether all potential risks associated with the development have been identified (i.e. mobilisation of groundwater contaminants, and gas migration);
    b. Whether Arrow's assumptions, groundwater modelling and subsequent conclusions are accurate;
    c. Whether the proposal has the potential to mobilise contaminants and migrate them away from the site;
2. Advise whether the groundwater mitigation measures proposed by Arrow are considered appropriate and commensurate to the risk.
3. Inform the department what contingency measures may be appropriate to manage the risks of the project e.g. exclusion from area, containment measures, treatment of underground water, flaring.

This document is structured to address each of the three items of the scope as separate sections. It has been prepared utilising background knowledge of the Linc operations, the site and the information available in the documents provided for technical review, viz:

- Arrow Energy's application documents: supporting application report and 2020 groundwater model report
- Information Request (i.e. items/questions raised by DES relevant to groundwater and the potential migration of contaminants) – item (k) on page 4 onwards
- Arrow's response to the information request relevant to the above matters – item (k) on page 26 onwards.

In addition to these documents, DES provided permission to use the bore completion reports (AECOM, 2018) for the DES monitoring bores installed on the perimeter of the site and DES provided the most recent version of the Groundwater Characteristics Monitoring Program (GHD, 2020). This report was prepared on the information provided and does not consider information that may become available at a later date.

Figure 1 Site location



2. Background Understanding

Linc carried out research and trials of UCG at the site between 1999 and 2013 in five gasifiers across the site (Figure 2).

The gasifiers targeted the Macalister seam of the Walloon Coal Measures at a depth of approximately 125m below ground. The Macalister seam is the uppermost coal seam of the Walloon Coal Measures beneath the site. The overall thickness of the Walloon Coal Measures in the Hopelands area may be roughly 350m (Arrow, 2014), with less than approximately 10% of the total thickness comprising coal, and the remainder comprising low permeability[1] siltstones, mudstones, and sandstones, collectively called interburden. Individual coal seams are usually thin and not laterally extensive. The CSG industry usually targets gas production from the entire Walloon Coal Measures interval.

Separated by low permeability overburden, the Springbok Sandstone overlies the Walloon Coal Measures. The Springbok Sandstone is a highly heterogeneous (variable) formation, and the sandstone matrix is usually filled with bentonitic clays that result in very low hydraulic conductivities. OGIA (2019) classifies the Springbok Sandstone as a “tight aquifer”, although it aligns more with the ranges of hydraulic conductivities presented for aquitards presented by OGIA (2019).

The complexity of the geology is shown in the block model from OGIA (2019) which is based on real data from the general vicinity of Hopelands (the eastern Surat Basin CSG gas fields). The heterogeneity of the formations, discontinuity of the coal seams and the generally low permeability are important in the potential for contaminant transport. They would all tend to reduce the distance that groundwater and entrained contaminants would move.

In sedimentary formations such as those of the Surat Basin, permeability is usually higher in a horizontal sense (parallel to the layering of the rock) than the vertical sense (perpendicular to the layering of the rock). Lateral fluid (water or gas) movement and the potential for contaminant transport is therefore also usually greater compared with vertical movement. Fractures (natural or induced) may provide a preferential pathway for more rapid contaminant movement. If the fractures are not horizontally oriented they could provide preferential pathways for contaminant movement into overlying formations as the fractures could provide conduits through low permeability interburden.

[1] Permeability is the intrinsic property of a material to transmit a fluid. The movement of the fluid is dependent on the viscosity and density of the fluid. Hydraulic conductivity is the permeability of the material to water. Permeability and hydraulic conductivity may be used interchangeably in this report.

Figure 2 Site layout – MDL309

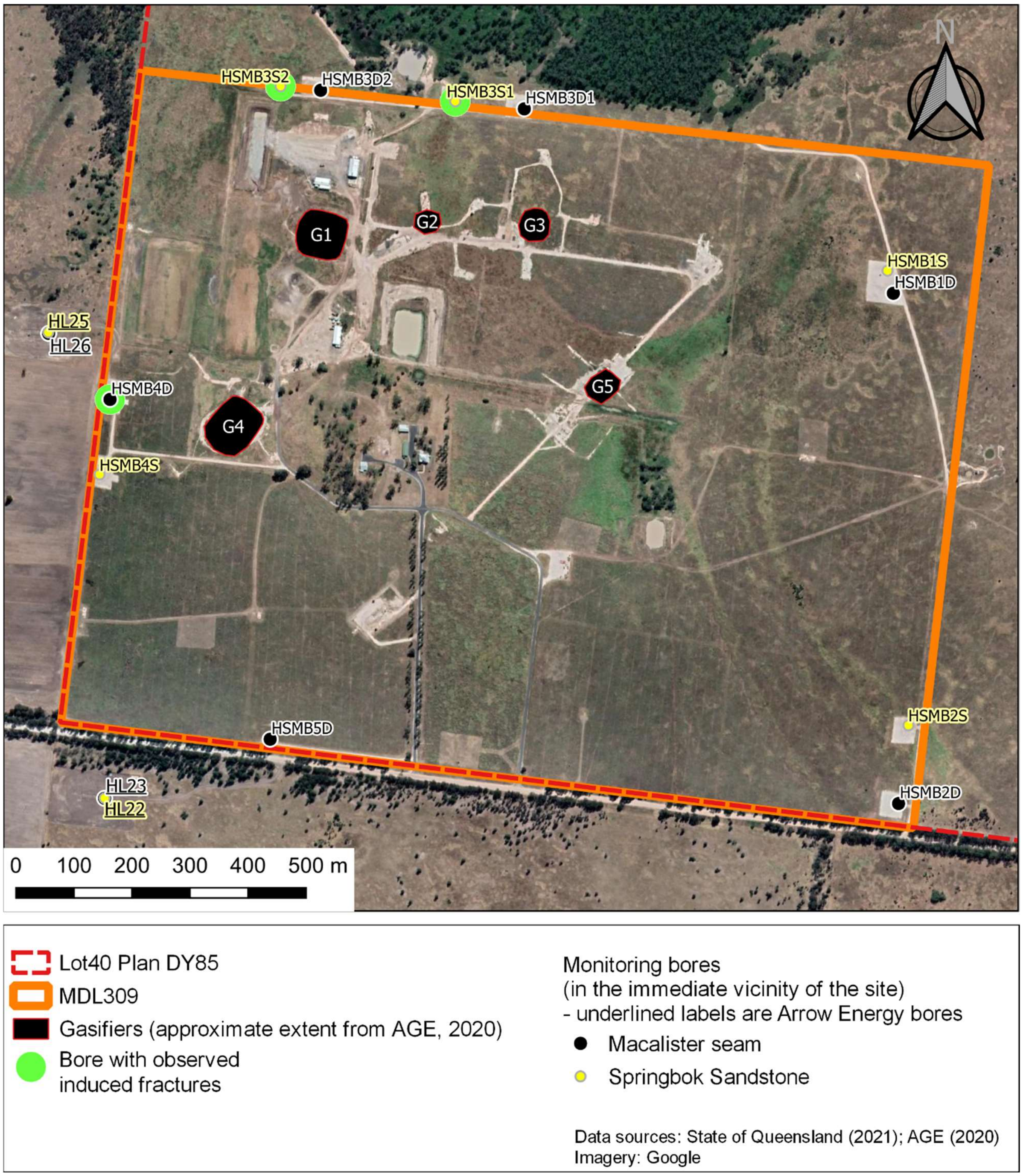
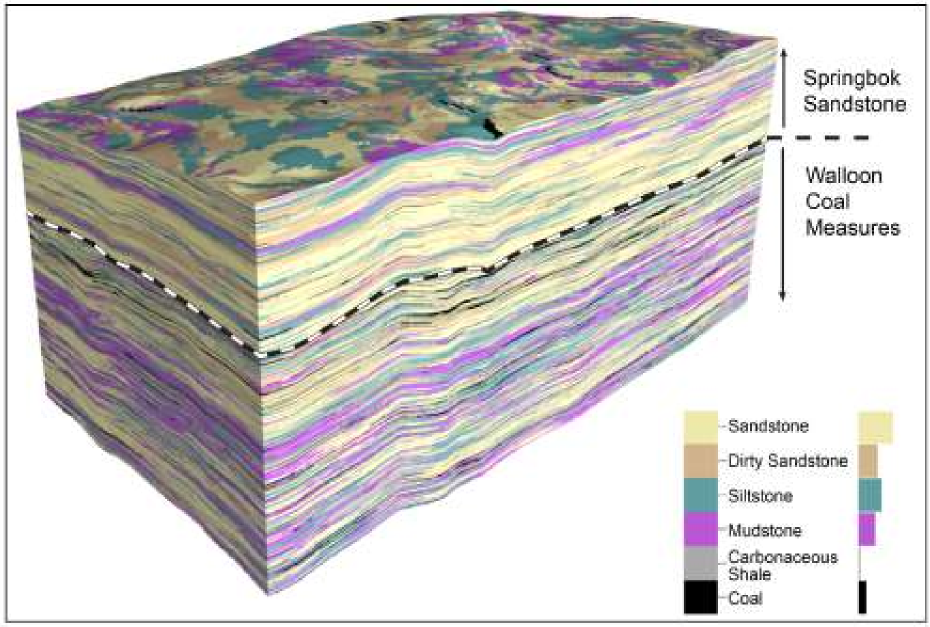


Figure 3 Geological visualisation of the Springbok Sandstone and Walloon Coal Measures (OGIA, 2019)



The UCG process involves in-situ pyrolysis to convert hydrocarbon materials (such as coal) into gas. During the UCG process, the intention is to maintain a lower pressure within the burn cavity compared with the surrounding groundwater system. This is intended to ensure hydraulic gradients are toward the cavity and any potential contaminants are captured by the process. Residual ash and tar remaining in the cavity following pyrolysis provides a potential source of primarily organic contaminants. The chambers in which the trials were performed are termed gasifiers.

