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Memorandum

Recipient	Arrow Energy Pty Ltd
Memo date	25/09/2018
Author	Coffey Environments Australia Pty Ltd
Project number	ENAUABTF20484AA
Memo Subject	SGP Stage 1 CSG WMMP: Subsidence Technical Memorandum

1. Introduction

This memorandum presents a subsidence monitoring technical memorandum as part of development of recommendations for a monitoring network and sampling regime for the Arrow Energy Pty Ltd (Arrow) Surat Gas Project.

The work was carried out as part of a programme of work by Coffey Services Australia Pty Ltd (Coffey) to establish the Stage 1 Coal Seam Gas (CSG) Water Monitoring and Management Plan (WMMP) for the Arrow Surat Gas Project (SGP). This programme includes development of a monitoring network and sampling regime compliant with approval conditions, the Environmental Impact Statement (EIS) and a Supplementary Report to the EIS (SREIS).

This memorandum responds to Condition 13g which calls for:

> *A program to monitor subsidence impacts from the action, including trigger thresholds and reporting of monitoring results in annual reporting required by condition 28.*
>
> *If trigger thresholds are exceeded, the approval holder must develop and implement an action plan to address impacts within 90 calendar days of a trigger threshold being exceeded.*

Coffey interpret that compliance with Condition 13g will require:

1) A subsidence monitoring program.

2) Trigger thresholds.

3) Reporting of monitoring results in annual compliance reporting.

4) Action plan for trigger exceedances.

Arrow contributes with other CSG proponents to a subsidence monitoring program involving use of satellite imaging using Interferometric Synthetic Aperture Radar (InSAR) which provides baseline data and a regular interpretation of ground movement over the area of CSG extraction or planned extraction.

Development of a subsidence monitoring program that utilises information available, together with dedicated subsidence measuring devices, establishes trigger thresholds and defines an action plan for trigger exceedances will require:

- Calculated assessments of indicated subsidence for different regions within areas potentially affected by CSG drawdown.
- A risk assessment process to establish locations for strategic geodetic monitoring and/or extensometers.
- Trigger levels, derived from the calculated assessments of potential subsidence, and taking into account the outcomes of the risk assessment process.
- A program for annual monitoring or longer term monitoring if considered necessary.
- Reporting of the results of the ongoing monitoring, including interpretation, and an action plan for trigger exceedances that would be included in the annual reporting.

The objective of the subsidence monitoring program will be to identify whether assets or the environment are adversely affected by ground subsidence resulting from SGP CSG extraction activities.

This memorandum provides:

- Assessment of long term subsidence associated with proposed Arrow Surat Gas Project operations based on:
  - Review of measurement of subsidence and groundwater levels carried out in proximity to existing Arrow domestic gas CSG projects (these current domestic gas projects do not form part of the SGP); and
  - Estimates of subsidence based on predicted groundwater drawdown from the EIS and SREIS.
- An assessment of risks posed by subsidence to assets within or in close proximity to Arrow SGP operations.
- Recommendations for additional ground movement monitoring such as strategically located geodetic monitoring and extensometers.
- Recommended trigger levels for the SGP.
- Recommendations for continuing monitoring for the SGP.

2. Background

This memorandum addresses the Arrow Surat Gas Project (SGP). The SGP will be developed in a series of Drainage Areas shown in Figure 1. The drainage areas define the extent of individual well fields which will be developed.

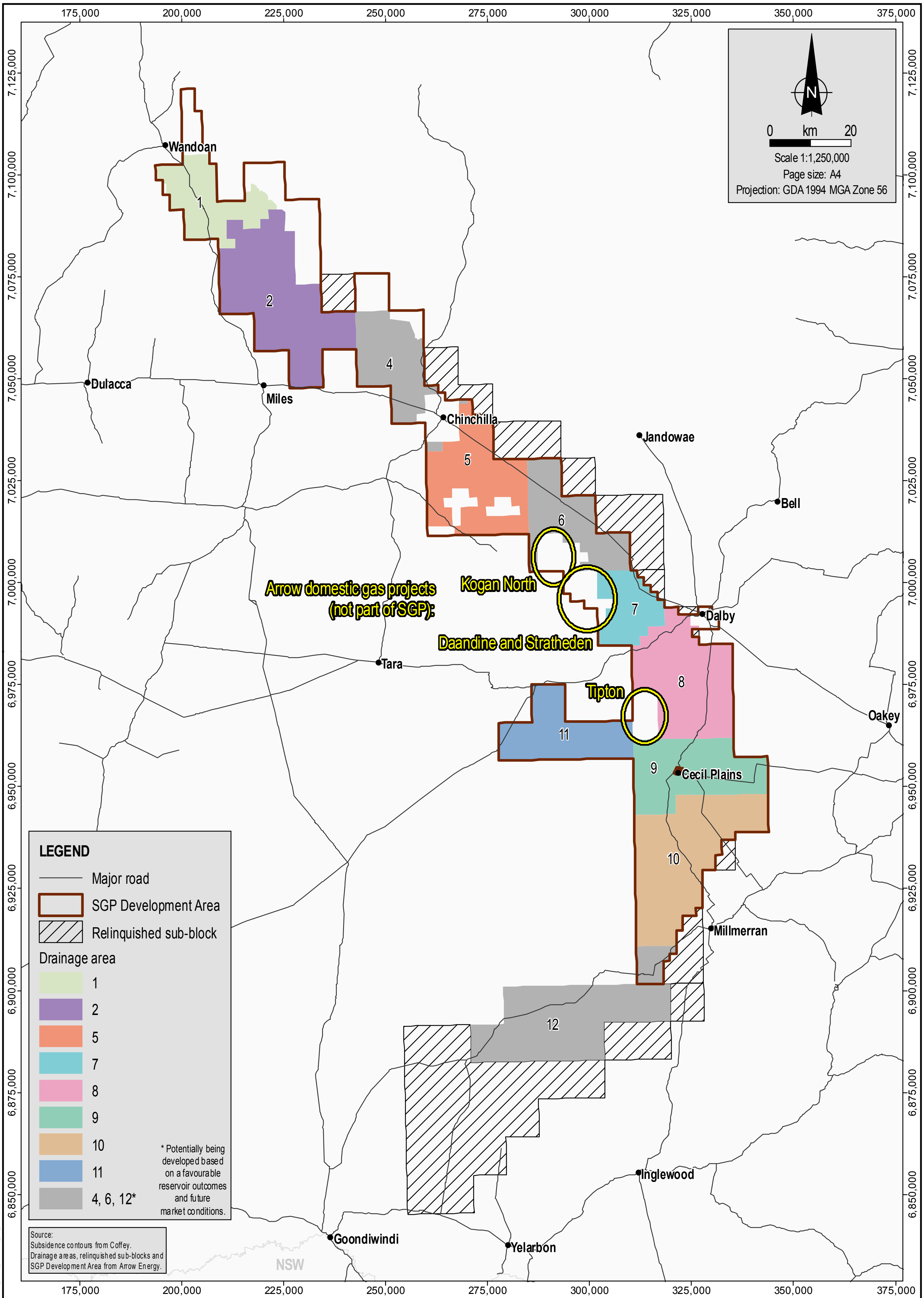
The SGP project development area totals 61,000 km^2 with projected CSG water production of 510 GL over 40 years involving approximately 6,500 wells.

Arrow also has four domestic gas production fields in the Surat Basin which do not form part of the SGP. The domestic gas production by Arrow has occurred since 2006 at:

- Tipton West - approximately 20 km south of Dalby in production since September 2006;
- Kogan North - approximately 40 km west of Dalby (owned in joint venture with Stanwell Corporation Ltd) in production since January 2006;
- Daandine - approximately 40 km west of Dalby in production since September 2006; and
- Stratheden - approximately 20 km west of Dalby.

Production drilling of Arrow's Surat Basin domestic gas fields started in 2005. Initial development began at Kogan North, followed by Tipton West, Daandine and Stratheden. The target coal seams in the Surat Basin are the Walloon Coal Measures. While these domestic operations do not form part of the Arrow Surat Gas Project they provide valuable experience in relation to groundwater drawdown and subsidence occurring during their operation. The locations of the Arrow domestic production fields are also shown in Figure 1.

Other proponents also have CSG developments in the Surat Basin. These are to the west of the Arrow SGP as shown in Figure 2.



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Date: 04.05.2017	Arrow Energy	arrow energy go further	Arrow Drainage Areas Surat Gas Project (Domestic CSG Projects also shown)	Figure No: 1
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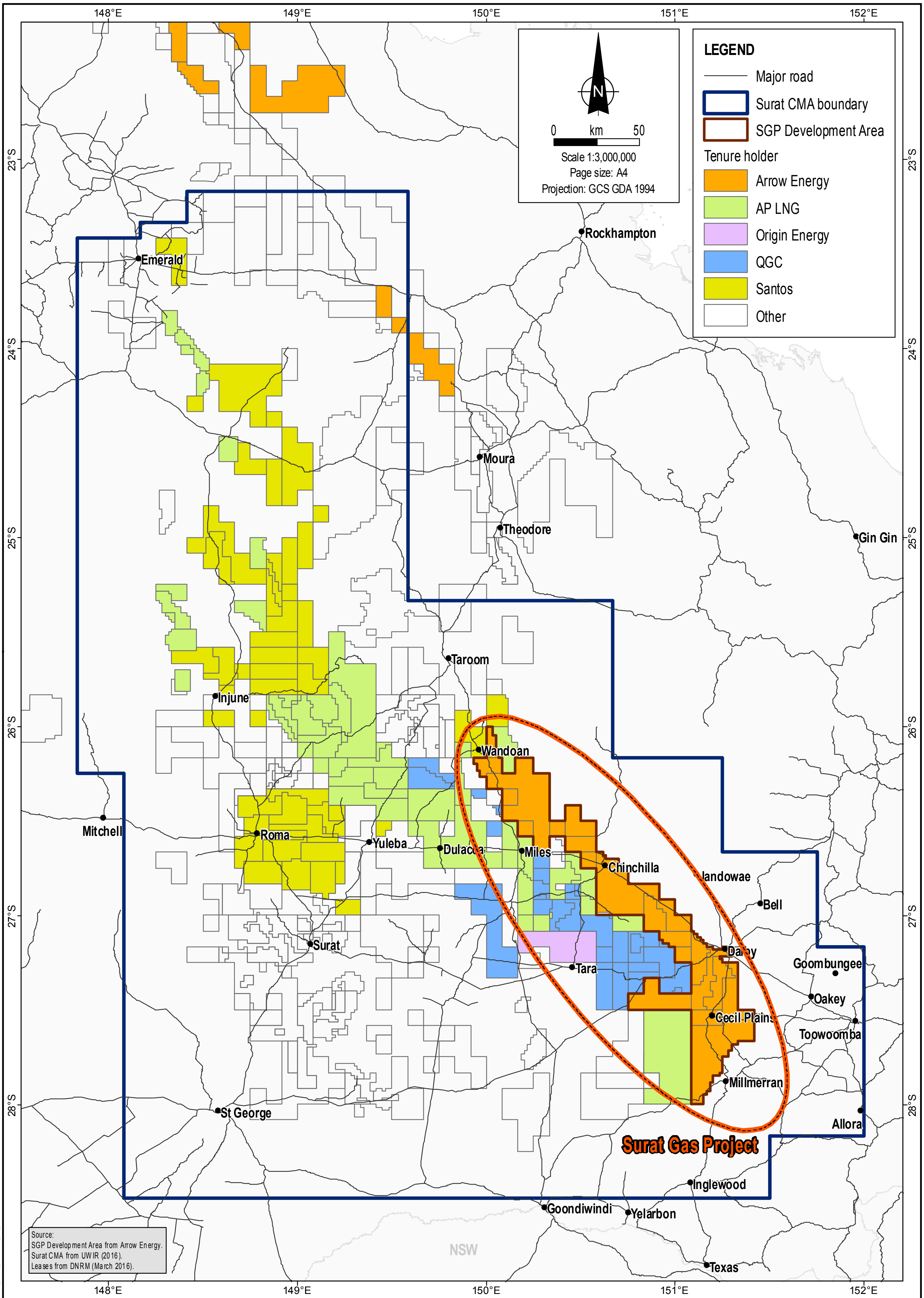

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Arrow Energy
Surat Gas Project WMMP

arrow energy
go further

Arrow CSG leases in relation to leases held by others

Figure No: 2

2.1. Cause of subsidence

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

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

This process commonly occurs during dewatering for construction, though, in the construction case, the materials involved are typically soils which are much more susceptible to settlement than the consolidated coal measure rocks that are subject to groundwater depressurisation for CSG production. Engineering methods for assessment of settlement from this effect are well developed and require knowledge of the mechanical properties of the ground and the changes in groundwater pressure across the full ground profile.

In addition to the above mechanism, liberation of adsorbed gas from coal surfaces can result in a reduction in coal volume and provide a further component of subsidence. Sorption-induced compaction has been measured in laboratory studies at around one per cent (for carbon dioxide and methane combined) of the coal thickness (Robertson 2005). The extent of this effect will relate to initial adsorbed gas content and the quantity of gas released.

The properties governing the contraction of coal due to gas removal from seams in the Walloon Coal Measures are not available. Robertson (2005) reported a strain of 0.001 for a gas pressure change of 500 kPa (equivalent to pressure under 50 m of water) in a bituminous coal seam. While it is unclear if this value would relate to Surat Basin coals, it does give an indication of potential for shrinkage due to reduction in gas content.

2.2. Geological setting

A description of the geological setting is provided in the SGP Environmental Impact Statement (EIS). Elements of this in the context of their properties as relevant to groundwater behaviour are discussed below.

The Surat Basin forms a north south oriented trough with the Arrow SGP operations concentrated along the eastern margin west of the Condamine River.

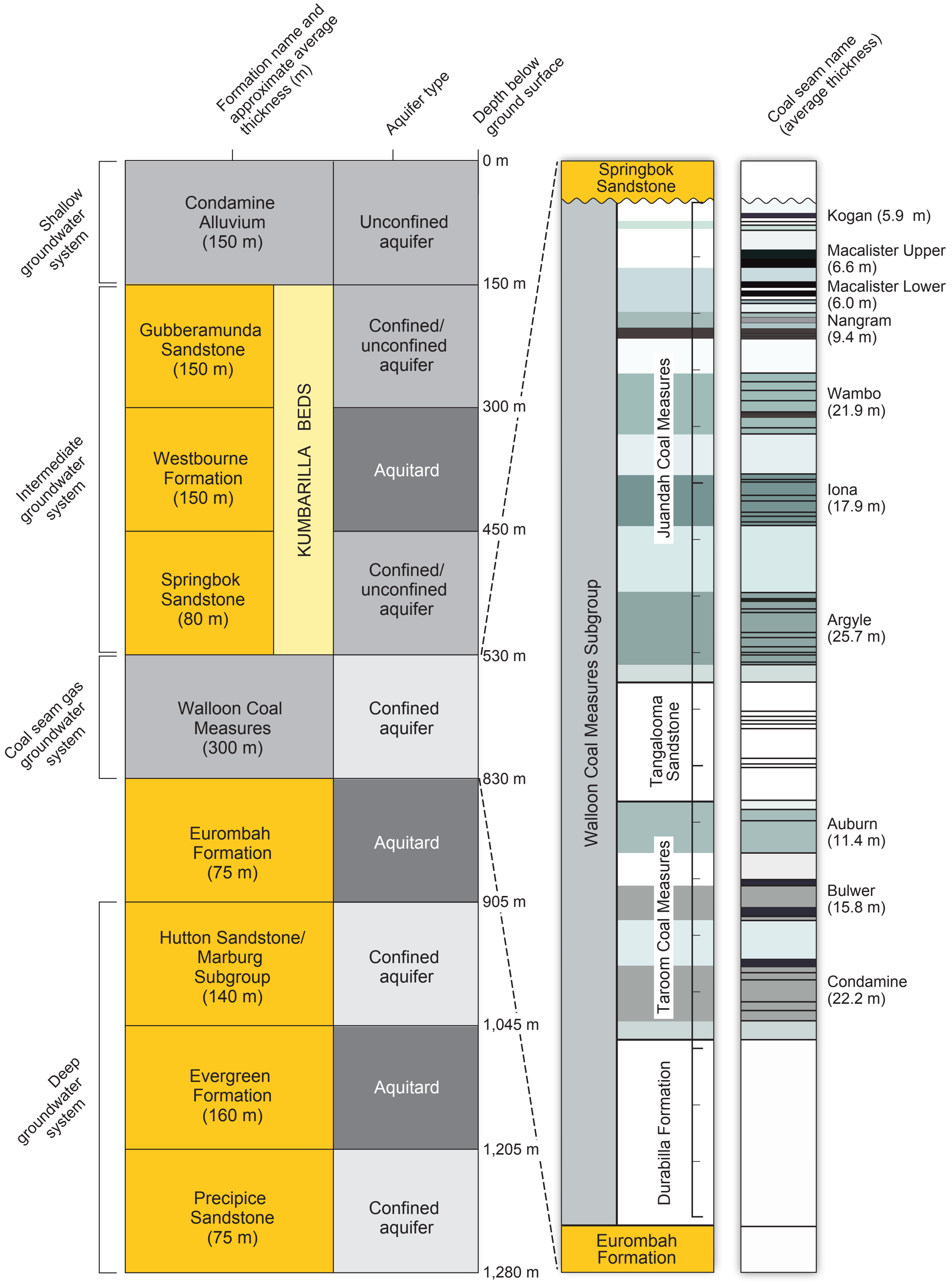
Figure 3 sets out the typical stratigraphic profile within the Surat Basin in areas of Arrow SGP operations. The Walloon Coal Measures is the host formation. It includes the Juandah and Taroom Coal Measures, the target strata normally screened in Arrow's Surat SGP wells. Lower permeability Tangalooma Sandstone separates the Juandah and Taroom.

Overlying the Walloon Coal Measures are the Kumbarilla Beds comprising the Gubberamunda Sandstone, the Westbourne Formation and the Springbok Sandstone. The Kumbarilla Beds are generally of low permeability and act to separate groundwater pressure changes in the Walloon Coal Measures from the overlying alluvial sediments of the Condamine Alluvium.

Underlying the Walloon Coal Measures is the Hutton Sandstone. This lower permeability aquifer formation reduces the influence of drawdown below the Walloon Coal Measures.