Operational details and the physical extents of the sub-surface operational footprint of Linc's activities are not available, however it is understood that during the Linc trials at least one of the gasifiers was operated at a pressure exceeding the fracture pressure of rock and in exceedance of the hydraulic pressure imparted by the groundwater. This/these events resulted in the reversal of the intended inward hydraulic gradients providing a mechanism for contaminants to be driven (from higher to low pressure) from the gasifier(s) and into the surrounding formations. The exceedance of the fracture pressure resulted in induced fracturing of the coals, as observed in some of the wireline geophysical image logs (included in AECOM, 2018) acquired in the bores installed by DES on the perimeter of the site[2]. Because of the stress regime at the depth of the coal seams, and as evidenced by the induced fractures observed in the image logs from the perimeter (HSMB) bores,

[2] Image log analysis is usually performed with digital data in specialist software, which was not available. This analysis is based on visual observations of the PDF logs in the bore completion reports, and may therefore not be comprehensive.

these fractures propagated laterally outwards in a vertical orientation and were contained within the coal seam (Figure 6). They would therefore form discrete preferential pathways for horizontal contaminants transport. Upward propagation of induced fractures into shallower formations may have also occurred, but at shallow depths the stress regime changes and it is likely the orientation of the fractures would turn horizontal (pancake fractures). Horizontally oriented fractures do not propagate as far laterally as vertical oriented fractures because the energy at the fracture tip dissipates quicker during propagation. It is highlighted that the induced fracturing was not ubiquitous across the site, was only observed in the Macalister seam at the site perimeter in the west and northwest of the site, closest to the gasifiers. The HSMB bores were mostly installed in pairs, with one bore targeting the Macalister Seam and a second targeting the Springbok Sandstone for monitoring. Sometime the Springbok Sandstone bores were drilled deeper than needed and provided additional data on the Macalister seam. Induced fractures were not observed in both bores of a pair (as close as ~70m apart), highlighting the complexity of fracture propagation, and the uncertainty in where these might provide potential preferential pathways for contaminant movement. Induced fractures would preferentially form in the coal as it is more brittle than the interburden. During propagation (growth), an induced fracture encountering interburden material, either at the top or bottom of the coal seam (as seen in Figure 6) or laterally, would cease to grow in that direction as the energy driving the fracture propagation would dissipate. The lateral discontinuity of the coal seams in the Walloon Coal Measures (per Figure 3) would likely limit the lateral extent of induced fracture propagation.

Conceptually, the overpressure operation drove contaminants out of the gasifier(s) and into the surrounding Macalister seam and overlying Springbok Sandstone. It is possible that the organic contaminants were “swept” by free gas rather than advective groundwater movement and precipitated out of the gas to remain in the formation. The subsequent reduction in gasifier pressures has resulted in present day formation pressures within the site being lower than the less affected formations pressures surrounding the site. Thus generally inward hydraulic gradients are currently observed at the site. Since fluids flow from high to low pressures, over time the influx of groundwater from surrounding areas into the site will result in a rise in the on-site pressure to be similar to that of the surrounding formation uninfluenced by site activites[3]. When the pressure on the site has increased to approximate the pressures prior to Linc activities, the potential for off-site contamination migration increases as there would no longer be an inward hydraulic gradient.

Contaminant concentrations (specifically benzene and naphthalene) measured in the Macalister Seam are more than one order of magnitude less than those measured in the Springbok Sandstone (Figure 5). The higher contaminant concentrations in the Springbok Sandstone compared with the Macalister seam are somewhat enigmatic, but it is generally assumed that this relates to the significant attenuation potential of the coals due to their high organic carbon content. AGE (2020) identifies that contaminant concentrations at the perimeter of the site have been decreasing over the period of data that was provided by DES. Contaminant concentrations in the recently installed

[3] This is termed pressure recovery and is referred to as such throughout this assessment.

Arrow monitoring bores around the periphery of Lot40 Plan DY85 (Figure 4) were reportedly below detection limits (AGE, 2020).

Free gas is present across most of the site and has been observed in both the Springbok Sandstone and the Macalister seam. As described above, and notwithstanding the low formation permeabilities which results in naturally slow pressure changes in a groundwater-only formation (as opposed to groundwater and free gas), the presence of free gas may be inhibiting pressure recovery of the reduced pressures induced by the Linc activities by effectively blocking the pore space to water movement. The presence of free gas in the Springbok Sandstone suggests a direct connection to the gasifiers, i.e. the intervening seal formed by the low permeability interburden separating the Macalister Seam from the Springbok Sandstone has been breached. This may be via failed wellbores, induced fracturing or collapse of the gasifier roofs. These failures are a potential mechanism for the presence of contamination in the Springbok Sandstone.

The locations of registered water bores surrounding the site are shown on Figure 4, which also shows the use and interpretation of the aquifer accessed by the bore (OGIA, 2019c). The closest active registered water supply bore to the former MDL309 boundary is RN15811, approximately 750m to the west of the site, followed by RN15868, approximately 850m north of the site. Both are interpreted by OGIA (2019c) to access the Walloon Coal Measures. A summary of information for the surrounding registered bores shown on the Figure 4 is provided in Table 1. This information was acquired from the respective borecards accessed via Queensland Globe.

Table 1 Registered water bore summary

Registered Number	Bore Card Status	Drilled Date	Bore Use	Accessed Formation (OGIA, 2019c)	Total dissolved solids (mg/L)
147941	Existing	28/04/2015	Monitoring	Walloons	-
160158	Existing	4/09/2008	Monitoring	Walloons	-
15868	Existing	6/04/1964	Supply	Walloons	2347
15812	Existing	21/03/1964	Supply	Springbok (Lower)	-
33553	Existing	25/11/1969	Supply	Springbok Sandstone	150
147004	Existing	1/05/2008	Supply	Springbok Sandstone	-
66757	Existing	-	Supply	Springbok Sandstone (Upper)	-
71483	Existing	1/01/1910	Supply	Springbok (Lower)	-
24466	Existing	1/01/1950	Supply	Walloons	1400
160157	Existing	8/09/2008	Monitoring	Walloons	-
107857	Existing	26/07/2002	Supply	Springbok (Lower)	-
147607	Existing	9/06/2010	Supply	Walloons	-
15811	Existing	31/03/1964	Supply	Walloons	1995
10790	Existing	11/11/1946	Supply	Walloons	2932
19982	Abandoned and Destroyed	1/01/1940	Abandoned and Destroyed	-	-

Figure 4 Extent of Lot40 Plan DY85 and surrounding registered water bores

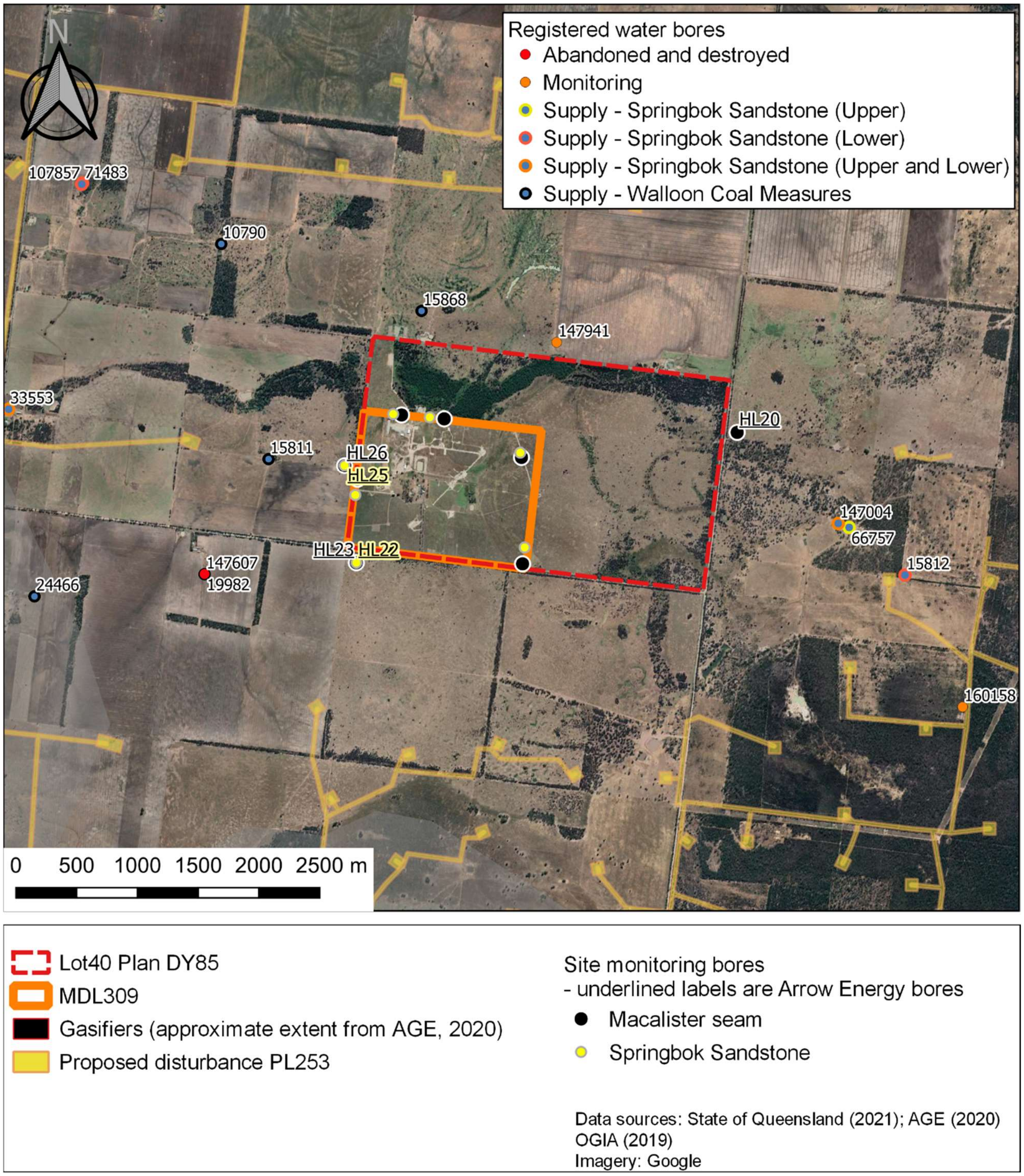
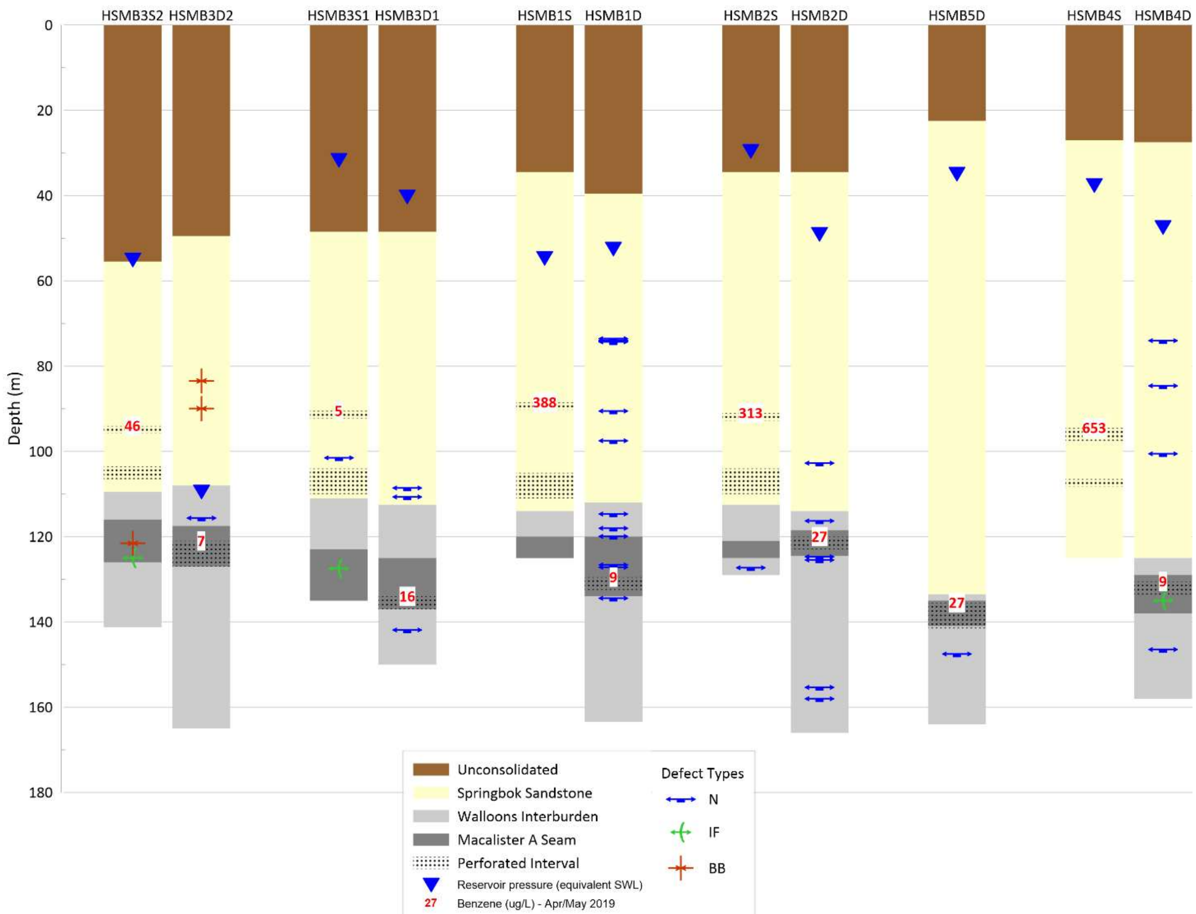
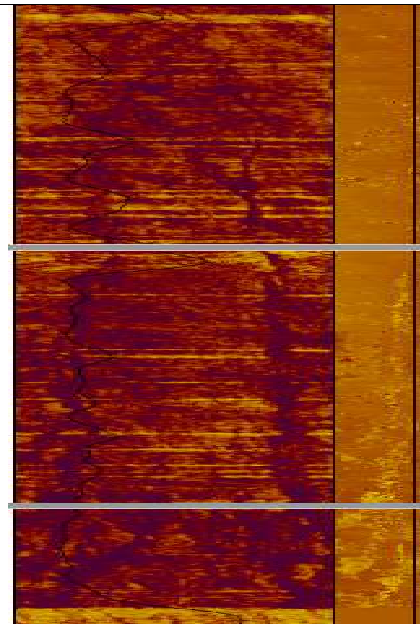
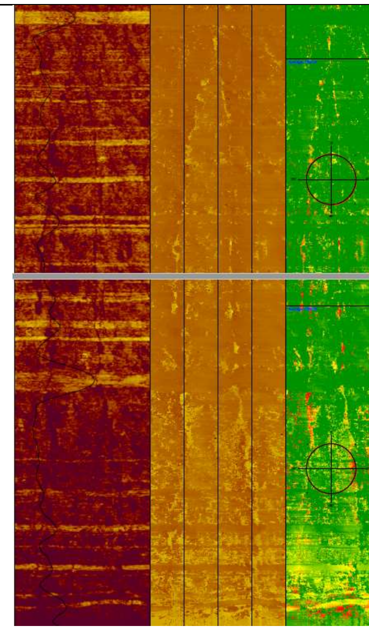


Figure 5 DES perimeter bore summary with observed fracturing[4] and benzene concentrations (data from AECOM, 2018)[5]



[4] Defect types: N = natural fracture; IF = induced fracture; BB = borehole breakout
[5] The reservoir pressure is the sum of the pressure imparted by the weight of the water column and the gas pressure above the monitoring point. It has been presented as a water level, where the gas pressure is assumed to be the equivalent pressure of water.

Figure 6 Example of an induced fractures in image logs (from AECOM, 2018)

HSMB4D 131.2-138m	HSMB3S1 125.7-130.4m
	

3. Assessment of risks

In its application assessment and the subsequent response to the request for information (RFI), Arrow addressed the following risks associated with the site:

- **Contaminant migration from the site** - The assessment focussed on the migration of benzene and naphthalene under following scenarios:
    - A **baseline** scenario that included currently authorised CSG Arrow wells on PLs 253, 185 and 493, and those CSG wells within the model domain operated by other CSG companies.
    - The **Arrow FDP** scenario, which incorporated the baseline scenario wells plus the 280 wells proposed under the EA amendment application. Of the proposed wells, Arrow is intending to not produce from the Macalister Seam from 124 wells in the northeast of the PL. The development of the proposed wells will progress from southwest to northeast and will occur between 2022 and 2037. A 20-year life-of-field is indicated.

  The numerical groundwater flow and contaminant transport model was calibrated to water level and chemistry data from the site (provided by DES) and from Arrow's monitoring activities in surrounding areas.
- **Migration of fugitive free gas from the site** - The assessment utilised a multiphase numerical model that considered the existing free gas at the site and its propensity for migration.

The following potential risk factors were not considered by Arrow in its assessment:

- Preferential flow paths of increased permeability caused by fracturing induced by the overpressure event(s)
- On-site activities by the Department of Resources (DoR) that may affect the scenarios assessed in the modelling
- The sweep of organic contaminants (e.g. BTEX) in free gas
- Increased gassiness of on-site bores

The risks have been considered and assessed in the following sections. For the purposes of this assessment, the boundary of the site is considered to be the receptor.

3.1. Groundwater flow modelling and implications for contaminant migration

Arrow utilised a groundwater flow model to assess the impacts of CSG development on contaminant movement in and around the former Linc site. The model underwent several iterations, with the most recent (in response to the DES RFI – Arrow, 2020b), summarised as follows:

- The model was constructed with Modflow-USG, an industry standard groundwater modelling code. It is a single phase (water only) model.
- Refinement of the geological structure of the model to incorporate dedicated coal layers in each sub-unit of the Walloon Coal Measures. This refinement is considered appropriate given the different attenuation potential of the coal versus clastic sediments and the likely overestimate of formation thickness of the previous model (GHD, 2019 in AGE, 2020), which would also have implications for contaminant transport. The coal layers were assumed to be laterally extensive and continuous throughout the model domain.
- Calibration to groundwater level data obtained from (AGE, 2020 Table 3.1):
    - A Queensland Government monitoring bore (screened in the Condamine Alluvium)
    - Baseline monitoring of surrounding landholder bores
    - Pilot CSG production wells
    - Arrow monitoring bores, including the HL20 to HL27 installed around the periphery of the site
    - The DES HSMB series monitoring bores installed on the perimeter of the site (AECOM, 2018)
- The model hydraulic properties (horizontal and vertical hydraulic conductivities and storage parameters) were calibrated using PEST and pilot points to water level monitoring data resulting in spatially variable hydraulic parameterisation. The report states that a scaled root mean square (SRMS) error of 9.5% inclusive of the Hopelands pilot data, and an SRMS of 6.4% exclusive of that timeseries water level data was achieved for the model calibration. Arrow considered the calibration acceptable as the SRMS is within the 10% recommended by the Australia Groundwater Modelling Guidelines (Barnett et al, 2012) for transient calibrations. The SRMS is an overall assessment of how well the modelled water levels compared with the measured water levels across the entire model domain. At the scale of the site and its immediate surrounds, there are some discrepancies that potentially influence the model predictions, as discussed in Section 3.1.1.
- At the sub-regional scale of the model, and not taking account of induced fracturing around the Linc site the calibrated horizontal hydraulic conductivities are toward the upper range of the OGIA (2019) calibrated model range for hydraulic conductivity (~10^{-6} to 0.1 m/day). The vertical hydraulic conductivities were up to an order of magnitude lower than OGIA (2019b) for the Walloon Coal Measures. The potential implications of the calibrated model hydraulic conductivities on the predicted contaminant transport are discussed in Section 3.1.1.