The upper units of the Kumbarilla Beds which overlie the coal measure rocks are truncated by erosion at the eastern margin of the basin where Arrow SGP operations are concentrated. As a result the Gubberamunda Sandstone is not present in some Arrow SGP leases. This is also true of the Westbourne Formation and Springbok Sandstone, such that in the east of some tenements the coal measures subcrop underneath the Condamine Alluvium. Low permeability clays at the base of the alluvium, as well as low permeability weathered and unweathered sediments interbedded in the coal measures also act to separate groundwater pressures between the alluvium and the coal measures.

The thickness of the Walloon Coal Measures changes over the Surat Basin. In particular, along the eastern margin the Walloon Coal Measures are truncated at the erosional contact with the Springbok Sandstone. Figure 4 presents contours of thickness of the Walloon Coal Measures obtained by adding the thicknesses of the component units provided by Arrow from their geological model of the area. Within the Arrow leases (the SGP Development Area) the thickness ranges from greater than 450 m to less than 50 m.



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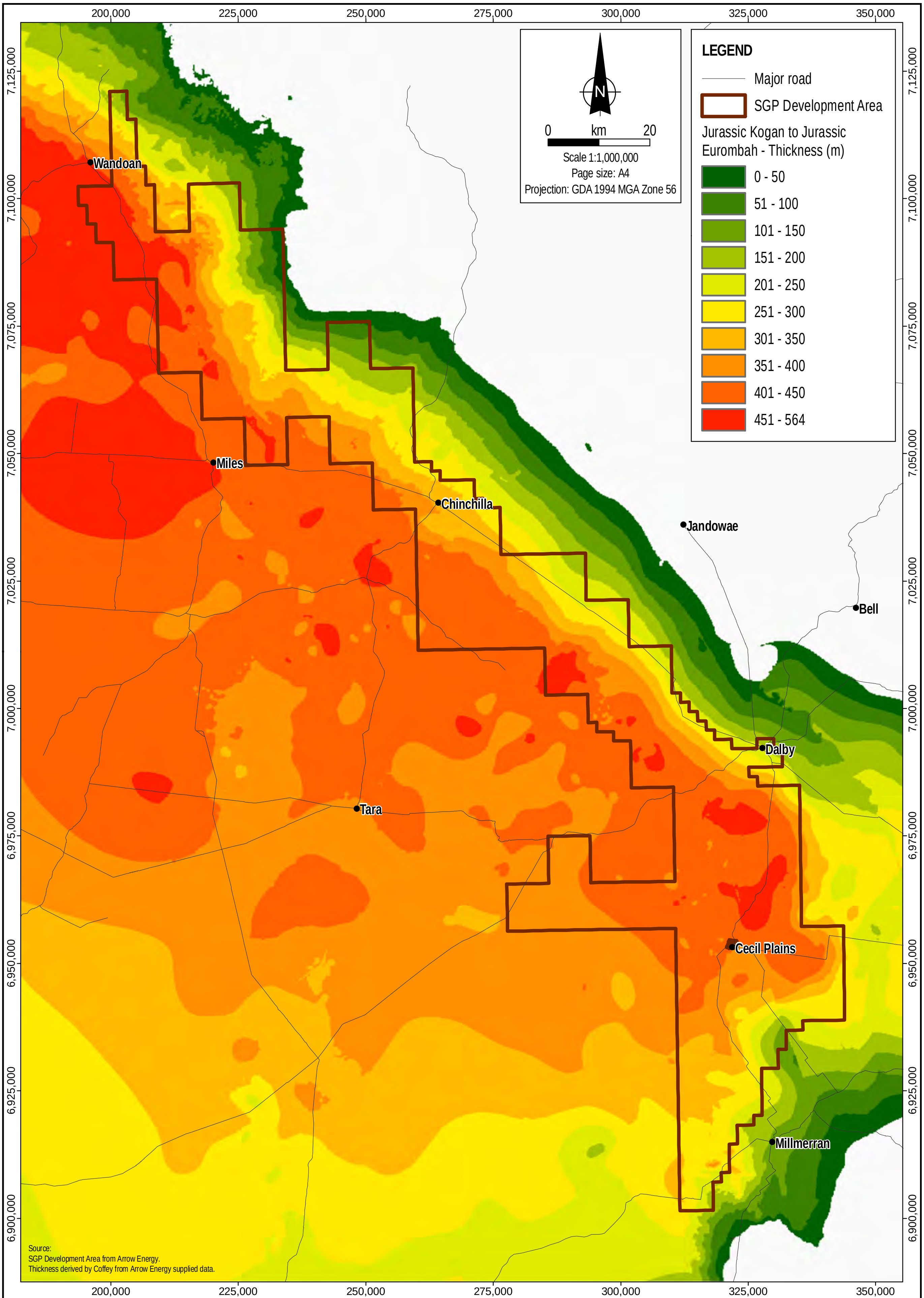
coffey A TETRA TECH COMPANY	Date: 05.05.2017 Project: 754-ENAUABTF20484AA File Name: 20484AA_M05_F003_GRA	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Typcial Surat geological profile in Arrow SGP tenements	Figure No: 3



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3. Subsidence Assessment

3.1. Subsidence monitoring

Monitoring of subsidence was carried out by Altamira (Altamira, 2016) using employed data obtained from Radarsat-2 satellite images covering 10,736 km^2 of Arrow SGP leases. Over the period July 2012 to December 2015 a total of 34 or 35 images were obtained for Arrow SGP leases (the number of images changed slightly depending on the ground location in relation to satellite paths). The images were generated using a radar with a working frequency of 5.3 GHz (C-band) and a wavelength of 5.6 cm.

The change in phase difference between locations was used to interpret changes in relative position. Interpretation involves identification of phase difference between points within the areas scanned for each data set and applying various corrections to account for the elevation of the points, the velocity of the satellite and atmospheric effects.

The phase difference between locations is recorded from the satellite which is not directly overhead on each traverse and the effect of ground slope also influences the phase shift from differing vantage points. These factors have an influence on the interpreted movement. For the purposes of this assessment movements interpreted from the InSAR monitoring have been treated as being vertical.

Some areas are unsuited to the use of this method of movement interpretation. For example ploughed fields produce variable response, and generally produce a low density of reliable interpretations. Altamira assessed the quality of each interpreted point and did not report those points of low reliability. The method produced results on an 8 m by 5 m grid, and further averaging appears to have been carried out to yield results at approximately 30 m spacing. The error of the resulting values is not identified explicitly by Arrow. An indication of the magnitude of error for individual points can be assessed from the time variation of results for individual locations. These show variability typically within 5 mm from point to point around a trend.

The interpreted results were presented in the form of coloured dots representing the rate of ground movement per year. Movement of less than 8 mm per year (rise or fall) was treated as stable and is marked with a green dot. Other colours were used to indicate upward or downward movement in the range 8 to 16 mm per year and greater than 16 mm per year. Areas where reliable data could not be obtained were not assessed and were left blank.

Figure 5 presents the interpreted average rate of ground movement from July 2012 to December 2015.

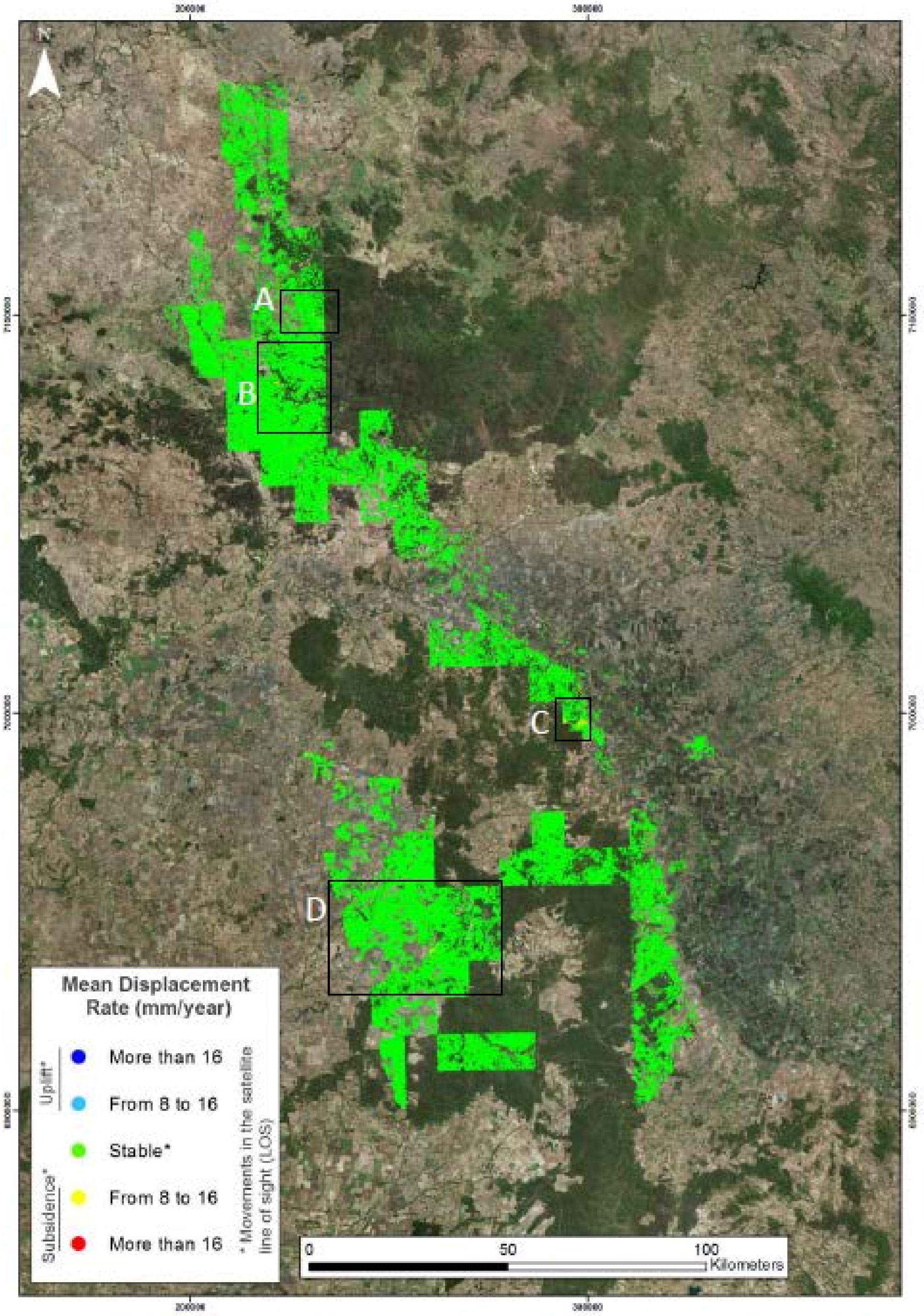


Figure 5 - Interpreted ground movement rate - Arrow SPG leases (Altamira 2016)

It is clear from Figure 5 that no widespread subsidence occurred over the period of monitoring. Altamira highlighted areas where ground movement (at rates greater than 8 mm per year) was detected. These are marked in Figure 5 as Areas A to D.

3.2. Domestic gas project

Of these areas the only area corresponding to active CSG extraction by Arrow is Area C which contains the Daandine CSG field. Figure 6 presents a more detailed view of this area.

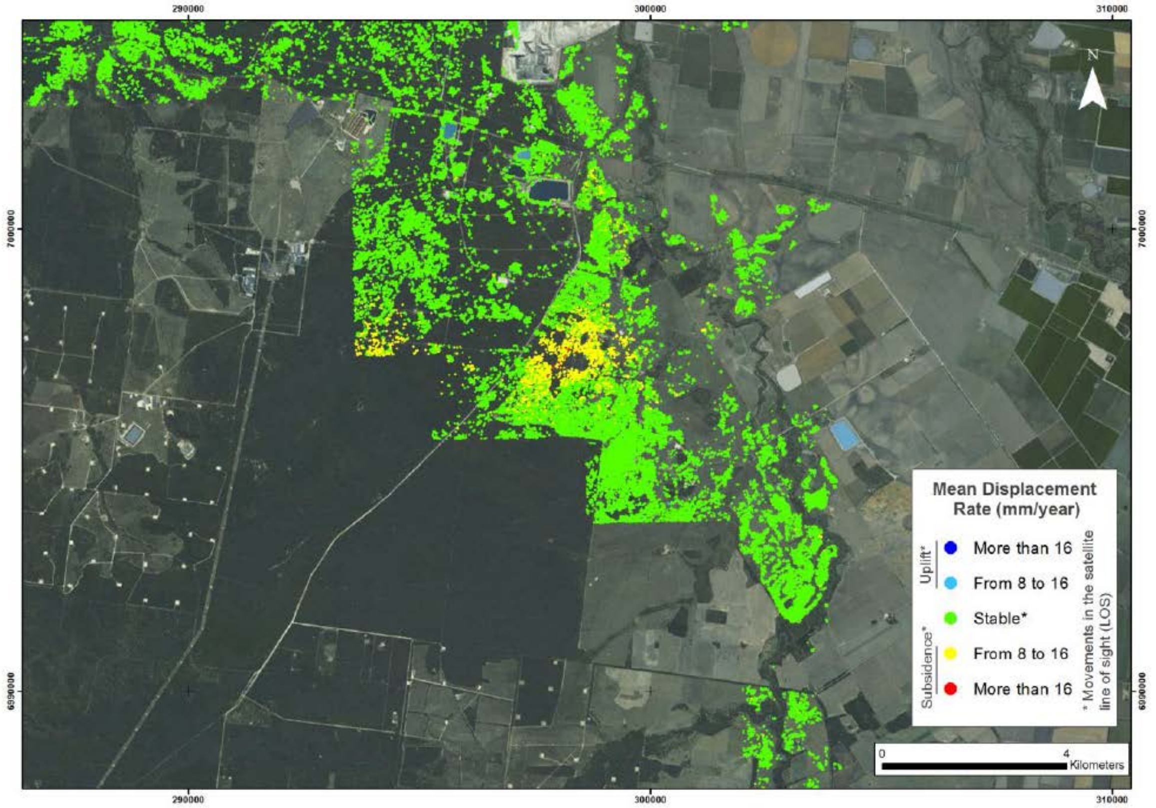


Figure 6 - Subsidence InSAR results - Area C - covering Daandine CSG field (Altamira 2016)

The area containing yellow shading (with some red points) at the centre of Figure 7 corresponds approximately to the Daandine CSG field, and is further enhanced (zoomed in) in Figure 7.

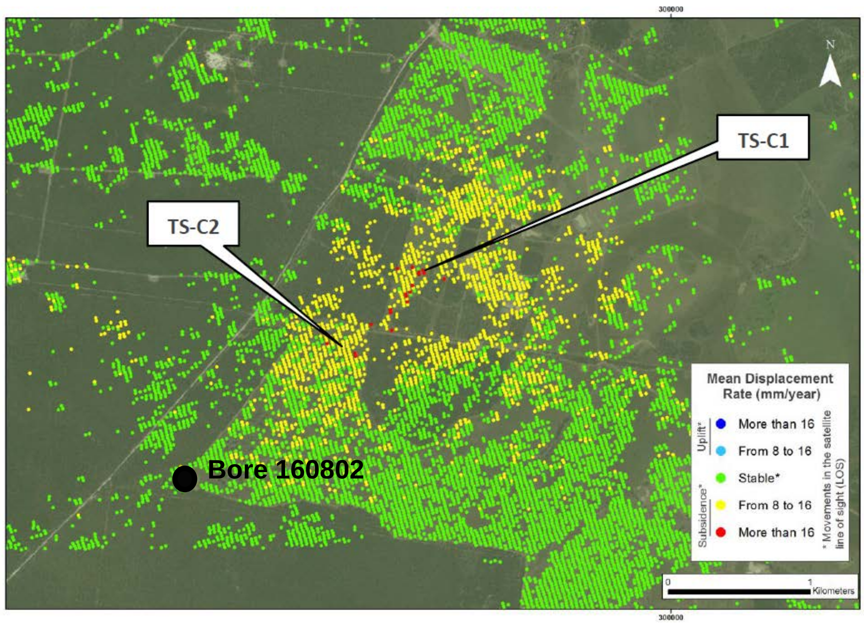


Figure 7 - Detail of ground movement interpretation - Daandine CSG field (Altamira 2016)

At highlighted time-series monitoring points TS-C1 and TS-C2 in Figure 7 Altamira provided an assessment of the variation of movement over the period of monitoring, as presented in Figure 8.

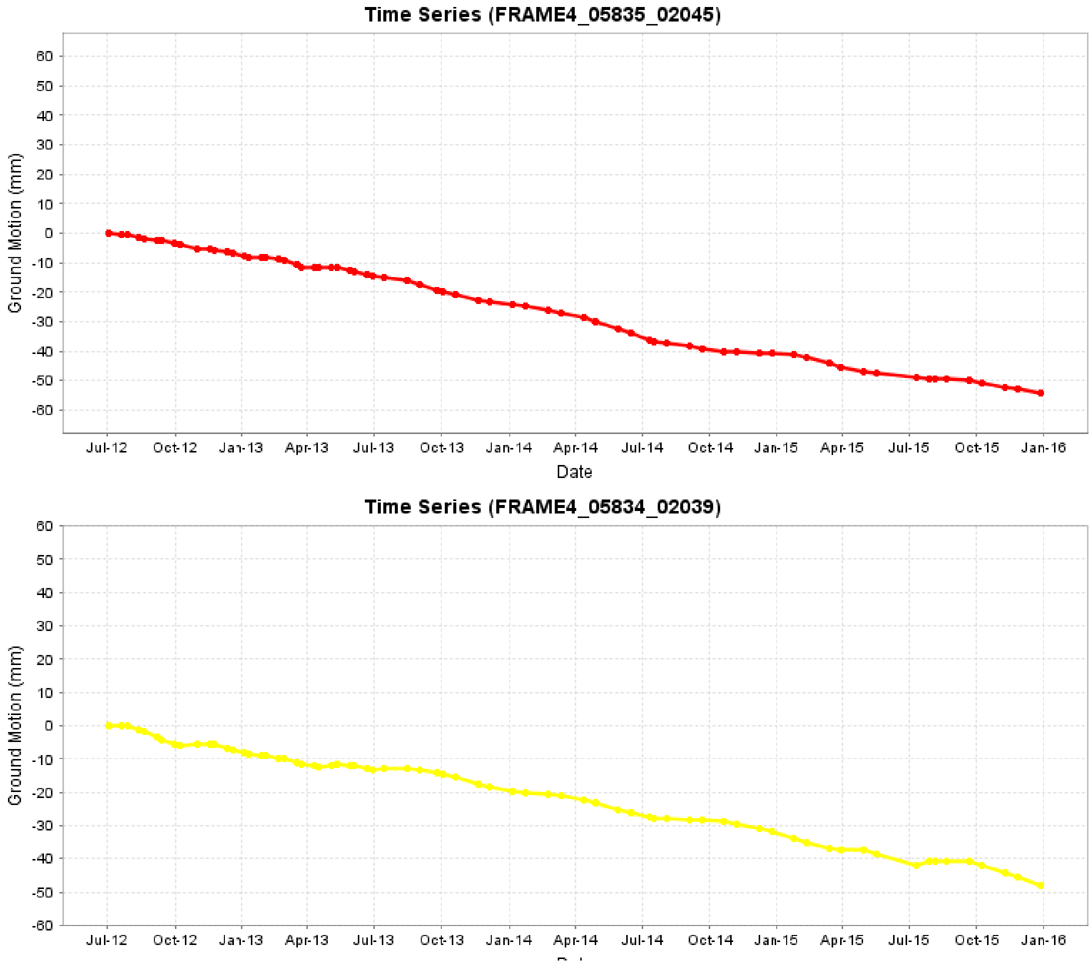


Figure 8 - Ground movement interpretation versus time TS-C1 (upper) TS-C2 (lower) (Altamira 2016)

Interpretation of the rate of downward groundwater movement based on these results is 17 mm/year for TS-C1 (50 mm over three years) and 14 mm/year for TS-C2 (41 mm/year over three years). From the form of the interpreted ground movement it is clear that the rate of movement is reasonably even over the affected area. Undulations in the response with time are apparent in the interpreted ground movement. Earlier work by ARUP (2014) compared early results from InSAR monitoring with rainfall records and concluded that widespread movements less than 5 mm occur and appear to be associated with seasonal rainfall and temperature.