- The possible collapse of the gasifier voids, the associated fracturing of the overlying Springbok Sandstone, and the effects of the fracturing on the hydraulic conductivity was incorporated in a manner similar to longwall mining, i.e. through collapse of the overburden. Induced lateral fracture propagation due to overpressure during Linc operations was not considered.
- The effects of existing (Arrow and non-Arrow) CSG production outside of PL253 was based on the OGIA 2019 UWIR model. The proposed development within ATP253 was simulated using individual wells.
- Contaminant transport was modelled using the Block Centred Transport (BCT) package which considers advective transport, dispersion, adsorption and first order decay. The model considers the implications of Arrow's proposed production on contaminant movement rather than trying to replicate the historical operations at the site. While the availability of information on the Linc operations effectively precludes the modelling of the historical operations, ignoring the mechanism(s) through which the contaminants were transported into the wider rock mass results in uncertainty in the validity of the model calibration and the accuracy of the model predictions.
- Transport parameters were calibrated by history matching to the observed benzene and naphthalene concentrations in several legacy Linc bores, the DES perimeter bores and Arrow's recently installed monitoring bores. DES monitoring data was available for 2018-2019 and generally showed declining contaminant concentrations.
- Effective porosities were obtained from OGIA (2019b), with initial interburden and coal porosities of 7%. Based on CSG industry experience, this value is considered too high and would result in an under-prediction of contaminant transport distances. This is discussed further in Section 0. The initially adopted first order decay coefficients were considered too high as they were incorrectly based on aerobic conditions, however this was addressed through remodelling in response to the RFI.
- SRMS of 7.9% and 4.7% were achieved for the calibration of the transport model for benzene and naphthalene respectively. However, comparison of the actual versus modelled results show model modelled concentrations generally less than their measured values. Measured concentrations were up to more than 400ug/L benzene greater than the modelled concentration (AGE, 2020 – Figure 6.1).
- Predictive uncertainty analysis was performed using PEST and 200 simulations were run. The use of only one base model does not consider the uncertainties in the underlying conceptual model, specifically with respect to the mechanisms of the contamination events and the subsequent implications for longer term contaminant fate and transport.
- AGE (2020) does not present predicted pressure surfaces for the transient model simulations, thus the validity of the predicted contaminant transport directions cannot be reviewed. This is however done indirectly from the data presented and discussed in Section 3.1.1. It is unclear from the information provided whether Arrow's activities are likely to result in the change in the direction of hydraulic gradients at the site.

- The particle tracking from the modelled estimates a maximum contaminant transport distance of 45m from the gasifier (AGE, 2020 – Table 7.2). The shortest distance from a gasifier to the site boundary is approximately 200m. The validity of this transport distance is considered in Section 0.
- AGE (2020 – Appendix E) undertook predictions of the timing in which contaminant concentrations would decrease to less than 1µg/L. In several cases, the predictions show longer time periods for the contaminants to decrease in the immediate vicinity of the perimeter monitoring bores (HSMB), with quicker decreases between the bore and the gasifier locations. It is unclear why this might occur in the model predictions. Also, it predicts that gasifier contaminant concentrations will decrease to less than 1 µg/L within the same short time periods. Conceptually this is problematic as the mechanism for the natural attenuation of the contaminants within the gasifiers is not apparent. The site-wide reduction in contaminant concentrations to less than 1 µg/L, including in the gasifiers, through natural attenuation is considered to be a low probability of occurring within the timeframes predicted by AGE (2020).
- The assessment did not consider the time period after the cessation of CSG production.

3.1.1. Model calibration

Groundwater flow directions

While an SRMS error within the limit recommended by the Australia Groundwater Modelling Guidelines (Barnett et. al., 2012) was achieved, this number is an overall assessment of how well the modelled water levels compared with the measured water levels and does not consider whether the model honours the measured data in a spatial sense on a local scale. The implication is that on a local scale (such as the site), the model may mis-represent the groundwater flow directions.

AGE (2020) tabulated the measured versus modelled hydraulic heads for the calibrated steady state model for the DES HSMB[6] bores and the Arrow HL bores. The comparison shows differences of up to roughly 60m. AGE suggested that these differences may be due to lack of coal connectivity or lower hydraulic conductivity values than what is incorporated in the calibrated model. To understand the implications of these hydraulic head differences, the data have been contoured[7], plotted spatially and presented as Figure 7.

The map based on the observed data for the Macalister seam shows a generally inward flow direction between the gasifiers, but with easterly flow (offsite) to the east of the gasifiers. In comparison, the modelled data show a westerly flow from the eastern site boundary (onsite). Both sets of data identify HSMB4D to be the lowest pressure and hence groundwater should flow towards it. The observed data shows a much higher pressure in HL26 (~45m) further to the west, thus limiting the potential for significant westward groundwater flow. A similar trend is seen in the

[6] For the HSMB bores the heads were estimated from graphs
[7] Using the Kriging algorithm in Surfer®

modelled heads, but with a lesser head difference. Within the Macalister seam, the implications of the differences between the observed and modelled heads may be:

- Understating the potential for offsite contaminant migration to the east of the site. The boundary of Lot 40 Plan DY85 is over 2,000m from the assumed extent of the closest gasifier.
- Overstating the potential for offsite contaminant migration to the west of the site.

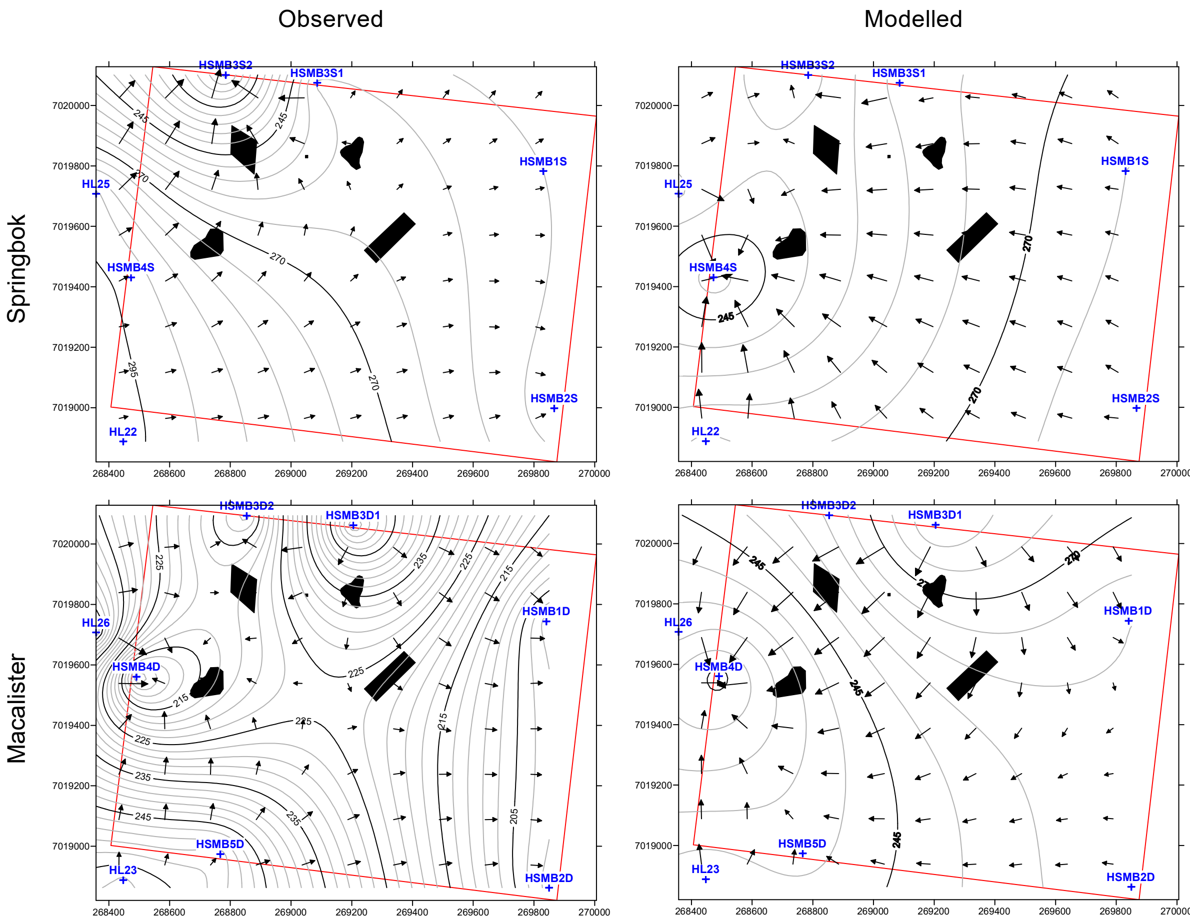
With regards to the Springbok Sandstone, the observed heads show groundwater flow potential to the east, with localised flow potential toward HSMB3S2 on the northeast boundary of the site. The modelled heads show primarily westward flow, with only minor flow potential towards the northeast. Both the observed and modelled heads show a potential for off-site movement to the north in the northwestern corner of the site. DES has recently installed an additional monitoring bore in this direction, but the data has not yet been collected (pers. Comm. DES, 2021). The model is likely to overstate the potential for offsite migration to the west – in the direction of development.

The complexity of the contours and the extremely high observed hydraulic gradients are suggestive of some degree of hydraulic disconnection across the site. This cannot be quantified with the data available to Arrow. It does, however, suggest that fracturing cannot be pervasive or sub-regionally extensive, as the increased bulk hydraulic conductivity due to pervasive fracturing would lead to flatter hydraulic gradients and more consistency in flow directions.