Coffey considers the semi-regular undulations in the time-series response (Figure 8) are due to effects of rainfall and temperature, but the overall decline is expected to be a result of drawdown associated with the Daandine CSG depressurisation.

By way of contrast with Daandine, the interpreted movement at the Tipton CSG field to the south is less than 8 mm per year, as is the interpreted movement for the Stratheden and Kogan CSG fields.

Daandine area ground movement

Arrow provided access to the detailed records from the Altamira InSAR analysis. These records were used to review InSAR results in the vicinity of monitoring bores. Ground movement in the vicinity of monitoring bore 160802 was obtained and revealed movement of 30 mm from April 2012 to December 2016.

Ground movement was extracted from the InSAR records covering an east-west section across the southern limit of the Daandine CSG well field, and crossing a series of CSG wells (Figure 9). InSAR results show settlement up to approximately 60 mm over the monitoring period (April 2012 to December 2016). This was carried out to assess the level of variability of ground movement between wells.

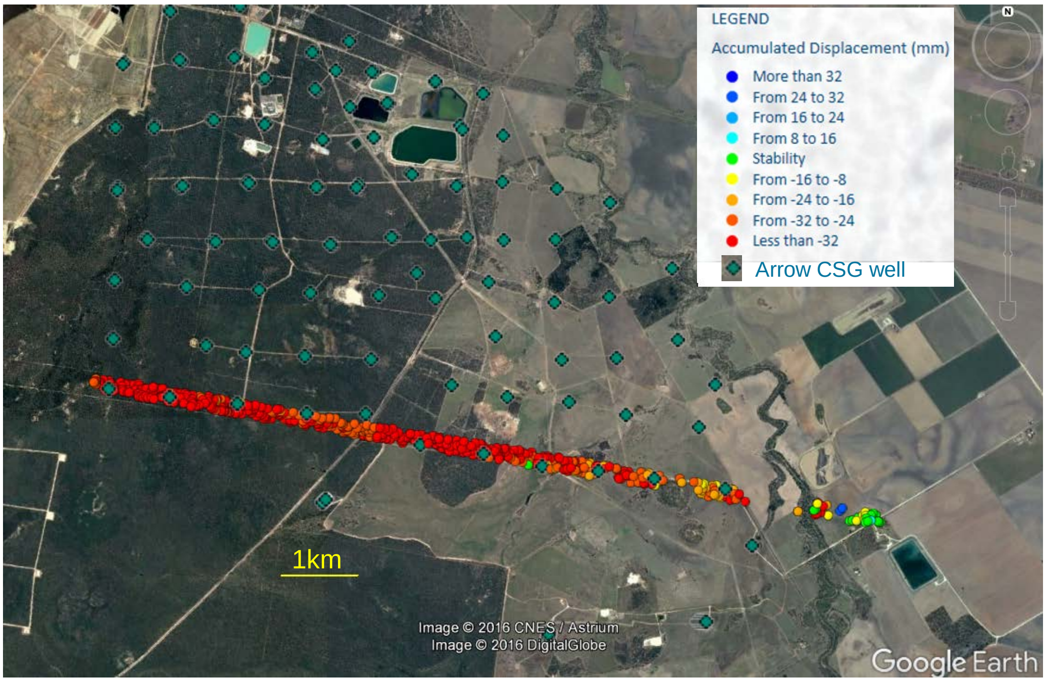


Figure 9 - East-west traverse through Daandine CSG Field – Displacement (April 2012 to December 2016)

Interpreted ground movement monitoring for this traverse is plotted in Figure 10, which also indicates the position of the individual CSG wells along the traverse. It is interesting to note that the scatter of result is greater in the cleared ground than in the wooded areas (darker green in Figure 9).

In comparing the ground movement results with the positions of the CSG wells there is no indication of greater settlement at the well locations with less settlement between wells. Within the scatter of the results, the ground movement is indicated to be quite even.

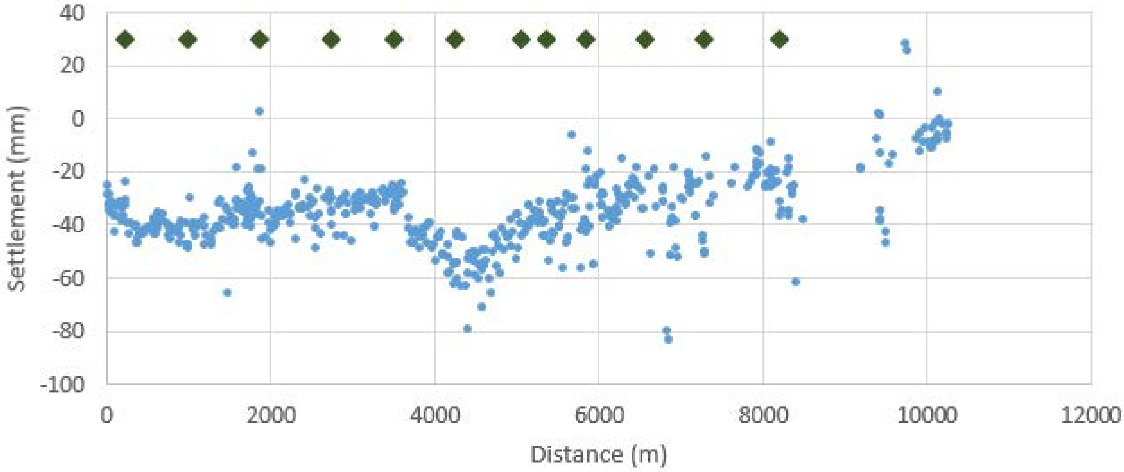


Figure 10 - Ground movement - East-west traverse at southern limit of Daandine CSG Well Field (Well locations marked as green diamonds)

It is also useful to note the steepest gradient of movement (at distance 4000 m in Figure 10) is approximately 30 mm per kilometre.

3.2.1. Groundwater level monitoring

A large number of groundwater monitoring bores are in operation in the Surat Basin in support of CSG operations. These results are accessible via the Queensland Government data globes on Google Earth. Monitoring bore 160802 is located at the southern limit of the Daandine CSG field (see Figure 7). Figure 11 presents measured drawdown from November 2014 to March 2016 for monitoring bores screened within the Juandah Coal Measures. The results show steady decline in groundwater level over this period. InSAR results averaged from the area surround Monitoring Bore 160802 showed a gradual downward movement of 30 mm over the period April 2012 to December 2016. Monitoring Bore 160802 is accompanied by two adjacent bores 160553 and 160394 each within 20 m horizontal distance of 160802. The cluster of bores covers a very useful set of monitoring results covering the target coal measures and the overlying and underlying formations.

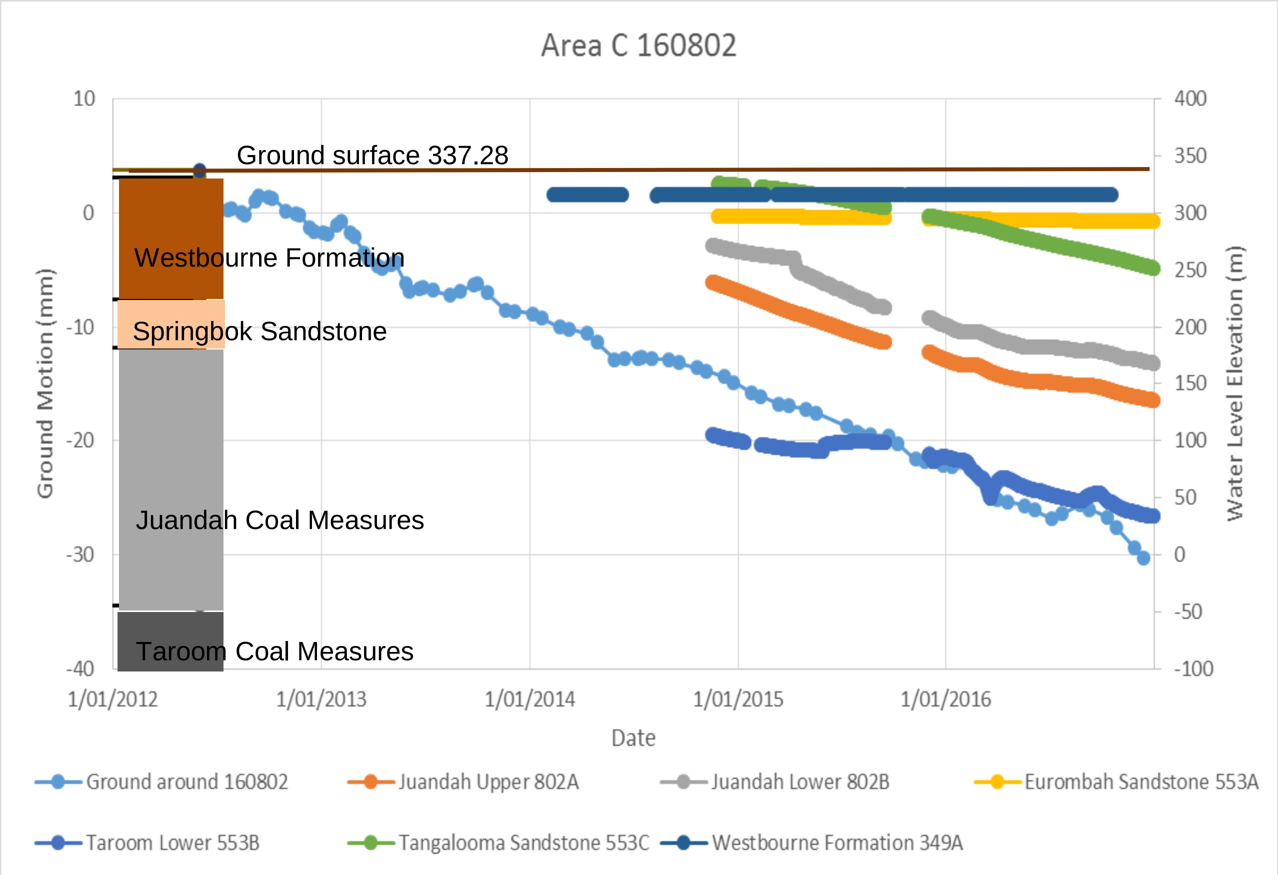


Figure 11 - Groundwater levels - Daandine CSG Field - Area C (Bore cluster 160802, 160349, 160553)

Groundwater levels obtained for 160802 for the Juandah Formation appear to have an offset in the data obtained from the Queensland Government Globe as Arrow advised that artesian pressures are not encountered in the Daandine CSG field. For this assessment it is assumed that the relative changes in groundwater pressure are correct, irrespective of any offset in the absolute level. Corrected values were obtained from Arrow and these were plotted in Figure 11. The length of record was greater than that available from the Queensland Globe records. The extended period was not available in time to be analysed for this memorandum. The cluster of bores is located approximately 50 m from the nearest CSG well. Arrow have advised:

> *The Target Flowing Pressure is around 35 Psi at the bottom of lowest Seam or Water Level around 5 to 10 meter below the lowest seam (Condamine coal seam).*

This is interpreted to mean that for the Juandah the groundwater level would be at 24 m (24 m water head is 35 psi) above the base of the Argyle and for the Taroom the groundwater level 24 m above the base of the Condamine. These values would reflect conditions at the CSG well. Away from the well groundwater level would rise and average groundwater level between wells could be substantially higher.

Groundwater monitoring in an adjacent Bore 160553 (part of the cluster of monitoring bores at 160802) shows little drawdown within the Taroom Coal measures during 2016 and an overall decline of 55 m from November 2014 to March 2016 but relatively stable levels in the Eurombah Formation (variation within 5 m of the starting level) over the same period. A further adjacent monitoring bore (Bore 160349) shows stable groundwater level in the Westbourne Formation (above the Walloon Coal Measures). This is interpreted to indicate that groundwater drawdown in this area has occurred over the full thickness of the Walloon Coal Measures (comprising the Juandah Coal Measures and the Taroom Coal Measures) but very limited drawdown has occurred in the units above and below the Walloon Coal Measures.

Groundwater levels in the Tipton CSG field as recorded in Bore 160799 (see Figure 12 below) show smaller changes compared with those recorded at Bore 160802.

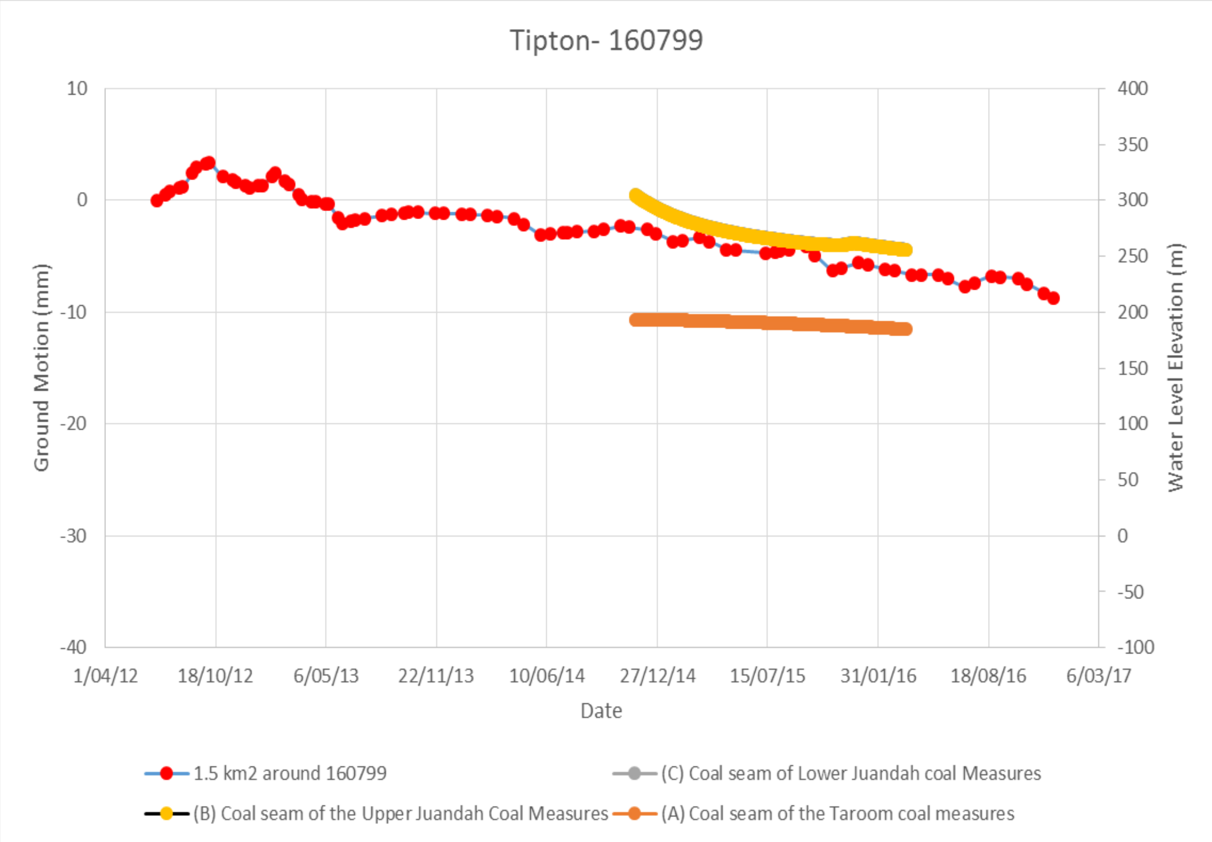


Figure 12 - Measured groundwater level change - Tipton (Bore 160799)

This monitoring illustrates that from November 2014 to March 2016 some 45 m of drawdown had occurred in the Juandah Coal Measures in this area but very little drawdown took place in the lower Taroom Coal Measures. Bore 160799 (see Figure 13) is at the western margin of the Tipton CSG field. CSG Bores are also present to the west of Bore 160799 on a lease owned by QGC Pty Ltd. Settlement records from the InSAR data for this period indicate a settlement of only 4 mm on average for the area surrounding Bore 160799 (see Figure 12).

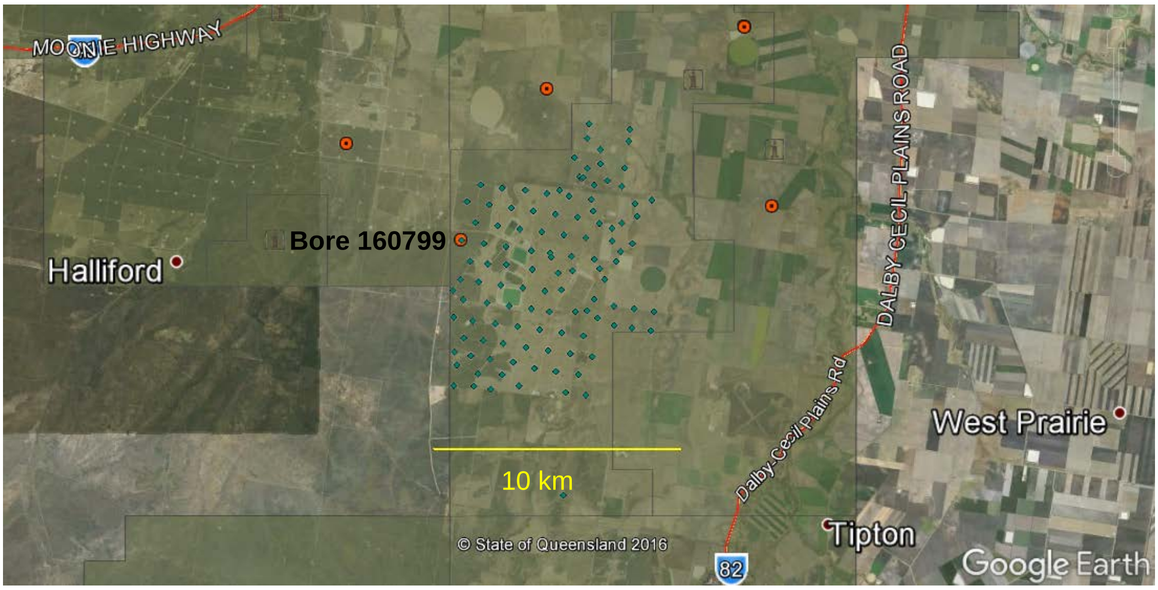


Figure 13 - Tipton CSG field (green dots) showing Bore 160799 location (Google Earth and Queensland Data Globe)

Bore 160678 located some 8 km to the east of the Daandine CSG field (see Figure 14) shows comparatively little change in groundwater level within the Juandah Coal Measures (see Figure 15 below). The groundwater level is presented together with the measured vertical movement at location TS-C1. Note that the scale of the water level axis is changed significantly from the previous water level plots to show the detail of the comparatively small change in groundwater level.

The monitoring shows a gradual reduction in groundwater level within the Juandah Coal Measures of approximately 2 m over a one year period. The InSAR data set does not cover the location of Bore 160678 but does provide results for a nearby area (see Figure 14). The average movement for these locations shows movement within a range of 5 mm from April 2012 to December 2016 and does not correlate with Arrow SGP operation.

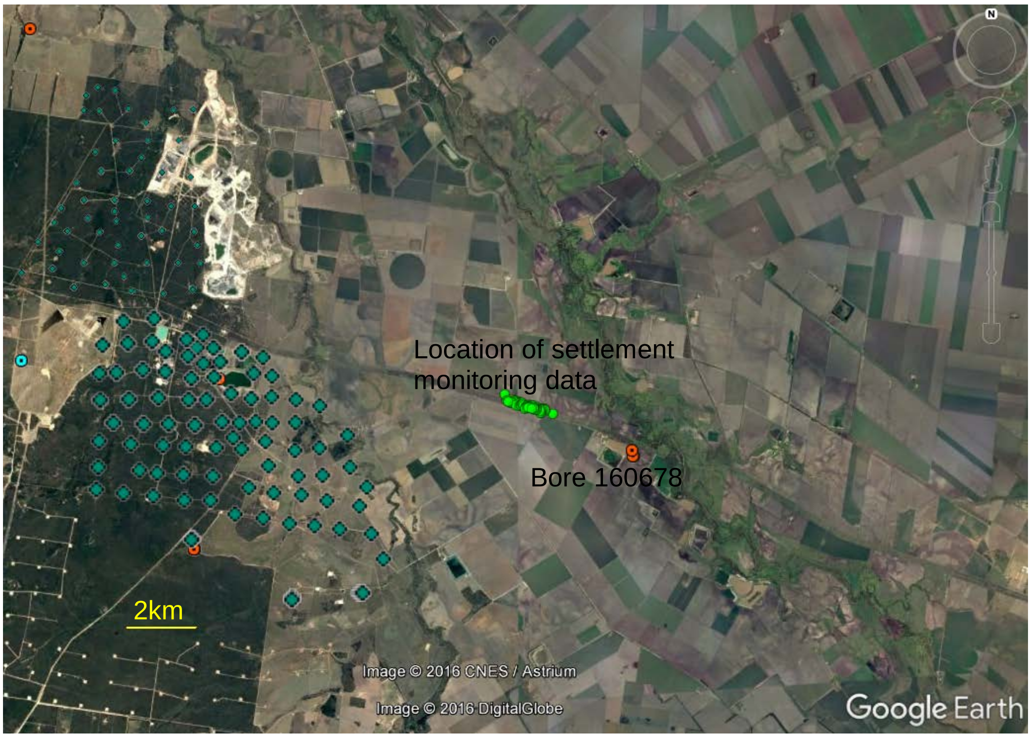


Figure 14 - Location Bore 160678 and settlement monitoring data location

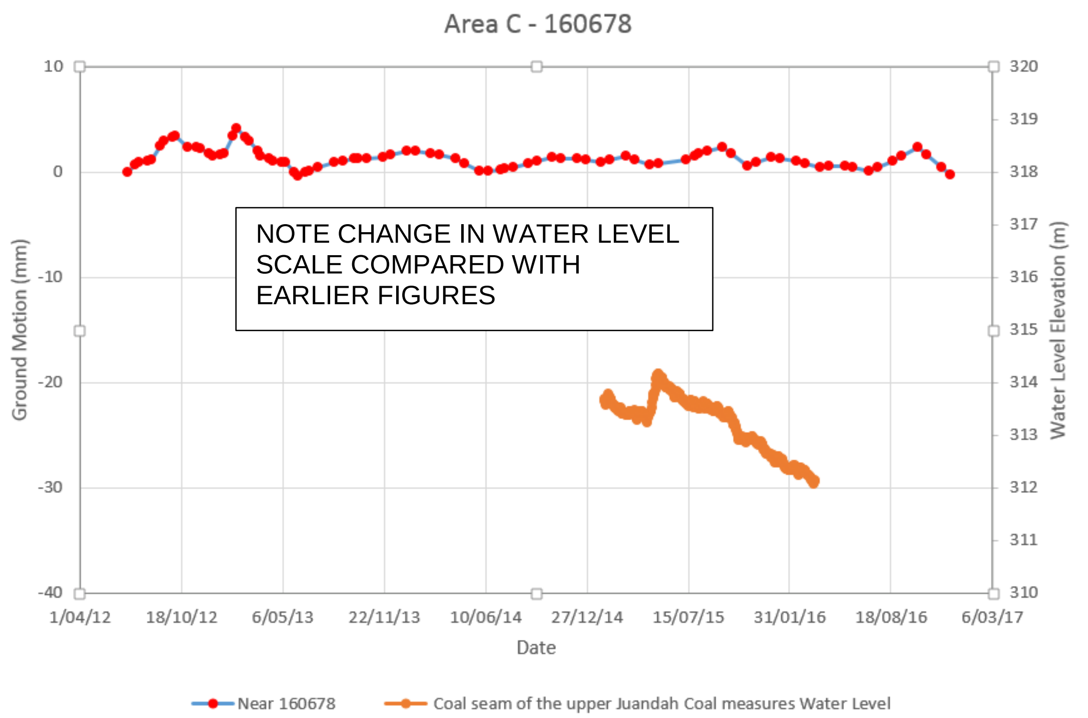


Figure 15 - Measured groundwater response Bore 160678 (8 km west of Daandine CAG field)

3.2.2. Settlement response to drawdown

The results of monitoring groundwater level variation and settlement provide a basis for assessing settlement as a function of groundwater level in the coal measure rocks of the Walloon Coal Measures. The Walloon Coal Measures are approximately 325 m thick in the current areas of operation of the Arrow domestic gas production fields (Tipton, Daandine, Kogan and Stratheden) as illustrated from drilling record for Bore 160802 (and adjacent bores) shown in Table 1 below. For the purposes of this assessment the Eurombah Formation (a sandstone unit) which is the lowest unit in the Walloon Coal Measures was not considered as it showed little drawdown response to CSG operations.

Table 1: Stratigraphy – Aggregated from Bore 160802 and adjacent 160553 (Daandine)

Formation	Top Depth (m)	Base Depth (m)	Top RL[1] (mAHD)	Base RL (mAHD)	Thickness (m)
Undifferentiated	0	5.99	337.18	331.19	5.99
Westbourne Formation	5.99	112.88	331.19	224.3	106.89
Springbok Sandstone	112.88	155	224.3	182.18	42.12
Juandah Sandstone	155	380.43	182.18	-43.25	225.43
Tangalooma Sandstone	380.43	381.63	-43.25	-44.45	1.2
Taroom Coal Measures	381.63	481.18	-44.45	-144	99.55
Eurombah Formation	481.18	not encountered	-144	-	-

1: Surface level 337.18 mAHD

Groundwater level monitoring in the Daandine CSG field indicated substantial drawdown in the Walloon Coal Measures (in both the Juandah and Taroom). Over the period November 2014 to March 2016 drawdown averaging 78 m occurred in the Juandah and 49 m occurred in the Taroom. Averaged over the Walloon Coal Measures, recognising the greater thickness of the Juandah, this corresponds to a decline in groundwater level of 69 m over the period November 2014 to March 2016. The InSAR results prepared by Altamira show a settlement of 11.4 mm over this period (see Figure 11).

Recognising that little drawdown occurred in the units above the Juandah Coal Measures or below the Taroom Coal Measures (taking a thickness of 325 m) an assessment of the average Young's Modulus of these units was made assuming a Poisson's ratio of 0.25. This gave a value of 16 GPa for Young's modulus using the relationship discussed in Section 5. This is higher than would be expected for the coal measure rocks. In other work, values of 10 GPa have been adopted for sandstone and 2 GPa for coal (Santos 2014). Allowing for 25 m of coal within a thickness of 300 m of Walloon Coal Measures, this would give an effective modulus of 7.6 GPa (note: harmonic averaging used rather than an arithmetic averaging).

$$E' = \frac{B\ \alpha\ \delta u}{\delta}\ \frac{(1+v')(1-2\ v')}{(1-v')} = \frac{325\ m\ x\ 690\ kPa}{11.4\ mm}\ \frac{(1+0.25)(1-2\ x\ 0.25)}{(1-0.25)} = 16\ GPa$$

Where:

δ is the subsidence at the ground surface (11.4 mm over the period)

δu is the average pressure change in the unit (690 kPa over the period)

B is the thickness of the unit (325 m)

v' is the Poisson's ratio of the unit (0.25 assumed)

α is the Biot's coefficient of the unit (0.85 assumed)

E' is the drained Young's modulus of the unit

The interpreted settlement is 30 mm over four years from mid-2012 to December 2016 (see Figure 11). The change in groundwater level over this period is not clear in the monitoring because the groundwater level monitoring records do not go back far enough. For this reason, it is not considered productive to use this period for back analysis. The records do show a steep decline in drawdown within the Taroom from 82.4 mAHD on 2 February 2016 to 49.1 mAHD on 19 March 2016 (a drawdown of 33.3 m). Over this period a ground movement of 3 mm was obtained from the InSAR records.

If this movement is attributed to the Taroom alone a modulus of the Taroom coal measure rock is assessed as 7.8 GPa using the approach described above. This is an uncertain assessment given the short period and small settlement involved. Settlement could also be affected by climatic factors resulting in movement of a similar magnitude.

An assessment of modulus was also made based on the records at monitoring bore 160799 in the Tipton CSG Well Field (see Figure 13 for location). A measured groundwater level change from mid-November 2014 to late March 2016 of 49 m in the Juandah (upper Juandah and lower Juandah experienced very similar response) was associated with a settlement of 4.2 mm over the same period based on InSAR results in the area surrounding this bore. Records from construction of Bore 160799 indicate a thickness of the Juandah Coal Measures of 165 m. Based on these results a modulus of 13.6 GPa for the Juandah is assessed using the approach described above. Again there is a significant level of uncertainty given the low magnitude of the settlement and the possibility of shallow influences from climatic or other effects.

The above assessments are based upon results at a single location and contain interpretation of settlement which is subject to uncertainty. It is therefore recommended similar assessments are carried out, as further data providing correlation between settlement and groundwater drawdown becomes available.

4. Surat Gas Project

4.1. Observed response

In order to assess the variability of the InSAR movement results, two sites well away from present CSG extraction were selected at the locations illustrated in Figure 16. Each selected area is rectangular and approximately 2 km^2 in area. One area was of cleared farmland (Site A) while the other contained tree cover (Site B). These sites are within Drainage Area DA5.

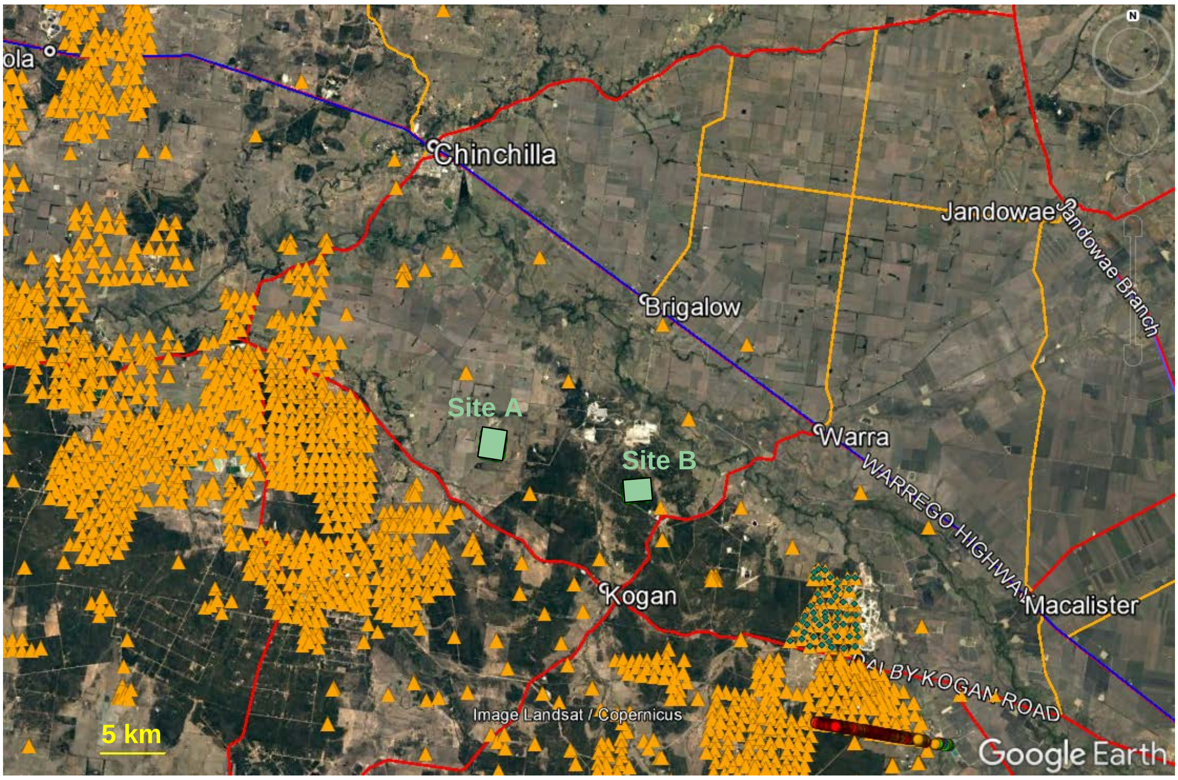


Figure 16 - Sites selected for background InSAR response (yellow triangles show locations of installed CSG wells based on the Queensland Government Globe)

The variation in InSAR interpreted movement over the period April 2012 to December 2016 is shown for the two sites in Figures 17 and 18. The cleared site (Site A) displays a substantially higher level of variability with a spread of results over a 90 mm span at the end of the period, while the tree covered site (Site B) showed less variability, with results predominantly within a 40 mm span at the end of the period.

The average of the results (as shown by the blue markers and line near the centre of the band of results) provides a consistent response in both cases. For the farmland the results indicated on average no vertical movement over the monitoring period while a gradual rise in ground level of 10 mm over the period for the area with tree cover. The reason for this rise is not clear.

Small scale changes in the average movement at each site of the order of 5 mm occur in a pattern consistent between the two sites, and are considered likely to relate to climatic effects influencing upper soil moisture and resulting shrink swell response.

It would be useful to select reference sites to check for background movements associated with climatic conditions for comparison with movement monitoring in the vicinity of SGP drainage areas.