The measurement of water levels by DES is performed using a wireline geophysical method, with an estimated accuracy of much less than 1m. This level of uncertainty is unlikely to affect the interpretation given the large differences in hydraulic head observed across the site. However, the potentiometric surface should be determined as the sum of the pressure exerted by the water column and the gas column. It is unknown whether AGE (2020) incorporated both water and gas pressures in their calculation of hydraulic head. The exclusion of the gas pressures could result in discrepancies of up to roughly 60m which would have significant implications with respect to the interpretation of the pressure regimes in the Macalister seam and Springbok Sandstone.

The pressure regime across the site is highly complex. There were only a small number of data locations available to Arrow. It is considered likely that additional hydraulic head data from other parts of the site would result in different interpreted flow directions to those presented herein.

Figure 7 Groundwater heads and flow directions (arrows) based on observed versus calibrated steady-state model heads



Vertical hydraulic conductivities

Vertical hydraulic conductivity (Kv) and the associated layer thickness controls the prediction of drawdown in overlying or underlying formations from where the water is withdrawn. The calibrated Kv's in the model were considered potentially too low. The implication is that the model would underpredict the drawdown in the Springbok Sandstone to the west of the site, and thus result in an underprediction of the potential for off-site transport.

To assess this possibility, MLU for Windows© was utilised to assess the sensitivity of the predicted drawdown in the Springbok Sandstone to Kv. MLU is an analytical model that is capable of transient simulations in a multiple aquifer system. It assumes that hydraulic parameters are constant within a layer, layers are laterally infinite and of constant thickness, and flow is horizontal in the aquifer units and vertical in the intervening aquitards.

In this assessment, the entire Arrow forecast water production was assumed to be extracted from one bore. The geology was based on a combination of the average thickness from the DES perimeter bores for the Springbok Sandstone and the Macalister seam, and layer thicknesses from the Hopelands-2 exploration well (Arrow, 2014) thereunder. The base case hydraulic parameters were based on the median values from the AGE (2020) model. The Kv of the upper Macalister was increased from $2x10^{-8}$ m/day to $2x10^{-3}$ m/day to assess the effect on the predicted drawdown in the Springbok Sandstone. All other parameters were held constant.

The model predictions are shown on Figure 9, and despite the highly conservative model assumptions, show a maximum predicted drawdown of roughly 1.5 m. The upper limit of the Kv assessed is the same order of magnitude as the horizontal hydraulic conductivity of the coals and is unrealistically high.

In conclusion, the very low Kv's used by AGE (2020) are unlikely to significantly affect the predicted drawdown in the Springbok Sandstone and thus will not result in unduly optimistic estimates of contaminant transport distances in that formation.

Figure 8 Water production profile (Arrow, 2020)

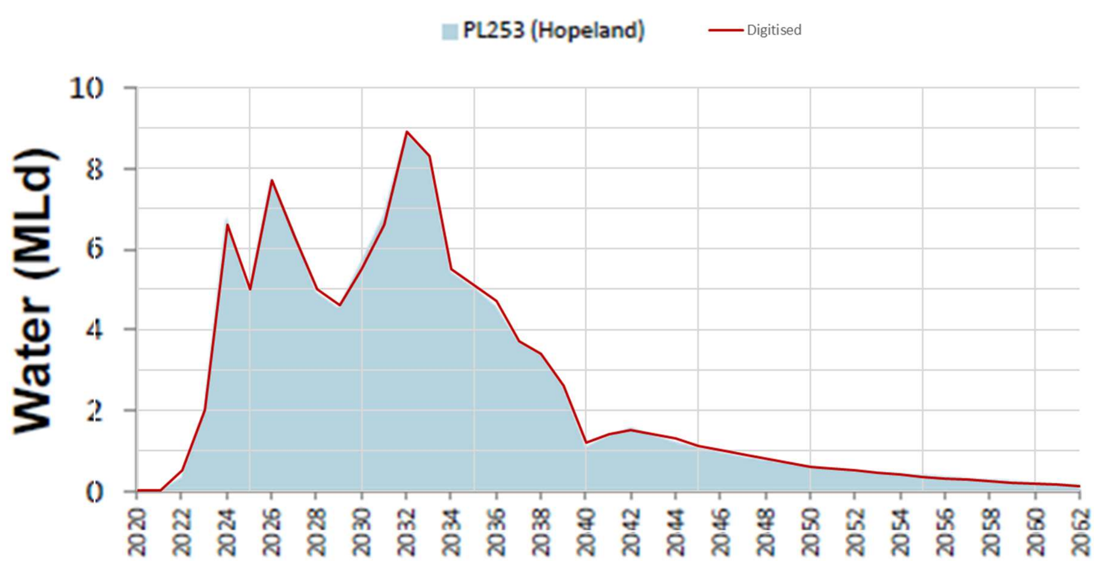
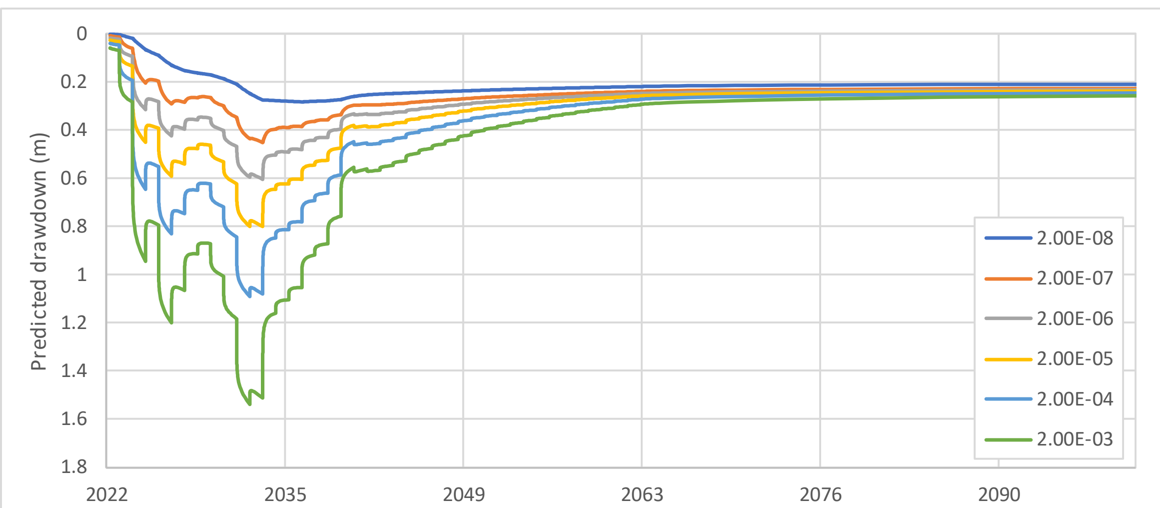


Table 2 MLU Model construction

Layer	Thickness (m)	Hydraulic Conductivity - horizontal (m/day)	Hydraulic Conductivity - vertical (m/day)	Storativity (-)
Springbok SST	116	0.2		3.13×10^{-05}
Upper Macalister	7		2.00×10^{-08} to 2.00×10^{-03}	0
Macalister Seam	8	0.001		2.16×10^{-06}
Macalister Interburden	43		1.00×10^{-08}	0
Wambo Seam	9.5	0.3		0.00019
Wambo Interburden	90		5.00×10^{-09}	0
Argyle Seam	4.5	0.3		6.75×10^{-06}
Argyle Interburden	56.5		8.00×10^{-09}	0
Upper Taroom Seam	8.9	0.3		4.81×10^{-05}
Upper Taroom Interburden	102.1		6.00×10^{-09}	0
Condamine Seam	6.3	0.3		6.93×10^{-05}
Condamine Interburden+ Eurombah	101		4.00×10^{-07}	0
Hutton Sandstone	200	0.03		2.00×10^{-04}

Figure 9 MLU model predictions for the Springbok Sandstone drawdown for various Kv's of the Upper Macalister interburden



3.1.2. Contaminant transport

While Arrow assessed sensitivity of the model predictions to hydraulic and transport parameters using Null-space Monte-Carlo (NSMC) analysis (AGE, 2020), an underlying assumption of the NSMC analysis is that the specified parameter distributions are correct. Per comments in Section 3.1, the range of effective porosity with which the model was initialised was much higher than what is commonly used in the CSG industry for history matching and prediction of water production rates. The effect of increasing porosity on contaminant transport model predictions is to reduce the physical transport distance. While porosity is the main input parameter of concern following the reduction of the first order decay coefficient in the modelling performed in response to the DES RFI, an assessment has been made that considers multiple input parameters that might affect the overall transport distance.

The Domenico (1987) solution was used to assess the validity maximum predicted contaminant transport distance (45m). The Domenico solution is an analytical model and is therefore much simpler than the BCT package used by AGE (2020). The assessment for the Macalister seam was undertaken by utilising the calibrated contamination transport model parameters from AGE (2020), and then stepwise adjusting the parameters to maximise the transport distance based on values of the calibrated ranges identified by AGE (2020). This is highly conservative and it is highlighted that this approach results in some physical inconsistencies. For example, an increase in hydraulic conductivity would result in a decrease in the hydraulic gradient, however a higher gradient was retained when this step was performed. A decrease in in porosity would result in a decrease in hydraulic conductivity in nature, however in the model both were decreased simultaneously. Model input parameters are presented in Table 3 and the output is shown graphically as Figure 10, Figure 11 and Figure 12.

Figure 10 shows the result of the step-wise increase in the model parameters which result in an extreme-case scenario where predicted contamination transport distances are maximised despite the physical inconsistencies in the model as discussed above. In comparison to Arrow's worst-case scenario (FDP Approximation), increasing the hydraulic conductivity and hydraulic gradient to the maxima of Arrow's reported ranges and reducing the porosity to that used by the wider CSG industry, the maximum predicted distance for contaminant transport was less than 180m after 100 years (as compared to Arrow's assessment of 20 years). While this is four times greater, it is highly conservative and suggests that Arrow's predicted contaminant transport distances are not unreasonable. The shortest distance from the gasifiers to the site boundary is roughly 200m.

For the Springbok Sandstone (Figure 11), this conservative assessment indicates a maximum transport distance of less than 90m, which is less than twice the maximum distance predicted by AGE (2020).

Because hydraulic gradients are currently inwards and contaminant concentrations appear to be decreasing over time, the AGE (2020) model initially results in benzene concentrations decreasing to less than the detection limit by 2025 (95th percentile), which is likely to predate the change in the direction of modelled hydraulic gradients (not presented by Arrow or AGE, 2020). Thus the model predictions for contaminant transport effectively assume future contaminant migration will be from the gasifiers only. However, due to the simplification of the modelling of the emplacement of the contaminants, and the discussion above regarding the local flow directions in and around the site not necessarily being accurately represented by the sub-regional scale model, an assessment was made of how far contaminants might travel that are not sourced from the gasifiers, i.e. contaminants that remain in formation outside of the gasifiers. Using the maximum reported benzene concentrations in a perimeter monitoring bore, and the most conservative hydraulic parameters (conductivity, gradient and porosity) as used in Scenario C, the maximum predicted transport distance was roughly 80m. It is not inconceivable that there would be off-site migration of residual contaminants if hydraulic gradients were to be in the off-site direction.

Table 3 Analytical contaminant transport model input parameters

Formation	Macalister seam				Springbok Sandstone	Macalister seam
Parameter	FDP Approximation	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Figure ID	Figure 10				Figure 11	Figure 12
Source concentration (mg/L)	40	40	40	40	1.5	0.21
Hydraulic conductivity (m/day) - horizontal	0.03	0.03	0.03	0.045	1.4	0.045
Hydraulic gradient	0.018	0.018	0.023	0.023	0.0024	0.023
Effective porosity (%)	7	1	1	1	6	1
First order attenuation rate (day)	25	25	25	25	25	25

Figure 10 Analytical transport model predictions: Macalister seam – FDP approximation, Scenario A, Scenario B and Scenario C

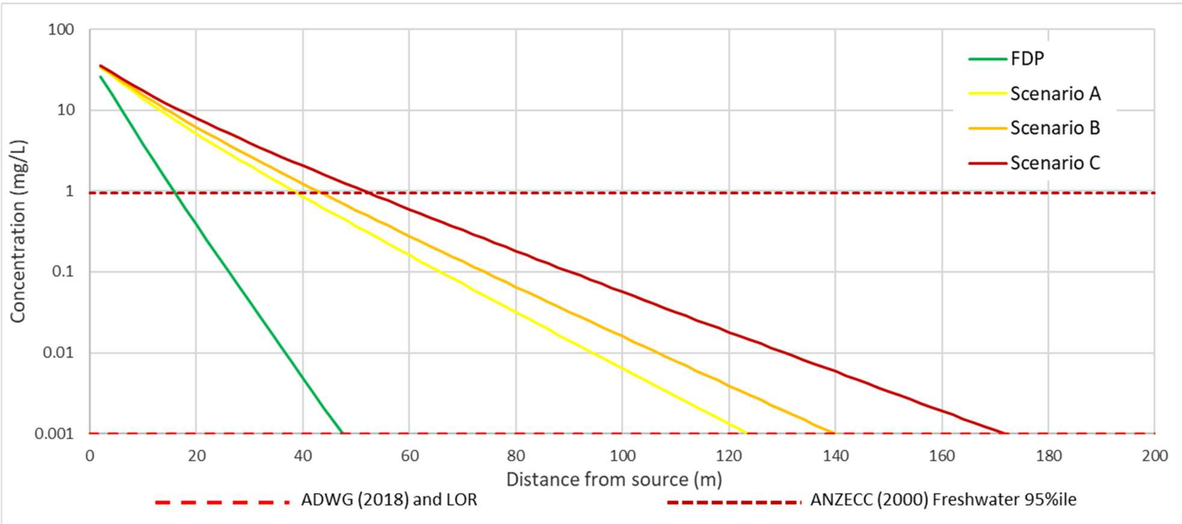


Figure 11 Analytical transport model predictions: Springbok Sandstone – Scenario D

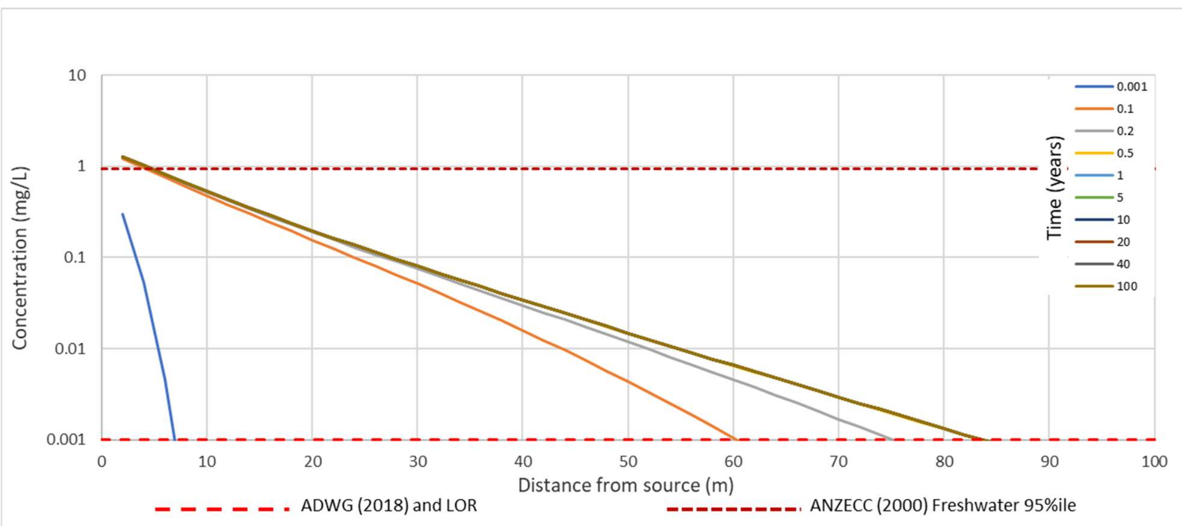
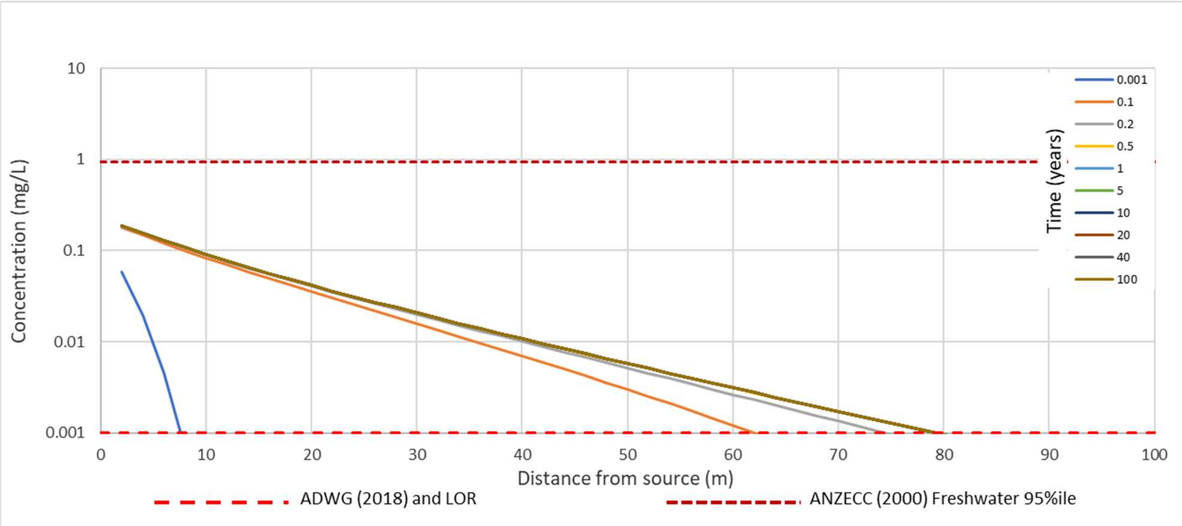


Figure 12 Analytical transport model predictions: Macalister seam – Scenario E



3.2. Migration of fugitive free gas

Arrow engaged the University of Queensland Centre for Natural Gas (UQ) to assess the RFI regarding how gas movement may be enhanced or affected by Arrow's development of PL253. Arrow reports that (in its response to the RFI) UQ prepared a multi-phase numerical model. It was concluded that the risk of change to the movement of free gas at the site was low because gas would be re-adsorbed into the coal thereby reducing volumes of free gas, or the free gas would be trapped by small structures in the coal.

Arrow reports that the UQ model was structurally based on the AGE (2020) model from which head calibration targets were also sourced. Arrow reports that the UQ model included a period of gasification by Linc and then pressure recovery, ensuring that current pressures showed 30-40m of residual depletion to match conditions observed at the site. Sensitivities to:

- Enhanced horizontal permeability through the coal and vertical permeability to connect the Springbok Sandstone
- Transmissive or sealing faults
- Higher coal saturation (which would allow less adsorption of the free gas)
- enhanced pressure gradients

were reported by Arrow to have been assessed. Similarly to the groundwater contaminant fate and transport modelling, a base case (no further production in PL253) and a development case were simulated to assess the effect of the PL253 development.

Arrow reports that the modelling indicated that because:

- their development would not significantly affect pressures at the site (approximately 10m of drawdown), and
- that free gas would re-absorb to the coal resulting in a decrease in the amount of free gas at the site over time

there would be little gas migration beyond the current extent of free gas presence at the site.

Mention is made of buoyancy causing some gas movement in the models, but Arrow report that UQ indicate that movement due to buoyancy is limited by the low permeability or the low relative permeability (of gas and water) around the site. Arrow reported that the spatial distribution of free gas was not predicted to change despite a change in the overall groundwater flow direction due to CSG production.