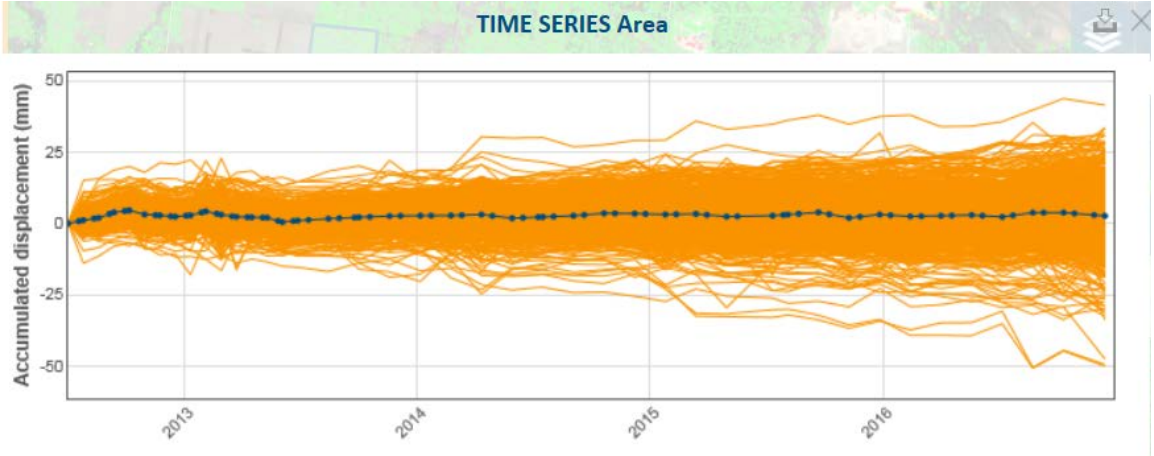


Figure 17 - InSAR movement results - Cleared farmland (Site A)

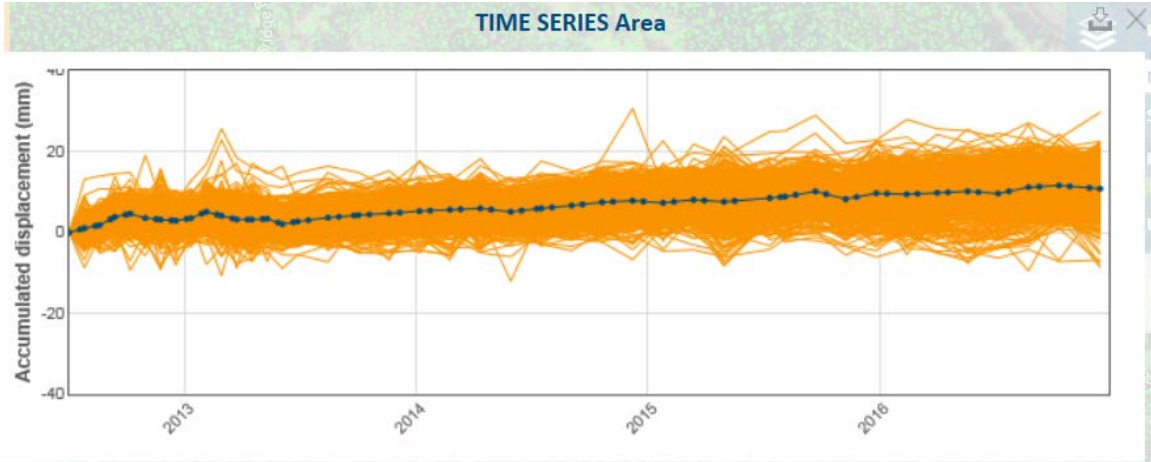


Figure 18 - InSAR movement results - Area with tree cover (Site B)

4.2. Predicted drawdown

Predictions of drawdown resulting from the Arrow SGP operations are presented in a technical memorandum prepared by Coffey (*SGP Stage 1 CSG WMMP: Groundwater modelling technical* memorandum, 1 December 2017) for Arrow. The predictions are based upon modelling carried out by GHD (2013) using the OGIA 2012 Groundwater Model (QWC, 2012). Predictions of drawdown were developed for the effects of operations by Arrow alone as well as predictions of Arrow in combination with the other CSG producers.

The effects of CSG operation take time to develop and so predictions were developed for three times (2030, 2050 and 2094) to account for the progressive geographical spread of CSG operations and the timing of drawdowns associated with development of individual leases.

Figure 19 presents the predicted drawdown at 2030 within the Springbok Sandstone (the unit overlying the Walloon Coal Measures), the Walloon Coal Measures and the underlying Hutton Sandstone (the unit underlying the Walloon Coal Measures) due to Arrow SGP operations alone.

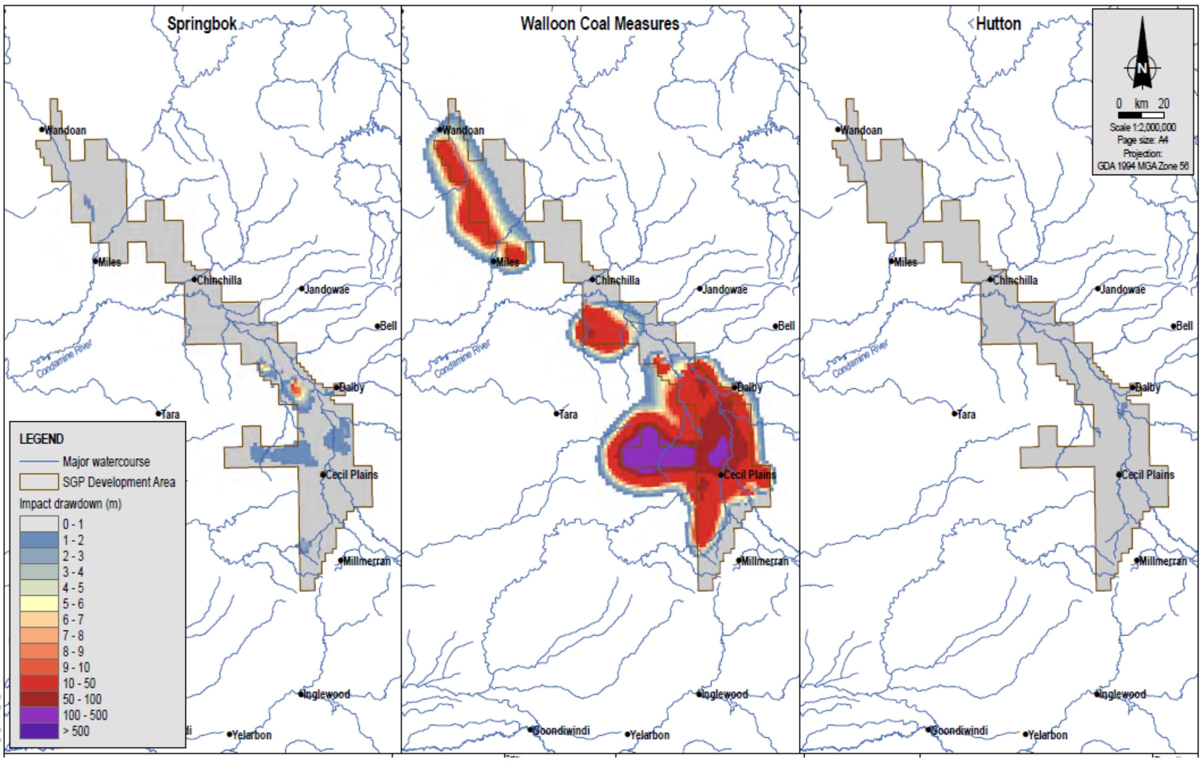


Figure 19 - Predicted drawdown by 2030 due to Arrow SGP operations

By 2030 in the Arrow SGP leases, the predicted drawdown in the Springbok Sandstone is less than 3 m and the predicted drawdown in the Hutton Sandstone is less 2 m with much larger drawdown of in excess of 100 m predicted within the Walloon Coal Measures.

Figures 20 and 21 present the prediction of drawdown for the same formations by 2050 for Arrow SGP operations alone for the years 2050 and 2095. In both cases the predicted drawdown within the Springbok Sandstone and Hutton Sandstone was much less than that predicted in the Walloon Coal Measures.

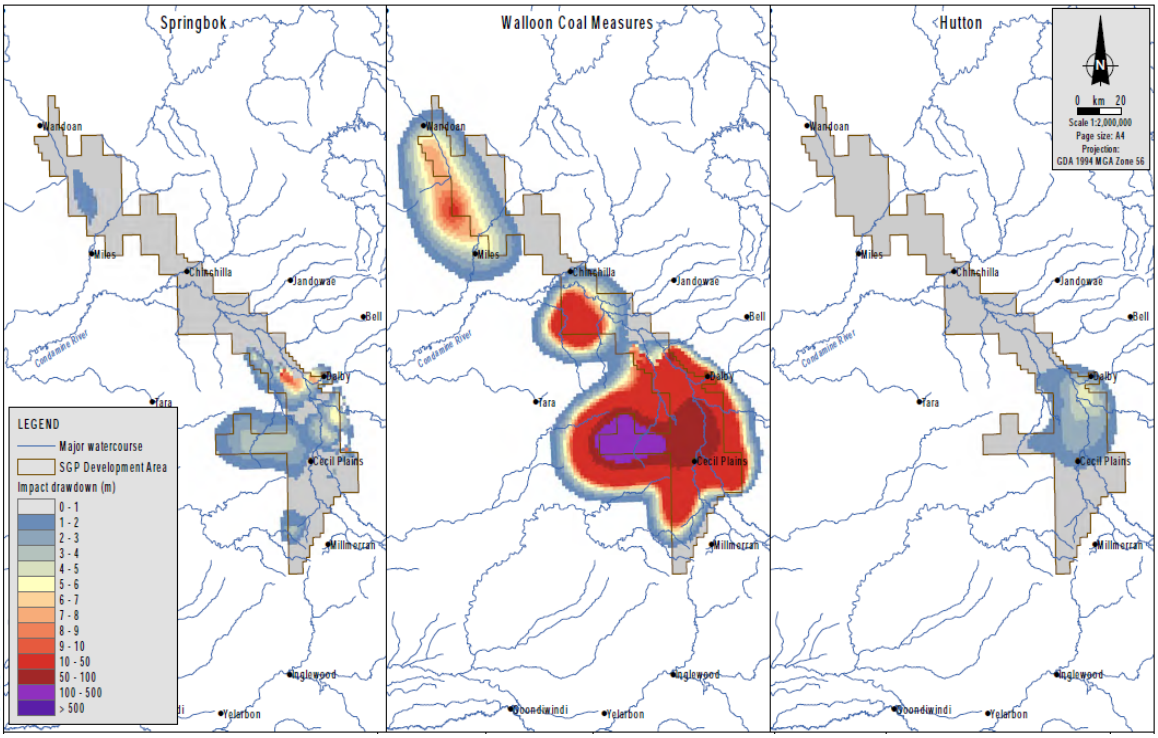


Figure 20 - Predicted drawdown by 2050 due to Arrow SGP operations

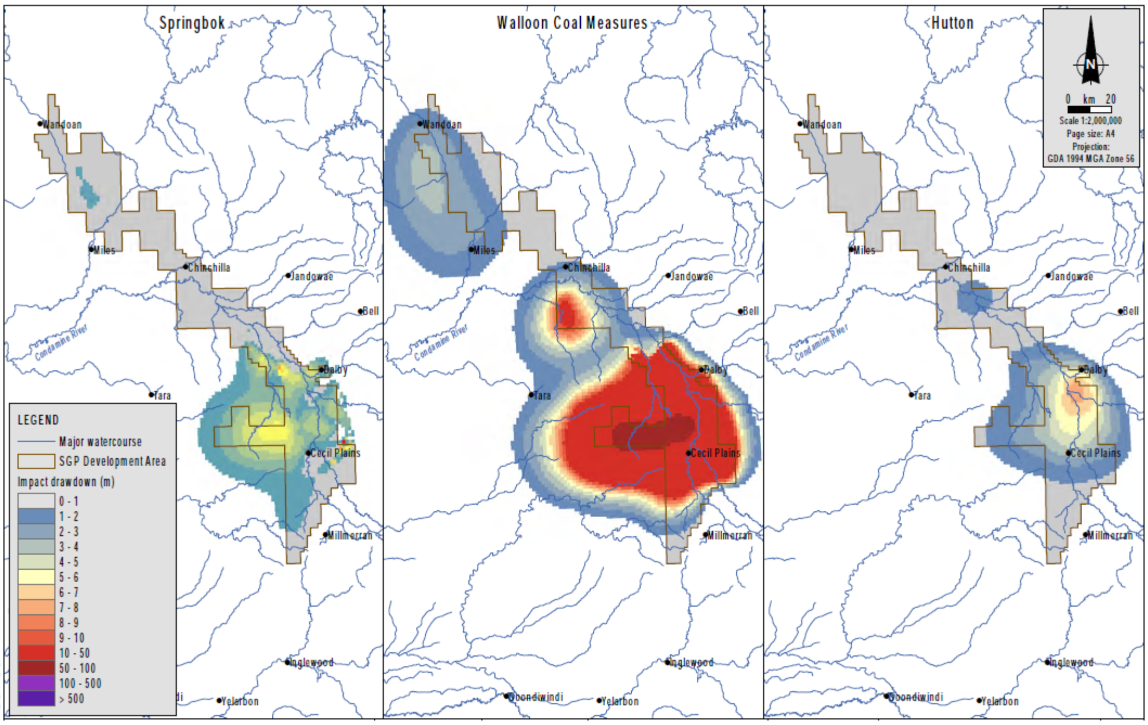


Figure 21 - Predicted drawdown by 2094 due to Arrow SGP operations

Based on the results of these predictions it is clear that the drawdowns predicted for 2030 are typically being larger than those predicted for 2050. The predictions for 2090 show reduction in the peak drawdown and spreading of the area of influence within the Walloon Coal Measures.

Figure 22 presents the predicted drawdown for Arrow plus the other CSG proponents for the year 2050. Over much of the area (and in particular in the Arrow SGP drainage areas and the nearby areas) the combined drawdown for 2050 is typically greater than that predicted for 2030 or 2094. Again the drawdown predicted in the Springbok Sandstone and Hutton Sandstone is substantially lower than that predicted for the Walloon Coal Measures.

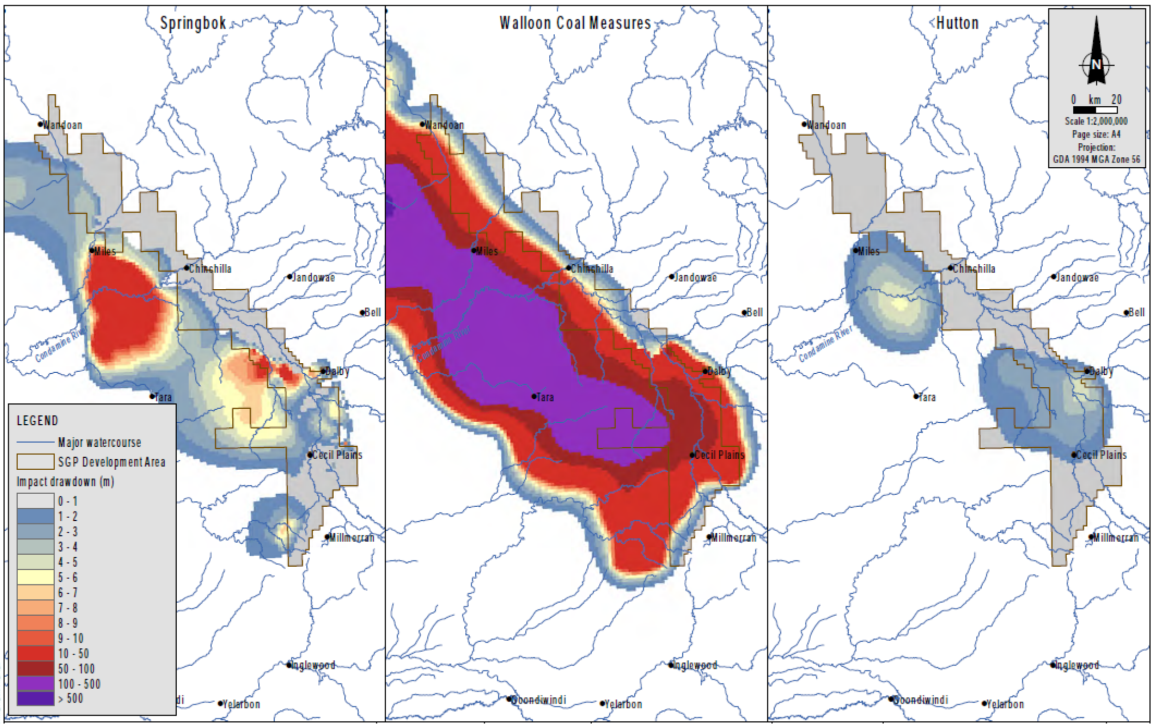


Figure 22 - Predicted drawdown by 2050 due to combined CSG operations (Arrow and other CSG proponents)

It is also clear that the magnitude of drawdowns predicted for the Arrow SGP are a small component of the overall predicted drawdown impacts.

In addition to the assessment of drawdown contained in the SREIS report Arrow have indicated that for production CSG well fields that:

> *The Target Flowing Pressure is around 35 Psi at the bottom of lowest Seam or Water Level around 5 to 10 meter below the lowest seam (Condamine coal seam).*

This is interpreted to mean that for the Juandah the groundwater level would be at 24 m (24 m water head is equivalent to 35 psi) above the base of the Argyle and for the Taroom the groundwater level 24 m above the base of the Condamine. These values would reflect conditions at the well. Away from the well, groundwater level would rise and average groundwater level between wells could be substantially higher. The extent to which average groundwater levels would depart from conditions in the vicinity of production wells will be a function of the local geology, the density of CSG operating wells, the timing and the operating conditions. For the purposes of this assessment the drawdown predictions based on groundwater modelling report by Coffey (2016) were used for subsidence assessments set out in Section 5.

5. Assessment of Subsidence

Subsidence can be assessed by considering the mechanical properties of each component within the geological profile together with predictions of water pressure changes, to predict compression of each stratigraphic component. The total subsidence experienced at the surface can then be determined by integrating the individual component compressions.

Subsidence associated with this mechanical process is expressed using the following relationship (based upon integration of one dimensional settlement of an elastic material under pore-pressure change – stress stain relationships are described in Sanderson (2012)):

$$\delta = \int_{z=\infty}^{z=0} \delta u \, \alpha \, \frac{(1+v')(1-2\,v')}{(1-v')E'} \, dz$$

Where:

δ	is the subsidence at the ground surface
z	is the depth below the ground surface
δu	is the pore pressure change at depth z below the ground surface
v'	is the Poisson's ratio of the ground at depth z
α	is the Biot's coefficient of the ground at depth z
E'	is the drained Young's modulus of the ground at depth z

Ideally, calculations would be based on the measured properties of each formation or rock type. However for the project area, measurements of the mechanical properties of each of the geological units affected are limited to unconfined compression tests of core samples from borehole Stratheden-61 (within lease PL252). The results in Table 2 are set out in the Arrow Well Completion Report for this borehole.

Table 2: UCS test results- Stratheden-61 core

Sample ID	Depth (m)	Lithology	Formation	Uniaxial Compressive Strength (MPa)	Secant Young's Modulus (GPa)	Corrected Poisson's Ratio
GT016	92.39	Sandstone	Kogan (Upper Juandah)	9.3	8.3	0.42
GT018	102.09	Siltstone	Kogan (Upper Juandah)	9.7	4.18	0.09
GT024	117.1	Coal	Macalister (Juandah)	7.0	2.45	0.22
GT025	123.49	Coal	Macalister (Juandah)	9.5	3.13	0.3
GT027	126.84	Sandstone	Macalister (Juandah)	9.4	1.34	0.25

Measurements in the area for other geological units have not been identified.

A review of the test results indicated that the secant Young's modulus values interpreted were based in some cases after the sample was in significant distress and may therefore not be representative of behaviour of intact material at depth under lateral confinement. In particular, sandstone is expected to be significantly stiffer than coal. In an earlier assessment of subsidence at Moranbah (located in the Bowen Basin) Coffey adopted the following values:

- Modulus of sandstone 10 GPa
- Modulus of coal seams 3 GPa

Biot's coefficient is a value relating the effective stress change in rock (the stress carried by the solid matrix) to the pore pressure change. For a sandstone this could be expected to be in the range 0.75 to 0.9 (Sanderson 2012). For the purposes of this study a value of 0.85 was adopted.

An assessment of potential subsidence carried out by ARUP (2014) employed a series of approaches for assessment of ground movement:

1. Use of shear modulus and Poisson's ratio to assess volume compressibility.
2. Use of specific storage adopted for groundwater modelling work to assess settlement.
3. Use of porosity and void ratio derived from geophysical testing.

These methods, that each involve different approaches to assess the relevant mechanical properties of the ground, are all subject to significant uncertainty. Therefore judicious interpretation is required. ARUP (2014) predicted settlement of up to 85 mm after 25 years though higher values were recognised as being possible.

For this work, Coffey makes use of results of subsidence measurements combined with measured drawdown in the Daandine CSG field. Use of direct measurements is considered to provide a more robust basis for assessment. This approach was unavailable to ARUP as no subsidence measurements due to CSG extraction were available at the time of their assessment. The use of field scale measurement readily takes account of the averaging across the thickness of the affected geological units to obtain average behaviour, without needing to make separate assessments for changes in lithology within each geological formation.

Hence, the approach adopted by Coffey for this assessment was as follows:

1. Records of subsidence within the Daandine CSG field were reviewed.
2. Records of drawdown measured within the Daandine CSG field were reviewed.
3. Correlation between the measured drawdown and interpreted subsidence used to develop an effective Young's modulus for the Walloon Coal Measures.
4. Predictions of maximum drawdown were used to assess maximum subsidence within Arrow SGP.

For the purposes of this memorandum two assessments of long term subsidence associated with CSG extraction were made for the Arrow SGP. These assessments used different modulus values and drawdown estimates, as follows:

- **Low assessment:** This assessment was made using the higher of the effective modulus values (13.6 GPa) assessed in Section 3.3 together with a range of drawdown values covering drawdown predictions. No contribution from reduction of coal thickness due to loss of coal seam gases is included.
- **High assessment:** A second assessment was made for a range of drawdown values and using the lower of the effective modulus values 7.8 GPa) assessed in Section 3.3. An additional allowance of settlement is included associated with reduction in thickness of the accumulated coal bands due to loss of coal seam gasses. This is based on an assumed strain of 0.001 across 25 m of coal seams for each 50 m head change (after Robertson (2005) as quoted in Section 2.1).

It should be noted that these assessments do not necessarily represent the encompassing range of settlement, as the linkage between settlement and drawdown is based upon very limited information. Other data might provide a different range. The assessments of modulus are based on limited field records and the assessment of volume loss due to coal seam gas loss for the coal components of the profile is based on a single published result which may not reflect the conditions in the Surat. As a result, the settlement predictions carry uncertainty.

Example calculations for the low assessment and high assessment cases are presented below. In each case a thickness of 325 m for the Walloon Coal Measures, including an aggregate thickness of 25 m of coal seams, was adopted.

Low Assessment

Allowing a typical thickness of 325 m for the Walloon Coal Measures for the low assessment, settlement of 0.17 mm is associated with each 1 m of average drawdown (10 kPa) across the Walloon Coal Measures (adopting the method in Section 3.3):

$$\delta = \frac{B\ \alpha\ \delta u}{E'} \frac{(1+v')(1-2\ v')}{(1-v')} = \frac{325\ m\ x\ 0.85\ x\ 10\ kPa}{13.6\ GPa} \frac{(1+0.25)(1-2\ x\ 0.25)}{(1-0.25)} = 0.17\ \text{mm}$$

The OGIA predicted drawdown indicates that the bulk of the drawdown response within the Arrow SGP leases is predicted to occur within the Walloon Coal Measures with little response in overlying and underlying units as indicated in the groundwater modelling results presented in Figure 19 to 21.

High Assessment

For the high assessment a settlement of 0.30 mm is associated with each 1 m of average drawdown in the Walloon Coal Measures:

$$\delta = \frac{B\ \alpha\ \delta u}{E'} \frac{(1+v')(1-2\ v')}{(1-v')} = \frac{325\ m\ x\ 0.85\ x\ 10\ kPa}{7.8\ GPa} \frac{(1+0.25)(1-2\ x\ 0.25)}{(1-0.25)} = 0.30\ \text{mm}$$

A further 25 mm is allowed for coal thickness reduction due to loss of coal seam gasses for each 50 m of drawdown.

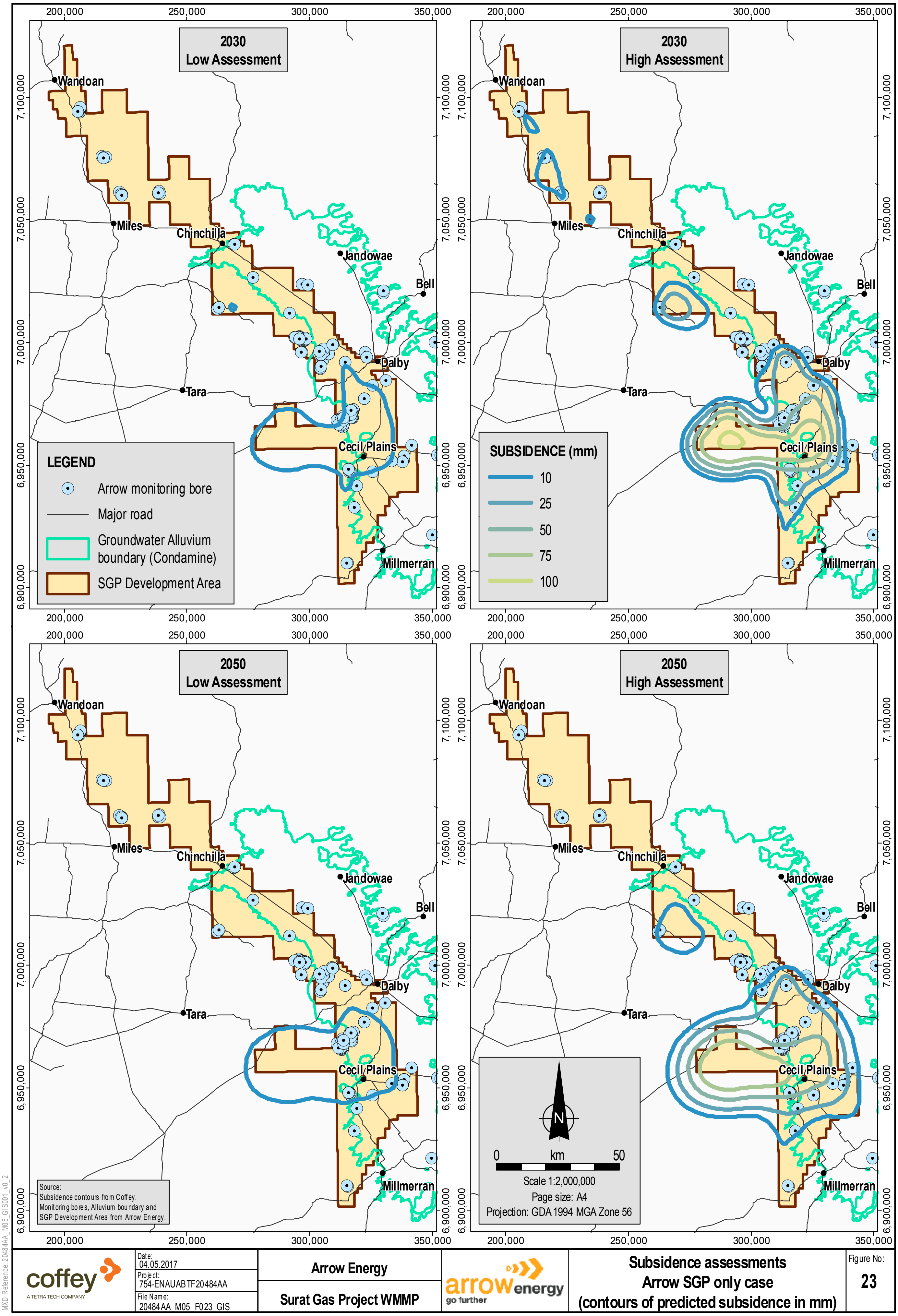
Thickness contours of the Walloon Coal Measures (shown Figure 4) were combined with the predicted drawdown showing in the figures in Section 4.2 using the methods described in this section to assess subsidence.

Figure 23 presents assessed subsidence contours associated with predicted drawdown from Arrow SGP operations alone for 2030 and 2050 for both the high and low settlement assumptions set out above. Predicted subsidence is limited to the Arrow SGP leases and their immediate surrounds. For the low assessment, predicted subsidence is minimal and based on experience to date would seem to understate potential subsidence. For the high assessment subsidence is predicted to be within 100 mm. Subsidence within the Condamine Alluvium is predicted to be up to 75 mm within the southern part of the SGP due to the Arrow SGP alone in 2030 and 2050.

Figure 24 present assessed cumulative subsidence contours associated with predicted drawdown from Arrow and other operations for 2030 and 2050 for the high and low settlement assumptions. Under this scenario, predicted subsidence in the vicinity of the Arrow leases is significantly greater than that predicted for the Arrow activities alone.

For these cumulative case assessment figures, the peak subsidence in 2050 is lower than in 2030 in some locations. These are shown in Figures 25 and 26 for the Arrow SGP Only Case and the Cumulative Case overlaid upon the Arrow SGP drainage areas. The assessment process adopted does not account for recovery of groundwater levels and the predicted reduction in subsidence shown in the contour plot is not anticipated as the subsidence process is considered to be largely irreversible. Subsidence should be taken as the maximum value over time obtained from the assessment process employed.

The largest subsidence of 100 mm associated with the Arrow SGP due to the SGP alone is predicted to occur within Drainage Area DA11. Larger subsidence values are predicted to the west of the SGP associated with drawdown due to CSG production by other proponents. Within the SGP subsidence including the effects of other proponents of up to 120 mm is predicted within Drainage Area DA11.



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Date: 04.05.2017
Project: 754-ENAUABTF20484AA
File Name: 20484AA_M05_F023_GIS

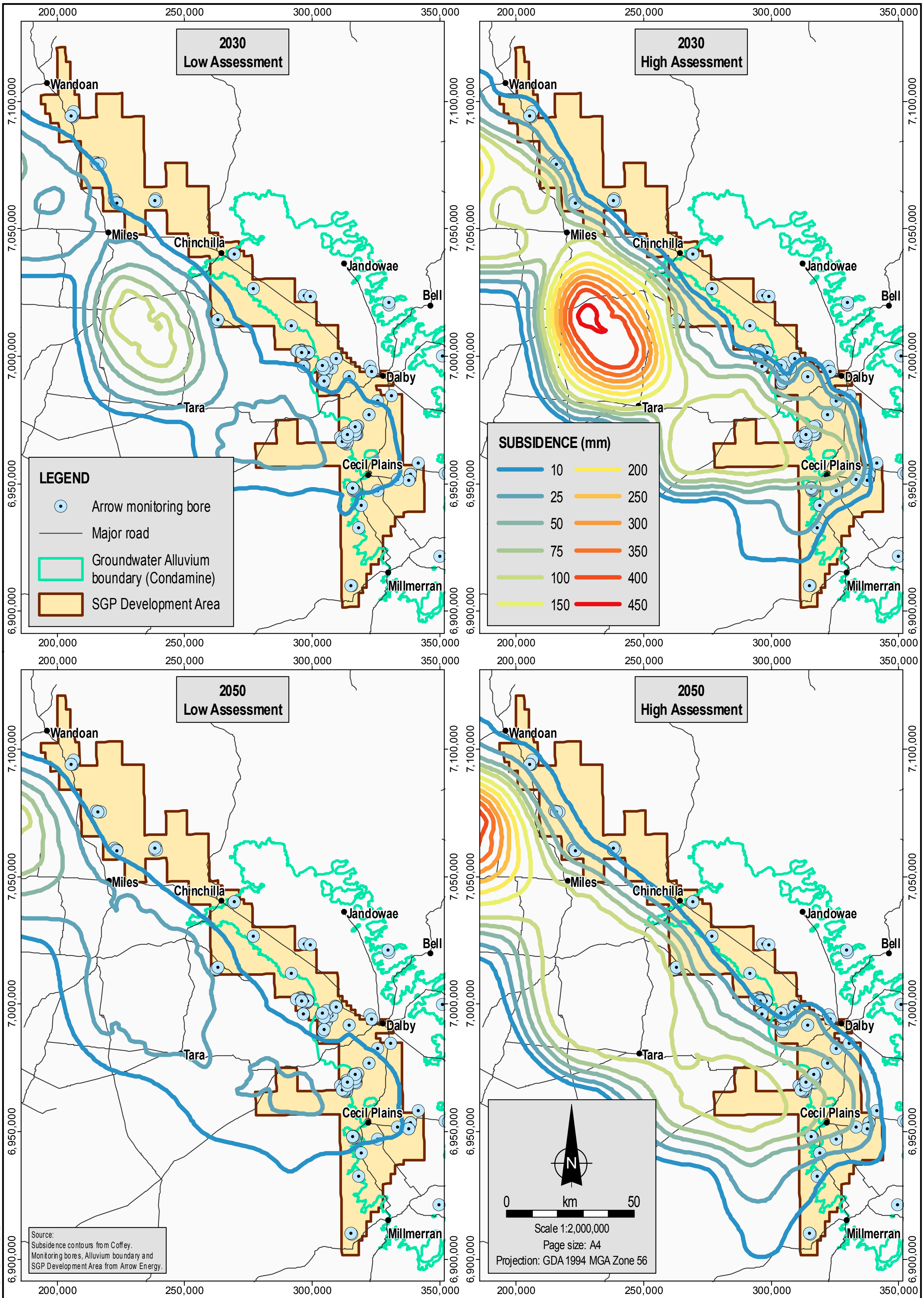
Arrow Energy

Surat Gas Project WMMP

arrow energy
go further

Subsidence assessments
Arrow SGP only case
(contours of predicted subsidence in mm)

Figure No:
23



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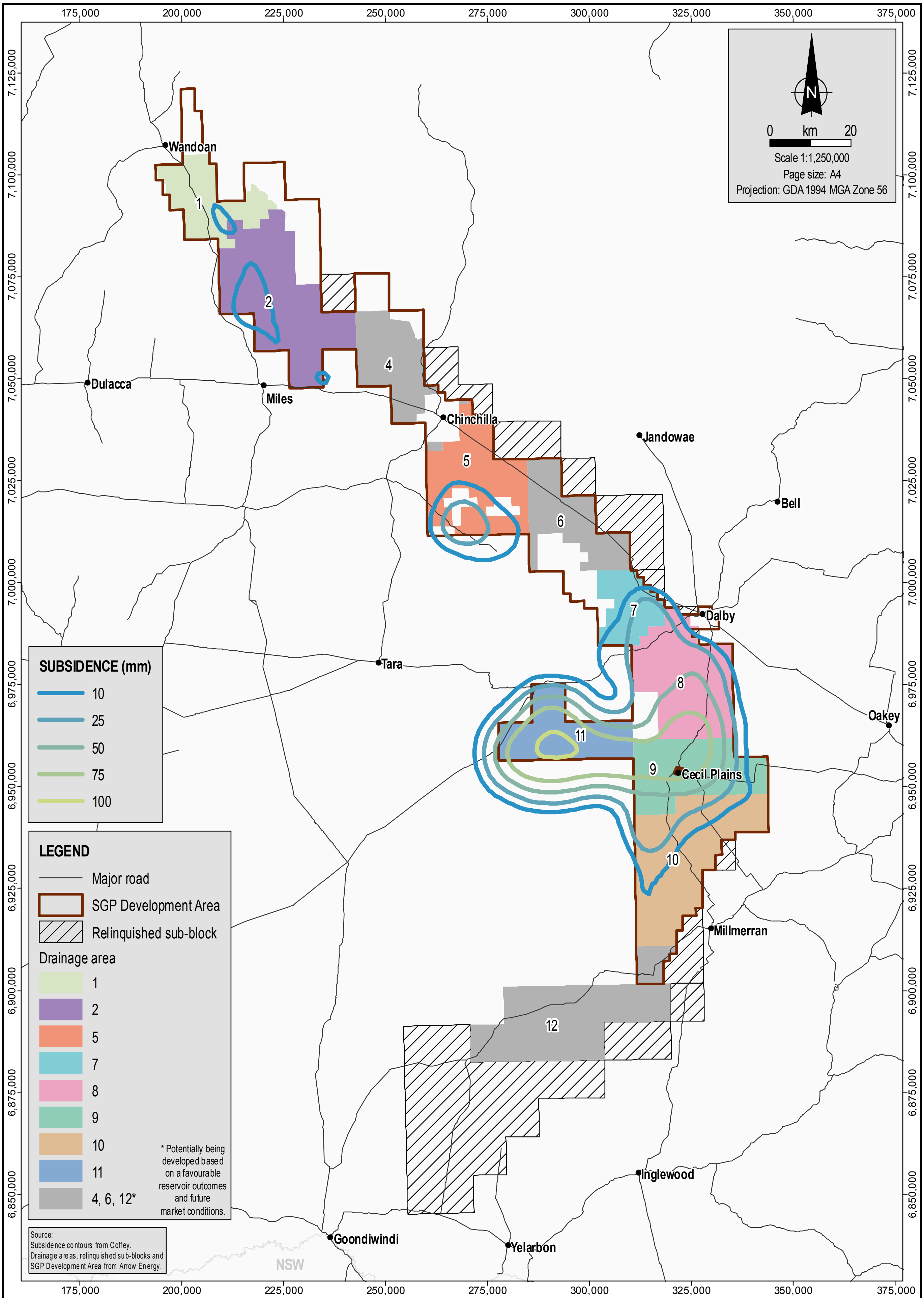