Arrow reports that the UQ modelling only considers gas migration due to increased drawdown at the site from Arrow's activities. From the figures presented by Arrow, the UQ model domain did not extend to Arrow's development wells. It essentially suggests that natural attenuation of the free gas will occur, and that gas volumes across the site will decrease over time despite Arrow's development. Based on Arrow's summary of UQ's report, the assessment does not however consider the potential for fugitive gas migration from Arrow's development, in particular the down-dip[8] development where the Macalister seam will be targeted.

It is highlighted that the discussion that follows regarding fugitive gas migration is highly conceptual, and the associated risks cannot be quantified. A schematic diagram is provided as Figure 13 to assist with the description.

An analogue exists for fugitive gas migration in the gas seeps to the Condamine River, however the geological environment at the seeps is somewhat unique in the Surat Basin. The location of the seeps is within the geological area known as the Undulla Nose, where faulting has caused natural fracturing that has significantly enhanced formation permeability. The faulting has also created small scale structural traps, and then provides natural pathways between these traps and the underlying coal seams. When gas pressures are sufficiently high and there is a pathway to surface via a fault, the gas escapes to surface. The Condamine "Bubbles" exist because the river overlies one of these systems. While the seeps are a natural system, the gas escape is enhanced by down-dip CSG production, which is approximately 1km away. The Condamine seeps were mitigated by reducing the pressure in the underlying traps through gas production combined with increased CSG production to capture more of the gas (APLNG, 2021). The seeps do however highlight that migrated free gas may not necessarily be reabsorbed onto the coal quicker than the rate at which it migrates.

In the case of the site and Arrow's proposed development:

- The range in hydraulic conductivity of the Macalister seam reported by AGE (2020) was $1x10^{-5}$ m/day to 0.09 m/day. This is compared with measured coal permeabilities on the Undulla Nose in the vicinity of the Condamine seeps of 0.5 m/day to 3.1 m/day (Origin, 2017). The coals outside of the Undulla Nose appear to be significantly less permeable than those at the seep, therefore migration would be slower providing more opportunity for reabsorption.
- the Hopelands development is to the east of the Undulla Nose, thus natural fracturing is likely to be less than that on the Undulla Nose, as evidenced by the lower horizontal hydraulic conductivities in the calibrated groundwater flow model.
- Arrow's closest down-dip development of the Macalister seam is approximately 2.5 km to the southwest of the site. If free gas was to migrate up dip, only a portion would be likely to intersect the site.
- Free gas already exists at the site. Wellbores with poor integrity and possibly fractured ground provide pathways to surface. Additional free gas from down-dip may increase the gasiness of onsite bores.

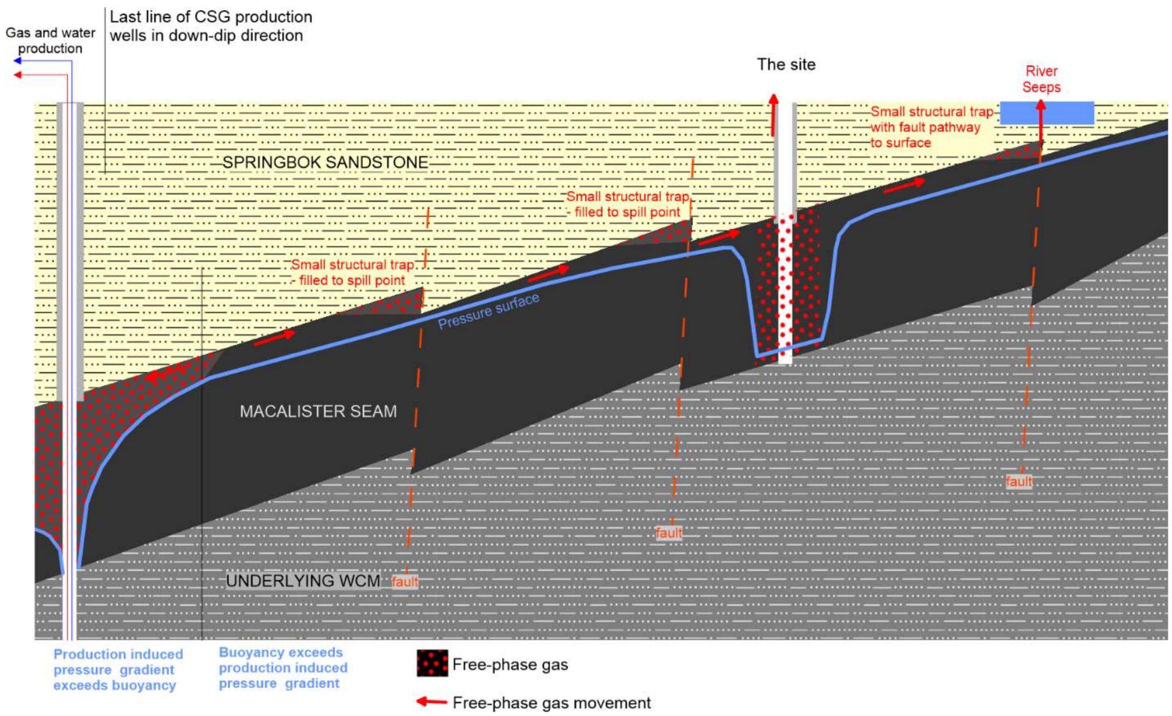
[8] The slope of a geological formation is called the dip. In the vicinity of the site, the formations dip to the southwest.

- If fugitive gas from Arrow's development migrated through the site, and the gas did not escape or get trapped within the site boundary, it is possible that the migrated gas could "sweep" contaminants off-site in the updip direction (nominally to the northeast). It is also possible that fugitive gas has migrated up dip from the site historically due to Linc's former activities. If encountered via drilling, it may not be possible to distinguish the differences between a contaminated gas pocked derived directly from Linc's activities and one that may have accumulated through fugitive migration and contaminant sweep from Arrow's activities.

Because of the lower permeability and reduced fracture density compared with the Undulla Nose, the potential for fugitive gas to migrate from is considered to be significantly lower than in the vicinity of the Condamine Bubbles. If gas did migrate to the site from downdip:

- Assuming the legacy wells are not yet decommissioned, there may be some additional fugitive emissions from the site via wells with poor integrity providing vertical pathways to the atmosphere. Gas may also escape from ground fractured during the overpressure event(s) and/or cavity collapse. This gas could possibly "sweep" volatile contaminants resulting in contaminant emissions to the atmosphere.
- Since induced fracturing has only be observed in the Macalister seam in the direction from which gas would migrate, the induced fractures are more likely to act as a gathering network to bring fugitive gas to the site, rather than enhance off-site gas migration.
- The continued maintenance of low pressure across the site (either via active extraction, or fugitive emissions) relative to its surrounds will minimise the potential for buoyant migration away from the site.

Figure 13 Conceptual model of fugitive gas migration (not realistic, not to scale)



3.3. Induced horizontal fracturing

The observed complexity of the pressure surface in the Macalister seam including the high hydraulic gradients, suggest limited hydraulic connectivity across the site and low hydraulic conductivities, particularly at some distance from the gasifiers. The steep inward hydraulic gradient between HL26 and HSMB4D indicates that the induced fracture observed in HSMB4D is unlikely to extend a significant distance off-site. Similarly, the steep gradient between HSMB3D1 and HSMB3D2 suggests lack of hydraulic connection between the two bores, despite induced fractures observed at both locations (but not in all bores – see Figure 5).

In terms of contaminant transport risk:

- the potential for migration from the fracture to the surrounding material will be controlled by the rock matrix. The rock matrix permeability is known to be low, therefore the propensity for contaminants to move out of the fractures will be low.
- The fracture must necessarily be connected to the gasifier(s) as they were induced during the over pressuring thereof, thus the pressure in the fractures is likely to be similar to that of the gasifier to which is connected than the surrounding rock, and the fracture would thus be at lower pressure. Groundwater movement would therefore most likely to be into the fractures from the surrounding rock matrix.

- With the subsequent reduction in pressure following the overpressure events during operation and the lack of proppant in the induced fractures[9], it is likely that the fractures have closed, at least partially, and may have low or negligible permeability.
- Since the HSMB bores in which the induced fracturing was observed are effectively on the site boundary, it is likely that the fractures extend an unknown distance off site. It is therefore possible for fractures to provide preferential pathways for off-site contaminant migration.

3.4. Department of Resource activities

In 2016 Linc Energy went into administration, and the liquidators subsequently disclaimed the land, property and associated tenures pursuant to the *Corporations Act 2001*. There is currently no environmental authority or resource tenure in force at the site, and the site is an abandoned mine as per Section 344 of the *Mineral Resources Act*. The Department of Resources is managing the site and associated remediation activities through the Abandoned Mines Land Program (AMLP).

The aim of the AMLP ensure the site is safe, secure, durable and, if feasible, productive. To achieve this aim, the AMLP may undertake activities that change the pressure regime on the site. These may include (but are not limited to):

- Extraction and flaring of gas
- Extraction of groundwater
- Decommissioning of wellbores with compromised integrity and
- Decommissioning of wellbores that are longer needed for site monitoring and management

The first two activities will necessarily reduce pressures, which will retain the inward hydraulic gradients. During this time, existing contamination would be drawn further into the site. While pressures may be further reduced in the short-term, in the longer term, if gas is removed from the system, it may cause quicker pressure recovery, which could then lead to the potential for oss-site migration.

Leaking wellbores provide a continual pressure sink, thus maintain the inward hydraulic gradient. As mentioned above, the presence of free gas may also be slowing the rate of pressure recovery following the cessation of Linc's activities. It is unknown how decommissioning of leaking wellbores (i.e. the removal of the existing pressure sink) would affect the maintenance of an inward hydraulic gradient, and its effect on the model predictions made by Arrow.

[9] In hydraulic fracturing (fraccing) a proppant such as sand is pumped into the fracture to keep it open after the pumping pressure is reduced. If proppant isn't used the fracture closes and the benefit is lost.

It is expected that the Department of Resources would initially trial any potential activities prior to longer-term implementation to ensure that the activities would not exacerbate the potential for off-site contamination migration.