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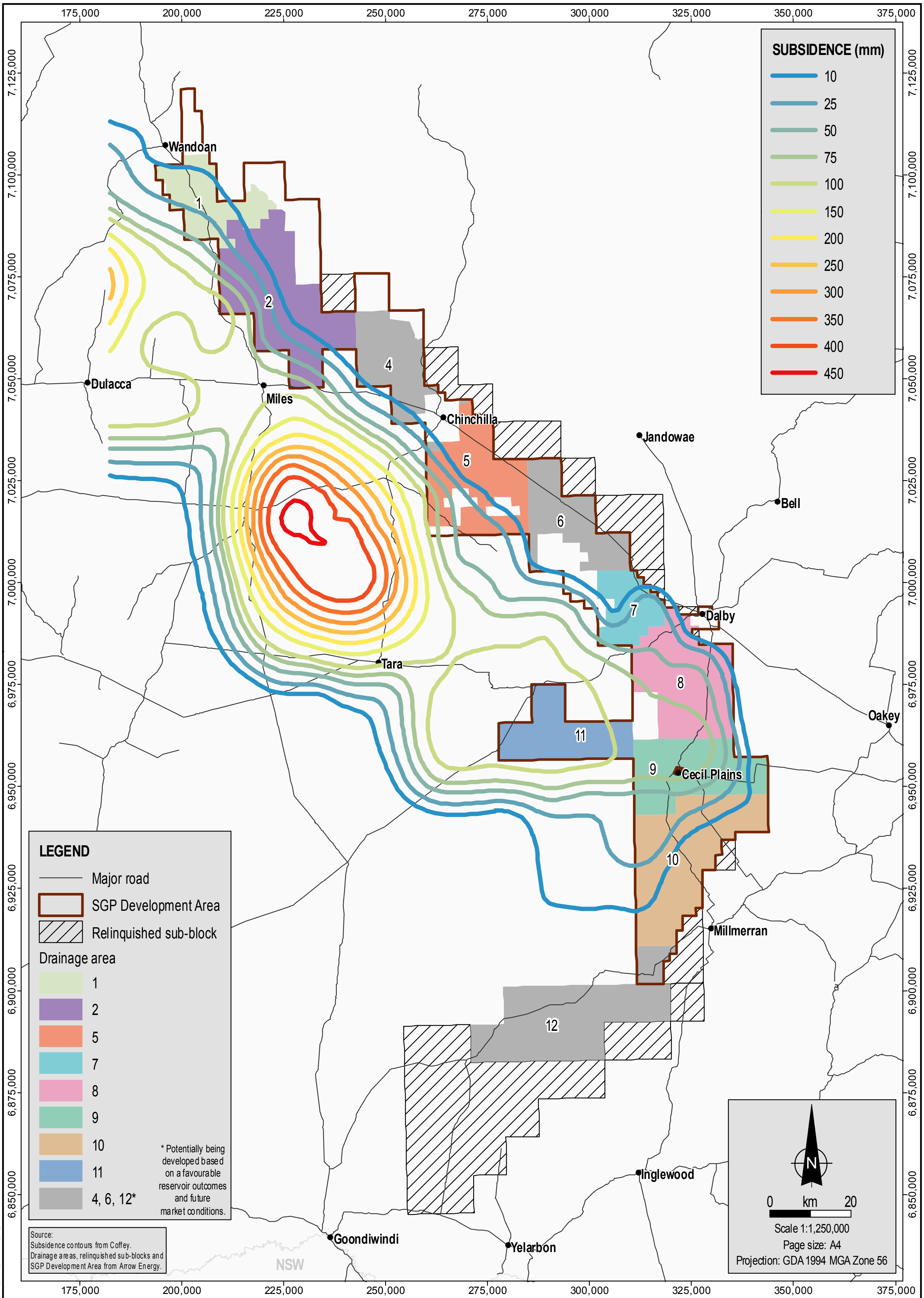
Date: 04.05.2017 Project: ENAUABTF20484AA File Name: 20484AA_M05_F025_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted Subsidence 2030 (contours in mm) High Assessment - Arrow Only Case	Figure No: 25

MXD Reference: 20484AA_M05_GIS003_v0_2



MXD Reference: 20484AA_M05_GIS004_v0_2

coffey A TETRA TECH COMPANY	Date: 04.05.2017 Project: ENAUABTF20484AA File Name: 20484AA_M05_F026_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted Subsidence 2030 (contours in mm) High Assessment - Cumulative Case	Figure No: 26

6. Risk Assessment

An assessment of risk associated with ground subsidence associated with the Arrow SGP was carried out.

Risk associated with subsidence are developed though consideration of the likelihood of impacts of a nominated magnitude and the consequence of such an event. Subsidence can have an impact on the following assets:

- Linear infrastructure – roads, pipelines, rail lines, power lines, irrigation canals.
- Buildings and structures.
- Rivers and streams.
- Farm irrigation systems.
- Swamps and low lying areas.

Review of the existing use of the areas within the Arrow SGP and in the vicinity reveals the following assets:

- Roads, rail lines, power lines, pipelines.
- Farmland including irrigation on land laser levelled land.
- Forested areas.
- Small dams.
- Condamine River and tributaries.
- Farmhouses and other small buildings.
- Mines and mine infrastructure.

The potential impacts upon these assets are discussed in the following sections. In considering potential impacts consideration needs to be given to absolute magnitude and the differential settlement.

Potential impacts on general farmland, small dams, and river flow for movements of less than 100 mm over distance of 1 km are not considered likely to result in adverse impacts and these have not been considered further. Mines and mine infrastructure are typically subject to ground movement associated with the mining operation and are considered unlikely to be adversely affected by the magnitudes of subsidence anticipated. Hence, they are not considered further. Farmhouses, farm sheds and other small buildings can be assessed under the criteria for other buildings and structures.

Laser levelling is carried out for farms to facilitate efficient use of irrigation water. Subsidence occurring after farm levelling has taken place could potentially affect irrigation performance by changing the slope of the ground. The orientation of the change in slope in comparison with the alignment of furrows and drainage channels is relevant to the assessment of potential impacts on laser levelled farm plots. A change in gradient of 30 mm per 100 m (refer Section 6.6) is used as an investigation level at which further investigation will be carried out for affected areas.

6.1. Risk assessment approach

The risk management strategy for Arrow SGP should comprise the following:

- Formulate a risk assessment and mitigation measures register.
- Adopt appropriate design to reduce residual risk to acceptable levels.
- Implement appropriate field monitoring during various stages of construction.
- Conduct additional geotechnical investigations at the appropriate time.

The proposed risk assessment is further discussed below.

Risks associated with subsidence caused by CSG extraction are assessed using the approach set out in the Australian and New Zealand Standards Association Handbook SA/SNZ HB 89:2013. Within this framework, an ‘event’ is considered as CSG induced subsidence movement affecting an existing asset. The likelihood of subsidence of a particular magnitude has been assessed by reference to the subsidence measured to date, and the predictions for future subsidence. The consequence of an event of particular magnitude is assessed based on the nature of an asset and its sensitivity to movement.

The risk associated with particular events is assessed based on the likelihood of movement above a particular magnitude and the sensitivity of the asset affected. A consequence/likelihood matrix approach has been adopted for assessment of risks. The definition and risk evaluation matrix are recommended to be reviewed following consideration by Arrow for consistency with their corporate risk stance.

For the purpose of this assessment the definitions of likelihood (Table 3) and consequence (table 4) are adopted

Table 3: Likelihood category definition

Likelihood Category	Description
Rare	The event may not occur or if it does it will occur over less than 0.1% of the lease area
Unlikely	The event may occur over a small proportion 1% of the lease area
Possible	Instances of the event would occur in a number of places though not more than 10% of the area
Probable	Will occur over most of the area
Certain	The event will occur over a widespread area

Table 4: Consequence category definition

Consequence	Description
Insignificant	Little influence on
Minor	Noticeable influence without serious consequences Damage caused tolerated with possible compensation payment (less than $10,000)
Medium	Rectification works or substantial additional monitoring required (costs less than $1,000,0000) Local press critical of outcome
Major	Substation rectification works in excess of $5m required Environmental damage requiring intervention or remedial works National press critical of outcome
Catastrophic	Serious environmental consequences Damage with major disruption to public facilities Loss of life or serious injury to people

The risk evaluation matrix in Table 5 is employed.

Table 5: Risk Matrix

Likelihood Category Rating	Consequence Category Rating				
	Insignificant	Minor	Medium	Major	Catastrophic
Rare	Very Low	Very Low	Low	Medium	High
Unlikely	Very Low	Low	Medium	High	High
Possible	Low	Medium	High	High	Very High
Probable	Medium	High	High	Very High	Very High
Certain	High	High	Very High	Very High	Very High

6.2. Linear infrastructure

The sensitivity of various structures to subsidence including roads, rail lines and pipelines are discussed in Commonwealth of Australia (2014). Table 6 summarises material from that document.

Table 6: Thresholds of adverse impact from ground movement – Linear infrastructure

Asset	Guideline	Potential impacts from SGP induced subsidence
Pipelines	Tensile strain less than 2% Slope change less than 1/140 Sewer pipeline 0.4% grade change	Negligible
Roads and highways	0.3 % over a chord length of 10 m	Negligible
Rail lines	Operation of railway services over areas affected by mine subsidence has proven manageable	Negligible
Drainage channels	Slope change relative operating gradients should be checked	Slope changes unlikely to significant

6.3. Buildings and structures

Guidelines for assessment of settlement impacts upon buildings exist for assessment of potential impacts from activities such as construction dewatering. Damage is a function of differential settlement rather than the absolute value and damage is also a function of horizontal strain. Figure 27 below by Burland (2012) provides an indication of the significance of differential movement on buildings. Results are presented in the form of damage categories for differing levels relative to deformation.

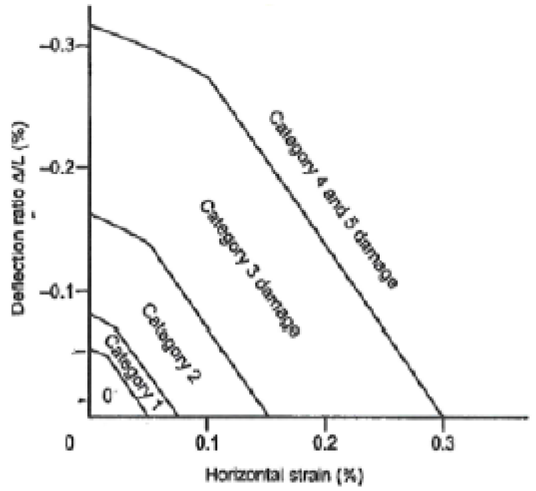


Figure 27 - Damage categories for buildings as a result of ground movement (Burland, 2012)

In Category 0 damage is described as negligible, limited to minor hairline cracks. Category 1 corresponds to minor architectural damage and Categories 4 and 5 correspond to major damage and risk of instability.

The deflection ratio is a measure of the change in vertical movement between two points and is illustrated in Figure 28.

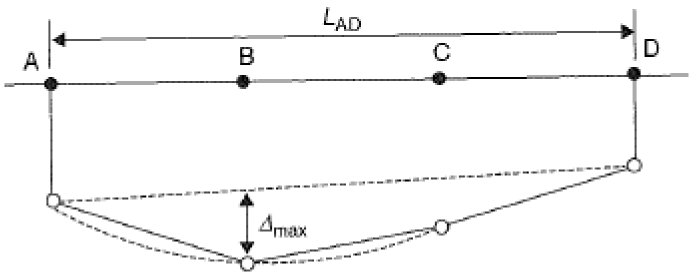


Figure 28 - Definition of deflection ratio (Burland, 2012)

As subsidence associated with SGP arises from compression of geological units at depth the changes at the surface will be gradual and no measureable horizontal strain is anticipated at the ground surface.

Rather than use of deflection ratio, use of differential settlement is adopted for assessment of the significance of differential movement for structures. For a uniform curvature the maximum differential settlement (the gradient of settlement) would be four times the deflection gradient. Taking a deflection ratio of 0.025% (half the limit for Class 0 damage (defined by Burland as negligible with hairline crack less than about 0.1 mm) this corresponds to a deflection gradient (change in deflection per unit length) of 0.1% or 1/1000. This is considered a conservative threshold for damage to buildings and other structures.

6.4. Dams

A water storage dam approximately 800 m by 450 m in area is present to the north of the Daandine CSG field. It is constructed using a raised perimeter embankment. Other water storages are present within or near Arrow SGP (including raw water dams, treated water dams and brine dams).

Tensile strains associated with CSG related subsidence could potentially result in cracking of embankment materials. For a compacted clay core, tensile strain of less than 0.5% is considered unlikely to have a material influence on its performance in a water retaining structure. Tensile strains approaching this magnitude are assessed as being highly unlikely to arise from subsidence induced by SGP CSG extraction.

No major dams are present within or in proximity to the Arrow SGP in the Surat Basin. If major dams where failure would cause significant risk to human life or the environment are to be constructed in the area (either project related or for other purposes) it is recommended that a separate assessment be made of subsidence potential and susceptibility as part of design studies.

6.5. Rivers and watercourses

Dafny and Silburn (2013) note that:

> *The Condamine plain occupies the area between Ellangowan (E151.67o, S27.92o) and Chinchilla (E150.72o, S27.74o), southern inland Queensland. It stretches over an area of about 7,000 km2, and is ~190 km long. Its upstream and downstream edges are narrow, but most of floodplain is 15-40 km wide. The topography drops steadily from the south-west to the north-east, from +400 m near Ellangowan to +350 m near Dalby and to +310 m near Chinchilla, with an overall topographic gradient of 0.5 m/km.*

Using the existing topographic gradient as a guide it is assessed that subsidence leading to changes in gradient of less than 5% of the existing gradient (0.025 m/km) would be unlikely to have significant impact on the performance of the Condamine River or tributary watercourses.

6.6 Farmland

Farming involving irrigation is carried out in the area potentially affected by Arrow SGP operations. Laser levelling is widely used to improve the efficiency of irrigation. The Cotton Research and Development Corporation (2012) recommend slopes in the range 1 in 500 to 1 in 1650 for furrow irrigation, advising that slopes steeper than 1 in 500 are subject to erosion and slopes flatter than 1in 1650 are subject to waterlogging. Similar experience is reported in research on the effects of slope on furrow irrigation of grain-legumes (soybean, navy bean, pigeon pea, adzuki bean, cowpea and mung bean) at Narrabri, New South Wales (Hodgson *et al* 1989). Field slopes of 1:500, 1:1000, 1:1500 and 1:2000 were evaluated.

As slopes established using laser levelling will generally be greater than 1 in 1650 (a gradient of 0.06 %) an investigation level of a 0.03 % (1 in 3300 or 30 mm in 100 m) change in slope is adopted as half the gradient of the flattest slopes likely to be employed below which changes in slopes are considered unlikely to be significant.

7. Subsidence Trigger Thresholds

Trigger thresholds have been developed for CSG induced subsidence as required by approval condition 13(g). They are derived from the calculated risk assessments of potential subsidence, and taking into account the outcomes of the risk assessment process.

An initial screening level has been set to identify areas for targeted assessment of settlement and assessment of whether the trigger thresholds have been exceeded. The general assessment process that will be implemented is presented in Figure 29.

It is clear from the discussion of potential impacts of subsidence on existing assets that absolute ground movement is generally less important than the differential movement over the extent of a relevant asset. Sensitivity to horizontal strain has been noted as relevant for a range of assets including dams, buildings, pipelines and roads. The form of subsidence that has been recorded to date indicates that development of horizontal strain will be extremely small. As a result investigation levels are nominated which do not include consideration of horizontal strain and risk associated with horizontal strain on assets is considered negligible.

Review of potential impacts on various assets indicates that differential settlement or change in slope is more relevant than total subsidence. A three-step assessment process is set out. Initial assessment would involve screening of areas where significant subsidence is occurring based upon the annual rate of subsidence reported from InSAR monitoring results. In areas where this significant movement is recorded further investigation will be carried out to identify movement with potential to impact on particular assets. The assets identified where potential impacts are identified will be subject to further investigation using conventional survey checking movement against the trigger thresholds in Section 6.

7.1. Screening level

Initial screening will involve identification of areas where significant subsidence is occurring based upon the annual rate of subsidence reported from InSAR monitoring results. This initial screening will involve identification of areas of 1 km by 1 km where more than 50% of the InSAR monitoring points indicate an annual subsidence rate of more than 8 mm/yr (a movement rate discernible using InSAR methods). In areas where this level of movement is recorded, further assessment will be carried out to assess whether the trigger thresholds as nominated in Table 7 are exceeded.

7.2. Investigation levels

In areas where the screening level is exceeded, further assessment of relevant data relating to subsidence will be undertaken. This will include an assessment of the CSG-related subsidence component of the reported InSAR measurements with consideration for the cumulative industry impact and reported subsidence since the commencement of the Arrow SGP operations.

Investigation levels have been defined as set out in Table 7. Where the CSG-related subsidence exceeds the investigation levels set out in Table 7, further assessment will be carried out to assess the site-specific infrastructure that may be impacted and identify whether an impact has occurred as a result of the Arrow SGP operations.

7.3. Trigger threshold

Where the investigation levels nominated in Table 7 are breached additional investigation of the affected area will be carried out using conventional survey methods for a period of six months. The results of the survey will be tested against asset-specific thresholds set out in Section 6 of this memo. For example in the case of structures, assessment of damage categories as a result of ground movement would be based upon the guidance presented in Burland, 2012.

Where adverse impacts are identified to have occurred based on the results of the site-specific investigation, a trigger threshold is considered to have been exceeded and mitigation measures will be employed following the approach set out in Section 7.6.

Table 7: Subsidence monitoring screening level, investigation levels and trigger threshold

Item	Description	Criteria	Relevant assets	Basis for selection / comment
Screening level	Settlement rate	8 mm/year (for >50% of sampling points in 1 km by 1 km block)	All natural features, man-made features and built infrastructure	Areas where this criteria is exceeded will be subject to investigation of subsidence.
Investigation levels	Gradient change	0.03 % (300 mm per 1,000 m)	Irrigation system (laser levelled)	Based upon half the slope of minimum grades recommended by the Cotton Research and Development Corporation for furrow irrigation. Areas where this criteria is exceeded will be subject to investigation of subsidence (refer Section 6), including review of laser levelling practices.
	Differential settlement (built infrastructure)	0.001 m/m	Buildings, structures	• Selected for buildings as the most sensitive item in this group (refer Section 6). • Not relevant to linear infrastructure (roads, rail, transmission lines and pipelines) as predicted differential settlement is well within the tolerance of these facilities. • Not relevant to bushland or farmland.
	Change in slope (natural features)	25 mm/1,000 m	Flood flow in watercourses	• Taken as 5% of topographic gradient of the Condamine Plain. • Applies only to the main channel of the Condamine River. • Review of effects on flow and conventional survey would be carried out to assess the significance of the change.
Trigger threshold	Outcome of site specific monitoring using conventional survey and review of risk to asset.	Individual threshold based on the local conditions	Irrigation system, structure or watercourse	Site specific assessment based upon conventional survey of identified asset. In the case of potential impacts on structures within populated areas the assessment will be based upon selected structures considered to be most vulnerable.