4. Groundwater mitigation measures

Since Arrow's modelling indicates low potential for off-site contaminant migration, Arrow's position was that mitigation measures are unnecessary. However, there remains sufficient uncertainty in the accuracy of the model predictions, that the need for management and mitigation measures should be considered.

Arrow identifies the following three mitigation options that could be implemented if trigger criteria in their monitoring plan are exceeded:

- Enhanced insitu remediation
- Interception system
- Containment system

No further information is provided regarding any of these proposals.

Given the spatial extent of the gasifiers, the depth of the coal measures and the consolidated nature and low permeability of the formations, and the potential fracture pathways, it is considered unlikely that either in-situ remediation or an interception system would be technically and economically feasible. The first two would necessarily need to be undertaken on-site to ensure that contaminants do not reach the site boundary.

A containment system whereby inward hydraulic gradients are maintained is considered the most achievable. To ensure that contamination did not migrate off site, a containment system could comprise an extraction system which would necessarily be inside the site boundary, an injection system that would need to be off-site, or a combination of extraction and injection. To implement, this may require (but not be limited to):

- An access agreement to the land
- Authority to extract the gas, for example via petroleum lease
- Access to DES and Department of Resources monitoring data and or/infrastructure
- Additional regulatory approvals

Through the current Environmental Authority (EA) for PL253, EA0001401 (DES, 2018), Arrow is required to *develop and submit a comprehensive Groundwater Characteristics Monitoring Program that will provide early notification of changes in groundwater flow direction and quality in relation to groundwater conditions on Lot 40 DY85*. Additional EA conditions require routine monitoring and construction of, and annual calibration of, a groundwater model.

Arrow identifies 33 bores as the monitoring network in the most recent version of its Groundwater Characteristics Monitoring Program (GCMP – GHD, 2020). The majority of these bores are on-site legacy bores or the DES HSMB perimeter monitoring bores. Ongoing use of the bores will require a mechanism to ensure availability of the data to Arrow. Also included are five registered groundwater bores, of which four are landholder bores which are within the long-term affected area (OGIA, 2019) for their respective formations accessed. The longevity of this component of the network is therefore questionable, and since these bores form the outer ring of the monitoring network, they may be critical to the assessment of groundwater flow directions. It is recommended that Arrow provide greater justification for the monitoring network in the GCMP and identify how access to relevant data will be maintained and ensured, especially since Arrow potentially has no control over the collection of data from the DES bores.

In its response to the RFI (Arrow, 2020b), identifies the following decision statements in response to the request to provide additional information on the monitoring/identification and mitigation measures proposed to prevent contamination migration:

- If the contaminant concentrations are not detected off-site and the hydraulic gradient remains within predicted level, continue monitoring.
- If hydraulic gradients change and contaminants are detected off-site at levels below trigger criteria conduct formal risk assessment and update the predictions to assess the source of the impacts to the hydraulic regime
- If hydraulic gradients change and contaminants are detected off-site at levels exceeding trigger criteria due to changes in the hydraulic regime induced by Arrow Energy, implement management actions.

These statements are based on tailing indicators, i.e. the event has already happened. The GCMP should include leading indicators as triggers, i.e. they should be based on monitoring data (or a combination of monitoring data and a calibrated model) that suggest off-site contaminant migration may occur in the future. The following is recommended for consideration for inclusion to the requirements of the GCMP:

- *Justification that the groundwater monitoring network required by condition Water 1A will be sufficient to identify changes to groundwater flow directions which could lead to contaminants migrating from Lot40 DY85.*
- *The description of a trigger system, based on the monitoring data required by condition Water 1F, that will provide an early warning of changes to groundwater flow directions which could lead to contaminants migrating from Lot40 DY85.*
- *Identification of the year in which hydraulic gradients are predicted to change in the Springbok Sandstone and shallow Walloon Coal Measures or any other relevant aquifers which could lead to contaminants migrating from Lot40 DY85 during or after authorised activities.*
- *Identification of potential management and mitigation measure(s), including the evaluation of the efficacy of the proposed measure(s), in ensuring that contaminants do not migrate from Lot40 DY85 during or after authorised activities. The evaluation must consider the timing to implement the measures, the surface and sub-surface infrastructure to*

implement the measures, and an assessment of the technical feasibility in the site's geological environment.
- *The GCMP should be reviewed and, if necessary, updated following the annual recalibration of the groundwater flow model.*

Trigger thresholds for comparison are stated in the EA (Water 1F). Exceedance of the contaminant triggers requires an investigation to be undertaken (Water 1G). The triggers for the primary contaminants of concern (BTEX, PAHs) are concentrations greater than the laboratory limit of reporting (LOR). Since current contaminant concentrations in the Arrow monitoring bores are below LOR, if the LOR is exceeded, it implies that there has been additional off-site contaminant migration. It is recommended that the LOR is changed to the contaminant limit in Water 1F.

Where free gas is present, it exerts a pressure on the water within a formation. It is the relative spatial distribution of the combined free gas pressure of the water that controls the direction of fluid movement. To ensure that pressure gradients can be correctly assessed, the following minor changes are recommended to current EA conditions:

- Water 1A(3) – monitoring program of *formation pressure* and quality
- Water 1(F) – wellhead pressure should be added to the required analytes.

5. Conclusions

Concluding remarks regarding the identified scope of works are provided as follows.

a. **Whether all potential risks associated with the development have been identified (i.e. mobilisation of groundwater contaminants, and gas migration);**

Arrow assessed the risk associated with:

- the movement of groundwater contaminants from the site
- the migration of free gas from the site

While these are the primary risks associated with the development of PL253, the assessments did not consider all potential pathways or mechanisms associated with these risks. Semi-quantitative and qualitative assessments (with a high degree of conservatism) performed as part of this technical assessment suggest that Arrow's subsequent conclusions regarding contaminant transport from the gasifiers are likely to be mostly accurate.

However, the modelling predicted the ubiquitous decrease in contaminant concentrations to less than 1µg/L prior to the change in hydraulic gradients when contaminants could migrate from the gasifiers. It is considered unlikely that all contamination would be naturally attenuated to such an extent thus, it is possible that contaminants present outside of the gasifiers could migrateoff-site when hydraulic gradient change.

b. **Whether Arrow's assumptions, groundwater modelling and subsequent conclusions are accurate;**

The assessment was based on a necessary simplification of a highly complex system. The uncertainty in the understanding of the system was not considered (e.g. the mode of contaminant emplacement and the acknowledged geological complexity not incorporated in the model). Although the model calibration was acceptable according to the Australian Groundwater Modelling Guidelines (Barnett et. al., 2012), this was based on relatively small number of points spatially across the site and it did not agree with observed hydraulic heads at the site-scale and generally underpredicted contaminant concentrations relative to their measured concentrations.

Current groundwater flow directions appear to be primarily inward towards the site, thus inhibiting the potential for off-site contaminant movement. Arrow assessed a maximum contaminant transport distance of 45m from the gasifiers (following reduction in contaminant concentrations across the site to less than 1µg/L) using its calibrated numerical groundwater contaminant fate and transport model. A simplified, but conservative, assessment was performed herein to assess the transport distance through the porous formation, which indicated that Arrow's transport distances are not unreasonable. Should hydraulic gradients change so that groundwater flow is towards the site boundaries, it is considered unlikely that Arrow's activities would mobilise contaminants from the gasifiers that would reach a site boundary.

Arrow's modelling predicted that contaminant concentrations within the site would decrease to less than 1µg/L prior to the change in direction of hydraulic gradients, from inward to off-site, as a result of Arrow's development. The model therefore effectively assumes that the gasifiers are the only source of contamination on the site when, in the future and due to Arrow's development, hydraulic gradients could enable off-site migration. This prediction is based on the observed decreasing trend in contaminant concentrations at a limited number of locations across the site. The underlying geological model is a necessary simplification of a highly complex system and it is considered likely that there will be residual contaminants will remain outside of the gasifiers. Consequently Arrow's conclusion that there will be no off-site contaminant migration may be incorrect.

While the modelling presented in AGE (2020) suggested that contaminants will not migrate off-site, it cannot be conclusively stated that contaminants will not migrate beyond the site boundaries due to Arrow's development.

c. Whether the proposal has the potential to mobilise contaminants and migrate them away from the site;

The proposal has the potential to change hydraulic gradients due to drawdown associated with CSG production. Hydraulic gradients are currently generally into the site and therefore the potential for off-site contamination is currently low, with DES monitoring data also indicating that contaminant concentrations are decreasing. With the likely change in hydraulic gradients due to the proposal, there is the potential that onsite contamination may move off-site. Indications from existing data and the modelling performed by Arrow are that contaminant transport distances are likely to be short (<100m).

2. **Advise whether the groundwater mitigation measures proposed by Arrow are considered appropriate and commensurate to the risk.**

Arrow considered the risks associated with their proposal to be negligible, therefore no detail was provided of potential mitigation measures. Of the three potential measures mentioned, two (enhanced in situ remediation and interception) are considered unlikely to be technically feasible due to the hydrogeological environment and the scale of the source. A containment system (either on-site extraction, off-site injection or a combination thereof) is likely to be feasible. This may require additional regulatory approvals to implement.

3. **Inform the department what contingency measures may be appropriate to manage the risks of the project e.g. exclusion from area, containment measures, treatment of underground water, flaring.**

As mentioned above, a containment system, whereby inward hydraulic gradients are maintained, is likely to be a feasible solution if regulatory approval can be gained.

For Arrow's development to induce off-site contaminant migration, Arrow's activities would need to alter the direction of the hydraulic gradients. While Arrow did not present the timing of this change, it is unlikely to be imminent and therefore mitigation measures do not need to be immediately implemented.

The existing EA requires a GCMP. Additional requirements for the GCMP have been recommended that include:

- a combined monitoring-modelling-management approach
- an early warning trigger system
- identification and evaluation of potential mitigation measures.

This approach should ensure that the risk of future off-site contaminant migration from Arrow's proposal can be managed.

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