7.4. Industry trigger levels

A review has been undertaken of subsidence trigger levels and thresholds prepared by other CSG proponents in the Surat Basin. This has been presented here for reference.

Other proponents have nominated alternative trigger levels. For the Santos GLNG Project a subsidence trigger has been nominated as:

- *The subsidence trigger associated with CSG production (natural and anthropogenic non-CSG effects removed) is defined as an annual average ground motion of 16 mm/yr for over 50% of data points of a 1.5* km *x 1.5 km region*.

No explicit trigger level for subsidence was noted in QCG (2016). QGC listed the following activities in monitoring and management of subsidence in their 2016 water monitoring and management plan 2016 annual report:

- Ongoing Monitoring and Collection – The first year of analysed and processed data from the Stage 3 data acquisition (January 2015 to December 2015) was delivered on schedule in April 2016.
- Satellite Data Interpretation - The analysis of the average annual ground motion indicates that more than 98% of the study area is stable for the period from July 2012 to December 2015. Where there was movement above 8 mm per year it was primarily subsidence, 76% of which occurs in the CDA. Over the last 12 months of data acquisition, the rate of subsidence appears to have slowed over most areas.
- Ground Motion Trigger Assessment - An aggregation of the data from July 2012 to December 2015 into UWIR grid squares does not result in the triggering of the response plan for any area.
- Monitoring Data Management - Processed ground motion data, including the electronic vector files showing the location of the points, information on data quality and deformation values have been uploaded to the Web-based database, hosted by TRE Altamira and accessible to QGC, for the period from July 2012 to December 2015. The database is currently operating as planned, and has been successful in enabling the quick and accurate review and assessment of results.
- Ground Truthing - Condition 65a of the Department of the Environment approval specifies that the ground motion monitoring program must consist of a geodetic survey, so ground truthing is required.
- Five surveys have been completed for 29 identified permanent survey markers during the data acquisition period from July 2012 to December 2015. The results show an overall trend that is consistent with the results from the satellite-derived data.
- Predictive Assessments - In order to potentially predict ground deformation over time, QGC has used cumulative groundwater model outputs in conjunction with geo-mechanical theory to characterise potential deformation. The results of this geo-mechanical modelling indicate that the project is not expected to have any impact on the flow (direction or volume) of identified waterways of interest, and no wetlands within the QCLNG tenure are currently predicted to be impacted by ground motion.
- This predictive deformation assessment is being rerun using the outputs of the revised OGIA cumulative groundwater model which was delivered in September 2016.

7.5. Assessment of subsidence against screening, investigation and trigger levels

Assessment of subsidence measurement against the screening, investigation and trigger levels set out above should be carried out in a way that can allow comparison against the proposed thresholds. An initial screening should be carried out on the basis of movement exceeding 8 mm/yr to avoid assessment of areas of low movement. It is recommended that assessments of areas where movement rate exceeds 8 mm/yr over an area of 1 km by 1 km be investigated using aggregate subsidence since the commencement of CSG extraction in each drainage area. As the guidelines are expressed in terms of differential settlement and change of slope, the following approach is proposed:

1) Based on InSAR results identify areas of 1 km x 1 km for which 50% of the values exceed a settlement rate of 8 mm/yr.

2) For areas which meet the criteria in 1) above:

    a. Obtain interpreted cumulative subsidence since the commencement of CSG extraction for areas of active production.

    b. Where subsidence exceeding 100 mm[1] over areas greater than 1 km^2 (a reasonable measure of area surrounding a single CSG well) are encountered apply the following method:

        i. Prepare traverses averaging subsidence assessed using InSAR results over a 100 m wide band crossing the area affected.

        ii. Interpret the maximum differential settlement and change in slope along the traverse for comparison with the investigation values.

        iii. Where investigation levels are exceeded check if these relate to the activities or land use nominated in Table 7.

        iv. If investigation levels are exceeded in the relevant areas, carry out further site specific assessment using conventional survey methods over a period of six months to assess the significance of the impact. Impact on structures within populated areas are to be based upon evaluation of structures considered to be the most sensitive to subsidence.

        v. Where adverse impacts are demonstrated based upon the threshold values nominated in Section 6 mitigation measures are to be employed.

7.6. Trigger threshold exceedance response actions

Approval condition 13(g) requires the development and implementation of an action plan to address identified subsidence impacts within 90 calendar days of a trigger threshold being exceeded.

Trigger threshold exceedance response actions are dependent on the evaluation of the cause of the exceedance, and if the potential for detrimental impacts is confirmed, a Trigger Threshold Exceedance Action Plan will be developed and implemented within 90 days to minimise impact.

The action plan will:

- Identify potential mitigation measures and response actions.
- Select suitable response actions, tailored to site-specific conditions, impact cause, timing and magnitude.
- Evaluate time frames within which impacts would be expected to occur and within which mitigation actions would need to be successful.
- Schedule mitigation implementation, with consideration for the anticipated timing of the indicated impact.
- Contain procedures to evaluate the effectiveness of the mitigation measures.

Where an action plan is not developed and implemented within 90 calendar days of the identified trigger threshold exceedance this represents a non-compliance and the Minister will be notified.

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[1] Accumulated vertical movement of less than 100 mm is considered unlikely to result in breach of the nominated thresholds.

This process is illustrated in Figure 29.

Assessment of subsidence for SGP alone

Within the SGP predicted subsidence due to SGP alone is not predicted to exceed 100 mm except within Drainage Area DA11. The steepest subsidence gradient is assessed to occur under high assessment prediction near the western margin of DA11. The predicted gradient is approximately 50 mm over 7 km. This is well below the adopted investigation levels for protection of buildings, road, railways, pipelines of 1 in 1000 and for protection of field irrigation systems and the flow in the Condamine River of 25 mm/km.

Assessment of subsidence for Cumulative Case

An assessment of the predicted subsidence due to SGP and CSG extraction by other proponents is assessed as having a maximum value of 120 mm within DA11. The steepest predicted gradient is at the western margin of Drainage Area DA5 of 50 mm over 6 km. This is well below the adopted investigation thresholds for protection of buildings, road, railways, pipelines of 1 in 1000 and for protection of field irrigation systems of 0.3 m/km and the flow in the Condamine River of 25 mm/km.

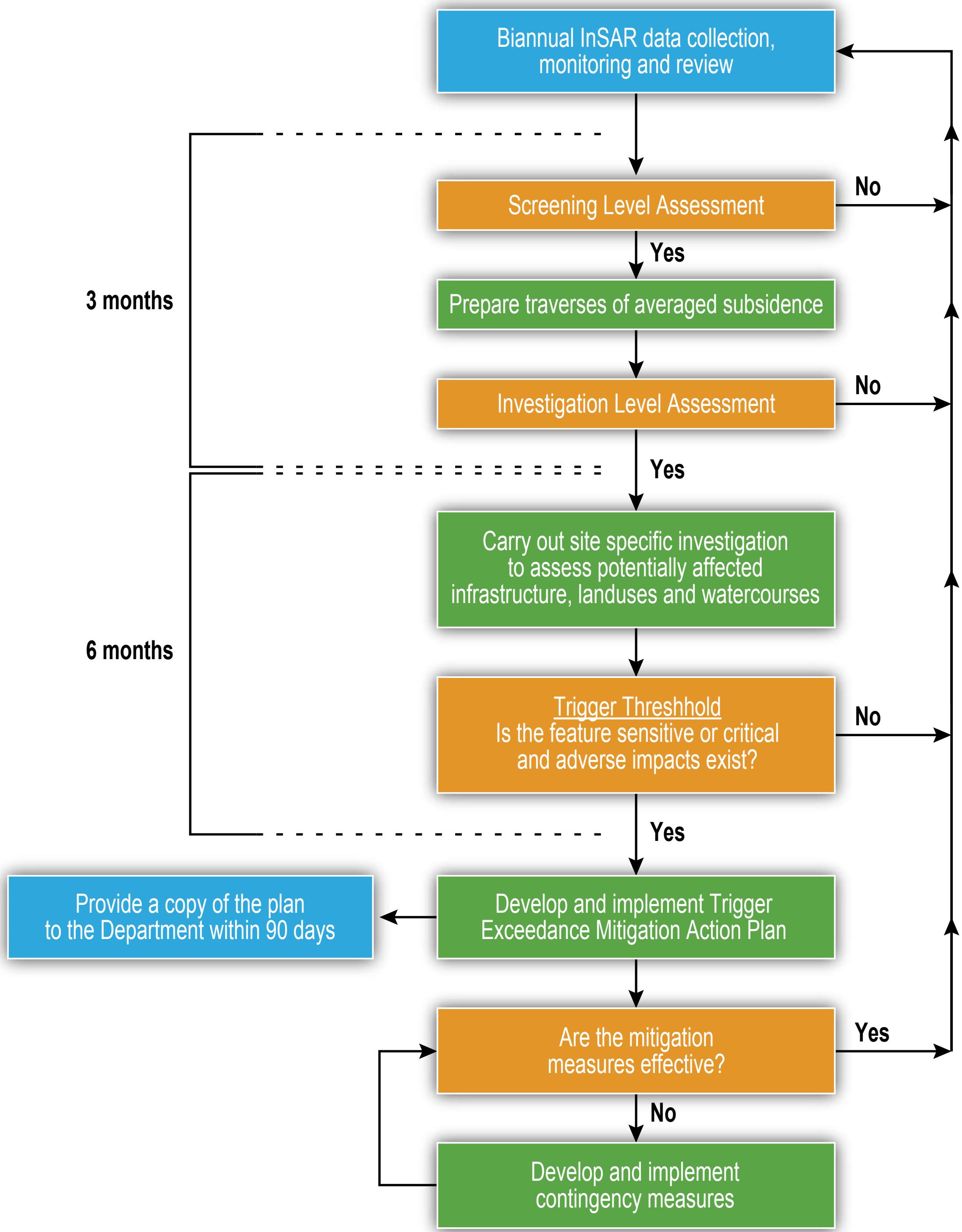
For the impacts assessed in Section 6 the nominated investigation levels wold not be breached.

7.7. Uncertainties

While the predicted subsidence would not breach the adopted investigation levels it must be recognised that the assessment is based on limited data and contains significant uncertainty. The assessment is sensitive to the adopted values of:

- Modulus of the coal measure rocks.
- Volume loss of coal associated with removal of coal seam gas.
- Predicted groundwater drawdown.

It is recommended that the subsidence assessment be reviewed as groundwater monitoring becomes available for the initial development of the SGP and as further assessments of groundwater drawdown are developed.



coffey A TETRA TECH COMPANY	Date: 19.09.2018 Project: 754-ENAUABTF20484AA File Name: 20484AA_M05_F029_GRA	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Subsidence monitoring assessment flow chart	Figure No: 29

8. Monitoring Program Development

The current monitoring program provides groundwater level monitoring and monitoring of subsidence using InSAR technology. The interpretation of subsidence responses and prediction of future subsidence, requires good quality groundwater level monitoring over the depth of the affected ground, and collocated ground movement measurements. The review described in the Altamira report encountered the following difficulties:

- Groundwater level monitoring did not capture initial response within a key formation
- Water production records relevant to particular areas were not readily accessible
- Gas yield results relevant to particular areas were not accessible.

While the InSAR technology provides high resolution and wide coverage, it is recommended that alternative geodetic measurement of ground movement are taken at selected locations to provide a ground-truthing check on the InSAR results. It is recommended that locations for geotechnical ground movement monitoring are collocated with groundwater monitoring bores which provide coverage of the full ground profile potentially influenced by Arrow SGP operations. It is recommended that these instrumented sites are located at the centre of selected Arrow SGP well fields and are installed to provide baseline information prior to the initiation of production pumping in the area.

Measures which can be of value in assessment of subsidence impacts include:

- Tiltmeters can measure small changes ground slope.
- Survey using traditional or GPS methods.
- Extensometers.
- Condition assessments of structures at risk.

Of these methods use of extensometers and survey to ground truth the results of InSAR monitoring are considered most useful. Extensometers allow identification of the horizons in the ground profile contributing to surface settlement. It is considered that tiltmeters would be subject to shallow influences unrepresentative of movements originating from Arrow SGP activities.

Figure 30 sets out locations recommended for establishment of subsidence monitoring stations. These stations would comprise:

- Groundwater monitoring at multiple locations including within, above and below the Walloon Coal Measures.
- Geodetic ground movement (vertical) monitoring monument (installed to avoid shrink swell movement of the upper soils).

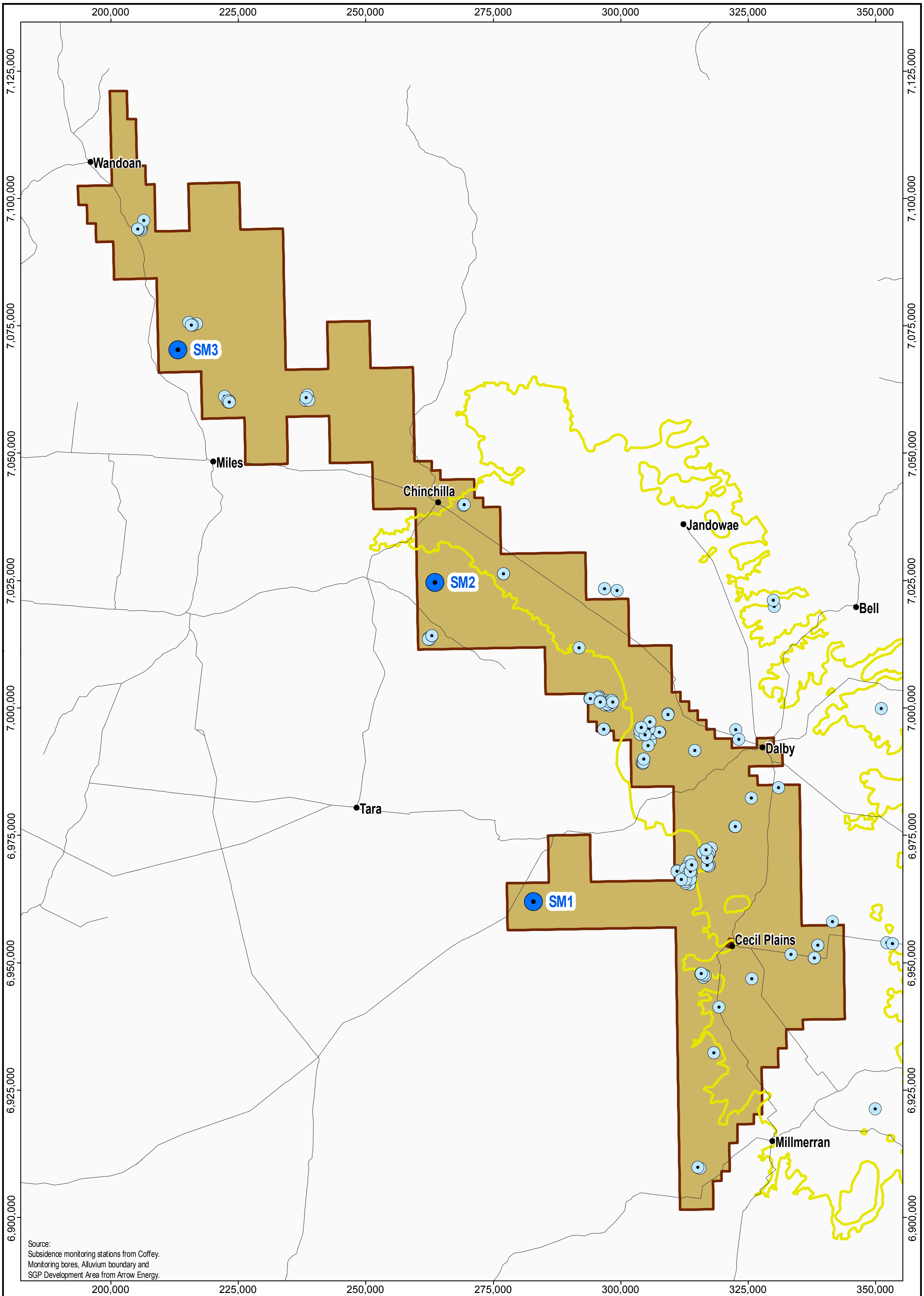
In addition, at one station (SM1 in Drainage Area 11) an extensometer array is recommended to separately record compression within the Juandah Coal Measures and the Taroom Coal Measures.

8.1. Ongoing monitoring

Measurement of settlement and extensometers is proposed on an initially monthly frequency. Ongoing reviews of the baseline established will determine when changeover to monitoring commences on a quarterly basis (with associated continuous groundwater level measurement using data loggers).

A program for ongoing monitoring will be implemented to confirm that subsidence is within the predicted behaviour of the strata over time. Where deviation from predictions is observed, revised predictions will be prepared and assessment of the significance of the predictions made.

InSAR data updates will be received on a 6-monthly basis. Review of the updated InSAR data will be undertaken within 3 months of the data being received.



Source:
Subsidence monitoring stations from Coffey.
Monitoring bores, Alluvium boundary and
SGP Development Area from Arrow Energy.

coffey A TETRA TECH COMPANY	Date: 24.03.2017 Project: ENAUABTF20484AA File Name: 20484AA_GT1_F002_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Recommended subsidence monitoring stations	Figure No: 30

MXD Reference: 20484AA_GT1_GIS002_v1_1 AI Reference: 20484AA_GT1_GRA001.ai_1

9. Reporting recommendations

Monitoring of subsidence and groundwater level variation based on existing data indicates that settlement is gradual and accompanies groundwater level drawdown. The changes develop gradually over months and years, and as a result it is recommended that a review of subsidence is carried out on an annual basis. It is recommended that surveillance reports are prepared annually providing diagnostic plots of drawdown and ground movement for each of the subsidence monitoring stations. Annual review and reporting is recommended covering:

- Changes from the baseline condition.
- Incremental changes in groundwater level and ground movement over the previous twelve months.
- Review of ground movement monitoring against adopted trigger level.
- Review of trigger levels.
- Consideration of complaints in relation to ground movement.
- Recommendations for actions in response to breaches of trigger levels.
- Recommendations in relation to the future frequency of monitoring, repair or investigation of instruments producing inconsistent results, revision of trigger levels.

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